An investigation of the factors associated with running-related injuries among recreational runners

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A thesis submitted for the award of Doctor of Philosophy

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Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Doctor of Philosophy is entirely my own work, and that I have exercised reasonable care to ensure that the work is original, and does not to the best of my knowledge breach any law of copyright, and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work

Signed: Sarah Dillon Student ID:17213915 Date: 13/06/2022

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List of Abbreviations

Abbreviation	Abbreviated Term
RRI	Running related injuries
GRF	Ground reaction force
TL	Time loss
PR	Performance related
MA	Medical attention
N/A	Not applicable
N/R	Not reported
INJ	Injured group
UN	Uninjured group
CON	Control
TSI	Tibial stress injury
PFPS	Patellofemoral pain syndrome
ITBS	Iliotibial band syndrome
CI	Confidence interval;
n	Number in the population
MTSS	Medial tibial stress syndrome
PT	Patellar tendinosis
TSF	Tibial stress injury
PFJP	Patellofemoral joint pain
HR	Hazard ratio
BMI	Body mass index
OR	Odds ratio
Hx	history
NS	Not specified
ERLP	Exercise related leg pain
SF	Stress fracture
AT	Achilles tendon
FPI	Foot Posture Index
RR	Risk ratio
AKP	Anterior knee pain
ROM	Range of motion
DF	dorsiflexion
PF	Plantarflexion
ER	External rotation
IR	Internal rotation
T	Treadmill
O	Overground
VIP	Vertical impact peak
SD	Standard deviation
VAP	Vertical active peak
VALR	Vertical active peak
VILR	Vertical impact peak
vGRF	Vertical ground reaction force
PPA	Peak positive acceleration
3D	3 dimensional
SA	Symmetry angle
FCA	Foot contact angle

FSP	Foot strike pattern
FS	Foot strike
No.	Number
2D	2 dimensional
BW	Body weight
I RFS	Instructed rear foot strike
I FFs	Instructed forefoot strike
N FFS	Natural forefoot strike
N RFS	Natural rearfoot strike
NF	Navicular fracture

List of Publications

<u>Journal Articles</u>

Published

Dillon, S., Burke, A., O'Connor, S., Whyte, E., Gore, S., Moran, K., 2021. Do injury-resistant runners have distinct differences in clinical measures compared with recently injured runners? Medicine and Science in Sport and Exercise, 53 (9).

Burke, A., **Dillon, S**., O'Connor, S., Whyte, E., Gore, S., Moran, K., 2021. Risk factors for injuries in runners; A systematic review of foot strike technique and its classification at impact. Orthopaedic Journal of Sports Medicine, 9 (9).

Under Review

Dillon, S., Burke, A., O'Connor, S., Whyte, E., Gore, S., Moran, K., 2022. Are peak and rate of acceleration during treadmill running representative of those produced overground? Gait and Posture (Awaiting decision).

Dillon, S., Burke, A., O'Connor, S., Whyte, E., Gore, S., Moran, K., 2022. Are there differences in impact accelerations between recently injured and injury resistant runners? Sports Biomechanics (Awaiting decision).

Burke, A., **Dillon, S.,** O'Connor, S., Whyte, E., Gore, S., Moran, K., 2022. Relative and absolute reliability of shank and sacral impact accelerations over a short- and long-term time frame. Sports Biomechanics (Revisions submitted).

Burke, A., **Dillon, S.,** O'Connor, S., Whyte, E., Gore, S., Moran, K., 2022. Comparison of impact accelerations between injury-resistant and recently injured recreational runners. Plos One (Revisions submitted).

<u>Conference Proceedings</u>

Oral Presentations

Dillon, S., Whyte, E., Burke, A., O'Connor, S., Gore, S. and Moran, K., 2019. A prospective investigation of the association between isometric muscle strength and running-related Injury among novice and recreational runners. ECSS Congress Prague, Czech Republic.

Burke, A., **Dillon, S.,** O'Connor, S., Whyte, E., Gore, S., Moran, K., 2019*. "A novel comparison of impact accelerations between prospectively injured runners and runners with and without a history of injury". IOC World Conference on Prevention of Injury & Illness in Sport. Monaco. *Re-scheduled due to Covid-19.

Burke, A., O'Connor, S., Whyte, E., **Dillon, S.,** Gore, S. and Moran, K., 2019. “Impact accelerations in recreational runners with and without a history of injury. ECSS Congress Prague, Czech Republic.

Burke, A., O'Connor, S., Whyte, E., **Dillon, S**., Gore, S., Moran, K., 2019. An Injury Profile of Irish Recreational Runners. All Ireland Postgraduate Conference in Sport Science, Physical Activity and Physical Education, Athlone, Ireland.

Dillon, S., Whyte, E., Burke, A., O'Connor, S., Gore, S. and Moran, K., 2019. The differences in isometric muscle strength between recreational runners with and without a history of running-related injury. All Ireland Postgraduate Conference in Sport Science, Physical Activity and Physical Education. Athlone, Ireland.

Burke, A., O'Connor, S., Whyte, E., **Dillon, S.,** Gore, S., Moran, K., 2018. The development of the RISC prospective injury surveillance research project. Faculty of Sports and Exercise Participation, Optimising Health for Sport and Exercise Participation. Limerick, Ireland.

Poster Presentations

Dillon, S., Whyte, E., Burke, A., O'Connor, S., Gore, S. and Moran, K., 2019. Are lower limb isometric muscle torque and dorsiflexion range of motion associated with calf and Achilles tendon injuries among runners? A prospective study. IOC World Conference on Prevention of Injury and Illness in Sport. Monaco.

Dillon, S., Whyte, E., Burke, A., O'Connor, S., Gore, S. and Moran, K., 2019. Is Navicular Drop Associated with Running Related Injuries? Insight Student Conference, Galway, Ireland.

Burke, A., O'Connor, S., Whyte, E., **Dillon, S.,** Gore, S., Moran, K., 2018. Running related injuries in Irish runners: Return to Play. Spring Study Day, Royal College of Surgeons, Dublin, Ireland.

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Abstract

Sarah Dillon- An investigation of the factors associated with running-related injuries among recreational runners

Background:

Running-related injuries (RRIs) occur when load exceeds tissue strength and therefore, purportedly result from a complex interaction of factors. However, research regarding factors associated with RRI remains inconclusive. Very few prospective, multifactorial, large-scale studies exist exploring general or specific RRIs, with even fewer examining segmental loading and running technique throughout the body. Additionally, although runners who have never been injured or have not been recently injured may have distinctive factors explaining their resistance to (re-)injury, this has seldom been examined.

Aims:

Primary aim: To prospectively investigate factors associated with general and specific RRIs using a multifactorial, large-scale approach.

Secondary aim: To retrospectively investigate differences in clinical and loading factors between injury-resistant and recently injured runners.

Methods:

This thesis incorporates work from four research questions (Chapters 3, 4, 5, 6) and one methodological chapter (Section 8.3). A baseline assessment of 274 recreational runners examined: (1) loading (via impact accelerations), (2) running technique (via motion analysis) and (3) clinical measures of: strength, range of motion and foot alignment, (4) demographics and injury and training history. RRIs were tracked for one year.

Results:

There was a 1-year incidence of general RRI of 52%, and 14% for calf-complex injury. Prospectively, running technique and foot alignment were associated with both general (Chapter 5) and calf-complex injuries (Chapter 6). Some factors were injury-specific, including running pace and sagittal plane motion. Overall, there was a limited potential identified for the use of any measure in RRI screening. Retrospectively, recently injured runners displayed greater lower back loading compared to those injured >2 years ago and strength differences (plantar flexion and hip abduction) were noted among runners with and without a history of RRI (Chapters 3,4).

Conclusion:

This thesis adds important insights into potential factors that are associated with RRIs. These may form the basis of intervention programmes.

Chapter 1: Introduction to Thesis

1.1. Introduction

Running is an extremely popular activity, with participation levels of 10% within the Irish population (Sports Ireland, 2021). Positive effects of running have been reported on a number of physical (Lee *et al.,* 2017) and mental (McDowell *et al.*, 2018) health-related factors. Unfortunately, despite the non-contact and typically submaximal nature of running, there is a high incidence of running related injuries (RRIs), with estimated percentage incidences ranging between 19% to 79% (Van Gent *et al.*, 2007). These injuries impose a burden at an economic and personal level, with RRIs being associated with increased healthcare costs (Hespanhol-Junior *et al.*, 2016), as well as psychological distress (Chan and Grossman, 2011) and curtailment of the positive physical health effects gained from involvement. Therefore, in order to address these issues, it is essential to identify the underlying causes of injury (Meeuwisse *et al.*, 2007a).

RRIs are considered to be multifactorial in nature (Hein *et al.*, 2014; Messier *et al.*, 2018), with various proposed models pertaining to the complex interaction of internal and external factors which precipitate injury (van Mechelen, Hlobil and Kemper, 1992; Bahr and Krosshaug, 2005; McIntosh, 2005; Buist *et al.*, 2007; Meeuwisse *et al.*, 2007a; Bertelsen *et al.*, 2017). Based on a biomechanical approach to injury, RRIs are due to high forces relative to tissue strength (Hreljac, 2004; Hespanhol Junior, van Mechelen and Verhagen, 2017; Edwards, 2018). In consequence, a number of factors have been proposed to be associated with RRIs, including: (1) loading (Hreljac, 2004), (2) running technique (Azevedo *et al.*, 2009; Hesar *et al.*, 2009) and (3) clinical measures, such as strength (Esculier, Roy and Bouyer, 2015; Neal *et al.*, 2019), functional foot alignment (Neal *et al.*, 2014; Pérez-Morcillo *et al.*, 2019) and range of motion (Becker *et al.*, 2017). Although previous studies have explored these factors, findings thus far are inconsistent and inconclusive. A key limitation is the lack of large-scale prospective studies examining a number factors associated with RRIs within one study. To date, one large-scale prospective study (Messier *et al.*, 2018) has examined all of the above components among recreational runners. Therefore, further investigation is required. The importance and manner in which each of the above factors are addressed is outlined below.

In light of the prominent role of excessive loading in causing injury, whole-body loading assessed via ground reaction force (GRF) is commonly examined (Van Der Worp, Vrielink and Bredeweg, 2016); however, there is conflicting evidence relating GRF and RRIs (Zadpoor and Nikooyan, 2011; Van Der Worp, Vrielink and Bredeweg, 2016). These mixed findings may, in part, be explained by the focus of assessment on whole-body level loading, rather than examining discrete segment-specific loading. A potentially promising way to investigate segment-specific loading is to use small wearable accelerometers to measure impact accelerations (Sheerin, Reid and Besier, 2019), with some studies finding associations between segment loading and RRIs (Milner *et al.*, 2006b; Zifchock, Davis and Hamill, 2006). However, this method has only been employed in one prospective study (Winter *et al.*, 2020) and four retrospective studies (Milner *et al.*, 2006; Zifchock, Davis and Hamill, 2006; Zifchock *et al.*, 2008; Schütte *et al.*, 2018). Furthermore, when accelerometery has been used, it is commonly measured at the lower leg, despite RRIs also occurring at the hip and lower back (Buist, Bredeweg, Lemmink, *et al.*, 2010). To date, only two studies investigating RRIs have examined impact accelerations at the lower back (Schütte *et al.*, 2018; Winter *et al.*, 2020). Finally, the rate of impact acceleration does not appear to have been investigated in relation to RRIs, despite rate of GRF loading being more related to RRIs than peak GRF (Ferber *et al.*, 2002; Milner *et al.*, 2006b; Ribeiro *et al.*, 2015; Bigouette *et al.*, 2016; Davis, Bowser and Mullineaux, 2016).

Running technique may also contribute to the development of RRIs (Chuter and Janse de Jonge, 2012; Messier *et al.*, 2018) by affecting the magnitude and distribution of loading throughout the body (McMahon, Valiant and Frederick, 1987; Kulmala *et al.*, 2013). However, to date, much of the research into running technique and RRIs has been retrospective, with inconsistent and inconclusive findings (Milner, Hamill and Davis, 2010; Dierks *et al.*, 2011; Willy *et al.*, 2012; Bazett-Jones *et al.*, 2013; Esculier, Roy and Bouyer, 2015; Bramah *et al.*, 2018; Luz *et al.*, 2018) due to the uncertainty in identifying whether differences are causative of or as a result of injury. Moreover, a lack of consideration of pelvis and trunk motion exists, despite the fact that movement of these segments is associated with changes in distal kinematics (Schache *et al.*, 1999, 2005) and loading (Simic *et al.*, 2011; Teng and Powers, 2014)

Clinical measures are frequently employed to screen for injury risk and as markers of readiness to return to play (Creighton *et al.*, 2010). Among the most commonly utilised clinical measures are: range of motion (Hubbard, Carpenter and Cordova, 2009; Jungmalm *et al.*, 2020), foot position (Buist, Bredeweg, Lemmink, *et al.*, 2010; Yagi, Muneta and Sekiya, 2013) and muscle strength (Esculier, Roy and Bouyer, 2015; Becker, Nakajima and Wu, 2018). Extremes of these factors may lead to alterations in technique and loading, which subsequently cause injury (Dierks *et al.*, 2008; Ferber *et al.*, 2009; Loudon and Reiman, 2012; Foch, 2013; Fukuchi *et al.*, 2013; Baggaley *et al.*, 2015). Understanding the association between clinical measures and RRIs may be of particular interest because they are modifiable and easy to assess, although evidence surrounding the relationships is largely conflicting (Peterson *et al.*, 2022).

As indicated above, the landscape of RRI research is largely dominated by retrospective study designs. However, a well-recognised limitation of retrospective studies is the difficulty in ascertaining whether the relationship of measured factors is causative or as a result of injury. As such, prospective studies are superior in examining the underlying causes of RRIs. However, they are expensive, time consuming and can present issues with recruitment and loss to follow up, reducing the sample size. To date, it appears that few studies have directly compared a retrospective to a prospective approach in order to determine their appropriateness. This information would be useful in defining how much credence should be placed on findings from retrospective research. This may also enable distinction between possible causes and consequences of injuries.

With respect to retrospective research, the majority of the available research surrounding clinical and biomechanical factors relating to injury involves a comparison of currently injured and uninjured participants (Dierks *et al.*, 2011; Bramah *et al.*, 2018; Johnson, Tenforde, *et al.*, 2020; Koldenhoven *et al.*, 2020). However, analyses of different groups may facilitate better understanding of the association of biomechanical factors and injury. Separation of participants into subcategories of 'never injured' versus 'previously injured' groups presents a relatively underutilised method of comparison. Very few studies have compared never injured and injured cohorts (Zifchock *et al.*, 2008; Davis, Bowser and Mullineaux, 2010), despite differences in loading being noted between these groups. This may be due to the high prevalence of injury among runners (Lun *et al.*, 2004; Vitez *et al.*, 2017), making the sourcing of a never injured sample difficult to obtain. However, it is possible that examining this group and comparing how they differ biomechanically from those who have sustained injury may give us an insight into what may make them injury resistant.

This thesis will address a number of research questions (detailed below), which aim to shed light on factors relating to RRIs.

1.2. Aims and objectives of thesis

The primary aim of this thesis is to undertake a large-scale multifactorial prospective examination of the factors associated with both *general* and *specific* RRIs among recreational runners. Among the factors included in these studies are segmental loading (via impact accelerometery), running technique (at the foot, ankle, knee, hip, pelvis and trunk), clinical measures (of strength, functional foot alignment and range of motion), and injury and training history. Notably, this thesis includes the largest study to date to examine impact accelerations and RRIs and is one of only two prospective studies to examine this. Additionally, this thesis examines kinematics at the pelvis and trunk and their association to RRIs, which has rarely been examined in large-scale prospective research studies. Furthermore, clinical measures are examined in this multifactorial approach. Increased knowledge surrounding clinical measures could help in the identification of easily measurable, clinician-friendly factors associated with RRIs. Throughout this thesis, a running related injury was classified using the consensus definition by Yamato et al. (2015, p. 377), as "any (training or competition) musculoskeletal pain in the lower limbs that causes a restriction/stoppage of running (distance, speed, duration, or training) for at least 7 days or 3 consecutive scheduled training sessions, or that requires the runner to consult a physician or other health professional". Chapter 3, 4, 5 and 6 involve the exploration of data collected during a single baseline assessment exploring multiple factors associated with running related injuries. Data were explored using both retrospective and prospective approaches.

A secondary aim of this thesis is to retrospectively explore loading and clinical measures among recently injured and injury resistant runners. This may explain the factors that contribute to (re-) injury resistance.

Objectives:

1. To prospectively investigate factors associated with general RRIs via a multifactorial approach including examinations of segmental loading, running technique and clinical measures (Chapter 5).
2. To prospectively investigate factors associated with calf-complex RRIs via a multifactorial approach, including examinations of segmental loading, running technique and clinical measures (Chapter 6).
3. To examine the effect of RRI status and sex on measures of strength, functional foot alignment, and joint motion using three distinct injury status groups: those who have recently returned from injury (injured 3 months–1 year previously), those who have acquired reinjury resistance (remained uninjured for >2 year), and those who have

never been injured (never injured). A secondary aim was to investigate whether asymmetry values would be distinctive among these groups, (Chapter 3).

4. To investigate the effect of RRI status and sex on measures of tibial and lower back impact accelerations using three distinct injury status groups: recently injured runners, runners who have acquired injury resistance and never injured runners (Chapter 4).

Additionally, Appendix C (Section 8.3) examines whether loading produced during running on treadmills is 'representative' of that produced during overground running. A secondary aim of Appendix C is to investigate if the impact accelerations measured on treadmills of different stiffness are 'representative' of each other.

2. Chapter 2: Literature Review

This review of literature is divided into three main sections. The first section examines the aetiology of running related injuries (RRIs), and the prevalence and incidence of general and specific RRIs. The lack of consensus in RRI definitions will be highlighted, which affects consistency of findings. The second section focuses on non-modifiable factors associated with RRIs, including sex, age, and previous injury history. A particular focus is on previous injury history, which is considered to be a strong risk factor for RRIs. The third section focuses on modifiable factors associated with RRIs. This is further divided into clinical measures (functional foot alignment, strength and range of motion), loading and technique. The clinical measures section highlights the inconsistencies in evidence in relation to clinical measures, hampered by limited large-scale prospective studies. The loading section indicates the need for more research investigating the association between loading at individual body segments using impact accelerometers, rather than whole-body vertical ground reaction forces. Finally, the technique section highlights the limited number of prospective studies examining kinematics in relation to general RRIs, in particular the very limited investigation of technique at the trunk and pelvis and its association to RRIs.

A scoping review was first performed to identify key gaps and trends in the research with regard to factors associated with RRIs, as well as to identify injury aetiology and prevention frameworks. Having identified the main intrinsic and extrinsic factors associated with RRIs, the literature was then systematically searched via the major databases (MEDLINE, PubMed, SPORTDiscus, Scopus, and Web of Science) and were reviewed by their abstracts for inclusion in the literature review. The full text was reviewed where necessary. Literature examining prospective or retrospective running injury (specific or general) and the topics identified within the scoping review were then included in this review. In relation to the discussion of modifiable and non-modifiable risk factors for injury, prospective research was primarily presented. If very little or none existed, retrospective research was also presented. Where possible, this review of literature includes a qualitative synthesis of studies examining similar risk factors associated with RRIs. These are described in line with categories for literature appraisal outlined by (Ceyssens *et al.*, 2019):

- *"Strong evidence: Consistent findings among three or more studies, including a minimum of two high-quality studies.*
- *Moderate evidence: Consistent findings among two or more studies, including at least one high-quality study.*
- *Limited evidence: Findings from at least one high quality study or two low- or moderate-quality studies.*
- *Very limited evidence: Findings from one low- or moderate quality study.*
- *Inconsistent evidence: Inconsistent findings among multiple studies (e.g., one or multiple studies reported a significant result, while one or multiple studies reported no significant result)."*

This literature review is intended for online publication in the form of a book or narrative review.

2.1. The epidemiology and aetiology of running related injuries

Epidemiological studies are broadly divided into experimental and observational designs (Munnangi and Boktor, 2019). Experimental designs explore the effects of an intervention by constructing control and intervention groups, for example within randomised control trials. The incidence and prevalence of injury is predominantly explored using observation studies, in which no intervention is assigned, and injuries are noted using retrospective, prospective or current observations. This approach may also enable the identification of factors associated with injury. Within the observational study design type, lies a number of further subdivisions. Case control studies take a retrospective approach by examining the association between factors and outcomes between individuals with and without an exposure. Although cost-effective and efficient, these studies are subject to recall bias, an issue previously noted in injury research (Gabbe and Finch, 1999). However, this approach may have a role when examining the etiology of rare outcomes (Munnangi and Boktor, 2019). Another approach is a cross sectional study design, which examines the prevalence of a disease at point in time. Therefore, cross sectional studies are a cost-effective method of data collection, however the single point in time means that this study cannot identity a cause-effect association. Finally, cohort studies may be used in injury epidemiology research for the classification of individuals with respect to their exposure to injury. Cohort studies may take a prospective approach, which enables the calculation of relative risk a potential outcome of interest (Ranganathan, Aggarwal and Pramesh, 2015). Odds ratio may also be used and can also be employed with a retrospective design. Whilst both of these ratios indicate the association between an exposure and an outcome, risk ratio represents the ratio of risk of injury in one group compared to the risk of injury in the other group, with a risk ratio of 1 indicating that there is no difference in risk between groups. Whereas odds ratio of odds of an event in one group versus the odds of the event in the other group. These values should not be interchanged, especially when the outcome is not rare.

In light of the high prevalence and incidence of running related injuries (RRI), in addition to their detrimental effects on health, prevention has been at the forefront of running injury research. A number of models have been proposed to describe methods of developing injury prevention protocols (van Mechelen, Hlobil and Kemper, 1992; Pless and Hagel, 2005; Van Tiggelen *et al.*, 2008). Common to all of these models is the need to identify the underlying causes of injury in order to mitigate injury risks (e.g. Step 2 of Van Mechelen's model, Figure 1).

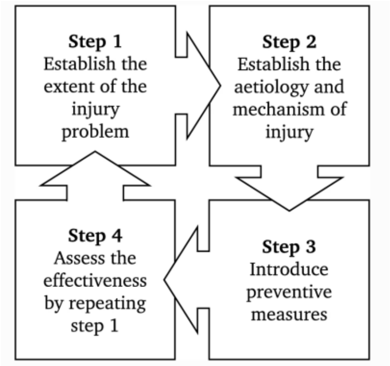

Figure 1 The 'Sequence of Prevention' Model proposed by Van Mechelen (1992).

The original *Injury Prevention Model*, which acts as the basis for many of these models, describes three types of injury prevention- primary, secondary and tertiary, referring respectively to the prevention of the "event" or injury in its entirety, the detection and minimising of the "event" in its early stages and the management post-injury, including rehabilitation (Pless and Hagel, 2005). Perhaps the most commonly cited model of injury prevention is that outlined by Van Mechelen and colleagues (1992). This four-step model outlines a 'Sequence of Prevention' in which the first step is to establish the incidence and severity of the injury, the second is to establish the aetiology and mechanisms of injury, the third is introducing preventative measures and the final step is assessing the effectiveness of these interventions by repeating an assessment of the incidence and severity of the problem (van Mechelen, Hlobil and Kemper, 1992). The second step in Van Mechelen's Sequence of Prevention model is the investigation of the aetiology and mechanism of injury. Previous authors have also described models exploring the development of injury, highlighting the complexity of interaction of risk factors for injury. One such prominent model that is commonly referred to in the literature is the recursive dynamic model described by Meeuwisse and colleagues (2007). Underpinning this model is the idea that athletes possess intrinsic risk factors for injury which interact with extrinsic risk factors as part of sport participation, resulting in injury. These risk factors are dynamic and may change as the athlete participates, in both adaptive and maladaptive manners. Therefore, it is suggested that risk factors should be continually assessed. This model also proposes that the end point of the sports injury model is not always finite (complete stoppage of participation) and therefore, the intrinsic and extrinsic risk factors may change following injury.

In recent years, the Complex Systems Approach to sports injury has also been developed, which proposes that injuries should be examined through a "lens of complexity" (Bittencourt *et al.*, 2016). This method criticises reductionist approaches to injury such as the assumption of the existence of a simple cause and effect relationship between a risk factor and an injury and instead proposes that researchers and clinicians examine patterns of the interaction of a number of factors (risk profiles) that may culminate in injury (Bittencourt *et al.*, 2016). This model of injury aetiology describes the need to consider the non-linearity of the development of sports injuries (i.e. the exposure or input required to contribute to an injury is uncertain). This approach has been examined in a very limited capacity in the running research domain (Hulme *et al.*, 2017; Hulme *et al.*, 2019), however, it could prove relevant for clinicians and researchers alike.

Perhaps the most detailed model of injury, specific to running, is that of Bertelsen and colleagues (2017). These authors identify a number of risk factors, which primarily; (1) capture the ability of tissue to withstand load and (2) capture the magnitude and distribution of loading on the tissue (Figure 2). A central principle of their model is that load in excess of tissue tolerance, in the presence of inadequate recovery, causes injury. These risk factors take many forms. For example, the ability of tissue to withstand load may be affected by factors such as sex, previous injury history and age and the distribution and magnitude of load may be affected by the forces at impact and running technique. Therefore, examining factors that capture tissue strength and loading is of utmost importance in RRI research. Therefore, this is a primary focus of the following literature review,

However, before examining potential risk factors for RRIs, it is first important to examine the extent of RRIs, including their prevalence, incidence and injury burden, as outlined in Van Mechelen's model (van Mechelen, Hlobil and Kemper, 1992). This is addressed in the following section.

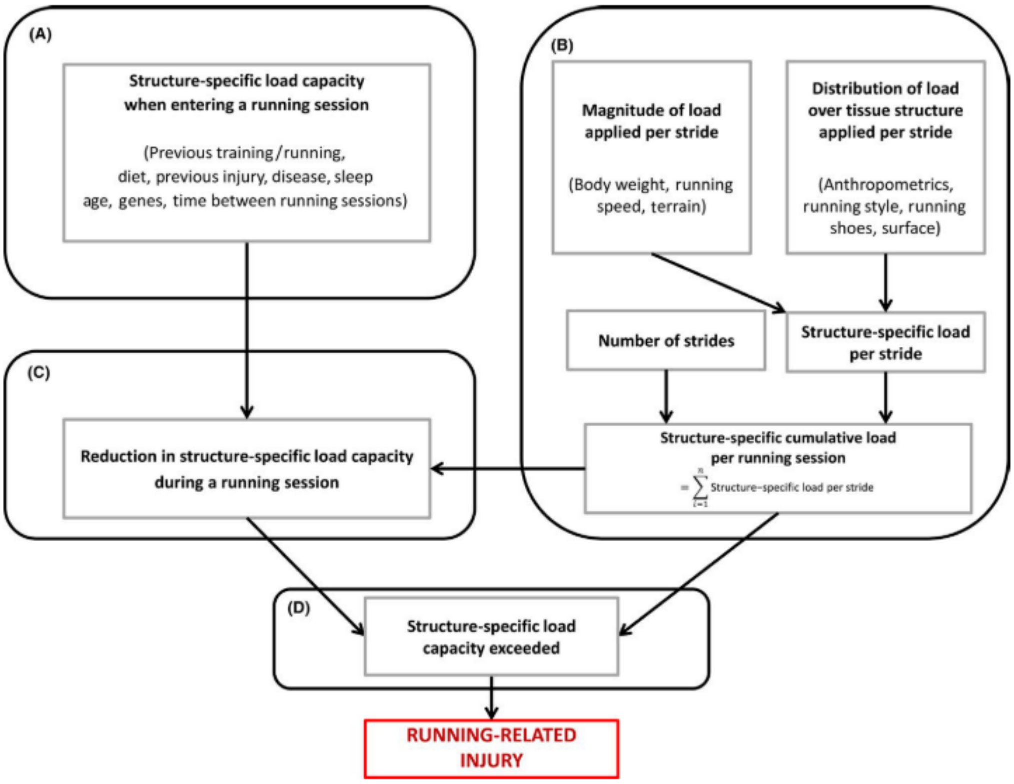

Figure 2 A framework for the etiology of running- related injuries (Bertelsen *et al.*, 2017).

2.1.1.Incidence and prevalence of RRIs

Prevalence is the proportion of individuals who report an injury/disease over a specific period of time or at a specific time point, whereas incidence captures the occurrence of *new* reports of injury/disease over a specific period of time (Centers for Disease Control and Prevention, 2012).

RRI prevalence among recreational runners has been examined in five retrospective studies, with values ranging between 19% (injuries in the past year) (Cahanin *et al.*, 2019) to 92% (lifetime prevalence) (Lun *et al.*, 2004) (Table 1), with a recent systematic review finding an overall prevalence of 44.6% ± 18.4% (Kakouris, Yener and Fong, 2021).

Table 1 Studies investigating the prevalence and incidence of running related injuries among recreational runners.

Study	n	Population	Type of definition	Tracking Period	Surveillance and diagnosis method	Injury Prevalence	Injury Incidence
Prospective							
Di Caprio *et al.*, 2010	166	86♂, 80♀ INJ: 98; CON: 68	TL	5 years	N/R	N/R	59%
Kemler *et al.*, 2018	3215	1931♀, 542690♂ INJ: 416	Unclear	4 years	Telephone or online	N/R	Injury incidence per 1000 hours: 4.24 (4.11–4.37)
Messier *et al.*, 2018	300	INJ: 145♀, 54♂, CON: 63♀, 38♂	PR/TL	2 years	Bi-weekly email RRI consultation	72% reported lifetime history of injury	2-year injury incidence proportion: Overall: 66% ♂: 62% ♀: 73%
Davis, Bowser and Mullineaux, 2016	249	INJ: 144♀, CON: 105♀	MA	2 years	Monthly training log RRI consultation	N/R	58%
Jakobsen *et al.*, 1994	20	18♂, 2♀ INJ: 13, CON: 7	TL	1 year	Weekly training log Self-documented RRI	N/R	76% Injury incidence per 1000 hours: 6.9 (Training) 62.5 (Race)
Desai *et al.*, 2021	224	135♂, 89♀ INJ: 75; CON: 149	TL/PR/MA	1 year	Self-reported RRI Offered clinical assessment	N/R	Cumulative 1-year incidence proportion Overall: 45.9, $CI_{95\%}$= 38.4, 54.2 ♂: 45.8, $CI_{95\%}$= 36.4, 56.5 ♀: 46.0, $CI_{95\%}$= 34.3, 59.5
Lun *et al.*, 2004	87	INJ: 35♂; 34♀; CON: 18	PR/TL	6 months	Monthly training log Self-documented RRI	92% reported lifetime history of injury	Overall: ♂: 79% ♀: 79%
Mulvad *et al.*, 2018	839	INJ: 30♂, 82♀, CON: 717	TL/PR	6 months	Weekly injury questionnaire Clinical assessment	N/R	32%
Hendricks and Phillips, 2013	50	INJ: 32♂, 14♀ CON: 2♂, 2♀	TL/MA	4 months	Weekly visit to club RRI consultation	N/R	32%
Theisen *et al.*, 2014	247	136♂, 111♀; INJ: 69, CON:178	PR	5 months	Weekly training log Self-documented RRI	N/R	28%
Hespanhol Junior, Oliveira Pena Costa and Dias Lopes, 2013	191	INJ: 49♂, 11♀ CON: 92♂, 39♀	TL	3 months	Bi-monthly survey Self-documented RRI	N/R	31% ♂: 35% ♀:18% 10.0 per 1,000 hours of running
Taunton *et al.*, 2003	844	205♂, 634♀ INJ: 249, CON: 639	TL/PR	13 weeks	Monthly survey Self-documented RRI	N/R	30%
Hespanhol Junior *et al.*, 2016	89	INJ: 38♂, 11♀; CON: 30♂, 10♀	TL	3 months	Bi-monthly survey Self-documented RRI	N/R	27% 7.7 per 1,000 hours of running
Van Der Worp *et al.*, 2016	417	INJ: 93♀, CON: 324♀	TL	3 months	Monthly email Self-documented RRI	N/R	26%
Ogwumike and Adeniyi, 2013	920	INJ: 129♂, 24♀;	N/R	2 events	RRI consultation	N/R	17%

		CON: 727♂, 296♀					
van Mechelen, 1992	32	UN: 16♂; INJ: 16♂	Unclear	1 month	Survey Self-documented RRI	N/R	16% (Training) 17% (Race)N
Van Mechelen *et al.*, 1993	167	INJ: 10♂; CON: 147♂	TL/PR/MA	4 months	Monthly training log RRI consultation	N/R	14% 5.2 per 1,000 hours of running
Malisoux *et al.*, 2015	517	336♂, 181♀ INJ: 157; CON: 350	TL	9 months	TIPPS and follow up phone call	N/R	32% 6.68 per 1,000 hours of running
Malisoux *et al.*, 2015	264	195♂, 69♀ INJ: 87, CON: 177	TL	22 weeks	TIPPS and follow up phone call	N/R	33% 7.64 per 1,000 hours of running
Retrospective							
Lopes *et al.*, 2011	1049	796♂, 253♀ INJ: 227, CON: 228	Unclear	N/A	Survey	In previous year: 22%	N/A
Dallinga *et al.*, 2019	678	INJ: 142, CON: 536; 347♂, 331♀	TL	N/A	Survey Self-documented RRI	In previous year: 32%	N/A
Cahanin *et al.*, 2019	91	45♂, 55♀ INJ: 17, CON: 74	Unclear	N/A	Survey Self-documented RRI	In the previous year: 19% Lifetime prevalence was 57%	N/A

Abbreviated terms: N= number of participants, ♂= males, ♀=females, INJ= injured, CON= control, RRI= running related injury, TL= time loss, PR=performance related, N/R= not reported, MA= medical attention, N/A= not applicable, TIPPS= online injury database.

The incidence of RRIs among recreational runners has been studied in nineteen prospective studies (Table 1). Two main metrics of incidence reporting have been utilised: RRI incidence proportion in a specified tracked time period (number of injured runners during specified time period/number of runners at the start of the time period) and incidence rate per 1,000 hours of running (number of injuries/1,000 hours). Two prospective studies investigated 1 year incidence proportion among recreational runners, reporting of RRIs ranging from 46-76%, with a recent systematic review of many different types of runners (e.g. novice, recreational) reporting a range of 40.2% ± 18.8% (Kakouris, Yener and Fong, 2021). Incidence rates of 5-10 injuries per 1,000 hours of running were also identified (Table 1). Clearly, large discrepancies in prevalence, one year incidence proportion and incidence rate/1000 hours exist between studies, potentially explained by the differences in injury definitions. Injury definition is typically characterised by either time-loss from running, restriction of performance, medical attention, or by a combination of these factors. A recent systematic review has identified that injury rates among runners ranged between 3% and 85%, and tended to increase with less specific definitions (Yamato *et al.*, 2015). The impact of varying injury definitions on the reporting of injuries was also examined among novice runners undertaking a structured running programme (Kluitenberg *et al.*, 2016). This study found that using six different definitions of injury resulted in large variations in incidence (incidence proportion: between 7.5%- 58.0%, incidence per 1,000 hours: 18.7- 239.6 injuries per 1000 hours of running). This also had some effects on the time to recovery reports and pain severity values. No significant differences in anatomical locations of injuries classified under a 'day definition' or a 'week definition' were identified, however, using a time loss definition, the knee was more often relatively identified as a RRI location, whereas using a pain definition injuries at the pelvis/sacrum/buttock were captured. Therefore, where possible a consensus definition, as has been recently proposed via a Delphi study (Yamato, Saragiotto and Lopes, 2015) should be implemented in future research. However, interestingly, even this definition of injury has been criticised for its inclusion of a "medical attention" aspect to its definition, i.e. this definition specifies that a running injury is confirmed when the runner seeks medical advice and/or in the presence of time loss or restriction of running due to pain. It is argued that inclusion of medical definitions maybe very changeable based on the culture of the area in which the research takes place, leading to potential problems with the generalisability of injury incidence/prevalence reports (Yamato, Saragiotto and Lopes, 2015). Furthermore, reporting of prevalence and incidence of injuries may be affected by the runners perception of "pain" and "injury". In a study of 1049 runners participating in recreational events, 22% reported pain at the start of the race, indicating that runners may run through injury (Lopes *et al.*, 2011).

2.1.2. The location of RRIs

The location of injuries among recreational runners has been reported in 26 studies, with 81% (n = 21) of those finding the knee to be the most common location of injury (Table 2), with the remaining 24% (n = 5) of studies finding the lower leg (including calf and Achilles injuries) to be the most common location of injury. The prevailing finding that the knee was the most common location of injury was echoed in a systematic review which found that among the 10,688 injuries reported from 18,195 runners in 36* studies found that the knee (28%) and ankle-foot (26%) and shank (16%) were the most common sites of injury (Francis *et al.*, 2019).

With regard to sub-analysis by sex, six of seven studies found that the knee was the most common location of injury among both males and females (Table 2), with one study finding that the foot/ankle was the most common RRI among females, with males experiencing most injuries at the knee (Desai *et al.*, 2021). The finding that the proportion of injuries with respect to sex is largely similar is also echoed in a systematic review (Francis *et al.*, 2019) which found that the location of RRIs was most commonly at or below the knee in both men (78%) and women (75%). However, when subdividing these RRIs and examining the proportion of each, some values varied between the sexes, with the knee accounting for 40% of all injuries in women, followed by the ankle-foot (19%) and shank (16%). With respect to males, the location of RRIs were distributed more evenly between knee (31%), ankle-foot (26%) and shank (21%).

*Please note that the present literature review examined incidence and prevalence of injury among recreational runners. Francis et al. (2019) examined many types of runners.

Table 2 Most commonly reported running related injuries.

Authors	***n***	***Population***	***Location 1***		***Location 2***		***Location 3***		***Location 4***		***Location 5***	
Kemler *et al.*, 2018	3215	2093♀, 1122♂	Knee	30.5%	Lower leg	16.7%	Ankle	15.9%	Achilles tendon	8.4%	Foot/heel	8%
McKean, Manson and Stanish, 2006	2712	Masters: INJ: 466, CON: 949	Knee	20%	Foot	16%	Hamstring	12%	N/R	-	N/R	-
		Young runners INJ: 843, CON: 1876	Knee	25%	Foot	16%	Leg	11%	N/R	-	N/R	-
Mohseni *et al.*, 2019	1667	204♂, 837♀ half marathoners, 218♂, 406♀ ♂marathoners; INJ: 250, CON: 791 half marathoners	Knee	14%	Foot	12%	Toenail	9%	Other	8%	Ankle / Hip	7%
		218♂, 406♀ ♂marathoners; INJ: 187, CON: 437 marathoners	Knee	12%	Foot	9%	Hip	7%	Other	5%	Toenail/lower back/ upper leg	4%
Walter *et al.*, 1989	1281	980 ♂, 301 ♀	Knee	27%	Foot	16%	Foot	15%	Lower back	11%	Hip	9%
Lopes *et al.*, 2011	1049	796♂, 253♀ INJ: 227, CON: 228	Knee	28%	Foot/ankle	20%	Spine	13%	Hip	11%	Leg	11%
		Sub analysis: ♂	Knee	28%	Foot/ankle	20%	Spine	13%	Leg	10%	Thigh	9%
		Sub analysis: ♀	Knee	27%	Hip	16%	Foot/ankle	13%	Spine	13%	Leg	12%
Taunton *et al.*, 2003	844	205♂, 634♀; INJ: 249, CON: 639	Knee	34%	Shin	16%	Foot	14%	Ankle	10%	Achilles/Calf	9%
		Sub analysis: ♂	Knee	36%	Shin	17%	Foot	14%	Ankle	10%	Achilles/Calf	8%
		Sub analysis: ♀	Knee	32%	Shin	15%	Foot	13%	Ankle	10%	Achilles/Calf	10%
Van Middelkoop *et al.*, 2008	694	INJ: 195♂, CON: 499♂	Knee	29%	Calf	27%	Thigh	16%	N/R	-	N/R	-
Dallinga *et al.*, 2019	678	INJ: 142, CON: 536; 347♂, 331♀	Knee	22%	Lower leg	15%	Achilles	10%	N/R	-	N/R	-
Rasmussen *et al.*, 2013	662	531♂, 131♀	Knee	32%	Ankle/Foot	32%	Lower leg	18%	Thigh	6%	Lower back	4%
Buist *et al.*, 2010	629	207♂, 422♀; INJ: 163, CON: 466	Knee	31%	Lower leg	34%	Other	11%	Hip/Groin	7%	Ankle	6%
		Sub analysis: ♂	Knee	39%	Lower leg	31%	Other/ Hip/Groin	8%	Foot	6%	Ankle	5%
		Sub analysis: ♀	Knee	23%	Lower leg	36%	Other	14%	Hip/Groin	11%	Ankle	6%
Laurent Malisoux *et al.*, 2015	517	INJ: 157; CON: 350 336♂, 181♀	Lower leg	23%	Knee	22%	Thigh	21%	N/R	N/R	N/R	N/R

Messier *et al.*, 2018	300	INJ: 145♀, 54♂; CON: 63♀, 38♂	Knee	28%	Foot	21%	Hip	13%	Ankle	12%	Lower leg	12%
van Poppel *et al.*, 2014	291	181♂, 110♀ INJ: 45, CON: 158	Knee	19%	Calf	16%	Achilles tendon	N/R	-	-	N/R	-
			Knee	20%	Hip	15%	Thigh	N/R	-	-	N/R	-
		Sub analysis: ♂	Knee	17%	Achilles tendon	17%	Calf	14%	N/R	-	N/R	-
		Sub analysis: ♀	Knee	22%	Shin	14%	Calf	14%	N/R	-	N/R	-
Malisoux *et al.*, 2015	264	195 ♂, 69 ♀ INJ: 87, CON: 177	Knee	20%	Lower leg	20%	Thigh	18%	Ankle	16%	Lower back/Pelvis	10%
Theisen *et al.*, 2014	247	136♂, 111♀; INJ: 69, CON:178	Knee	25%	Lower leg	22%	Thigh	17%	Trunk	10%	Foot	10%
Desai *et al.*, 2021	224	135♂, 89♀ INJ: 75; CON: 149	Knee	27%	Achilles tendon/calf	25%	Foot/ankle	20%				
		Sub analysis: ♂	Knee	30%	Achilles Tendon/Calf	26%	Foot/ankle	17%	Hip/pelvis	7%		
		Sub analysis: ♀	Foot/ankle	24%	Achilles tendon/calf	24%	Foot/ankle	24%	Knee	20%		
Ellapen *et al.*, 2013	200	107♂, 73♀; INJ: 180, CON: 20	Knee	26%	Tibia/Fibula	22%	Lower back/Hip	16%	Thigh	14%	Ankle	10%
		Sub analysis: ♂	Knee	27%	Tibia/Fibula	20%	Thigh	16%	Lower back/Hip	15%	Ankle	12%
		Sub analysis: ♀	Knee	26%	Tibia/Fibula	23%	Lower back/Hip	16%	Foot	12%	Thigh	11%
Benca *et al.*, 2020	196	99♀, 79♂; INJ: 178, CON:18	Knee	41%	Ankle	16%	Foot	11%	Lower back	10%	Hip/pelvis	9%
		Sub analysis: ♂	Knee	41%	Ankle	15%	Calf/Achilles	12%	Lower back	11%	Hip/pelvis	7%
		Sub analysis: ♀	Knee	42%	Ankle	15%	Foot	13%	Lower back	10%	Hip/pelvis	10%
Hespanhol Junior, Oliveira Pena Costa and Dias Lopes, 2013	191	INJ: 38♂, 11♀; UN: 30♂, 10♀	Knee	19%	Foot/Toe	17%	Lower leg	14%	Lower back	14%	Thigh	14%
Van Mechelen *et al.*, 1993	167	INJ: 10♂; CON: 147♂	Knee	25%	Calf	14%	Pelvis/Groin	14%	Posterior Thigh	14%	Foot	14%
Franke, Backx and Huisstede, 2019	161	90♂, 71♀; INJ: 93, CON: 68	Lower leg	18%	Knee	16%	Hip	8%	Upper leg/hamstring	7%	Head, spine, trunk	7%

Cahanin *et al.*, 2019	91	45♂, 55♀ INJ: 17, CON: 74	Knee	29%	Ankle	24%	Buttocks	18%	Hip	12%	Foot	12%
Hespanhol Junior *et al.*, 2016	89	INJ: 38♂, 11♀; CON: 30♂, 10♀	Knee	15%	Achilles	15%	Lower back	7%	Foot	7%	Shin	7%
Mann *et al.*, 2015	88	INJ: 33♂, 11♀; CON: 33♂, 11♀	Lower leg	34%	Knee	14%	Thigh	14%	Foot	14%	Hip	7%
Winter *et al.*, 2020	76	INJ: 22♂, 17♀; CON: 23♂, 14♀	Achilles/calf complex	15%	Lower leg/ankle	15%	Hip/pelvis	15%	Hamstring	13%	Foot	8%
Hendricks and Phillips, 2013	50	INJ: 49♂, 11♀ CON: 92♂, 39♀	Calf	20%	Knee	18%	Lower back	18%	Ankle	8%	Hamstring	8%
Williams, McClay and Hamill, 2001	40	INJ: 32♂, 14♀; CON: 2♂, 2♀	Knee	23%	Foot	18%	Ankle	17%	Lower leg	16%	Back	5%

The locations of the most common (location 1) to the 5th most common (location 5) injury reported within each study, with corresponding percentages.

Abbreviated terms: N= number of participants, ♂= males, ♀=females, RRI= running related injury, N/R= not reported.

2.1.1.Common RRI diagnoses

Fourteen studies investigated injury diagnoses among recreational runners (Table 3). Of the eight studies investigating tissue type, muscle and combined muscle and tendon injuries were the most commonly injured tissues. Tendon was the most commonly injured tissue in the two remaining studies (Hespanhol Junior, de Carvalho, *et al.*, 2016; Dallinga *et al.*, 2019). Of the six studies investigating specific diagnoses, two studies identified medial tibial stress syndrome (MTSS) (Mulvad *et al.*, 2018; Napier *et al.*, 2018) and patellofemoral pain syndrome (PFPS) (Benca *et al.*, 2020; Johnson, Tenforde, *et al.*, 2020) as the most common injuries.

2.1.1.Severity of Injury

The severity of sports injuries can be categorised using six classifications: time to recovery, time lost from work, nature of injury, permanent damage and cost (van Mechelen, Hlobil and Kemper, 1992). Time to recovery is the most common of these methods reported in RRI research, with a combined mean time to recovery of 38 days among recreational runners (Bovens *et al.*, 1989; Hespanhol Junior, Pena Costa and Dias Lopes, 2013; Hespanhol Junior, de Carvalho, *et al.*, 2016; Mulvad *et al.*, 2018; Dallinga *et al.*, 2019).

Table 3 Top five most commonly reported anatomical structures and diagnoses of RRI.

Authors	***n***	***Population***	***Type 1***		***Type 2***		***Type 3***		***Type 4***		***Type 5***	
Tissue type												
Smits *et al.*, 2016	1696	364 ♂, 1332♀; INJ; 135, CON: 1561	Muscle & Tendon	50%	Not specified	30%	Joint	8%	Ligament	6%	Bone	6%
Dallinga *et al.*, 2019	678	INJ: 142, CON: 536; 347♂, 331♀	Tendon	20%	Muscle	17%	N/R	N/R	N/R	-	N/R	N/R
Malisoux *et al.*, 2015	264	195 ♂, 69 ♀; INJ: 87, CON: 177	Muscle & Tendon	68%	Capsule & Ligament	23%	Contusion	3%	N/R	N/R	N/R	N/R
Davis, Bowser and Mullineaux, 2016	249	INJ: 144♀; CON: 105♀	Muscle	23%	Tendon	19%	Fracture or Bone Trauma	19%	Tendon-bone	11%	Ligament	8%
Theisen *et al.*, 2014	247	136♂, 111♀; INJ: 69, CON:178	Muscle & Tendon	70%	Capsule & Ligament	16%	Fracture or Bone Trauma	4%	Contusion	3%	Nervous system	3%
Van Mechelen, Hlobil, H. Kemper, *et al.*, 1993	167	INJ: 10♂; CON: 147♂	Muscle	25%	Tendon	21%	Joint	21%	Tendon-muscle	18%	Tendon-bone	9%
Hespanhol Junior, Oliveira Pena Costa and Dias Lopes, 2013	191	INJ: 49♂, 11♀ CON: 92♂, 39♀	Muscle	30%	Lower back pathology	14%	Tendon	12%	Fascia	8%	Meniscus	7%
Hespanhol Junior *et al.*, 2016	89	INJ: 38♂, 11♀; UN: 30♂, 10♀	Tendon	30%	Lower back pathology	7%	Fascia	7%	Tendon-bone	7%	N/R	N/R
Specific Pathology												
Mulvad *et al.*, 2018	839	INJ: 30♂, 82♀, CON: 717	MTSS	16%	Achilles tendon pain	8%	PFPS	8%	ITBS	7%	Plantar fasciopathy	7%
Benca *et al.*, 2020	196	99♀, 79♂; INJ: 178, CON:18	PFPS	13%	ITBS	12%	PT	12%	Spinal injuries	11.2%	Ankle instability	8.4%
Johnson *et al.*, 2020	125	INJ: 25♂, 40♀; CON: 61♂, 64♀	PFPS	25%	ITBS	22%	TBSI	18%	Plantar fasciitis	18%	Achilles tendon pain	17%
Bovens *et al.*, 1989	73	58♂, 15♀; INJ: 62, CON: 11	ITBS	12%	Gluteus Medius	12%	Patellar Chondropathy	9%	MTSS	9%	Ankle Distortion	9%
Napier *et al.*, 2018	65	INJ: 22♀, CON: 33♀	MTSS	27%	ITBS	14%	Tendonitis	14%	Muscle strain	14%	Piriformis Syndrome	9%
Williams, McClay and Hamill, 2001	40	18 ♂, 22 ♀; 134 injuries	Plantar Fasciitis	10%	Patellar Tendinitis	7%	Lateral Ankle Sprain	7%	ITBS	6%	Tibial Stress Fracture	5%

Abbreviated terms: N= number of pariticpants, ♂= males, ♀=females, RRI= running related injury, N/R= not reported, PFPS= patellofemoral pain, ITBS= iliotibial band syndrome, TSF= tibial stress fracture, MTSS= medial tibial stress syndrome, PFJP= patellofemoral joint pain.

The following sections discussing non-modifiable and modifiable risk factors for RRI primarily examine prospective evidence. This was done due to the unclear cause-effect relationship of these factors to RRIs in retrospective research. Where limited prospective research exists, both prospective and retrospective studies are discussed.

2.2. Non-modifiable factors for RRIs

Identifying risk factors for injuries is instrumental in the injury prevention process (Section 2.1) Risk factors are generally termed modifiable (have the ability to be altered) and non-modifiable (do not have the ability to be altered). The following section outlines the main risk factors for injury that have been studied in previous research. Although non-modifiable factors are not amenable to change, knowledge of the association between injury and factors such as previous injury history, sex and age may allow clinicians, coaches and runners to identify who is at risk of injury and guide future management strategies.

2.2.1. The association between injury history and RRIs.

One of the most frequently examined non-modifiable factors for RRI is a history of previous injury, with two systematic reviews finding moderate to strong evidence to support its association with a greater risk of future injury (Saragiotto *et al.*, 2014; Van Der Worp *et al.*, 2015). This association has been examined in seventeen prospective studies (Table 4), with thirteen (76%) finding history of injury was associated with increased odds of general RRIs and four (24%) finding no relationship to exist. The studies reporting significantly greater odds of injury reported odds ratios as high as 2.7 ($CI_{95\%}$= 1.9-3.9) (Macera *et al.*, 1989).

Seven prospective studies examined the link between *specific* RRIs and a previous history of that injury (Table 5). Of these, six (86%) found a significant positive association, including: exercise related leg pain (pain between knee and ankle) (Reinking, Austin and Hayes, 2007; Bennett, Reinking and Rauh, 2012), stress fractures (Kelsey *et al.*, 2007; Tenforde *et al.*, 2013), Achilles tendon pain (Hirschmüller *et al.*, 2012; Lagas *et al.*, 2020), knee pain and Iliotibialband syndrome (ITBS) (Benca *et al.*, 2020).

Of eight prospective studies investigating the association between lifetime history of injury and general RRIs, just three (34%) found that previous injury was associated with future RRI (Hespanhol Junior, Pena Costa and Dias Lopes, 2013; Ramskov *et al.*, 2015; Desai *et al.*, 2021). Of the six prospective studies investigating the association between lifetime history of injury and specific RRIs, five (83%) found an increased odds likelihood of future injury (Table 5).

Table 4 Studies investigating the association between previous injury history and general RRIs.

Authors	n	Population	Tracking Period	Runner Type	Independent Variable	Finding
Prospective						
Buist, Bredeweg, Lemmink, *et al.*, 2010	532	226♂ and 306♀; 100 RRIs	13 weeks	Novices preparing for 4-mile event	Hx of injury 3-12 months prior, >12 months prior. Reference group: No hx of INJ. General injuries included.	Unadjusted Cox Regression: ♂: Previous injury 3 to 12 months prior increases risk of injury (HR= 1.90, p=.05). No association between future injury and injury > 12 months (HR= 1.48, p=.25). ♀: Previous injury 3 to 12 months prior (HR= 0.88, p= .74)/ >12 months prior (HR= 1.45, p=.27) not associated with injury. Adjusted multiple regression: ♂: Higher BMI per unit (HR:=1.15, $CI_{95\%}$= 1.05-1.26), previous injury (HR: 2.7, $CI_{95\%}$= 1.36-5.55), and type of previous sports activities (HR0 2.05, $CI_{95\%}$= 1.03-4.11) were significantly (p<.05) associated with RRIs. ♀: Previous injury not included in model.
Mohseni *et al.*, 2019	1667	204♂, 837♀ half marathoners, 218♂, 406♀ marathoners; INJ: 250, CON: 791 half marathoners, INJ: 187, CON: 437 marathoners	2 weeks	Half marathon /marathon	Hx of RRI in year prior. Reference group: no hx of INJ in year prior. Specifically RRIs	Univariate Analysis: Runners who sustained a RRI within the past year had a significantly higher odds of sustaining a race-related injury (OR= 2.11, $CI_{95\%}$= 1.56-2.84, p<.001). Significant also for multivariate analysis (OR=2.03, $CI_{95\%}$= 1.50-2.75, p<.001).
Walter *et al.*, 1989	1288	303♀,985♂; INJ: 637, CON: 628	1 year	Recreational	Hx of RRI in year prior. Unclear if RRI or general injury	Injury in previous year increases relative risk of injury (RR=1.51). ♂: Injury in previous year increases relative risk of injury (RR=1.64, $CI_{95\%}$= 1.27-2.25). ♀: Injury in previous year increases relative risk of injury (RR=2.35, $CI_{95\%}$= 1.33-4.07).
Van Der Worp *et al.*, 2016	417	INJ: 93♀, CON: 324♀	12 weeks	5/10km racers	Hx of RRI <3 months previously, 3-12 months previously, >1 year previously Specifically RRIs	Univariate analysis= Previous INJ not associated with injury. Multivariate analysis= Weekly running distance of greater than 30 km (HR=3.28; $CI_{95\%}$= 1.23, 8.75; p=.02) and a previous RRI >12 months prior (HR=1.88; $CI_{95\%}$= 1.03, 3.45, p=.04) were significantly associated with the occurrence of RRI. Previous injury <3 months, 3 to 12 months prior not associated with INJ.
Winter *et al.*, 2020	76	INJ: 22♂, 17♀; CON: 23♂, 14♀	1 year	Recreational	Hx of RRI in year prior Unclear if RRI or general injury	♂: No significant differences. ♀: Significantly more injured runners reported sustaining a running injury in the previous year (p=.002).

Macera *et al.*, 1989	583	INJ: 252♂, 48♀; CON: 233♂, 50♀	1 year	Habitual	Hx of RRI in year prior General injuries included	♂: RRI in past 12 months was a significant predictor of RRI (OR= 2.70, $CI_{95\%}$= 1.90 -3.90) ♀: RRI in past 12 months not a significant predictor of RRI (OR= 1.80, $CI_{95\%}$= 0.80-4.00).
Hespanhol Junior, Oliveira Pena Costa and Dias Lopes, 2013	191	INJ: 11♂, 49♀; CON: 92♂, 29♀	12 weeks	Recreational	Lifetime hx of RRI Specifically RRIs	No significance difference in number of RRI between groups. Univariate analysis: Previous RRI increased risk of injury (OR=2.21, $CI_{95\%}$=1.22 to 4.01, p=.009). Multivariate analysis: Previous RRI (OR=1.88, $CI_{95\%}$= 1.01 to 3.51), duration of training session (OR=1.01, $CI_{95\%}$= 0.00-1.02), and speed training (OR=1.46, $CI_{95\%}$= 1.02-2.10).
Nielsen *et al.*, 2014	874	INJ: 85, CON: 242; ♀/♂- NS	1 year	Novice	Lifetime hx of RRI and non RRI	Previous RRI was significantly associated with future RRI (p<.01). Previous injury (non RRI) not significantly associated with future RRI (p=.13).
Malisoux *et al.*, 2015	517	INJ: 167 CON: 350; 336♂, 181♀	9 months	Recreational	Hx of RRI in previous year Specifically RRIs	Previous injury was identified as an effect-measure modifier on weekly volume (relative excess risk due to interaction = 4.69; $CI_{95\%}$= 1.42-7.95; p=.005). The subpopulation of individuals with low weekly volume and with previous injury are vulnerable to injury.
Desai *et al.*, 2021	224	INJ: CON:	1 year	Recreational	Lifetime hx of injury General injuries included	Previous injury was associated with a higher injury rate (HR=1.90; $CI_{95\%}$=1.20-3.20).
Kluitenberg *et al.*, 2015	1696	INJ: 46♂, 139♀; CON: 318♂, 1193♀	6 weeks	Novice	Lifetime hx of RRI and General injuries included	Previous injury was not significantly associated with increased risks of injury (HR=0.74, $CI_{95\%}$=0.49-1.13, p=.160). Previous musculoskeletal complaints not attributable to sports was a significant risk factors for injury (HR=1.87, $CI_{95\%}$=1.33-2.64, p< .001).
Nielsen *et al.*, 2013	930	INJ: 676; CON: 254; 468♂, 462♀	1 year	Novice	Lifetime hx of RRI and General injuries included	No difference in injury survival after 500 km of running was found between individuals with no previous RRI compared to those with a previous RRI (5.2 %, $CI_{95\%}$= -8.90-19.30%, p=.470). Runners with previous injuries not related to running had sustained 11.1% ($CI_{95\%}$= -0.20%- 22.4%, p=.05) more injuries than healthy persons.
Dallinga *et al.*, 2019	678	INJ: 142, CON: 536; 347♂, 331♀	3 months	Runners preparing for 8/16 km event	Hx of RRI in previous year General injuries included	Increased risk of injury with history of injury in past year (OR=1.67, $CI_{95\%}$=1.14-2.44)
Buist, Bredeweg, Bessem, *et al.*, 2010	629	INJ: 112; CON: 320; 226♂, 206♀	8 weeks	Novice	Hx of injury < year prior, history of injury >1 year General injuries included	Not significant, p>.05.
Lun *et al.*, 2004	87	INJ: 69; CON: 18	6 months	Recreational	Lifetime hx of RRI Unclear if RRI or general injury	Not significant, p>.05.

Messier *et al.*, 2018	290	INJ: 199 CON: 91, 128♂, 172♀	2 years	Recreational	Lifetime hx of injury Unclear if RRI or general injury	Not significant, p>.05.
Satterthwaite *et al.*, 1999	885	♂/♀- NS; INJ: 345, CON: 530	During and two weeks after a marathon	Marathon	Lifetime hx of injury Unclear if RRI or general injury	Not significant, p>.05.

Abbreviated terms: n= number of participants, hx= history, RRI= running related injury, ♂= males, ♀= females, PC= prospective control study, RC= retrospective control study, INJ= injured group, CON= control group, HR= hazard ratio, RR= risk ratio, $CI_{95\%}$= $_{95\%}$ Confidence Interval, NS= not specified, N/A= not applicable. Rows shaded in grey signify that this study found that previous injury history was associated with increased risk of injury. Rows shaded in black signify that this study found that previous injury history was associated with decreased risk of injury. White shading indicates that no association was found.

Table 5 Prospetcive studies investigating the association between previous injury history and specific RRIs.

Authors	*n*	*Population*	*Injury*	*Tracking Period*	*Injury Description*	*Runner Type*	*Finding*
Kelsey *et al.*, 2007	127	INJ: 18♀; CON: 109♀	SF	Up to 4 years	Lifetime hx of stress fracture	Cross country	Runners with previous stress fracture at increased risk of stress fracture (OR= 5.24, $CI_{95\%}$=1.88, 14.49).
Hirschmüller *et al.*, 2012	634	INJ: 20♂, 9♀; CON: 242♂, 124♀	Midportion AT	12 months	Lifetime hx of healed Achilles tendon complaints	Recreational	History of healed AT complaints was a predictor of symptomatic Midpoint PT (OR= 3.80, $CI_{95\%}$=1.70–8.50, p= .0001).
Reinking, Austin and Hayes, 2007	88	44♂; 44♀	ERLP (pain between knee and ankle)	Cross country season	Lifetime hx of ERLP	Cross country	Most athletes (80.8%) who reported season incidence of ERLP had a previous history of ERLP.
Bennett, Reinking and Rauh, 2012	77	44♂, 33♀	ERLP (pain between knee and ankle)	Cross country season	Hx of ERLP in previous year	Cross country	Previous RRI was a risk factor for in-season occurrence of ERLP (OR=12.30, $CI_{95\%}$=3.1-48.90).
Lagas *et al.*, 2020	1929	INJ: 67♂, 33♀, CON: 9539♂, 3876♀,	AT	1 year	Hx of AT in previous year	Recreational	Presence of AT in the previous 12 months increased likelihood of future AT (OR=6.30, $CI_{95\%}$=3.90-10.00)
Tenforde *et al.*, 2013	748	INJ: 23♀, 11♂; CON: 405♀, 262♂	SF	11 months	Lifetime hx of injuries	Competitive school	♀: Previous history of fracture (p=.001) increased risk of stress fracture injury sixfold. No association between stress fracture injury risk and tibial stress fracture (p=.832), sprained ankle (p=.828), patellofemoral pain (p=.133), ITBS (p=.068), Achilles tendonitis (p=1.00), plantar fasciitis (p=.618). ♂: No association between stress fracture injury risk and previous injuries (above).
Plisky *et al.*, 2007	105	59♂, 46♀	MTSS	13 weeks	Lifetime hx of injury	High school cross country	Not significant, p>.05.

Abbreviated terms: n= number of participants, ♂= males, ♀= females, INJ= injured group, CON= control group, HR= hazard ratio, RR= risk ratio, $CI_{95\%}$= $_{95\%}$ Confidence Interval, Hx= history, NS= not specified, MSK= musculoskeletal, N/A= not applicable, SF= stress fracture, AT= Achilles tendinopathy, ERLP= exercise related leg pain, MTSS= medial tibial stress syndrome. Rows shaded in grey signify that this study found that previous injury history was associated with increased risk of injury. Rows shaded in black signify that this study found that previous injury history was associated with decreased risk of injury. White shading indicates that no association was found.

History of previous injury is suggested to increase the risk of RRI for three primary reasons. Firstly, a previous injury may not be adequately healed or rehabilitated at return to sport. Injury-induced reduction in tissue strength and impaired proprioception may create long-term changes to running kinematics and kinetics that may persist and predispose runners to re-injury (Marti *et al.*, 1988; Iverson, 2007; Fulton *et al.*, 2014). Secondly, injury-related pain may lead to an alteration in running technique (Noehren, Sanchez, *et al.*, 2012), which may persist following return to sport. Thirdly, runners who have not been injured before may have advantageous biomechanical features that make them resistant to injury. This has been demonstrated in some research which has found that never injured runners demonstrate lower loading compared to those who have a history of RRI (Zifchock, Davis and Hamill, 2006; Davis, Bowser and Mullineaux, 2016).

Differences in reported prevalence and incidence of RRIs between studies may be attributed to two main reasons. Firstly, differences in the definition of previous injury exists between studies. There is a lack of clarity in some studies as to whether previous lower limb injuries must be running related or if general previous injuries are included under this term. It has been argued that running-specific injuries may increase the likelihood of future running injuries compared general injuries that are not caused by running (Buist, Bredeweg, Lemmink, *et al.*, 2010), although this has sparsely been investigated in the research. It may be important to differentiate between these terms when investigating injury history. Secondly, the timeline of previous injury varies within the research, with the most common definition of injury pertaining to injury in the previous year. Nine prospective studies (Table 4, Table 5) investigated previous injury in the past year, with eight (89%) finding injury in the past year to be associated with increased injuries. Just one found no association between RRIs and previous injury history in the 12 months prior (Buist, Bredeweg, Bessem, *et al.*, 2010). However, this study involved novice runners who have had less running exposure, and therefore less risk of RRI. Both prospective studies examining specific RRIs in the previous year, found this to be significantly associated with sustaining a future RRIs of the same type (Bennett, Reinking and Rauh, 2012; Lagas *et al.*, 2020). Interestingly, one study investigated the association between race related injuries and previous RRI injury 0-3 months prior and 4-12 months prior, finding that those who were more recently injured (0-3 months prior) had a higher odds ratio of injury (OR=3.95, $CI_{95\%}$=2.32–6.72, p<.001) compared to those who were injured 4-12 months prior (OR= 1.92, $CI_{95\%}$=1.13–3.26, p=.015) (Leppe and Besomi, 2018). This may indicate that the effects of injury are more prominent at a more recent time since the injury and that perhaps the longer duration the person has stayed injury-free, the less likely they are to experience an RRI.

In summary, there is inconsistent evidence to suggest that there is an association between general RRIs and lifetime history of injuries, however there is strong evidence to suggest that injury in the past year is related to general and specific RRIs. This may add further credence to the idea that the longer the duration from injury, the less likely a person is to re-injure. Given the clear association between history of injury and future RRIs, future research should include this factor as part of a multifactorial analysis.

2.2.2.The association between age and RRIs.

Eighteen prospective studies investigated the association between age and general RRIs (Table 6), with inconsistent findings. Of these studies, four (22%) have found older age to be associated with increased RRIs, whilst three studies (17%) found younger age to be associated with increased RRIs. The remaining eleven (61%) found no association between RRIs and age.

Of the six prospective studies investigating the association between age and specific RRIs age (Table 7), older age was associated with increased incidence of quadriceps and hamstring tendinitis (McKean, Manson and Stanish, 2006), Achilles (McKean, Manson and Stanish, 2006), and meniscal (McKean, Manson and Stanish, 2006) injuries, and lower incidence or risk of shin splints (McKean, Manson and Stanish, 2006), ITB injuries (McKean, Manson and Stanish, 2006), stress fractures (Kelsey *et al.*, 2007) and calf injuries (Satterthwaite *et al.*, 1999). No association was established between age and injuries to the, groin, back, foot, hip and ankle (McKean, Manson and Stanish, 2006), lower leg injuries (Hesar *et al.*, 2009), MTSS (Bennett, Seaton and Killian, 2001) or stress fractures (Tenforde *et al.*, 2013). The evidence relating specific RRIs to age is difficult to draw conclusions from due to the low number of studies investigating similar RRIs. However, even among similar injuries, evidence is conflicting. For example, with regard to stress fractures, whilst Kelsey *et al.* (2007) found increased risk of stress fracture injury among younger cross-country runners, Tenforde *et al.* (2013) found no association to exist between age and stress fractures in adolescent runners. This may be due to the differences in types of runners examined (cross country vs adolescent). This could indicate that the type of runner may affect risk factors for injuries.

A number of explanations have been suggested to account for the significant associations between RRI and age. In terms of older age, age-related changes to range of motion, strength, technique and loading have been suggested to be related to RRI. Significantly decreased range of motion of hip adduction, ankle dorsiflexion, hip internal rotation and external rotation have been found in older runners compared to younger runners (Fukuchi *et al.,* 2014). Although these factors have not been definitively linked to RRIs, they may be potential contributors to injury, exposing older runners to greater strain-related injuries, for example, as tissues may be more amenable to overstretching. In relation to muscle strength, skeletal muscle atrophy is characteristic of aging, starting at age 50, leading to an approximate 50% reduction in fibres by age 80 (Akima *et al.*, 2001). However, many of the studies categorise age as </>40 years old (Satterthwaite *et al.*, 1999; McKean, Manson and Stanish, 2006), and so analyses may not be investigating this age-related change specifically. Although decline in strength may vary depending on the habitual level of activity of the individual (Faulkner *et al.*, 2007), older runners have been found to show significant decreases in strength of the hip abduction, hip extension and ankle plantar flexion muscles (Fukuchi *et al.*, 2014). The evidence linking aging to technique and loading is even more unclear. It is suggested that kinematic differences may alter loading and loading rates (Noehren, Scholz and Davis, 2011; Makinejad *et al.*, 2013), leading to injury. However, evidence is conflicting and while some research has found that older runners display greater vertical impact peak, greater loading rate and lower vertical active peak (Kline and Williams, 2015), other research suggests that a significant inverse correlation exists between increasing age and decreasing anterior and vertical ground reaction force (DeVita *et al.*, 2016).

The association between younger age and RRIs has been explained by two main theories. Firstly, selection bias may exist for studies, in that the runners who remain injury free continue to run, and are therefore older (Marti *et al.*, 1988; Mohseni *et al.*, 2019). Secondly, runners may adapt in response to loading over time, decreasing injury risk (Mohseni *et al.*, 2019). It is also possible that age may have a non-linear U shaped relationship with injury, with extremes of younger and older age being associated with RRI (Mohseni *et al.*, 2019), which may explain the inconsistent findings.

In summary, the evidence investigating age and both general and specific RRIs is largely inconsistent. Factors such as how age was examined (in categories or as a continuous variable) and differences in type of runners (e.g. recreational, novice, competitive) included within studies may have influenced results. However, given that strength of tissue declines with age, it may be pertinent for age to be considered in future studies when investigating the association between kinematic or loading measures and RRIs.

Table 6 Prospective studies investigating the association between age and general RRIs.

Authors	*n*	*Population*	*Tracking Period*	*Independent Variable*	*Runner Type*	*CON Mean ± SD*	*INJ Mean ± SD*	*Finding*
McKean, Manson and Stanish, 2006	2712	Masters: INJ: 466, CON: 949; Young runners INJ: 843, CON: 1876 ♀/♂- NS	1 year	Categorical: ≤40 years, >40	Recreational and marathon	N/R	N/R	Significantly increased injury rate among runners > 40 years old.
Nielsen *et al.*, 2013	930	INJ: 130♂, 124♀; CON: 338♂, 338♀	1 year	Categorical: 18-30 years, 30-45 years (reference) and 45-65 years	Novice	N/R	N/R	Association of greater risk of injury with ages 45-65 compared with ages 30-45 years (p=.08).
Taunton *et al.*, 2003	844	INJ: 249, CON: 639; 205♂, 634♀	13 weeks	Categorical: <30 years, 31-49 years, 50-55 years, >56 years	Recreational and novice	N/R	N/R	♀: Older age (>50 years) was associated with an increased risk of overall injury (RR=1.92, $CI_{95\%}$=1.11-3.33). Age < 31 years protective against new injury (RR=0.58 $CI_{95\%}$=0.34-0.97). ♂: No association between age and injury
Kluitenberg *et al.*, 2015	1696	INJ: 46♂, 139♀; CON: 318♂, 1193♀	6 weeks	Continuous	Novice	43.1 ± 9.9	45.1 ± 10.2	Univariate analysis: Older age increased risk of RRI (HR=1.02; $CI_{95\%}$=1.00–1.04, p=.009).
Satterthwaite *et al.*, 1999	885	♂/♀- NS; INJ: 345, CON: 530	2 weeks	Categorical: < 25 (reference), 25-29, 30-34, 35-39, > 40	Marathon	N/R	N/R	Significant decrease in risk of injury among runners 35–39 years old (OR=0.43; $CI_{95\%}$=0.21- 0.87) and for those aged ≥40 (OR=0.43; $CI_{95\%}$=0.22- 0.85) compared to those ≤ 25.
Buist, Bredeweg, Bessem, *et al.*, 2010	629	207♂, 422♀; 100 RRIs	8 weeks	Continuous	Novice	N/R	N/R	Univariate analysis: ♂: Younger age increased risk of RRI (p= .001).
Mohseni *et al.*, 2019	1667	INJ: 248, CON: 795; 837 ♀, 204♂ (half marathoners); INJ: 190, CON: 434; 406♀, 218 ♂ (marathoners)	2 weeks	Categorical: ≤40, > 41-50, > 51 (reference)	Half marathon/marathon	N/R	N/R	Univariate analysis: Half marathon runners: Race-related injuries significantly more common in younger runners [≤40 years old compared (OR=1.63, $CI_{95\%}$=1.13-2.34, p=0.01) and 41-51 years old (OR=1.29, $CI_{95\%}$=0.89-1.88), reference group>51]. Full marathon runners: No association between age and RRIs.
Hespanhol Junior *et al.*, 2016	89	INJ: 38 ♂, 11 ♀; CON: 30♂, 10♀	12 weeks	Continuous	Recreational	42.9 ± 10.5	41.8 ± 10.2	Not significant, p>.05.
Dallinga *et al.*, 2019	678	INJ: 142, CON: 536; 347♂, 331♀	3 months	Continuous	Runners preparing for 8/16 km event	44.0 ± 11.7	43.5 ± 11.8	Not significant, p>.05.
Desai *et al.*, 2021	224	135♂, 89♀ INJ: 79, CON: 145	1 year	Continuous	Recreational	N/R	N/R	Not significant, p>.05.
Buist *et al.*, 2010	532	INJ: 112; CON: 320; 226♂, 206♀	13 weeks	HR with every 10-year increase in age	Novice	N/R	N/R	Not significant, p>.05.
Jungmalm *et al.*, 2020	224	CON: 55, INJ: 179; 135♂, 89♀	1 year	Continuous	Half marathon runners	N/R	N/R	Not significant, p>.05.

Vlahek and Matijević, 2018	271	INJ: 65♂, 108 ♀; CON: 98	8 month s	Continuous	Novice	35.2 ± 6.4	35.8 ± 8.2	Not significant, p>.05.
Lun *et al.*, 2004	87	INJ: 35♂, 34♀; CON: 9♂, 18♀	6 month s	Continuous	Recreational	38.3	38.1	Not significant, p>.05.
Walter *et al.*, 1989	1288	INJ: 483♂, 137♀; INJ: 497♂, 164♂	1 year	Categorical: 14-19, 20-29, 30-39, 40-49, >50	Recreational	N/R	N/R	Not significant, p>.05.
Van Der Worp *et al.*, 2016	417	INJ: 93♀, CON: 324♀	12 weeks	Continuous	5/10km racers	N/R	N/R	Not significant, p>.05.
Veras *et al.*, 2020	37	INJ: 3♂, 7♀ CON: 3♂, 14♀	24 weeks	Continuous	Treadmill	29.9 ± 7.5	34.4 ± 8.4	Not significant, p>.05.
Messier *et al.*, 2018	290	INJ: 199 CON: 91, 128♂, 172 ♀	2 years	Continuous	Recreational	40.0 ± 10.3	42.3 ± 9.7	Not significant, p>.05.

Abbreviated terms: n: number of participants, ♂: males, ♀: females, INJ: injured group, CON: control group, HR: hazard ratio, RR: risk ratio, $CI_{95\%}$= $_{95\%}$ Confidence Interval, Hx: history, NS: not specified, MSK: musculoskeletal, N/A: not applicable, N/R=not reported, SF: stress fracture, AT: Achilles tendinopathy, ERLP: exercise related leg pain, MTSS- medial tibial stress syndrome. Black shading signifies that this study found lower age was associated with increased risk of injury. Grey shading signifies that older age increased risk of injury. White shading indicates that no association was found.

Table 7 Prospective studies investigating the association between age and specific RRIs.

Authors	*n*	*Population*	*Injury*	*Tracking Period*	*Variable Type*	*Runner Type*	*CON Mean ± SD*	*INJ Mean ± SD*	*Finding*
McKean, Manson and Stanish, 2006	2712	Masters: INJ: 466, CON: 949; Young runners INJ: 843, CON: 1876	RRIs (subdivided)	1 year	Categorical: ≤40 years, >40	Young vs masters	N/R	N/R	Older runners reported more quadriceps and hamstring tendinitis, Achilles, and meniscal injuries than younger runners (p<.01). Younger runners reported more shin splints and ITB injuries than masters runners (p<.001). No significant differences in the number of injuries to the groin, back, foot, hip, or ankle, between masters and younger runners.
Satterthwaite *et al.*, 1999	885	INJ: 345, CON: 530	RRIs (subdivided)	2 weeks	Categorical:<25 (reference), 25-29, 30-34, 35-39, > 40	Marathon	N/R	N/R	Decreased risk of front of thigh injury in those <25 and those >≥ 40, increased risk in those aged 30–34 (OR=1.83, $CI_{95\%}$=1.04- 3.22). Decreased risk of calf injury in those aged 30–34 (OR=.43, $CI_{95\%}$=.31-1.01) and those ≥ 40 (OR=0.40, $CI_{95\%}$=0.23-0.73).
Kelsey *et al.*, 2007	127	INJ: 18♀; CON: 109♀	Stress Fracture	Up to 4 years	Continuous (per year younger)	Cross country	N/R	N/R	Multivariate Analysis: Increased risk of injury among younger runners when considered as part of multivariate analysis (RR=1.42, $CI_{95\%}$=1.05–1.92 per 1-yr. decrease, p< .01).
Bennett, Seaton and Killian, 2001	125	INJ: 2♂, 13♀; CON: 13♂, 8♀	MTSS	8 weeks	Continuous	High school	15.7±1.5	15.3 ± 1.0	Not significant, p>.05.
Lagas *et al.*, 2020	1929	INJ: 67♂, 33♀, CON: 9539♂, 3876♀,	AT	1 year	Continuous	Recreational	45.0 ± 10.6	41.7 ± 12.1	Not significant, p>.05.
Hesar *et al.*, 2009	131	INJ: 5♂, 22♀; CON: 15♂, 89♀	Lower leg overuse RRI	10 weeks	Continuous	Novice	38.7 ± 10.7	40.6 ± 8.4	Not significant, p>.05.
Tenforde *et al.*, 2013	601	INJ: 23♀, 11♂; CON: 405♀, 262♂	Stress Fracture	2.3 ± 1.2 cross country seasons	Continuous	Adolescent NS	♂:15.4 ± 1.2 ♀:15.6 ± 1.2	♀:15.5 ± 1.0 ♂:15.3 ± 1.1	♂: Not significant, p>.05. ♀: Not significant, p>.05.

Abbreviated terms: RRIs= Running related injuries, HR= Hazard ratio, RR= Relative risk, OR= Odds ratio, ♂= Males, ♀= Females, ITBS= Iliotibial band syndrome, MTSS= Medial tibial stress syndrome, AT= Achilles Tendinopathy, PF= plantar fasciitis INJ= injured, CON= Uninjured, ERLP= Exercise related leg pain, N/R= not reported. Grey shading indicates that younger age was associated with injury. Black shading indicates that older age was associated with injury. White shading indicates that no association was found.

2.2.3. The association between sex and RRIs.

Sixteen studies investigated the relationship between general RRIs and sex (Table 8) Of these, four (25%) found male sex to be associated with RRIs, two studies (12%) found female sex to be associated with RRIs, whilst the remaining nine studies (63%) found no significant association between sex and RRIs (Table 8). These inconsistent results are highlighted in systematic reviews which did not establish a strong link between RRI and sex (Van Gent *et al.*, 2007; de Wijer *et al.*, 2015; Hulme, Rasmus, *et al.*, 2017; Hollander, Rahlf, *et al.*, 2021). A recent systematic review and meta-analysis found no differences between males and females per 100 runners (RR= 0.99, CI $_{95\%}$ = 0.90-1.10, n = 24), with an overall injury rate of 20.8 (CI $_{95\%}$ 19.9-21.7) injuries per 100 for female runners (RR 0.94, CI $_{95\%}$ = 0.69-1.27, n = 6) and 20.4 (CI $_{95\%}$ = 19.7-21.1) injuries per 100 for male runners (Hollander, Rahlf, *et al.*, 2021).

Differences in the distribution of type and location of running injuries between the sexes have been noted in previous research (Francis *et al.*, 2019; Hollander, Rahlf, *et al.*, 2021). The association between specific RRIs and sex has been investigated in eight prospective studies (Table 9). Of these, one study found an association between increased prevalence of hamstring, calf and hip injuries among male marathon runners, three studies (38%) found female sex to increased risk of MTSS and two found female sex to increase risk of stress fractures. No association between sex and exercise related leg pain, Achilles tendon pain or lower leg overuse injury was found (Table 9).

Interestingly, the majority of studies finding a significant association between RRIs and female sex were in relation to two specific injuries, MTSS and stress fractures (Bennett, Seaton and Killian, 2001; Plisky *et al.*, 2007; Tenforde *et al.*, 2013; Yagi, Muneta and Sekiya, 2013). This suggests that female runners may be more susceptible to lower leg, bony type injuries, somewhat in line with a recent systematic review and meta-analysis which found females to have greater occurrence of bone stress injury (Hollander, Rahlf, *et al.*, 2021). This could suggest that bone is weaker among females, and therefore more vulnerable, or that females have different technique and loading, which may predispose them to these injuries. Weakened bone may be as a result of hormonal factors. There is some evidence to suggest that female athletes with a history of higher age of menarche (>15 years) and who were currently amenorrhoeic were at an increased risk of injury (Tenforde *et al.*, 2013). This is related to the decrease in bone strength that has been found to accompany amenorrhea (Warren and Chua, 2008). Similarly, low energy availability, characteristic of Relative Energy Deficiency in Sport (RED-S), which has to date been primarily associated with females, has been proposed to contribute to low bone mineral density, altered hormonal factors and, ultimately, injury (Mountjoy *et al.*, 2014). However, thus far, prevalence of RED-s among runners has not been examined. Potentially, sex differences in specific RRI susceptibility may be related to the distinct differences in running biomechanics between males and females. Largely, differences have been found in frontal plane knee and hip kinematics, with female recreational runners displaying significantly greater peak hip adduction (Ferber, Davis and Williams, 2003; Chumanov, Wall-Scheffler and Heiderscheit, 2008), greater peak hip internal rotation (Ferber, Davis and Williams, 2003; Chumanov, Wall-Scheffler and Heiderscheit, 2008) and greater peak knee abduction angle (Ferber, Davis and Williams, 2003).

In summary, there is inconsistent evidence to suggest an association exists between sex and general RRIs. There is moderate evidence to suggest that female sex is associated with increased incidence of specific bony lower leg injuries, such as MTSS and stress fractures.

Table 8 Prospective studies investigating the association between sex and general RRIs.

Authors	*n*	*Population*	*Tracking Period*	*Runner Type*	*Finding*
McKean, Manson and Stanish, 2006	2712	Masters: INJ: 466, CON: 949; young runners: INJ: 843, CON: 1876	1 year	Younger vs masters	♂: increased likelihood of injury in those <40 years old (OR=1.28, p= .012), but not > 40 years old (OR= 1.10, p=.501).
Buist, Bredeweg, Lemmink, *et al.*, 2010	532	INJ: 112 CON: 226♂, 206♀	13 weeks	Novice	♂: More likely to sustain RRIs (HR=1.5, p=.04).
Vlahek and Matijević, 2018	271	INJ: 65♂, 108♀; CON: 98	8 months	Novice	♂ sex: Increased proportion of RRIs (♀: 46.70% vs. ♂:62.90% (RR=0.88, $CI_{95\%}$=0.79-0.98).
Messier *et al.*, 2018	290	INJ: 199 CON: 91, 128♂, 172♀	2 years	Recreational	♀ sex predictor of injury incidence (♀:73% vs ♂:62%, p=.05).
Mohseni *et al.*, 2019	1667	837♀, 204♂ (half marathoners),	2 weeks	Half Marathon	♀ sex: Increased proportion of RRIs (p=.03).
Buist, Bredeweg, Bessem, *et al.*, 2010	629	100 RRIs (♂ and ♀-N/R)	8 weeks	Novice	The number of RRIs per 100 runners at risk, was significantly higher in ♂ than ♀ (31.4% vs 23.2%, p=.03).
Hespanhol Junior *et al.*, 2016	89	INJ: 38♂, 11♀; CON: 30♂, 10♀	12 weeks	Recreational	Not significant, p>.05.
Hespanhol Junior, Oliveira Pena Costa and Dias Lopes, 2013	191	INJ: 49♀, 11♂; CON: 92♂, 29♀	12 weeks	Recreational	Not significant, p>.05.
Dallinga *et al.*, 2019	678	INJ: 142, CON: 536; 347♂, 331♀	3 months	Runners preparing for 8/16 km event	Not significant, p>.05.
Nielsen *et al.*, 2013	930	INJ: 676 CON: 254	1 year	Novice	Not significant, p>.05.
Lun *et al.*, 2004	87	INJ: 69 CON: 18	6 months	Recreational	Not significant, p>.05.
Jungmalm *et al.*, 2020	224	CON: 55, INJ: 179; 135♂, 89♀	1 year	Half marathon runners	Not significant, p>.05.
Walter *et al.*, 1989	1288	985♂, 303♀	1 year	Recreational	Not significant, p>.05.
Veras *et al.*, 2020	37	INJ: 3♂, 7♀ CON: 13♂, 14♀	24 weeks	Treadmill	Not significant, p>.05.
Kluitenberg *et al.*, 2015	1696	INJ: 46♂, 139♀; CON: 318♂, 1193♀	6 weeks	Novice	Not significant, p>.05.
Desai *et al.*, 2021	224	135♂, 89♀ INJ: 79, CON: 145	1 year	Recreational	Not significant, p>.05.

Abbreviated terms: RRIs= Running related injuries, HR= Hazard ratio, RR= Relative risk, OR= Odds ratio, ♂= Males, ♀= Females, ITBS= Iliotibial band syndrome, MTSS= Medial tibial stress syndrome, AT= Achilles Tendinopathy, INJ= injured, CON= Uninjured, ERLP= Exercise related leg pain. Black shading indicates that female sex is associated with RRIs. Grey shading indicates that male sex is associated with RRIs. White shading indicates that no association was found.

Table 9 Prospective studies investigating the association between sex and specific RRIs.

Authors	*n*	*Population*	*Injury*	*Tracking Period*	*Runner Type*	*Finding*
Satterthwaite *et al.*, 1999	885	INJ: 345, CON: 530	RRIs (subdivided)	2 weeks	Marathon	♂: Hamstring injuries were more prevalent (OR= 1.60, $CI_{95\%}$=1.04 to 2.47 p=.003). Hip injuries more prevalent (OR=1.88, $CI_{95\%}$=1.15-3.06, p=.006). Calf injuries more prevalent (OR 1.86, $CI_{95\%}$=1.29-2.68, p=.0008).
Tenforde *et al.*, 2013	601	428♀, 273♂	SF	2.3 ± 1.2 cross country seasons	Adolescent	Higher percentage of stress fractures in 5.4% of girls (n = 23) compared to 4.0% of boys (n = 11).
Bennett, Seaton and Killian, 2001	125	INJ: 2♂, 13♀; CON: 13♂, 8♀	MTSS	8 weeks	High school	♀ sex was found to correctly predict MTSS in 84% of our case limbs and noninjury in 64% for an overall prediction percent-age of 74% (p=.001).
Yagi, Muneta and Sekiya, 2013	230	MTSS: 58♂, 44♀, SF: 7♂, 14♀; CON: 88 ♂, 54♀	MTSS and SF	10 weeks	High school	MTSS: no significant sex difference of the injury rate was noticed (♂- .29 per 1,000; ♀- .29 per 1,000) SF: ♀ (.08 per 1,000) runners had a higher incidence of SF than ♂ (.03 per 1,000).
Plisky *et al.*, 2007	105	59♂, 46♀	MTSS	13 weeks	High school cross country	♀ sex was a significant risk factor for MTSS (OR= 3.2, $CI_{95\%}$=1.1-10.0).
Hesar *et al.*, 2009	131	INJ: 5♂, 22♀; CON: 15♂, 89♀	Lower leg overuse RRI	10 weeks	Novice	Not significant, p>.05.
Lagas *et al.*, 2020	1929	INJ: 67♂, 33♀, CON: 9539♂, 3876♀,	AT	1 year	Recreational	Not significant, p>.05.
Bennett, Reinking and Rauh, 2012	77	44♂, 33♀	ERLP	Cross country season	Cross Country	Not significant, p>.05.

Abbreviated terms: RRIs= Running related injuries, HR= Hazard ratio, RR= Relative risk, OR= Odds ratio, ♂= Males, ♀= Females, ITBS= Iliotibial band syndrome, MTSS= Medial tibial stress syndrome, AT= Achilles Tendinopathy, SF= stress fracture, INJ= injured, CON= Uninjured, ERLP= Exercise related leg pain, PFPS= patellofemoral pain syndrome. Black shading indicates that female sex is associated with RRIs. Grey shading indicates that male sex is associated with RRIs. White shading indicates that no association was found.

2.2.4.The association between running experience and RRI.

The interaction between risk factors and dosage of running (collectively termed injury exposure) is suggested to effect the occurrence of an RRI (Bertelsen *et al.*, 2017). One measure of injury exposure is running experience (typically quantified by years running). In one respect, increased experience may be related to RRIs, as the cumulative load may exceed the structural capacity. However, long exposure to repetitive loads may increase the body's resilience to loads as the body adapts. Ten studies investigated the association between general RRIs and running experience (Table 10). Of these, two (20%) found that running experience of less than three years was a risk factor for RRI (Macera *et al.*, 1989; Mohseni *et al.*, 2019). However, for both of these studies, this finding of significance applied to subpopulations of the sample. i.e., males (Macera *et al.*, 1989) and full marathon runners (Mohseni *et al.*, 2019), indicating that factors such as sex and runner type (e.g. recreational, novice) may be important considerations. The remaining seven studies (78%) did not find a significant association between years running and RRIs. Three prospective studies investigated the association between running experience and specific RRIs, with no significant associations found in relation to MTSS (Bennett, Seaton and Killian, 2001; Plisky *et al.*, 2007) or Achilles Tendonitis (Lagas *et al.*, 2020).

In summary, evidence is conflicting with regard to the association between running experience and general RRIs, with moderate and very limited evidence to suggest that there is no association between running experience and MTSS and Achilles tendonitis, respectively.

Table 10 Prospective studies investigating the association between running experience and RRI.

Authors	*n*	*Population*	*Tracking Period*	*Variable Type*	*CON Mean ± SD (years)*	*INJ Mean ± SD (years)*	*Runner Type*	*Finding*
Macera *et al.*, 1989	583	INJ: 233♂, 48♀; CON: 252♂, 50♀	1 year	Categorical: 0-2 years, 3-9 years (reference), 10+ years	N/R	N/R	Recreational	♂: Running regularly for less than 3 years (OR= 2.6, $CI_{95\%}$= 1.9-3.9, p<.05) was associated with increased injury compared to those running for 3-9 years, ♀: Not significantly associated with INJ.
Mohseni *et al.*, 2019	1667	837♀, 204♂ (half marathoners), 406♀, 218♂ (marathoners)	2 weeks prior to race	Categories: ≤12 years (reference), 4-10 years, >10 years	N/R	N/R	Half Marathon /Marathon	Half marathon: No significant association between years of running experience and injury (p= .12). Full marathon: Significantly more RRIs in full-marathon runners with less experience (p=.02).
Nielsen *et al.*, 2013	930	INJ: 676; CON: 254	1 year	Categorical: yes/no	N/R	N/R	Novice	Not significant, p>.05.
Messier *et al.*, 2018	290	INJ: 199 CON: 91, 128♂, 172♀	2 years	Continuous (years)	10.5 ± 9.9	10.5 ± 9.9	Recreational	Not significant, p>.05.
Hespanhol Junior, Oliveira Pena Costa and Dias Lopes, 2013	191	INJ: 49♀, 11 ♂; CON: 92♂, 29♀	12 weeks	Continuous (years)	4.0 ± 6.0	5.0 ± 6.0	Recreational	Not significant, p>.05.
Walter *et al.*, 1989	1288	985♂, 303♀	1 year	Continuous (years)	N/R	N/R	Recreational	Not significant, p>.05.
Veras *et al.*, 2020	37	INJ: 3♂, 7♀; CON: 13♂, 14♀	24 weeks	Continuous (months)	44.7 ± 49.6	30.1 ± 37.7	Treadmill	Not significant, p>.05.
Desai *et al.*, 2021	224	135♂, 89♀ INJ: 79, CON: 145	1 year	Continuous (years)	N/R	N/R	Continuous	Not significant, p>.05.
Buist, Bredeweg, Lemmink, *et al.*, 2010	532	INJ: 112; CON: 320; 226♂, 206♀	13 weeks	Categorical: yes/no	N/R	N/R	Novice	Not significant, p>.05.
Van Middelkoop *et al.*, 2008	694	INJ: 195♂; CON: 499♂	N/A	Continuous	N/R	N/R	Marathon	Not significant, p>.05.

Abbreviated terms: Running related injuries, HR= Hazard ratio, RR= Relative risk, OR= Odds ratio, ♂= Males, ♀= Females, INJ= injured, CON= Uninjured. N/A= not applicable, N/R=not reported. Grey shading indicates that a significant relationship was identified between RRI and lower running experience. Black shading indicates that a significant relationship was identified between RRI and greater running experience.

Table 11 Prospective studies investigating the association between running experience and specific RRIs.

Authors	*n*	*Population*	*Injury*	*Tracking Period*	*Runner Type*	*Variables (units)*	*CON Mean ± SD*	*INJ Mean ± SD*	*Finding*
Lagas *et al.*, 2020	1929	INJ: 67♂, 33♀, CON: 9539♂, 3876♀,	AT	1 year	Recreational	Continuous (years)	4.0	4.6	Not significant, p>.05.
Plisky *et al.*, 2007	105	59♂, 46♀	MTSS	13 weeks	High school cross country	Categorical: 0 years, 1 years, 2 years, 3 years, ≥4 years	N/R	N/R	Not significant, p>.05.
Bennett, Seaton and Killian, 2001	125	INJ: 2♂, 13♀; CON: 13♂, 8♀	MTSS	8 weeks	High school runners	Continuous (years)	2.2 ± 1.2	1.7 ± 1.2	Not significant, p>.05.

Abbreviated terms: Running related injuries, HR= Hazard ratio, RR= Relative risk, OR= Odds ratio, ♂= Males, ♀= Females, AT=Achilles tendoninjury, MTSS= Medial tibial stress syndrome, CON= control, INJ= injured, PFPS= patellofemoral pain syndrome, N/A= not applicable, N/R= not reported. Black shading indicates that a significant relationship was identified between RRI and greater running experience. Grey shading indicates that a significant relationship was identified between RRI and lower running experience.

2.3. Modifiable risk factors for RRI

Modifiable risk factors are those that can be altered, and are therefore the subject of much scrutiny within the research and the target of RRI prevention and rehabilitation programmes (Willy and Davis, 2011; Esculier, Bouyer and Roy, 2016). Modifiable factors that have been suggested to most frequently relate to RRI will be explored in the following section. These include body mass index (BMI), training load, functional foot alignment, muscle strength, range of motion, impact loading and running technique (including spatiotemporal factors). Additional factors such as training surface (Warne *et al.*, 2021) and shoe type (Sun *et al.*, 2020) may also be related to RRI but were considered to be outside of the scope of this review.

2.3.1. The association between BMI and RRI

Body mass index (BMI) is a long-utilised measure of obesity, primarily used in the healthcare setting (Department of Health, 2016). A major criticism of BMI is that it fails to account for body composition, which may lead to individuals with high muscle mass being classified as overweight or obese (Guy-Grand, 2014). However, it still remains a highly utilised and researched metric, with the benefits of being easy and inexpensive to capture. Twenty-one prospective studies examined the association between general RRIs and BMI (Table 12). Of these, nine (43%) found higher BMI to be related to RRI. In contrast, one study found that females were 13% *less* likely to suffer a race-related injury with each 1-unit increase in BMI (Vadeboncoeur *et al.*, 2012) and another finding that a BMI > 26 kg/m^2 was protective of RRI in males (Taunton *et al.*, 2003). The remaining ten studies (48%) found no association between BMI and RRIs. Interestingly, of the nine studies finding higher BMI to be related to RRIs, six of them related to novice runners, suggesting that novice runners of a high BMI may display higher magnitude of loading per stride (Bertelsen *et al.*, 2017), without having built up the capacity to effectively dissipate these loads. Higher load per stride may also be an issue for recreational runners, however, they may build up tissue tolerance to this load over time.

Ten prospective studies examined the association between specific RRIs and BMI (Table 13), with three studies (30%) finding a significant relationship. However, the direction of the relationship varied within the studies, with greater BMI being related to MTSS (Plisky *et al.*, 2007) and lower leg injuries (Juhler *et al.*, 2020), while lower BMI was related to stress fractures (Kelsey *et al.*, 2007) and knee injuries (Juhler *et al.*, 2020). No association was found between exercise related leg pain (ERLP) (Bennett, Reinking and Rauh, 2012; Reinking, Austin and Hayes, 2013) or patellofemoral pain syndrome (Thijs *et al.*, 2008, 2011) and BMI.

In addition to the above theories pertaining to increased load-per-stride, increased BMI may be related to RRI due to the chronic inflammatory response may be stimulated as a result of obesity (Aicale, Tarantino and Maffulli, 2018). This prolonged low-grade inflammation may impede the healing process of biological tissues, such as tendons, which may be particularly at risk of failed healing.

In summary, there is inconsistent evidence to suggest that there is an association between BMI and general RRIs, however there is a moderate association between greater BMI and injury among novice runners. Evidence with regard to specific RRIs is inconsistent.

Table 12 Prospective studies investigating the association between BMI and general RRIs.

Authors	***n***	***Population***	***Runner Type***	***Tracking Period***	***Measure***	***INJ Mean ± SD (kg/m²)***	***CON Mean ± SD (kg/m²)***	***Finding***
Buist, Bredeweg, Lemmink, *et al.*, 2010	532	100 RRIs (226♂ and 306♀ runners)	Novice	13 weeks	BMI per unit	N/R	N/R	Univariate analysis: ♂: Significant association between higher BMI and RRI (HR=1.14, $CI_{95\%}$ 1.1-1.3 per unit of BMI increase). ♀: No association between BMI and RRI.
Theisen *et al.*, 2014	247	INJ: 69, CON 146	Leisure time distance	5 months	Continuous	N/R	N/R	Increase in risk of injury per 1kg/m^2 increase in BMI (p=.007).
Mohseni *et al.*, 2019	1667	837♀, 204♂ (half marathoners), 406♀, 218♂ (marathoners)	Half Marathon /Marathon	2 weeks	Categorical: ♂:<24, ♀:<22 (reference); ♂:24-26, ♀:22-24; ♂:>26 ♀:>24	N/R	N/R	Full marathon runners: Increased risk of injury for runners with BMI 24-26 kg/m^2 (♂), 22-24 kg/m^2 (♀) were at a higher risk of injury (OR=1.52, $CI_{95\%}$= 1.00- 2.36) compared to BMI <22 (♀) and <24 (♂) Increased risk of injury for runners with BMI >24 (♀) and BMI > 26 (♂), OR=1.74, $CI_{95\%}$= 1.14- 2.65, p=.04) compared to BMI <22 (♀) and <24 (♂) Half marathon runners: No association between BMI and INJ.
Van Der Worp *et al.*, 2016	417	INJ: 93♀, UN: 324♀	5/10km race	12 weeks	Continuous	23.8 ± 2.9	23.0 ± 2.9	Univariate: Higher BMI was associated with running-related injuries (HR=1.08; $CI_{95\%}$=1.01-1.15; P= .02)
Nielsen, Parner, *et al.*, 2014	873	INJ: 85, CON: 242	Novice	1 year	Continuous	25.9 ± 4.3	26.6 ± 4.2	BMI significantly higher in INJ group compared to CON (p=.05).
Buist *et al.*, 2008	629	INJ: 112; CON: 320; 226♂, 206♀	Novice	8 weeks	Continuous	N/R	N/R	Univariate analysis: ♂: No main group effect for injury with reference to BMI. ♀: BMI was related to the risk of sustaining an RRI (HR=1.08, $CI_{95\%}$= 0.70 to 1.67, p=.012). Multivariate analysis: ♀: BMI was related to the risk of sustaining an RRI (HR=1.06, $CI_{95\%}$= 1.01 to 1.13, p=.028).
Kluitenberg *et al.*, 2015	1696	INJ: 46♂, 139♀; CON: 318♂, 1193♀	Novice	6 weeks	Continuous	26.2 ± 4.5	25.4 ± 4.0	Higher BMI related to the occurrence of RRIs (HR=1.04, $CI_{95\%}$= 1.00-1.07)
Nielsen, Bertelsen, *et al.*, 2014	749	381♂, 368♀ INJ: 56, CON: 685	Novice	3 weeks	Categorical: BMI ≤ 30 BMI>30	N/R	N/R	A significantly greater number of individuals with BMI>30 sustained injuries if they ran between 3 to 6 km (cumulative risk difference (CRD) = 14.3% [$_{95\%}$CI: 3.3% to 25.3%], p<0.01) or more than 6 km (CRD = 16.2% [$_{95\%}$CI: 4.4% to 28.0%], p<0.01) the first week than individuals in the reference group (low distance and low BMI).
Nielsen *et al.*, 2013	930	INJ: 676; CON: 254	Novice	1 year	Categorical: <20 kg/m^2, 20-25 kg/m^2 (ref), 25-30 kg/m^2 >30 kg/m^2	N/R	N/R	Multivariate analysis: BMI >30 kg/m^2, age between 45 and 65 years, non-competitive behaviour, and previous injuries not related to running are associated with increased risk of injury among novice runners, while BMI <20 kg/m^2 was protective.
Taunton *et al.*, 2003	844	205♂, 635♀	Recreational	13 weeks	Categories (>26kg/m^2, <26kmh/m^2)	N/R	N/R	A BMI of > 26 kg/m^2 was reported as protective for men.

Vadeboncoeur *et al.*, 2012	194	INJ: 50♀, 12♂; CON: 87♀, 33♂	Half Marathon runners/Marathon	Unclear	Tertiles	N/R	N/R	Females were 13% less likely to suffer a race-related injury with each 1-unit increase in BMI. Rates of injury did not differ by BMI tertile in males.
Bredeweg *et al.*, 2010 CHEC	110	INJ: 11♂, 22♀; CON: 66♂, 110♀	Novice	9 weeks	Continuous	24.3 (3.2)	23.9 (3.4)	Not significant, p>.05.
Winter *et al.*, 2020	76	INJ: 22♂, 17♀; CON: 23♂, 14♀	Recreational	1 year	Continuous	22.2 ± 2.1	23.3 ± 2.8	Not significant, p>.05.
Desai *et al.*, 2021	224	135♂, 89♀ INJ: 79, CON: 145	Recreational	1 year	Continuous	N/R	N/R	Not significant, p>.05.
Jungmalm *et al.*, 2020	224	INJ: 179, CON: 55, 135♂, 89♀	Half marathon runners	1 year	Continuous	N/R	N/R	Not significant, p>.05.
Macera *et al.*, 1989	583	INJ: 252♂, 48♀; CON: 233♂, 50♀	Habitual	1 year	Percentiles of BMI	N/R	N/R	Not significant, p>.05.
Dallinga *et al.*, 2019	678	INJ: 142, CON: 536; 347♂, 331♀	Runners preparing for 8/16 km event	3 months	Continuous	23.6 ± 2.9	24.1 ± 3.1	Not significant, p>.05.
Hespanhol Junior, Oliveira Pena Costa and Dias Lopes, 2013	191	INJ: 49♀, 11♂; CON: 92♂, 29♀	Recreational	12 weeks	Continuous	24.5 ± 2.7	24.4 ± 3.3	Not significant, p>.05.
Messier *et al.*, 2018	290	INJ: 199, CON: 91, 128♂, 172♀	Recreational	2 years	Continuous	23.9 ± 3.3	24.5 ± 3.4	Not significant, p>.05.
Veras *et al.*, 2020	37	INJ: 3♂, 7♀; CON: 13♂, 14♀	Treadmill	24 weeks	Continuous	24.3 ± 3.3	25.3 ± 3.4	Not significant, p>.05.
Van Middelkoop *et al.*, 2008	694	INJ: 195♂; CON: 499♂	Marathon	1 month	Continuous	N/R	N/R	Not significant, p>.05.

Abbreviated terms: RRIs= Running related injuries, HR= Hazard ratio, RR= Relative risk, OR= Odds ratio, ♂= Males, ♀= Females, INJ= injured, CON= Uninjured, N/R= not reported. Grey shading indicates that lower BMI was associated with RRIs. Black shading indicates that greater BMI is associated with RRIs. White shading indicates that no association was found.

Table 13 Prospective studies investigating the association between specific RRIs and BMI.

Authors	*n*	*Population*	*Runner Type*	*Injury*	*Tracking Period*	*BMI Analysis*	*CON Mean ± SD (kg/m^2)*	*INJ Mean ± SD (kg/m^2)*	*Finding*
Plisky *et al.*, 2007	105	59♂, 46♀	High school cross country girls and boys	MTSS	13 weeks	Tertiles	N/R	N/R	Runners in the third tertile BMI group (20.2-21.6 kg/m^2) were 5 times more likely to incur MTSS than runners in the second tertile (18.8-20.1) reference group.
Kelsey *et al.*, 2007	127	INJ: 18 ♀; CON: 109♀	Cross country	SF	Up to 4 years	Continuous	N/R	N/R	Increase in risk of injury per decrease in kilograms per meter squared (HR: 1.20, 95% CI: 0.90, 1.61).
Juhler *et al.*, 2020	2612	221♂, 350♀ INJ: 567, CON: 2045	Mixed levels	RRIs: subdivided	Novice and recreational	Categorical: <25, 25-30, ≥30	N/R	N/R	The proportion of running-related knee injuries was 13% lower among overweight runners compared with normal-weight runners. The proportion of running-related knee injuries was 12% among obese runners compared with normal-weight runners. The proportion of running-related injuries to the lower leg was higher among overweight and obese runners compared to non-obese runners.
Reinking, Austin and Hayes, 2013	225	INJ: 143; CON: 82	Cross country	ERLP	Cross country season	Continuous	N/R	N/R	Not significant, p>.05.
Bennett, Reinking and Rauh, 2012	77	44♂, 33♀	Cross country	ERLP	Cross country season	Continuous	N/R	N/R	Not significant, p>.05.
Van Ginckel *et al.*, 2009	63	INJ: 10, CON: 53	Novice	AT	10 weeks	Continuous	24.7 ± 3.9	25.0 ± 4.1	Not significant, p>.05.
Lagas *et al.*, 2020	1929	INJ: 67♂, 33♀, CON: 9539♂, 3876♀,	Recreational	AT	1 year	Continuous	23.8 ± 3.3	23.6 ± 2.8	Not significant, p>.05.
Thijs *et al.*, 2008	102	INJ: 17, CON: 85	Recreational	PFPS	10 weeks	Continuous	25.1 ± 2.8	24.9 ± 3.5	Not significant, p>.05.
Thijs *et al.*, 2011	77	INJ: 16♀, CON: 61♀	Novice	PFPS	10 weeks	Continuous	24.4 ± 6 2.9	25.4 ± 6 2.7	Not significant, p>.05.

Abbreviated terms: Running related injuries, HR= Hazard ratio, RR= Relative risk, OR= Odds ratio, ♂= Males, ♀= Females, ITBS= Iliotibial band syndrome, MTSS= Medial tibial stress syndrome INJ= injured, UN= Uninjured, ERLP= Exercise related leg pain, PFPS= patellofemoral pain syndrome, N/R= not reported. Grey shading indicates that a significant association was identified between greater BMI and injury. Blacks shading indicates that a significant association was identified between lower BMI and injury. Black shading indicates that a significant association was identified between greater BMI and injury. White shading indicates that no association was found.

2.3.2. The association between training load and RRI

The biomechanical model of injury postulates that loading in excess of the tissue's capabilities contributes to eventual tissue damage and injury (Hreljac, 2004; Kalkhoven, Watsford and Impellizzeri, 2020). Measures of training load (running distance, running frequency, running duration) are thought to contribute to the volume of load applied to tissue (Damsted *et al.*, 2019a) and have been implicated in the aetiology of RRIs. In response to changes in load, with appropriate recovery, positive adaptation may occur as tissues remodel and strengthen (Soligard *et al.*, 2016). However, injuries are thought to occur with changes in load or repetitive load in the absence of adequate recovery. Among the measures of training load, the most frequently studied and easily measurable is weekly distance, therefore this will be explored primarily in this review of literature. Changes in training distance (Nielsen *et al.*, 2012; Rasmussen *et al.*, 2013; Winter *et al.*, 2020), frequency of training sessions (Taunton *et al.*, 2003; Hespanhol Junior, Pena Costa and Dias Lopes, 2013) and duration of running time (Buist, Bredeweg, Bessem, *et al.*, 2010; Mann *et al.*, 2015) have also been previously explored in relation to RRI, with inconsistent results.

2.3.2.1. The association between weekly running distance and RRI

Fifteen prospective studies investigated the association between weekly running distance and general RRIs. Of these, four (27%) found greater weekly running distance to be associated with RRIs, two studies (13%) found a relationship between RRI and lower weekly running mileage, and nine studies (60%) found no relationship (Table 14).

Four prospective studies investigated the association between specific RRIs and weekly running distance (Table 15). Of these, one (25%) study found greater weekly running distance to be associated with stress fracture injuries, but only in relation to the males in their study, and not when males and females were grouped together (Tenforde *et al.*, 2013). Interestingly, this is one of two prospective studies investigating the relationship between stress fractures and weekly distance, yielding conflicting results (Kelsey *et al.*, 2007; Tenforde *et al.*, 2013). The remaining prospective studies did not find an association between weekly running distance and the specific RRIs of ERLP (Reinking, Austin and Hayes, 2007) and Achilles tendinopathy (Lagas *et al.*, 2020).

Table 14 Prospective studies investigating the association between weekly running distance and general RRIs.

Authors	n	Population	Runner Type	Tracking Period	Method of distance tracking	Variables (units)	CON Mean ± SD	INJ Mean ± SD	Finding
Macera *et al.*, 1989	583	INJ: 252 ♂, 48 ♀; CON: 283	Habitual	1 year	At baseline	Categorical (miles/week)- 0-9, 10-19, 20-29, 30-39, 40+	N/R	N/R	♂: Running >64 km/week was a significant risk factor for injury (OR= 2.9). ♀: Weekly distance not a significant risk factor for injury.
Walter *et al.*, 1989	1288	985 ♂, 303 ♀	Recreational	1 year		>30 miles/week, <30 miles/week	N/R	N/R	Significantly greater distance/week (>30 miles/week) associated with increased risk of RRI compared to running <30 miles/week.
Winter *et al.*, 2020	76	INJ: 22 ♂, 17 ♀; CON: 23 ♂, 14 ♀	Recreational	1 year	Training diary – weekly	Continuous (km/week)	48.8 ± 18.4	44.3 ± 13.3	♂: Significantly greater distance/week among INJ (0.046; r = 0.32). ♀: No significant differences between INJ and CON runners for any of the training variables.
Van Der Worp *et al.*, 2016	417	INJ: 93 ♀, CON: 324 ♀	5/10km race	12 weeks	At baseline	>30 miles/week, <30 miles/week	N/R	N/R	Multivariate analysis: distance/week > 30 km (HR=3.28; $CI_{95\%}$:1.23, 8.75; p=.02) and a previous RRI >12 months prior significantly associated with the increased occurrence of RRIs.
Mohseni *et al.*, 2019	1667	837 ♀, 204 ♂ (half marathoners), 406 ♀, 218 ♂ (marathoners)	Half marathon /marathon	2 weeks prior to race	At baseline	Categorical: >15 miles/week, <15 miles/week	N/R	N/R	Significantly increased risk of injury with distance/week of ≤5 miles (OR=1.94, $CI_{95\%}$:1.29-2.92, p=.004) and 6-15 miles (1.47, $CI_{95\%}$=.98-2.21, p=.004) compared to >15 miles.
						Peak weekly mileage 3 months before race	N/R	N/R	Not significant, p>.05.
Hespanhol Junior, Oliveira Pena Costa and Dias Lopes, 2013	191	INJ: 49 ♀, 11 ♂; CON: 92 ♂, 29 ♀	Recreational	12 weeks	Running log every 14 days	Continuous (km/week)	30 (18.0 to 42.5) km/week	15 (2.5-26.3) km/week	Significantly lower distance/week among injured runners (p<.001), though not predictive of injury (OR=1.00, $CI_{95\%}$:0.99 - 1.01, p= .920).
Dallinga *et al.*, 2019	678	347♂, 331♀ INJ: 142, CON: 536	Runners preparing for 8/16 km event	3 months	At baseline	Categorical (km/week) >30 vs 5-10	N/R	N/R	Not significant, p>.05.
						>30 vs 10-20	N/R	N/R	Not significant, p>.05.
						>30 vs 20-30	N/R	N/R	Not significant, p>.05.
Lun *et al.*, 2004	87	INJ: 69; CON: 18	Recreational	6 months	At baseline	Continuous (km/week)	35.9	35.6	Not significant, p>.05.
Hespanhol Junior *et al.*, 2016	89	INJ: 38 ♂, 11 ♀; CON: 30 ♂, 10 ♀	Recreational	12 weeks	Running log every 14 days	Continuous (km/week)	40.0 ± 22.0	35.0 ± 25.0	Not significant, p>.05.
Damsted *et al.*, 2019	784	INJ: 136; CON: 648	Half marathon	14 weeks	Provided with training programme	>15 km/week, <15 km/week	N/R	N/R	Not significant, p>.05.
Desai *et al.*, 2021	224	135♂, 89♀ INJ: 79, CON: 145	Recreational	1 year	At baseline	Continuous	N/R	N/R	Not significant, p>.05.
Veras *et al.*, 2020	37	INJ: 3♂, 7♀; CON: 13♂, 14♀	Treadmill	Continuous	At baseline	Continuous (km/week)	19.0 ± 14.3	13.9 ± 3.3	Not significant, p>.05.

Jungmalm *et al.*, 2020	224	INJ: 179; CON: 55, 135♂, 89♀	Half marathon runners	1 year	At baseline	Continuous	N/R	N/R	Not significant, p>.05.
Messier *et al.*, 2018	290	INJ: 199 CON: 91, 128 ♂, 172 ♀	Recreational	2 years	At baseline, 6th month and 12 months follow up	Continuous (miles/week)	19.9 ± 14.5	20.4 ± 11.6	Not significant, p>.05.
Dudley *et al.*, 2017	21	INJ: 4♂,8♀; CON: 11♂, 8♀	Collegiate cross country	13 weeks	At baseline	Continuous (km/week)	3.9 (3.7, 4.0)	3.9 (3.7, 4.0)	Not significant, p>.05.
Van Middelkoop *et al.*, 2008	694	INJ: 195 ♂ CON: 499 ♂	Marathon	One month before race	At baseline	Categorical 0-10 km, 11-15 km, ≥16 km	N/R	N/R	Not significant, p>.05.

Abbreviated terms: Running related injuries, HR= Hazard ratio, RR= Relative risk, OR- Odds ratio, ♂- Males, F- Females, INJ- injured, CON= Uninjured, N/A= not applicable, N/R=not reported. Black shading indicates that a significant relationship was identified between greater RRI and increased running distance. Grey shading indicates that a significant relationship was identified between decreased running distance and RRI. White shading indicates that no association was found.

Table 15 Prospective studies investigating the association between weekly distance and specific RRIs.

Authors	*n*	*Population*	*Injury*	*Tracking Period*	*Runner Type*	*Method of distance tracking*	*Classification of groups*	*CON Mean ± SD*	*IN Mean ± SD*	*Finding*
Tenforde *et al.*, 2013	601	428 ♀, 273 ♂	Stress Fracture	2.3 ± 1.2 cross country seasons	Adolescents	At baseline	>32 km/week versus >32km/week	N/R	N/R	Weekly distance >32 km/week associated with injury among females (p= .006), but not males.
Nielsen *et al.*, 2013	873	INJ: 85 CON: 242	Distance related injuries	1 year	Novice	GPS watch	Progression of weekly distance over time.	N/R	N/R	An increased rate of distance-related injuries (patellofemoral pain, iliotibial band syndrome, medial tibial stress syndrome, gluteus medius injury, greater trochanteric bursitis, injury to the tensor fascia latae, and patellar tendinopathy) existed in those who progressed their weekly running distance by more than 30% compared with those who progressed less than 10% (HR=1.59; $CI_{95\%}$=0.96-2.66; p=.07)
Reinking, Austin and Hayes, 2007	88	44 ♂; 44 ♀, 60/88 retrospectively injured, 26/67 prospectively injured	ERLP	Season	Cross Country Runner	At baseline	Categorical: ≥64 km/week, < 64km/week	N/R	N/R	Not significant, p>.05.
Kelsey *et al.*, 2007	127	INJ: 18 ♀; CON: 109 ♀	Stress Fracture	Up to 4 years	Cross Country Runner	At baseline	Continuous variable (km/week)	♂- 25.5 ± 18.3, ♀-27.9 ± 19.2	♀- 27.9 ± 19.2, ♂- 34.5 ± 26.8,	Not significant, p>.05.

Abbreviated terms: Running related injuries, HR= Hazard ratio, RR= Relative risk, OR= Odds ratio, ♂= Males, ♀= Females, INJ= injured, CON= Uninjured, ERLP= Exercise related leg pain, N/A= not applicable, N/R= not reported. Black shading indicates that a significant relationship was identified between RRI and greater weekly running distance. Grey shading indicates a significant association was identified between RRI and lower weekly running distance. White shading indicates that no association was found.

It should be noted that training load is typically not the main focus of RRI studies and therefore in the majority of studies it is collected at a single time point, which may not be accurate as it is subject to recall bias (Gabbe and Finch, 1999). An exception to this, and perhaps the most detailed exploration of the relationship between training load and injury to date among runners specifically, is work by Malisoux *et al.* (2015) who found weekly volume over 2 hours and weekly session frequency exceeding 2 times per week were associated with increased injury rate (hazard ratio= 2.41, $CI_{95\%}$ = 1.71-3.42). This study was particularly strong in collecting data in real time using training diaries. Consideration of wider research involving other sports indicates that there may be a relationship between sporting injury and training load (L Malisoux *et al.*, 2015; Gabbett, 2016; Eckard *et al.*, 2018). However, some inconsistency in the literature exists, in particular regarding the direction of this relationship. A systematic review by Eckard *et al.* (2018) found that although the majority of the studies investigating training load in athletes found a positive relationship to exist between load and injury risk, some reported an inverse or U-shaped relationship. Similarly, this review of the running related literature found limited evidence for a negative relationship, positive relationship and no relationship between weekly distance and RRI. This conforms to the Bertelsen theory of the aetiology of RRI, which outlines that a band of 'optimal loading' may exist (Bertelsen *et al.*, 2017). However, challenges remain in finding resource-light methods of tracking training load.

2.3.3. The association between functional foot alignment and RRI

A number of modifiable clinical measures have also been suggested. Among the most commonly investigated are functional foot alignment, muscle strength, and range of motion measures. These measures have been suggested to be related to loading (Ferenczi *et al.*, 2014; Mason-Mackay, Whatman and Reid, 2017; Mei *et al.*, 2019) and, in some cases, injury itself (Becker *et al.*, 2017; Mucha *et al.*, 2017; Pérez-Morcillo *et al.*, 2019). Their time-efficient, low cost and readily available nature make their potential association with RRI of particular clinical relevance.

Functional foot alignment has received considerable attention in both the research (Hollander *et al.*, 2019) and clinical domains for its possible association with RRIs. As the linking segment between the body and the ground, the foot is subject to considerable forces, as well as affecting the forces generated at the ground and transferred up the leg. During running, pronation of the foot allows it to adapt to different terrains and absorb impact loads, while the raising of the arch via supination enables forward propulsion (Chan and Rudins, 1994). Whilst the movements of pronation and supination are typical movements of the foot and required for running, extremes of both have been associated with increases in lower limb loading (Chang *et al.*, 2012; Williams, Tierney and Butler, 2014; Resende, Pinheiro and Ocarino, 2019), and therefore RRI, although this has been debated within the literature (Hollander *et al.*, 2019).

It is thought that clinical measures of functional foot alignment may indicate whether the foot is exposed to excessive pronation or supination. Two main functional foot alignment classifications have been established; continuous scale measurements (e.g. arch height index (Williams and McClay, 2000), dorsal height during sit to stand (Mcpoil *et al.*, 2008), navicular drop (Brody, 1982)) and foot type categorisation (FPI-6 (Redmond, Crosbie and Ouvrier, 2006)). This section examines the association between two foot position classifications, navicular drop and the Foot Posture Index, and RRIs.

2.3.3.1. The association between navicular drop and RRI

Navicular drop (ND) is a measure of pronation at the subtalar joint and is thought to represent the movement of the medial longitudinal arch (Zuil-Escobar *et al.*, 2018). ND is also suggested to be related, although weakly, to rearfoot eversion (McPoil and Cornwall, 1996). ND is calculated by measuring the difference in distance between the navicular bone and the floor between sitting and weight bearing during standing (Buist, Bredeweg, Lemmink, *et al.*, 2010). It can be measured using absolute values (distance in mm) or by categorisation (ND < 5mm = supinated, ND of 5-8 mm = pronated, ND > 9 mm = pronated (Langley, Cramp and Morrison, 2016a)). Clinically, it is a useful test owing to its minimal equipment and time efficiency.

Three prospective studies have investigated the association between general RRIs and ND (Table 16), with just one finding a significant association between greater ND and RRIs among novice runners (Buist, Bredeweg, Lemmink, *et al.*, 2010). The remaining two studies found no association (Reinking, Austin and Hayes, 2007; Van Der Worp *et al.*, 2016; Dudley *et al.*, 2017). The aforementioned studies examined novice, cross country and marathon runners and therefore a lack of prospective research investigating ND and general RRIs among recreational runners exists.

Seven prospective studies investigated the association between specific RRIs and ND (Table 17). Of these, five investigated MTSS (Bennett, Seaton and Killian, 2001; Plisky *et al.*, 2007; Hubbard, Carpenter and Cordova, 2009; Raissi *et al.*, 2009; Yagi, Muneta and Sekiya, 2013), with two (40%) finding significantly greater ND among injured runners (Bennett, Seaton and Killian, 2001; Raissi *et al.*, 2009). The remining three (60%) found no association to RRI. Two studies investigated medial exercise related leg pain (Reinking, Austin and Hayes, 2007; Bennett, Reinking and Rauh, 2012), with one finding significantly greater ND among injured runners (Bennett, Reinking and Rauh, 2012).

Cut-off points for ND have been examined in one prospective study, which found ND in excess of 10 mm increased the odds of developing exercise related leg pain by 6.6 times (Bennett, Reinking and Rauh, 2012). However, this finding is not consistent across the research, with a similar retrospective study finding insignificant changes in odds of sustaining MTSS with ND over 10 mm among high school runners (Plisky *et al.*, 2007). Conflicting results may be attributed to the different types of injury used in each study, potentially indicating that ND is more relevant for those with exercise related leg pain.

It is important to note that ND has been criticised in some literature due to lack of consistency between raters (Langley, Cramp and Morrison, 2016b). Therefore, it is important that if multiple clinicians are testing that high levels of interrater reliability are maintained. Potential issues with intra-rater reliability may be due to lack of consistency in identifying the navicular bone and/or in determining subtalar neutral. Another criticism is that this is a measure of the pronation of the foot from sitting to standing and may not reflect the dynamic pronation that occurs during running (Deng, 2010).

In summary, the findings with regard to the relationship between ND and general RRIs are inconsistent, with very limited evidence to suggest that it may be a relevant injury risk factor among novice runners. Similarly, there is inconsistent evidence to suggest that ND in excess of 10 mm is a risk factor for RRIs. Regarding specific RRIs, there is also inconsistent evidence regarding an association. It is possible that differences in study methodologies with respect to factors such as experience of the runner may be responsible for inconsistencies in results.

Table 16 Prospective studies investigating the association between navicular drop and general RRIs.

Study	*n*	*Population*	*Type of Runner*	*Tracking Time*	*Groups compared*	*CON Mean ± SD (mm)*	*INJ Mean ± SD (mm)*	*Findings*	*Percentage Difference (%)**
Buist, Bredeweg, Lemmink, *et al.*, 2010	532	INJ: 112 CON: 226♂, 206♀	Novice	13 weeks	INJ vs CON= ♂	Lower	Higher	ND not a significant predictor of injury, p=.40.	N/A
					INJ vs CON= ♀	Lower	Higher	Greater ND was a predictor of RRI, HR=.85, $CI_{95\%}$= 0.75-0.97, p=.01.	N/A
Van Der Worp *et al.*, 2016	417	INJ: 93♀ CON: 324♀	Marathon	12 weeks	INJ vs CON	6.3 ± 2.9	6.3 ± 3.3	Not significant, p>.05.	0
Dudley *et al.*, 2017	31	INJ: 4♂, 8♀ CON: 11♂, 8♀	Cross country college	14 weeks	INJ vs CON	6.8 (5.6, 7.9)	5.8 (3.9, 7.7)	Not significant, p>.05.	-15

Abbreviated terms: ♀= Female, ♂= Male, ND= Navicular Drop, INJ= injured, CON= control group, SD= Standard deviation, N/R= not reported, N/A= not applicable. Black shading indicates that greater navicular drop was associated with RRI.

Table 17 Prospective tudies investigating the association between navicular drop and specific RRIs.

Authors	*n*	*Population*	*Type of Runner*	*Injury*	*Tracking Time*	*Groups compared*	*CON Mean ± SD (mm)*	*INJ Mean ± SD (mm)*	*Findings*	*Percentage Difference (%)*
Bennett, Seaton and Killian, 2001	125	INJ: 13♂, 8♀ CON: 104	High school	MTSS	8 weeks	INJ vs CON	3.6 ± 3.3	6.8 ± 3.7	Greater ND among INJ group, p=.003.	89
Raissi *et al.*, 2009	66	INJ: 13 CON: 53;	Non-professional athletes	MTSS	17 weeks	INJ vs CON= left side	5.0 ± 1.6	6.5 ± 2.2	Greater ND among INJ group, p=.24	30
						INJ vs CON= right side	5.1 ± 1.3	6.1 ± 1.6	Greater ND among INJ group, p=.027	20
Bennett, Reinking and Rauh, 2012	59	INJ: 26 CON: 33	Cross Country	Medial ERLP	College Season	INJ vs CON= right side	8.5 ± 4.0	9.0 ± 4.7	Greater ND among INJ group, p<.05	6
						INJ vs CON= left side	8.6 ± 4.1	8.5 ± 4.3	Greater ND among INJ group, p<.05	-1

									ND >10 mm OR= 6.6	
Hubbard, Carpenter and Cordova, 2009	146	INJ: 29 CON: 177	College athletes	MTSS	College Season	INJ vs CON= right side	7.8 ± 3.0	8.6 ± 3.2	Not significant, p>.05.	10
Plisky *et al.*, 2007	105	INJ: 16 CON: 89	High school cross country	MTSS	13 weeks	INJ vs CON	11.0 ± 3.6	11.2 ± 4.5	Not significant, p>.05.	2
Reinking, Austin and Hayes, 2007	88	INJ: 60 CON: 28	Cross Country	ERLP	Cross country season	INJ vs CON= left side	8.5	8.2	Not significant, p>.05.	-4
						INJ vs CON= right side	8.6	8.4	Not significant, p>.05.	-2
Yagi, Muneta and Sekiya, 2013	146	INJ: 58♂ CON: 88♂;	High school	MTSS	3 yars	♂: Currently INJ Vs CON	4.5 ± 3.4	4.9 ± 3.0	Not significant, p>.05.	9
				Stress fracture		♂: Currently INJ Vs CON	4.5 ± 3.4	2.4 ± 3.1	Not significant, p>.05.	-47
	98	INJ: 44♀ CON: 54♀		MTSS		♀: Currently INJ Vs CON	4.2 ± 2.4	4.9 ± 3.0	Not significant, p>.05.	17
				Stress fracture		♀: Currently INJ Vs CON	4.2 ± 2.4	3.4 ± 2.9	Not significant, p>.05.	-19

Abbreviated terms: ♀= Female, ♂= Male, ND= Navicular Drop, INJ= injured, CON= control group, SD= Standard deviation, OR= Odds ratio, MTSS= Medial tibial stress syndrome, PFPS= Patellofemoral pain syndrome, ERLP- exercise related leg pain. Black shading indicates that greater navicular drop was associated with RRI.

*Where appropriate, a percentage difference between injured and uninjured values was calculated using the formula: (Injured mean-uninjured mean)/(Uninjured Mean)

2.3.3.2. The association between Foot Posture Index and RRI

The Foot Posture Index (FPI-6), developed by Redmond et al (2006), is a tool that examines both forefoot and rearfoot positioning; it is valuable as a relatively simple and equipment-free measure. This clinical tool rates six different measures of foot alignment, with higher scores indicative of more pronated foot posture and lower values indicative of a more supinated foot. In terms of synthesis of literature, a systematic review and meta-analysis by Tong and Kong (2013) found a significant association between non-neutral foot types and lower extremity injuries when using FPI (OR= 2.58; $CI_{95\%}$: 1.33- 5.02; p<.01), however it must be highlighted that this was in relation to lower limb injuries in general and not specific to those caused by running.

Due to the low number of studies investigating the FPI, retrospective research was included in this review. Two prospective and one retrospective studies have examined the association between FPI and general RRIs (Table 18), with two studies (67%) finding a significant association, with differences in the direction of the relationship. The prospective research, the largest study included 927 novice runners, found no risk differences after 250 km of running between participants with neutral feet and runners whose feet were highly supinated, supinated, pronated or highly pronated (Nohr *et al.*, 2013). However, significantly fewer RRIs among pronated runners were found per 1000 km of running compared to neutral feet (Nohr *et al.*, 2013), indicating that pronation may have a protective effect against injury in the presence of large volumes of running. In contrast, a large-scale retrospective study by Morcillo *et al.* (2019) found that among their cohort of novice runners (n=600), those with highly pronated feet had a 20-fold higher odds of injury than neutral FPI. Differences in results may have been due to the retrospective approach adapted by Morcillo *et al.* (2019). With regard to supination, one retrospective study found that highly supinated feet were associated with greater odds of RRI than feet with a neutral FPI score (Pérez-Morcillo *et al.*, 2019). Ramskov *et al.* (2013) was the only prospective study not to find an association between FPI and injury. However, this analysis only statistically examined runners with pronated and neutral feet (there were too few individuals classified as supinated or very pronated). Two prospective and one retrospective studies examined this relationship between FPI and specific RRIs (Table 19). All three studies found no association between RRIs and both exercise related lower leg pain (Ramskov *et al.*, 2013; Koldenhoven *et al.*, 2020) or PFPS (Thijs *et al.*, 2008).

In summary, it appears that there is inconsistent evidence to support an association between general RRI and FPI, with very limited evidence indicating that FPI is not associated with exercise related lower leg pain or PFPS. Interestingly, of all the studies, just one study examined recreational runners (Koldenhoven *et al.*, 2020), with four of six examining novice runners (Thijs *et al.*, 2008; Nohr *et al.*, 2013; Ramskov *et al.*, 2013; Pérez-Morcillo *et al.*, 2019). As such, further research involving recreational runners should be explored. As with navicular drop, the Foot

Table 18 Studies investigating the association between Foot Posture Index and general RRIs.

Authors	*n*	*Population*	*Type of Runner*	*Time Tracked*	*Groups compared*	*CON Mean ± SD*	*INJ Mean ± SD*	*Findings*
Prospective								
Nohr *et al.*, 2013	927	466♂, 461♀ 252 RRIs,	Novice	1 year	INJ vs CON	N/R	N/R	Pronated feet sustained significantly fewer injuries per 1000 km of running than neutral feet, p=.03.
Ramskov *et al.*, 2013	59	CON: 22♂, 24♀ INJ: 9♂, 4♀	Novice	10 weeks	INJ vs CON	6.0 ± 4.0	6.0 ± 3.0	No significant differences in cumulative relative risk between novice runners with pronated feet and neutral feet were found after 125 km of running (Cumulative relative risk = 1.65 [0.65; 4.17], p= 0.29).
Retrospective								
Pérez-Morcillo *et al.*, 2019	600	CON: 217♂, 83♀; INJ: 212♂, 88♀	Novice	N/A	Currently INJ vs CON	N/R	N/R	High supination was associated with 76.8 times higher odds of injury than a neutral FPI, p<.001. High pronation was associated with 20-fold higher odds of injury than neutral FPI, p<.001.

Abbreviated terms: ♀= Female, ♂= Male, FPI= Foot Posture Index, INJ= injured, CON= control group, SD= Standard deviation, OR= Odds ratio, N/R= not reported, N/A= not applicable. Black shading indicates that a significant association between FPI and injury was found. White shading indicates that no association was found.

Table 19 Studies investigating the association between Foot Posture Index and specific RRIs.

Authors	*n*	*Population*	*Type of Runner*	*Injury*	*Time Tracked*	*Groups compared*	*CON Mean ± SD*	*INJ Mean ± SD*	*Findings*	*Percentage Difference (%)*
Prospective										
Thijs *et al.*, 2008	102	13♂, 89♀ INJ:17 CON: 85	Novice	PFPS	10 weeks	INJ vs CON	N/R	N/R	Not significant, p>.05.	N/A
Reinking, Austin and Hayes, 2007	88	INJ: 60 CON: 28	Cross Country	ERLP	Cross country season	INJ vs CON	8.5	8.2	Not significant, p>.05.	-4
Retrospective										
Koldenhoven *et al.*, 2020	32	INJ: 8♂, 8♀ CON: 8♂, 8♀,	Recreational	ERLP	N/A	Currently INJ vs CON	4.9 ± 4.4	3.2 ± 2.7	Not significant, p>.05.	-30

Abbreviated terms: ♀= Female, ♂= Male, FPI= Foot Posture Index, INJ= injured, CON= control group, SD= Standard deviation, OR= Odds ratio, PFPS= Patellofemoral pain syndrome, ERLP- exercise related leg pain, N/R= not reported, N/A= not applicable. Black shading indicates that a significant association between FPI and injury was found. White shading indicates that no association was found.

Posture Index has some limitations, namely the static nature of this measure which may not accurately represent the position of the foot during running.

It has been hypothesised that the alignment of the foot may mitigate the upward directed forces at impact. However, there is limited kinematic and kinetic data to support or refute these assertions. Foot alignment has been studied in relation to lower limb vertical loading, with inconsistent findings. With respect to impact acceleration, it appears that tibial accelerations may not be significantly different between low and high arched runners (Nachbauer and Nigg, 1992; Barnes, Wheat and Milner, 2011), however, there is evidence to suggest that peak and rate of lumbar acceleration is lower among high arched runners (Ogon *et al.*, 1999). In relation to vertical ground reaction forces, there is mixed evidence to associate foot position with either loading rate (Nachbauer and Nigg, 1992; Hargrave *et al.*, 2003; Williams *et al.*, 2004; Lees, Lake and Klenerman, 2005) or peak ground reaction force (GRF) (Nachbauer and Nigg, 1992; Hargrave *et al.*, 2003; Lees, Lake and Klenerman, 2005). Nevertheless, functional foot alignment remains a key clinical measure theorised to be related to RRI and is a feature of many rehabilitation or prevention programmes via orthoses (Murley *et al.*, 2009; Warne *et al.*, 2021). Therefore, more research is required.

2.3.4. The association between lower limb muscle strength and RRI

Muscle strength is theorised to be implicated in the aetiology of RRIs. As the mediators of joint movement, muscles contract in a coordinated manner to control motion (Perry and Burnfield, 1992; Hamner, Seth and Delp, 2010). They are also pivotal in the weight acceptance phase of running in the attenuation of forces at impact (Coventry *et al.*, 2006). Unsurprisingly, considering their role in generating muscle torque, injuries involving the musculotendon unit are one of the most commonly cited RRIs (Hespanhol Junior, Pena Costa and Dias Lopes, 2013). Often injuries result in weakness and loss of function (Brumitt and Cuddeford, 2015), with muscle strength being proposed as an intrinsic risk factor for reinjury. Muscle strengthening has been incorporated into many rehabilitation programmes (Kozinc and Šarabon, 2017) and has been proposed as a factor requiring assessment prior to return to play in injury models (Creighton *et al.*, 2010). Furthermore, a positive correlation has been found between muscle strength and bone health (Torres-Costoso *et al.*, 2020), meaning that it may reflect the strength of underlying tissue.

Several methods are available to measure muscle strength. While isokinetic dynamometry is commonly considered the gold standard, it is cumbersome, expensive and time-consuming. Handheld dynamometry (HHD) is a low cost and portable alternative whereby the participant exerts a maximal isometric force against an unmoving dynamometer (Bohannon, 2019). A systematic review and meta-analysis of seventeen studies comparing HHD and isokinetic testing found differences between the testing methods to be minimal (Stark *et al.*, 2011). Therefore, with consideration of its practicality in a clinical setting, this review focuses on HHD and the literature surrounding this mode of muscle strength measurement. Due to the low numbers of studies investigating HHD and RRIs, retrospective research is included in some reviews (plantar flexion strength), where necessary.

2.3.4.1. The association between hip abduction strength and RRI

The strength of the hip abductor group is the most frequently investigated in relation to general RRIs, but only two prospective studies have been completed (Table 30). There is moderate evidence to suggest that no association exists. Both a 16-week prospective study by Torp *et al.* (2018) and a 24-week prospective study by Veras *et al.* (2020) found no significant difference in muscle strength between injured and uninjured runners.

Five prospective studies investigated the association between hip abduction strength and specific RRIs, with three studies finding significant, but somewhat contrasting, associations (Table 31). Of these, one found significantly lesser (30%) muscle strength to be associated with MTSS (Becker, Nakajima and Wu, 2018) and one found those in the weakest tertile had proportionally greater shin and anterior knee pain (Luedke *et al.*, 2015). However, one study found 22% greater hip abduction strength in runners with prospective knee injuries (Finnoff *et al.*, 2011). The remaining two prospective studies did not find an association between injury and hip abduction strength (Table 31). Among these is a study by Yagi et al. (2013), which is one of the largest prospective studies investigating hip abduction strength (n=230) and RRI. These authors did not find a link between stress fractures or MTSS and hip abduction strength. This may be due to the fact that this study investigated high school runners, and hip strength was inappropriately not normalised to body mass or height, which are confounders of muscle strength (Jaric, 2002).

The association between lower hip abduction strength and injury has also been attributed to the role of the gluteal muscles in maintaining knee position. Decreased gluteal strength has been theorised to be related to both excesses in valgus and varus knee positions (Powers, 2010). During gait, the gluteal muscles function to stabilise the pelvis during single limb stance (Gottschalk, Kourosh and Leveau, 1989). Gluteal weakness of the stance leg may lead to contralateral pelvic drop, causing a shift in centre of mass away from the stance limb (Figure 5). This may in turn lead to a shift in the resultant overall ground reaction force vector, leading to greater knee varus moment, potentially increasing compressive forces and tensile strain on lateral structures such as the iliotibial band (Powers, 2010). Conversely, in an effort to compensate for hip abductor weakness the centre of mass can be shifted over the stance limb during single leg support, creating a valgus moment at the knee, potentially leading to injury

(Powers, 2010). This has been validated using electromyography, finding that weakness of gluteal muscles is significantly related to dynamic valgus during single leg ballistic tasks (Dix *et al.*, 2019).

Table 30 Prospective studies investigating isometric hip abduction strength by hand held dynamometry and general running related injuries.

Authors	***n***	***Population***	***Type of Runner***	***Time Frame***	***CON Mean ± SD***	***INJ Mean ± SD***	***Unit***	***Findings***	***Percentage Difference (%)***
Torp *et al.*, 2018	50	INJ: 15♀ CON: 35♀	Recreational	16 weeks	1.2 ± 0.3	1.1 ± 0.3	Nm/kg*m	Not significant, p>.05.	-8.3
Veras *et al.*, 2020	37	INJ: 3♂, 7♀ CON: 13♂, 14♀	Treadmill	24 weeks	20.3 ± 4.1	17.8 ± 3.5	Kgf/kg	Not significant, p>.05.	-12.3

Abbreviated Terms: n= number of participants, CON= control, INJ= injured, ♂= males, ♀= females SD= standard deviation. Black shading indicates that greater strength was associated with injuries. Grey shading indicates that lower strength was associated with injuries. White shading indicates that no association was found.

Table 31 Prospective studies investigating isometric hip abduction strength as measured by hand-held dynamometry and specific running related injuries.

Authors	***n***	***Population***	***Type of Runner***	***Injury***	***Time Frame***	***Group Comparison***	***CON Mean ± SD***	***INJ Mean ± SD***	***Unit***	***Findings***	***Percentage Difference (%)***
Becker, Nakajima and Wu, 2018	28	INJ: 7 CON: 11	Cross country	MTSS	2 years	INJ vs CON	23.0 ± 5.5	16.0 ± 3.6	N/kg	Lower strength among INJ group, p<.001.	-30
Luedke *et al.*, 2015	68	INJ: 6♀, 10♂ CON: 41♀, 11♂	Cross country	Shin injury, AKP	Cross country season	Weakest tertile vs strongest tertile	N/R	N/R	Nm/kg	Lower strength among INJ group, p-=.046.	N/R
Finnoff *et al.*, 2011	98	INJ: 2♂, 3♀ CON: 61♂, 41♀	High school	Knee Pain	Running season	NJ vs CON	2.6 ± 0.5	3.1 ± 0.6	% BW X h	Greater among INJ group, p<.01. OR= 5.35, p<0.01.	19
Thijs *et al.*, 2011	75	INJ: 16♀ CON: 61♀	Novice recreational	PFPS	10 week	INJ vs CON	2.9 ± 0.6	2.8 ± 0.7	Nm/kg	Not significant, p>.05.	-3

Becker, Nakajima and Wu, 2018	230	INJ: 44♀ CON: 61♀	High school	Stress Fractures	3 years	NJ vs CON= SF	161.4 ± 4.2	195.0 ± 11.3	N	Not significant, p>.05.	21
				MTSS		INJ vs CON= MTSS F	209.2 ± 37.5	221.6 ± 40.9	N	Not significant, p>.05.	6
		INJ: 58♂ CON: 88♂		Stress Fractures		INJ vs CON= SF ♂	209.2 ± 37.5	201.8 ± 9.1	N	Not significant, p>.05.	-4
				MTSS		NJ vs CON= MTSS ♂	161.4 ± 42	169.2 ± 25.2	N	Not significant, p>.05.	5

Abbreviated Terms: n= numberof participants,, CON= control, INJ= injured, ♂= males, ♀= females SD= standard deviation, AKP= anterior knee pain, N/R= not reported, N/A= not applicable, MTSS=medial tibial stress syndrome PFPS= patellofemoral pain syndrome, SF= stress fracture. Black shading indicates that greater strength was associated with injuries. Grey shading indicates that lower strength was associated with injuries. White shading indicates that no association was found.

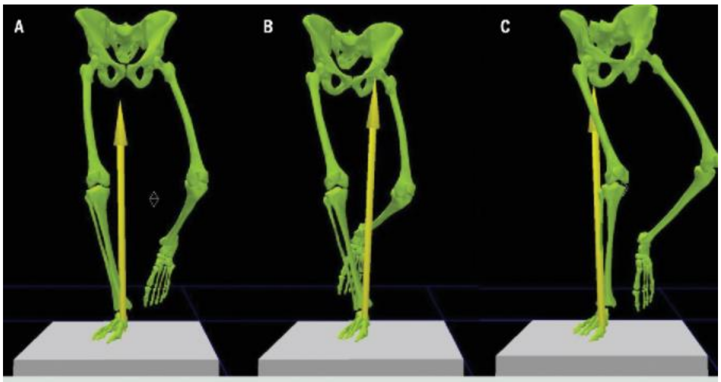

Figure 3 Diagram demonstrating the effect of proximal control on knee moment. (A) shows a pelvis level, with the resultant medially directed GRF vector creating a varus moment at the knee. (B) shows contralateral pelvic drop as a result of hip abductor weakness, with the resultant shift in centre of mass creating a varus moment at the knee. (C) shows pelvic drop as a result of hip abductor weakness, with the compensatory shift in centre of mass creating a valgus moment at the knee. (Powers, 2003).

In summary, the evidence to support the association between hip abduction muscle strength and general and specific RRIs inconsistent.

2.3.4.2. The association between hip extension strength and RRI

Isometric hip extension strength has been investigated in relation to general (Table 22) and specific RRIs (Table 23). Two prospective studies (Torp *et al.*, 2018; Veras *et al.*, 2020) found no association to exist between isometric hip extension strength and general RRIs. In terms of specific injuries, three prospective studies investigating knee pain (Finnoff *et al.*, 2011), PFPS (Thijs *et al.*, 2011) and MTSS (Becker, Nakajima and Wu, 2018) also found no significant association. This is somewhat surprising given that lower hip extensor strength has been related to greater frontal and transverse plane hip motion among long distance runners (Taylor-Haas *et al.*, 2014) and increases in hip internal rotation in a cohort of runners with PFPS (Souza and Powers, 2009); with these kinematics considered to be potentially injury-inducing among runners (Taylor-Haas *et al.*, 2014). A limitation of these three prospective studies however is the small sample size, with the largest study including just 98 runners (Finnoff *et al.*, 2011). Larger studies may strengthen our confidence in an association, or lack thereof, between hip extension strength and RRIs.

Table 22 Prospective studies investigating the association between hip extension isometric muscle strength and general running related injuries.

Authors	***n***	***Population***	***Type of Runner***	***Time Frame***	***CON Mean ± SD***	***INJ Mean (SD)***	***Unit***	***Findings***	***Percentage Difference (%)***
Torp *et al.*, 2018	50	INJ: 15♀ CON: 35♀	Recreational	16 weeks	0.71 ± 0.23	0.71 ± 0.13	Nm/kg*m	Not significant, p>.05.	0
Veras *et al.*, 2020	37	INJ: 3♂, 7♀ CON: 13♂, 14♀	Treadmill	24 weeks	20.2 ± 6.0	19.6 ± 4.3	Kgf/kg	Not significant, p>.05.	-3

Abbreviated Terms: n= number of participants, CON= control, INJ= injured, ♂= males, ♀= females SD= standard deviation. Back shading indicates that greater strength was associated with injuries. Grey shading indicates that lower strength was associated with injuries.

Table 23 Prospective studies investigating the association between hip extension isometric muscle and specific running related injuries.

Authors	***n***	***Population***	***Type of Runner***	***Time Frame***	***Injury***	***CON Mean ± SD***	***INJ Mean ± SD***	***Unit***	***Findings***	***Percentage Difference (%)***
Finnoff *et al.*, 2011	98	INJ: 2♂, 3♀ CON: 61♂, 41♀	High school athletes	Running season	Knee Pain	3.15 ± 0.79	2.87 ± 0.79	% BW X h	Not significant, p>.05.	-9
Thijs *et al.*, 2011	75	INJ: 16♀ CON: 61♀	Novice recreational	10 weeks	PFPS	4.25 ± 1.17	3.95 ± 1.55	Nm/kg	Not significant, p>.05.	-7
Becker, Nakajima and Wu, 2018	28	INJ: 7 CON: 11	Cross country	2 years	MTSS	20.02 ± 7.07	24.46 ± 9.44	N/kg	Not significant, p>.05.	22

Abbreviated Terms: n= number of particpants, CON= control, INJ= injured, ♂= males, ♀= females SD= standard deviation, AKP= anterior knee pain, N/R= not reported, N/A= not applicable, ITBS= iliotibial band syndrome, PFPS= patellofemoral pain syndrome, OR= odds ratio. Black shading indicates that greater strength was associated with injuries. Grey shading indicates that lower strength was associated with injuries.White shading indicates that no association was found.

2.3.4.3. The association between knee extension strength and RRI

Knee extension strength has been proposed to be associated with RRIs for two main reasons. Firstly, the quadriceps muscles serve an important role in shock absorption and preparation for ground contact (Novacheck, 1998). Secondly, knee extensor weakness, in particular deficits of the vastus medialus oblique, is thought to lead to lateral displacement of the patella and has been proposed to be involved in the development of common RRIs such as PFPS (Waryaz and McDermott, 2008). However, two prospective studies investigated general RRIs and knee extension strength, finding no association (Torp *et al.*, 2018; Veras *et al.*, 2020) (Table 24). In terms of specific RRIs, evidence is very limited, with one prospective study finding decreased strength among runners with shin and knee pain (Luedke *et al.*, 2015) (Table 24).

2.3.4.4. The association between knee flexion strength and RRI

The hamstrings, in conjunction with the gluteal muscles, aid hip extension during the latter half of swing and early stance, as well as decelerating the tibia prior to initial contact (Novacheck, 1998). The percentage incidence of hamstring RRIs is relatively high at 10.9% (Lopes *et al.*, 2012). These muscles may be particularly vulnerable to injury with increasing speeds (Chumanov, Heiderscheit and Thelen, 2011) as they transition from contracting eccentrically to decelerate the knee during late swing, to concentrically contracting to extend the hip joint. Only one prospective study investigated the association between knee flexion strength and general RRIs, finding no association (Torp *et al.*, 2018) (Table 24). In terms of specific RRIs, evidence is very limited; finding prospective anterior knee pain, but not shin injuries, to be associated with decreased knee flexion strength (Luedke *et al.*, 2015).

2.3.4.5. The association between plantar flexion strength and RRI

Plantar flexion strength appears not to have been commonly studied via HHD, possibly due to difficulty with positioning posed by the large forces applied by this muscle group. However, plantar flexor strength may be important due to the high proportion of lower leg RRIs (Buist, Bredeweg, Bessem, *et al.*, 2010; Van Der Worp *et al.*, 2016), as well as the high contributions of the soleus and gastrocnemius muscles during running, particularly in the push off phase of gait (Hamner, Seth and Delp, 2010). Due to the presence of just one retrospective study investigating RRI and HHD (Ferreira *et al.*, 2020), research involving isokinetic dynamometry was included in this review of literature. With reference to the single study using HHD, authors found an association between AT (Achilles tendon) injury and ankle plantar flexor torque below 0.76 Nm/kg and combined passive hip internal rotation ROM below 29.3 degrees (Ferreira *et al.*, 2020). In terms of isokinetic testing, plantar flexion strength has been measured in seven studies (Table 25). Just one

Table 24 Prospective studies investigating the association between knee flexion and knee extension strength and general RRIs.

Authors	***n***	***Population***	***Type of Runner***	***Time Frame***	***Injury***	***Groupings***	***Finding***	***CON Mean ± SD***	***INJ Mean ± SD***	***Unit***	***Percentage Difference (%)***
Knee Flexion- General RRIs											
Torp *et al.*, 2018	50	INJ: 15♀ CON: 35♀	Recreational	16 weeks	General RRI	INJ vs CON	Not significant, p>.05.	0.54 ± 0.12	0.53 ± 0.11	Nm/kg*m	-2
Luedke *et al.*, 2015	68	INJ: 6♀, 10♂ CON: 41♀, 11♂	Cross country	Shin injury, AKP	Cross country season	Weakest tertile vs strongest tertile	Lower strength among AKP group, p-=.046	N/R	N/R	Nm/kg.	N/R
Knee Extension- General RRIs											
Torp *et al.*, 2018	50	INJ: 15♀; CON: 35♀	Recreational	16 weeks	General RRI	INJ vs CON	Not significant, p>.05.	1.13 ± 0.25	1.02 ± 0.25	Nm/kg	-10
Veras *et al.*, 2020	37	INJ: 3♂, 7♀; CON: 13♂, 14♀	Treadmill	24 weeks	General RRI	INJ vs CON	Not significant, p>.05.	45.3 ± 11.0	47.1 ± 16.4	Kgf/kg	4

Abbreviated Terms: n=number of participants, CON= control, INJ= injured, ♂= males, ♀= females SD= standard deviation, AKP= anterior knee pain, N/R= not reported, RRI= running related injuries. Black shading indicates that greater strength was associated with injuries. Grey shading indicates that lower strength was associated with injuries. White shading indicates that no association was found.

Table 25 Studies investigating the association between plantar flexion strength and RRI

Authors	*n*	*Population*	*Type of Runner*	*Injury*	*Tracking Time*	*Groupings*	*Unit*	*CON Mean ± SD*	*INJ Mean ± SD*	*Findings*	*Percentage difference (%)*
General RRI- Concentric Strength											
Prospective											
Messier et al., 2018	300	INJ: 199, CON: 101	Recreational	General RRI	2 years	INJ vs CON	Nm	40.8 ± 15.1	40.6 ± 14.9	Not significant, p>.05.	-1
Specific RRI- Concentric Strength											
Retrospective											
Kibler, Goldberg and Chandler, 1991	87	INJ: 32♂, 11♀; CON: 44	Running athletes	Plantar fasciitis	N/A	INJ vs CON legs		N/R	N/R	Lower strength among INJ legs, p<.01.	N/R
					N/A	INJ vs CON		N/R	N/R	Lower strength among INJ runners, p<.01.	N/R
Pamukoff and Blackburn, 2015	38	INJ: 19♂; CON: 19♂	Endurance athletes	TSF	N/A	Hx of stress fracture vs no hx	N/kg	5.1 (4.3,5.8)	6.0 (5.4, 6.6)	Not significant, p>.05.	N/R
Annuar et al., 2021	88	INJ: 44♂; CON: 44♂	Recreational	AT	N.A	Current INJ vs CON	Kg/BW	1.50 ± 0.20	1.27 ± 0.17	Lower strength among INJ, p<.001.	-15%
Haglund-Åkerlind and Eriksson, 1993	40	INJ: 20; CON: 20	Recreational	AT	N/A	Hx of INJ vs no Hx of INJ	Nm	140.0 ± 15.2	122.4 ± 20.1	Lower strength among INJ runners, p<.05	18
McCrory et al., 1999	89	INJ: 31; CON: 58	Recreational and competitive	AT	N/A	Currently INJ vs CON	N/R	N/R	N/R	Lower strength among INJ runners, p=.008	-13
Specific RRI- Isometric Strength											
Retrospective											
Saeki et al., 2017	37	INJ: 15♂, CON: 12♂	Collegiate	MTSS	N/A	Currently INJ vs CON	Nm	84.2 ± 28.2	92.2 ± 28.2	Not significant, p>.05.	10

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, AT= Achilles tendon injury, *TSF= tibial stress fractures,* MTSS= medial tibial stress syndrome, N/A= not applicable, N/R=not reported, Hx= history. Black shading indicates that greater strength was associated with injuries. Grey shading indicates that lower strength was associated with injuries. White shading indicates that no association was found.

of these studies was prospective, finding no significant difference between concentric muscle strength and general RRI (Messier *et al.*, 2018). Retrospectively, four of the five (80%) studies investigating concentric muscle strength and specific RRIs found a significantly lower plantar flexor muscle strength among runners with plantar fasciitis (Kibler, Goldberg and Chandler, 1991) and Achilles tendon pain (Haglund-Åkerlind and Eriksson, 1993; McCrory *et al.*, 1999; Annuar *et al.*, 2021). No association was found between concentric plantar flexion strength and retrospective tibial stress fractures (Pamukoff and Blackburn, 2015), or isometric plantar flexion strength and retrospective MTSS (Saeki *et al.*, 2017). In summary, there is moderate evidence to suggest that there is an association between retrospective Achilles tendon issues among runners and lower plantar strength, with insufficient evidence to support any other conclusions.

2.3.5.The association between lower limb range of motion and RRI

Range of motion (ROM) is governed by the viscoelasticity of muscle, ligaments, and other connective tissue (Corbin and Noble, 1980). It has been theorised that both insufficient and excessive ROM may increase the risk of injury for four primary reasons. Firstly, it has been proposed that excessively short muscles, culminating in reduced ROM, are more likely to overstretch and exceed their normal ROM, exposing them to injury (Batt, 2005). Secondly, reduced ROM may increase stress on joints (Buist, Bredeweg, Lemmink, *et al.*, 2010), as it is theorised that flexible joints can withstand a greater amount of 'stress of torque' before injury, compared to relatively stiff joints (Arnheim and Klafs, 1985). Thirdly, a ROM beyond an ideal range may lead to instability of the joint (Corbin and Noble, 1980). Large amounts of joint motion may potentially increase demands on stabilising muscles (Cannon, Finn and Yan, 2018). Finally, adaptive shortening or lengthening of muscles over time may also place muscles at non-optimal lengths, limiting their functional ability (Kendall *et al.*, 2005). However, to date, increasing flexibility via stretching has not been proven to be successful in injury prevention in relation to sports in general (Thacker *et al.*, 2004) and there is largely inconsistent evidence to suggest that ROM is associated with RRIs (reviewed below).

2.3.5.1. The association between dorsiflexion range of motion and RRI

It is proposed that decreased dorsiflexion ROM may cause a compensatory increase in pronation to achieve forefoot contact with the ground (Becker *et al.*, 2017). This, in turn, is thought to increase the force applied on adjacent structures (Becker *et al.*, 2017). In addition to this, in landing studies it has been found that greater dorsiflexion ROM is associated with decreased ground reaction forces which may have implications for injury risk reduction (Fong *et al.*, 2011). Reduced dorsiflexion has been suggested to be related to specific RRIs such as MTSS, due to increases in anteromedial tibial loading (Franklyn and Oakes, 2015), and

Achilles tendon injury via increased absorption of impact forces by plantar flexor muscle-tendon units (Whitting *et al.*, 2011).

The association between dorsiflexion ROM and general RRIs was examined in three prospective studies, with none of them finding significant differences between injured and uninjured runners (Lun *et al.*, 2004; Buist, Bredeweg, Lemmink, *et al.*, 2010; Jungmalm *et al.*, 2020) (Table 26). One important note is that none of these examined dorsiflexion range with the weight bearing lunge test which may be more reflective of sagittal plane motion during running (Barrett and Caulfield, 2008).

The association between dorsiflexion ROM and specific RRIs has been examined in five prospective studies which investigated stress fractures (Yagi, Muneta and Sekiya, 2013), MTSS (Hubbard, Carpenter and Cordova, 2009; Yagi, Muneta and Sekiya, 2013; Becker, Nakajima and Wu, 2018), AT injury (Hein *et al.*, 2014) and PFPS (Lun *et al.*, 2004); with PFPS being the only injury in which significantly smaller values of dorsiflexion were related to injury (Table 27). However, it must be noted that this finding was in a small sample (n=6) and only significant on one side of the body.

In summary, there is moderate to strong evidence to suggest that dorsiflexion range is not related to general RRIs or MTSS. It must also be noted that different methodologies were employed within the studies, with some choosing to assess seated passive range of motion, some using the weight bearing lunge test and some assessing supine range of motion. Heterogeneity in these methods may limit the above comparison of studies.

Table 26 Prospective studies investigating the association between dorsiflexion range of motion and general running related injuries.

Authors	*n*	*Population*	*Type of Runner*	*Tracking Time*	*Method*	*Groupings*	*CON Mean ± SD(°)*	*INJ Mean ± SD(°)*	*Findings*	*Percentage Difference (%)*
Lun *et al.*, 2004	87	CON: 18; INJ: 35♂; 34♀	Recreational	6 months	Supine lying, passive	INJ vs CON	11.8 ± 2.5	12.6 ± 4.8	Not significant, p>.05.	7
							12.0 ± 3.7	12.3 ± 4.6	Not significant, p>.05.	3
Jungmalm *et al.*, 2020	224	CON: 55, INJ: 179	Recreational	52 weeks	N/R	INJ vs CON	N/R	N/R	Not significant, p>.05.	N/R
Buist, Bredeweg, Lemmink, *et al.*, 2010	532	226♂ and 306♀; 100 RRIs	Novice	13 weeks	Supine lying, passive	INJ vs CON	N/R	N/R	Not significant, p>.05.	N/R

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, PF= plantar flexion, DF= dorsiflexion, ROM= range of motion, Hx= history, N/R=not reported. Black shading indicates that greater ROM was associated with injuries. Grey shading indicates that lower ROM was associated with injuries. White shading indicates that no association was found.

Table 27 Prospective studies investigating the association between ankle dorsiflexion ROM and specific running related injuries.

Authors	***n***	***Population***	***Type of Runner***	***Injury***	***Tracking Time***	***Method***	***Groupings***	***CON Mean ± SD(°)***	***INJ Mean ± SD(°)***	***Findings***	***Percentage Difference (%)***
Lun *et al.*, 2004	87	INJ: 6; CON: 18	Recreational	PFPS	6 months	Supine lying, passive	CON vs INJ	6.1	0.3	Significant difference between groups, p<0.05.	-95
Yagi, Muneta and Sekiya, 2013	95	CON: 88♂, INJ: SF: 7♂	High school	SF	3 years	N/R, passive	CON vs INJ ♂	10.7 ± 4.6	9.0 ± 1.4	Not significant, p>.05.	-16
	146	CON: 88♂, INJ: MTSS: 58♂		MTSS				10.7 ± 4.6	11.2 ± 4.3	Not significant, p>.05.	5
	68	CON: 54♀; INJ: SF: 14♀		SF			CON vs INJ ♀	10.9 ± 4.2	10.3 ± 6.8	Not significant, p>.05.	-6
	98	CON: 54♀; INJ: MTSS: 44♀		MTSS				10.9 ± 4.2	10.8 ± 4.9	Not significant, p>.05.	-1
	95	CON: 88♂, INJ: SF: 7♂		SF			CON vs INJ ♂	22.1 ± 6.4	21.5 ± 2.1	Not significant, p>.05.	-3
	146	CON: 88♂, INJ: MTSS: 58♂		MTSS				22.1 ± 6.4	22.5 ± 5.0	Not significant, p>.05.	2
	68	CON: 54♀; INJ: SF: 14♀		SF			CON vs INJ ♀	21.4 ± 5.3	18.3 ± 2.9	Not significant, p>.05.	-15
	98	CON: 54♀; INJ: MTSS: 44♀		MTSS				21.4 ± 5.3	21.2 ± 5.3	Not significant, p>.05.	-2
Hubbard, Carpenter and Cordova, 2009	146	65♂, 81♀ CON: 177; INJ: 29	College athletes	MTSS	Cross country season	Seated, active	CON vs INJ	21.9 ± 7.4	21.0 ± 5.5	Not significant, p>.05.	-4
Becker, Nakajima and Wu, 2018	18	INJ: 4♂, 3♀; CON: 5♀, 6♂	Competitive	MTSS	2 years	Prone, active	CON vs INJ	14.4 ± 5.7	15.0 ± 6.2	Not significant, p>.05.	4
Hein *et al.*, 2014	142	INJ: 8♂, 2♀ CON: 8♂, 2♀	Recreational	AT	1 year	Active, knee flexed	INJ vs CON	N/R	N/R	Not significant, p>.05.	N/R

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, PF= plantar flexion, DF= dorsiflexion, ROM= range of motion, Hx= history, MTSS= medial tibial stress syndrome, AT- Achilles tendinopathy, MTSS= medial tibial stress syndrome. Black shading indicates that greater ROM was associated with injuries. Grey shading indicates that lower ROM was associated with injuries. White shading indicates that no association was found.

2.3.5.2. The association between hip external rotation range of motion and RRI

It has been suggested that both insufficient or excessive hip rotation ROM may increase the impact load during running or lead to alterations of the femoral angle, resulting in increased torque on the lower leg (Winkelmann *et al.*, 2016). The association between hip external rotation range and general RRIs was examined in two prospective studies (Buist, Bredeweg, Lemmink, *et al.*, 2010; Jungmalm *et al.*, 2020), with neither finding a significant association to exist (Table 28). With reference to specific RRIs, two prospective studies investigating MTSS (Yagi, Muneta and Sekiya, 2013; Becker, Nakajima and Wu, 2018) and one prospectively investigating Achilles tendon injuries (Hein *et al.*, 2014) found no association between hip external rotation ROM and RRIs (Table 29). Therefore, there is moderate evidence to suggest that hip external rotation ROM is not associated with general RRIs or MTSS.

2.3.5.1. The association between hip internal range of motion and RRI

Four prospective studies investigated hip internal range of motion and general RRIs (Table 28), finding no significant association between RRI and this measure. In relation to specific RRIs, hip internal rotation ROM has been studied in two prospective studies (Table 29). Of these, both Yagi *et al.* (2013) and Becker *et al.* (2018) investigated the association between MTSS and hip internal rotation, finding no significance between injured and uninjured groups. However, when sub-analysed by sex, Yagi et al (2018) found females with MTSS to have significantly greater internal rotation than uninjured controls. This was theorised to be related to hip range of motion contributing to changes in medial tibial loading, although this suggestion has not been thoroughly investigated. No significant prospective association was found for stress fractures (Yagi, Muneta and Sekiya, 2013).

2.3.5.1. The association between hip extension range of motion and RRI

Reduced hip extension range may heighten the risk of strain on the anterior hip muscles and tissue around the hip joint, particularly at the point of peak extension range at toe off (Novacheck, 1998). One prospective study investigated the association between hip extension range of motion and general RRI, finding no association (Jungmalm *et al.*, 2020). Similarly, no association was found among the two prospective studies examining AT injury (Hein *et al.*, 2014) and MTSS (Becker, Nakajima and Wu, 2018) (Table 30).

In summary, with regard to the association between clinical tests and RRI, the evidence to date is largely inconsistent. This is in agreement with a recent systematic review and metanalysis of prospective studies investigating clinical tests (Peterson *et al.*, 2022) and a previous systematic review (Christopher *et al.*, 2019). Highlighted in these studies, and this review of literature, was the low number of prospective studies investigating these factors.

Table 28 Prospective studies investigating the association between hip rotation range of motion and general RRIs.

Authors	*n*	*Population*	*Type of Runner*	*Tracking duration*	*CON Mean ± SD (°)*	*INJ Mean ± SD (°)*	*Findings*	*Percentage Difference (%)*
Hip External Rotation								
Buist, Bredeweg, Lemmink, *et al.*, 2010	532	226♂ and 306♀; 100 RRIs	Novice	13 weeks	N/R	N/R	Not significant, p>.05.	N/R
					N/R	N/R	Not significant, p>.05.	N/R
Jungmalm *et al.*, 2020	224	CON: 55, INJ: 179	Recreational	1 year	N/R	N/R	Not significant, p>.05.	N/R
Hip Internal Rotation								
Jungmalm *et al.*, 2020	224	CON: 55, INJ: 179	Recreational	1 year	N/R	N/R	Not significant, p>.05.	N/R
Lun et al 2004	87	CON: 18; INJ: 35♂; 34♀	Recreational	6 months	42.1 ± 8.8	35.2 ± 9.5	Not significant, p>.05.	-16
	87	CON: 18 INJ: 35♂; 34♀	Recreational		36.6 ± 7.9	7.5 ± 3.5	Not significant, p>.05.	-80
Veras *et al.*, 2020	37	INJ: 3♂, 7♀ CON: 13♂, 14♀	Treadmill	24 weeks	38.2 ± 9.9	34.3 ± 8.9	Not significant, p>.05.	-10
Buist et al 2010	486	100 RRIs out of 486 ♂ and ♀ runners	Novice	13 weeks	N/R	N/R	Not significant, p>.05.	N/R

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, IR= internal rotation, ER= external rotation, ROM= range of motion, Hx= history. Black shading indicates that greater ROM was associated with injuries. Grey shading indicates that lower ROM was associated with injuries. White shading indicates that no association was found.

Table 29 Prospective studies investigating the association between hip rotation range of motion and specific RRIs.

Authors	*n*	*Population*	*Type of Runner*	*Injury*	*Group Comparison*	*CON Mean ± SD (°)*	*INJ Mean ± SD (°)*	*Findings*	*Percentage Difference (%)*
Hip internal rotation									
Yagi *et al.* 2013	230	CON: 88♂, 54♀; INJ: MTSS: 58♀, 44♂ SF: 7♂; 14♀	High school	SF ♀	INJ vs CON	35.1 ± 9.0	43.3 ± 2.9	Not significant, p>.05.	23
	230	CON: 88♂, 54♀; INJ: MTSS: 58♂, 44♂ SF: 7♂; 14♀		MTSS ♂	INJ vs CON	39.7 ± 8.8	44.5 ± 8.9	Not significant, p>.05.	12
	230	CON: 88♂, 54♀; INJ: MTSS: 58♂, 44♂ SF: 7♂; 14♀		SF ♂	INJ vs CON	39.7 ± 8.8	40.0 ± 14.1	Not significant, p>.05.	1
	230	CON: 88♂, 54♀; INJ: MTSS: 58♂, 44♂ SF: 7♂; 14♀		MTSS ♀	INJ vs CON	35.1 ± 9.0	37.4 ± 8.5	Not significant, p>.05.	7
Becker *et al.*, 2018	18	INJ: 4♂, 3♀; CON: 5♀, 6♂	Competitive	MTSS	INJ vs CON	43.8 ± 11.1	42.5 ± 6.9	Not significant, p>.05.	-3
Hein *et al.*, 2014	142	INJ: 8♂, 2♀ CON: 8♂, 2♀	Recreational	AT	INJ vs CON	N/R	N/R	Not significant, p>.05.	N/R
Hip internal rotation									
Yagi *et al.* 2013	95	CON: 88♂, INJ: SF: 7♂	High school	SF	INJ vs CON ♂	12.4 ± 8.7	7.5 ± 3.5	Not significant, p>.05.	-40
	146	CON: 88♂, INJ: MTSS: 58♂	High school	MTSS		12.4 ± 8.7	12.9 ± 5.8	Not significant, p>.05.	4
	68	CON: 54♀; INJ: SF: 14♀	High school	SF	INJ vs CON ♀	25.5 ± 9.5	20.7 ± 7.6	Not significant, p>.05.	-19
	98	CON: 54♀; INJ: MTSS: 44♀	High school	MTSS		25.5 ± 9.5	31.1 ± 9.9	Significantly greater among injured runners, p<0.05. OR=0.91, p=0.02.	22
Becker *et al.*, 2018	18	INJ: 4♂, 3♀; CON: 5♀, 6♂	Competitive	MTSS	INJ vs CON	35.1 ± 10.7	39.0 ± 10.3	Not significant, p>.05.	11
Hein *et al.*, 2014	142	INJ: 8♂, 2♀ CON: 8♂, 2♀	Recreational	AT	INJ vs CON	N/R	N/R	Not significant, p>.05.	N/R

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, IR= internal rotation, ER= external rotation, ROM= range of motion, Hx= history, MTSS= medial tibial stress syndrome, ERLP- exercise related leg pain, SF= stress fracture, AT= Achilles tendinopathy, MTSS- medial tibial stress syndrome. Black shading indicates that greater ROM was associated with injuries. Grey shading indicates that lower ROM was associated with injuries. White shading indicates that no association was found.

Table 30 Prospective studies investigating the association between hip extension ROM and specific or general RRIs.

Study	***n***	***Population***	***Type of Runner***	***Injury***	***CON Mean ± SD (°)***	***INJ Mean ± SD (°)***	***Findings***	***Percentage Difference (%)***
Jungmalm e al., 2020	224	CON: 55, INJ: 179	Recreational	General RRIs	N/R	N/R	Not significant, p>.05.	N/R
Hein *et al.*, 2014	142	INJ: 8♂, 2♀ CON: 8♂, 2♀	Recreational	AT	N/R	N/R	Not significant, p>.05.	N/R
Becker *et al.*, 2018	18	INJ: 4♂, 3♀ CON: 5♀, 6♂	Competitive	MTSS	-9.3 ± 4.8	-11.8 ± 8.1	Not significant, p>.05.	27

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, PF= plantar flexion, DF= dorsiflexion, ROM= range of motion, Hx= history, AT= Achilles tendon pain, MTSS- medial tibial stress syndrome, N/R= not reported. Black shading indicates that greater ROM was associated with injuries. Grey shading indicates that lower ROM was associated with injuries. White shading indicates that no association was found.

2.4. Overview of the running gait cycle

Running is a cyclic activity which can be broken into units of measurement called gait cycles (Perry and Burnfield, 1992), which is defined as the period which begins with one foot making contact with the ground and ends with the consecutive contact of that same foot with the ground (King, 2020). Stance is the period during which at least one foot makes contact with the ground. Swing phase begins at toe off and denotes the period when the foot is off the ground and the limb is advancing (Perry and Burnfield, 1992). The running cycle is characterised by swing time in excess of 50% of the cycle (Novacheck, 1998), with the overlap in swing phases resulting in periods of double float, in which both feet are simultaneously suspended in the air (Novacheck, 1998; Dugan and Bhat, 2005). The running gait cycle is described in Figure 4.

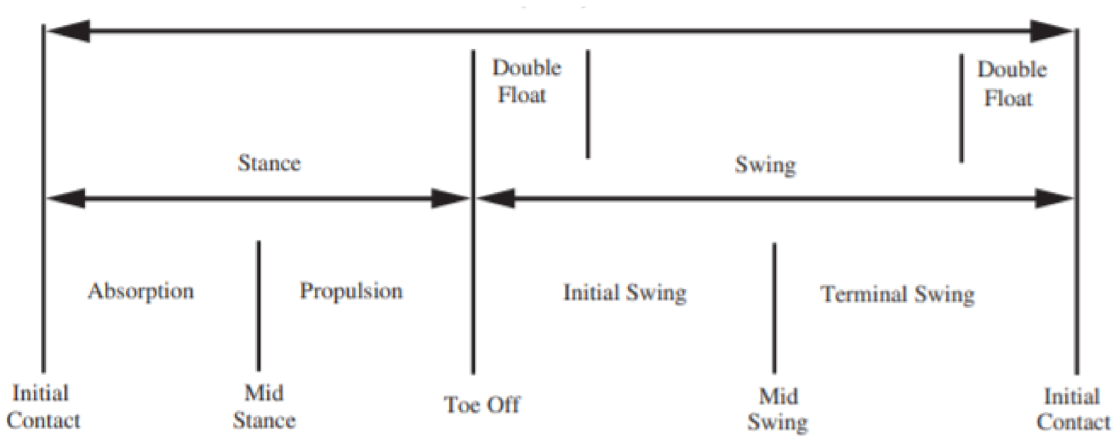

Figure 4 The running gait cycle. (Dugan and Bhat, 2005)

2.5. The association between loading during running and RRI.

2.5.1. The association between ground reaction force and RRI

In line with Newton's third law of motion, the force exerted by the body on the ground during running is counteracted by forces acting vertically, anteroposteriorly and mediolaterally, known collectively as the ground reaction force (GRF) (Nillson and Thorstensson, 1989). This measure reflects the summed loading on the *'body as a whole'*, representing the product of the mass of the body multiplied by the directional acceleration of the centre of mass. GRF may be captured using force plates embedded in the ground or in treadmills. The features of the vertical GRF curve are somewhat determined by whether the subject first strikes the ground with the rearfoot, midfoot or forefoot (Figure 5). The vertical GRF produced during the stance phase of rearfoot running is characterised by two peaks (Daoud *et al.*, 2012). The first of these is called the passive or impact peak. This rise in GRF by 1.5-2.5 times body weight is produced immediately after heel strike, with loading rates among rearfoot strikers of 70-100 times body weights per second (BW/s) when wearing shoes (Daoud *et al.*, 2012). The second peak within the ground GRF curve, commonly referred to as the active peak, is not as widely examined in relation to injury as the impact peak, but still remains a variable of interest (Van Der Worp, Vrielink and Bredeweg, 2016). This peak is larger and is frequently twice the magnitude of the impact peak (Davis, Bowser and Mullineaux, 2016). This component of the ground reaction force is produced as the body weight shifts over the stance limb during running in preparation for propulsion (Duffey *et al.,* 2000). In midfoot and forefoot runners the impact peak is not visually present or is diminished (Hamill and Gruber, 2017).

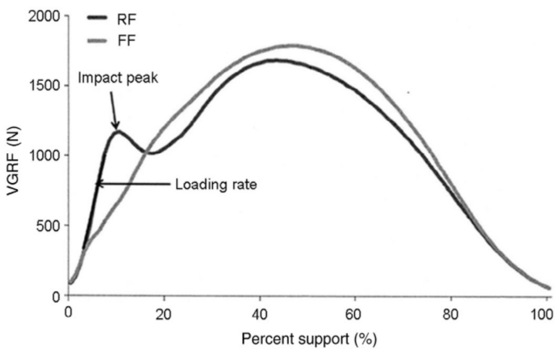

Figure 5. Vertical ground reaction force versus time for a rearfoot (RF) and forefoot (FF) strike runner. Source: Hammill and Gruber (2017).

Loading has been postulated to contribute to injury within the research and is a feature of the Bertelsen model (2017). Continuous loading in excess of the tissues capabilities is hypothesised to cause overload and, ultimately, tissue injury by way of structural failure (Hreljac, Marshall and Hume, 2000; Gerlach *et al.,* 2005; Ethier and Simmons, 2007). It has been suggested that impact peak forces (F_z1) in particular produce shock waves which travel through the body, placing high levels of stress and strain on musculoskeletal structures, which can cause subsequent injury (Hreljac, Marshall and Hume, 2000; Daoud *et al.*, 2012; Davis, Bowser and Mullineaux, 2016; Grimston *et al.*, 2016). Therefore, this review of literature will focus on the vertical impact peak, given that this value most appropriately captures the loading experienced at initial contact.

2.5.1.1. The association between vertical impact peak and RRI

Five prospective studies statistically investigated the relationship between vertical impact peak and general RRIs, with just one (20%) study finding significant differences in vertical impact peak among a subgroup of injured runners (Davis, Bowser and Mullineaux, 2016) (Table 31). Notably, in this study although no between-group significant differences were found between injured and uninjured groups as a whole (n=245), a subgroup of runners that had never been injured (n=21) presented with significantly lower (13%) impact peaks compared to those with medically diagnosed first RRI injuries (n=11). In contrast, no association was found between vertical impact peak between prospectively injured and uninjured runners. Owing to its large sample size and prospective design, one of the key research studies pertaining to vertical impact peak and injury is that by Messier et al (2018) (n=300), which did not find vertical impact peak to be associated with general RRI. The lack of significant findings is further supported by a prospective study of novice runners (n=210) which found no significant differences to exist between injured and uninjured groups (Bredeweg *et al.,* 2013).

No prospective studies have investigated the association between specific injuries and vertical impact peak. Therefore, nineteen retrospective studies were explored (Table 32). Just four studies (21%) found an association between greater vertical impact peak and tibial and femoral neck stress fractures (Grimston *et al.,* 2016), tibial stress fractures (Zifchock, Davis and Hamill, 2006), knee and lower leg injuries (Hreljac, Marshall and Hume, 2000) and chronic ankle instability (Bigouette *et al.*, 2016), with one study finding significantly lower vertical impact peak among runners with current anterior knee pain (Duffey *et al.*, 2000). A potentially important distinction is that this latter study, unlike the other four studies finding greater vertical impact peaks, included runners who were injured at the time of testing. Therefore, it is possible that lower impact may have been in response to pain and may not have represented a causative factor for the injury. Another important note is that one study with significant findings did not statistically compare ground reaction forces between injured and uninjured runner groups as a whole, but found significantly higher impacts among injured limbs compared uninjured limbs (Zifchock, Davis and Hamill, 2006). As this study was retrospective, it is unclear whether the injury was caused by higher loading or whether higher loading followed injury, however this highlights the potential need to consider the side of injury in RRI research. Interestingly, similar to the above study by Davis *et al.* (2016) who found a significant importance of studying those who are never injured, Hreljac, Marshall and Hume (2000) retrospectively found that those who had never been injured (n=12) displayed significantly higher vertical impact peaks than runners who had previously sustained an RRI (n=12). This may suggest that never injured runners may have unique protective factors against injury and that they are a potentially insightful group to study with regard to RRI research. Fourteen studies found no association between vertical impact peak and specific RRIs (Table 32).

Table 31 Prospective studies investigating the association between vertical impact peak during running and general RRI.

Study	*n*	*Population*	*Type of runner*	*Tracking Period*	*O/T*	*Running Speed (m/s ± SD)*	*Number of Foot Strikes*	*CON Mean ± SD*	*INJ Mean ± SD*	*Finding*	*Percentage Difference (%)*
Davis, Bowser and Mullineaux, 2016	249	INJ: 144♀ CON: 105♀	Recreational	2 years	O	Set Speed: 3.5	5	1.66 ± 0.31	1.67 ± 0.29	Not significant, p>.05.	1
	32	Sub analysis: Medically diagnosed with first injury= 11♀ Never INJ= 21♀						1.51 ± 0.22 BW	1.72 ± 0.21 BW	Greater VIP among INJ runners, p=.013.	14
Messier *et al.*, 2018	300	INJ: 145♀, 54♂ CON: 63♀, 38♂	Recreational	2 years	O	Self-selected: INJ: 2.94 ± 1.2; CON: 3.01 ± 1.2	3	1088 ± 239 N	1038 ± 237 N	Not significant, p>.05.	-1
Bredeweg *et al.*, 2013	210	INJ: 11♂, 23♀ CON: 66♂, 110♀	Novice	9 weeks	T	Set Speed: 2.5	10	1.34 ± 0.16 BW	1.29 ± 0.19 BW	Not significant, p>.05.	-4
Napier *et al.*, 2018	55	INJ: 22♀ CON: 33♀	Half marathon	15 weeks	T	Self-selected	30	N/R	N/R	Not significant, p>.05.	N/R
Gerlach *et al.*, 2005	87	INJ: 48♀ CON: 39♀	Run ≥20miles/week	1 year	O	Self-Selected 5km Race Pace: 2.7 – 4.5	6	1.89 ± 0.05 BW	1.87 ± 0.05 BW	Not significant, p>.05.	-1

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, RRI= running related injury, T= treadmill, O= over ground, N/R= not reported, VIP= vertical impact peak. Black shading indicates that greater VIP was associated with injuries. Grey shading indicates that lower VIP was associated with injuries. White shading indicates that no association was found.

Table 32 Studies investigating the association between vertical impact peak and specific RRIs.

Authors	***n***	***Population***	***Type of Runner***	***Injury***	***O/T***	***Running Pace (metres/second ± SD)***	***Number of Foot Strikes***	***Groupings***	***CON Mean ± SD (BW)***	***INJ Mean ± SD (BW)***	***Finding***	***Percentage Difference (%)***
Grimston, Engsberg and Hanley, 1991	14	INJ: 6♀ CON: 8♀	Run average 52 km/week	Tibial and Femoral Neck Stress Fractures	O	Set Speed 4.04	2	Previous INJ vs CON	1.85 ± 0.05	2.09 ± 0.09	Greater VIP among INJ runners, p<.05.	13
Bigouette *et al.*, 2016	24	12♂, 12♀	Experienced, college	CAI	T	Set Speed: 3.3	5	Previous INJ vs CON	1.69 ± 0.20	2.05 ± 0.2	Greater VIP among INJ runners, p=.001	21
Duffey *et al.*, 2000	169	INJ: 68♂, 31♀ CON: 48♂, 22♀	Distance	AKP	O	Self-selected: 3.35 ± 0.1	3	Current INJ vs CON	1.74 ± 0.04	1.66 ± 0.31	Lower VIP among INJ runners, p<.05.	-5
Hreljac, Marshall and Hume, 2000	40	INJ: 12♂, 8♀ CON: 12♂, 8♀	Running on a regular basis for 1 year	Knee or below knee	O	Set Speed 4	1	Previous INJ vs CON	2.13 ± 0.42	2.40 ± 0.4	Greater VIP among INJ runners, p<.05.	13
Zifchock, Davis and Hamill, 2006	24	INJ: 24♀ CON: 25♀	Run ≥20 miles per week	TSF	O	Set Speed: 3.7 ± 5%	5	Previous INJ vs CON limbs	12.6 ± 10.1	8.8 ± 13.6	Greater VIP on INJ side vs CON side, p=.04.	-30
Milner, Davis and Hamill, 2006	40	INJ: 20♀ CON: 20♀	Run ≥32 km/week minimum	TSF	O	Set Speed: 3.7 ± 5%	5	Previous INJ vs CON	1.70 ± 0.32	1.84 ± 0.21	Not significant, p>.05.	8
Azevedo *et al.*, 2008	42	INJ: 16♂, 5♀ CON: 16♂, 5♀	Run ≥15km/week for 3 years	AT	O	Self-Selected: CON: 3 ± 0.41; INJ: 2.97 ± 0.37	5	Currently INJ vs CON	1.34 ± 0.20	1.45 ± 0.23	Not significant, p>.05.	8
Baur *et al.*, 2004	22	N/R	Experienced Runners	AT	O	Set Speed: 3.33	10	Previous INJ vs CON	N/R	N/R	Not significant, p>.05.	N/R
Bennell *et al.*, 2004	36	INJ: 13♀ CON: 23♀	Run ≥20km/week	TSF	O	Set Speed: 4 ± 0.40	10	Previous INJ vs CON	2.08 ± 0.38	1.94 ± 0.30	Not significant, p>.05.	-7
Bischof *et al.*, 2010	24	INJ: 9♀ CON: 15♀	Run ≥10 miles/week	Metatarsal Stress Fracture	O	Set Speed: 3.3 ± 5%	5	Previous INJ vs CON	2.51 ± 0.09	2.40 ± 0.19	Not significant, p>.05.	-4
Crossley *et al.*, 1999	46	INJ: 23♂ CON: 23♂	–	TSF	O	Set Speed: 4 ± 10%	10	Previous INJ vs CON	1.97 ± 0.34	1.89 ± 0.387	Not significant, p>.05.	-4
Esculier, Roy and Bouyer, 2015	41	INJ: 16♀, 5♂ CON: 15♀, 6♂	Run ≥15 km/week	PFPS	T	Self-Selected: INJ: 9 ± 0.8; CON: 9.2 ± 0.8	50	Previous INJ vs CON	3.1 ± 0.3	3.0 ± 0.4	Not significant, p>.05.	-3

McCrory *et al.*, 1999	89	N/R	Run ≥10 miles/wee k for 1 year	AT	O	Average training pace ± -3.5%	3	Currently INJ vs CON	1.73 ± 0.04	1.81 ± 0.08	Not significant, p>.05.	5
Dixon, Creaby and Allsopp, 2006	20	INJ: 10 CON:10	Military Recruits	SF	O	Set Speed: 3.58	10	Previous INJ vs CON	1.88 ± 0.30	1.93 ± 0.43	Not significant, p>.05.	3
Creaby and Dixon, 2008	30	INJ: 10♂ CON: 20♂	Military Recruits	SF	O	Set Speed: 3.5 ± 5%	10	Previous INJ vs CON	1.90 ± 0.22	1.80 ± 0.26	Not significant, p>.05.	-5
Pohl, Hamill and Davis, 2009	50	INJ: 25♀ CON: 25♀	Run ≥20 miles per week	Plantar Fasciitis	O	Set Speed: 3.7 ± 5%	15	Previous INJ vs CON	1.70 ± 0.30	1.84 ± 0.30	Not significant, p>.05.	8
Messier *et al.*, 1991	36	INJ: 12♂, 4♀ CON: 14♂, 6♀;	Run ≥10 miles/wee k	AKP	O	Self-selected CON: 3.28 ± 0.22 INJ: 3.59 ± 0.16	3	Currently INJ vs CON	1.79 ± 0.08	1.65 ± 0.09	Not significant, p>.05.	-8
Messier *et al.*, 1995	118	INJ: 33♂, 23♀ CON: 53♂, 17♀	Run ≥10 miles/wee k	ITBS	O	Predetermined training pace	3	Currently INJ vs CON	1.75 ± 0.04	1.64 ± 0.04	Not significant, p>.05.	-6

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, VIP= vertical impact peak, N/R= not reported, CAI= chronic ankle instability, ITBS= iliotibial band syndrome, PFPS= patellofemoral pain syndrome, TSF= tibial stress fracture, SF= stress fracture, AKP= anterior knee pain, AT= Achilles tendon injury. Black shading indicates that greater VIP was associated with injuries. Grey shading indicates that lower VIP was associated with injuries. White shading indicates that no association was found.

The mechanism for higher impact loading among injured runners seen in some studies may be injury-specific. Bigouette *et al.* (2016) suggested that greater impact peaks among runners with chronic ankle instability may be explained by the decrease in tibialis anterior strength seen in the chronic ankle injury group compared to a control group. It was theorised that the tibialis anterior, a prominent dorsiflexor of the ankle joint, displayed decreased ability to manage the eccentric activity demanded during initial contact which may have resulted in increased impact peaks. Similarly, among participants with tibial stress fractures, the relationship between injury and greater ground reaction forces, examined by Grimston, Engsberg and Hanley (1991), are hypothesised to be related to altered landing kinematics during the early stance phase of gait. However, lack of such information restricts the ability to draw conclusions from the research. The ability to conclude whether kinematics and loading are interlinked with injury is hindered by the limited number of studies that combine all of these factors and also by the lack of sub-analysis by injury.

One study found a significantly lower impact peak (4.6%) for injured participants (n=99) versus healthy controls (n=70) (Duffey *et al.*, 2000). The reason for the lower ground reaction force was unclear owing to kinematic data being restricted to the rearfoot, although corresponding lower pronation was also observed. Lower impact peaks were seen among the injured group along with decreased pronation, contradictory to the belief that decreased pronation should result in a stiffer landing strategy, with a consequent increase in vertical impact peak (Duffey *et al.*, 2000). To explain this finding, it has been suggested that a decrease in ground impact force in relation to injury may have been as a result of an early compensation technique, however, a lack of available kinematic data further up the chain means this explanation is tenuous. This study also highlights the potential issue in using retrospective research to investigate risk factors for injury, as it is unclear if differences between injured and uninjured groups are as a result of or causative of RRI.

In summary, there is moderate evidence to suggest that there is no relationship between vertical impact peak and general RRIs, with inconsistent findings regarding its association with specific injuries. There is limited evidence to suggest that never injured runners may have significantly lower vertical impact peak than previously injured runners.

2.5.1.2. **The association between vertical loading rate and injury**

The vertical loading rate represents the slope of the ground reaction force curve (Figure 5), which measures how quickly the ground reaction force rises to its first peak (Zadpoor and Nikooyan, 2011). Both the average (VALR) and instantaneous vertical loading rate (VILR) are examined within the literature (Winiarski and Rutkowska-Kucharska, 2009). Greater loading rate is thought to be a contributor to injury (Schaffler *et al.,* 1989) due in part to a concurrent increase in the rate of strain on tissues. Animal studies have found greater cell matrix damage in response to high rates of loading when compared to low rates of loading, despite no significant difference in the peak load applied between groups (Ewers *et al.*, 2001).

2.5.1.3. The association between vertical average loading rate and RRI

The association between average loading rate and general RRI was investigated in three prospective studies (Table 33). Of these, one prospective (Davis, Bowser and Mullineaux, 2016) study found that mean VALR was greater among injured participants compared to uninjured runners. Interestingly, significant differences were only observed for a subgroup who had never been injured (n = 20) compared to those diagnosed medically with their first injury (n = 11), and not the group as a whole (n=249).

No prospective studies investigated VALR and specific RRIs. Therefore, retrospective research was examined. Seven retrospective studies investigated the association between VALR and specific RRIs (Table 34). Of these, five studies (71%) found higher mean VALR among runners with stress fractures (Ferber *et al.*, 2002) tibial stress fracture (Milner *et al.*, 2006b), chronic ankle instability (Bigouette *et al.*, 2016), plantar fasciitis (Ribeiro *et al.*, 2015; Johnson, Tenforde, *et al.*, 2020), and PFPS (Johnson, Tenforde, *et al.*, 2020). No association between VALR and PFPS (Esculier, Roy and Bouyer, 2015) or tibial stress injury (Zifchock, Davis and Hamill, 2006) was found.

Table 33 Prospective studies examining the association between vertical average loading rate during running and general RRI.

Authors	***n***	***Population***	***Type of Runner***	***Tracking Period***	***Surface***	***Running Pace (m/s)***	***CON Mean ± SD (BW/s)***	***INJ Mean ± SD (BW/s)***	***Finding***	***Percentage Difference (%)***
Davis, Bowser and Mullineaux, 2016	249	INJ: 144♀ CON: 105♀	Recreational	2 years	O	Set Speed 3.5	73.6 ± 20.7	71.3±18.7	VALR not significantly associated with injury, p=.357.	-3
	31	Never INJ= 20 Medically diagnosed with first injury=11					60.73 ± 12.77	78.22 ± 11.10	Greater VALR among INJ group, p=.001.	29
Dudley *et al.*, 2017	32	INJ: 12, 4♂, 8♀ CON: 19, 11♂, 8♀	Cross country runners	14 weeks	T	Self-selected: CON: 3.86 INJ: 3.84	58.07	68.25	Not significant, p>.05.	18
Napier *et al.*, 2018	65	INJ: 22♀ CON: 33♀	Recreational	15 weeks	T	Self-selected: 2.47 ± 0.33	N/R	N/R	Not significant, p>.05.	N/R

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, RFS= rear foot strike, FFS= fore foot strike, VALR= vertical average loading rate. Black shading indicates that greater VALR was associated with injuries. Grey shading indicates that lower VALR was associated with injuries. White shading indicates that no association was found.

Table 34 Retrospective studies investigating the association between vertical average loading rate and specific RRIs.

Authors	***n***	***Population***	***Injury***	***Surface***	***Running Pace (m/s)***	***Study Design***	***CON Mean ± SD (BW/s)***	***INJ Mean ± SD (BW/s)***	***Findings***	***Percentage Difference (%)***
Zifchock, Davis and Hamill, 2006	49	INJ: 25♀ Never INJ: 24♀	TSF	O	Set speed: 3.7	Previously INJ vs CON	23.3 ± 17.4	16.5 ± 11.7	VALR not significantly associated with INJ, p=.11.	-29
Ferber *et al.*, 2002	20	CON: 10♀; INJ: 10♀	Lower extremity Stress Fracture	O	Set Speed 3.7	Previously INJ vs CON	77.52 ± 29.44	117.93 ± 29.44	Greater VALR among INJ, p=.03.	52
Bigouette *et al.*, 2016	24	12♂, 12♀	Chronic Ankle Instability	O	Set Speed 3.5	Previously INJ vs CON	77.77 ± 10.04	93.84 ± 0.89	Greater VALR among INJ, p=.001.	21
Ribeiro *et al.*, 2015	75 (Subgroup)	INJ: 45 CON: 30	Unilateral Plantar Fasciitis-Acute	O	Set Speed 3.5	Currently injured vs CON	0.64 ± 0.16	Acute: 0.76 ± 0.20	Greater VALR among INJ, p=.001.	19
	75 (Subgroup)	INJ: 46 CON: 30	Unilateral Plantar Fasciitis-Chronic	O	Set Speed 3.5	Presently and past injury	0.64 ± 0.16	Chronic: 0.89 ± 0.27	Greater VALR among INJ, p=.034.	39
Milner *et al.*, 2006	40	INJ: 20♀ CON: 20♀	TSF	O	Set Speed 3.7 ± 5%	Previously INJ vs CON	66.31 ± 19.5	78.97 ± 24.96	Greater VALR among INJ, p=.041.	19
Esculier, Roy and Bouyer, 2015	41	INJ: 16♀, 5♂ CON: 15♀, 6♂	PFPS	T	Self-Selected INJ: 9 ± 0.8; CON: 9.2 ± 0.8	Previously INJ vs CON	69.7 ± 21.8	68.0 ± 17.3	Not significant, p>.05.	-2
Hollander *et al.*, 2020	190	INJ: 125 CON: 65	PFPS	T	Self-selected: CON: 2.60 0.22; INJ: 2.54 0.25	Currently injured vs CON	54.37 ± 18.25	70.91 ± 18.35	VALR >57.4 increased OR of 6.7 of injury, p<.001.	30
			Tibial bone stress injury				54.37 ± 18.25	61.18 ± 19.60	Not significant, p>.05.	13
			Plantar fasciitis				54.37 ± 18.25	66.77 ± 15.41	VALR >52.4 increased OR of 11.7 of injury, p<.003.	23
			AT				54.37 ± 18.25	62.55 ± 17.83	Not significant, p>.05.	15
			ITBS				54.37 ± 18.25	60.99 ± 16.24	Not significant, p>.05.	12

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, VAP= vertical active peak, ITBS= iliotibial pain syndrome, AT= Achilles tendon injury, PFPS= patellofemoral pain syndrome, TSF= tibial stress fracture. Black shading indicates that greater VALR was associated with injuries. Grey shading indicates that lower VALR was associated with injuries**.** White shading indicates that no association was found.

2.5.1.4. The relationship between vertical instantaneous loading rate and RRI

With respect to the more commonly investigated vertical instantaneous loading rate (VILR), six prospective examined its association to general RRIs (Table 35). Of these, two (33%) studies (Bredeweg *et al.*, 2013; Davis, Bowser and Mullineaux, 2016) found greater VILR to be associated with RRIs. However, one of these studies only found this relationship to exist among the male participants and caution was advised when interpreting results due to the low total number of men (n=77) (Bredeweg *et al.*, 2013). It was suggested that the increase in loading rates among this subgroup may be related to the shorter contact time experienced by male runners compared to their uninjured counterparts. Similarly, Davis et al. (2016) only found significance when investigating a sub-group of runners. This study found greater VILR among runners diagnosed with their first RRI compared to never injured runners. This suggests that never injured runners may have potentially advantageous loading rates which may explain their resistance to injury.

The association between VILR and specific RRIs has not been investigated prospectively, but it has been examined in twelve retrospective studies (Table 35). Significantly greater VILR was found in two of these studies (17%), among runners with plantar fasciitis (Pohl, Hamill and Davis, 2009; Johnson, Tenforde, *et al.*, 2020), PFPS (Johnson, Tenforde, *et al.*, 2020) and tibial stress fracture (Johnson, Tenforde, *et al.*, 2020). In contrast, Duffey *et al.*, (2000) found VILR to be significantly lower (8.9%) among subjects with anterior knee pain compared to uninjured controls. This may be because runners were currently injured and so results may be reflective of compensations in response to injury. The remaining nine studies found no association to exist (Table 35).

Of the studies investigating VALR and VILR, a common finding is moderate evidence to suggest that greater VILR and VALR is associated with plantar fasciitis among runners (Pohl, Hamill and Davis, 2009; Ribeiro *et al.*, 2015; Johnson, Tenforde, *et al.*, 2020). Plantar fasciitis is characterised by a decrease in elasticity at the heel as a result of fibrosis. This may inhibit the shock absorption at the heel, resulting in higher rearfoot loads (Pohl, Hamill and Davis, 2009; Ribeiro *et al.*, 2015). As such, increases in loading rate may be specific to the injury type. However, all research to date regarding loading rate and plantar fasciitis injury has been retrospective, making it unclear if significant findings reflect factors causative or as a result of RRIs.

Table 35 Prospective studies investigating the association between vertical instantaneous loading rate during running and general RRIs.

Authors	*n*	*Population*	*Type of Runner*	*Study Design*	*Surface*	*Running Pace (m/s)*	*CON Mean ± SD (BW/s)*	*INJ Mean ± SD (BW/s)*	*Finding*	*Percentage Difference (%)*
Bredeweg *et al.*, 2013	210	77♂, 133♀	Novice	9 weeks	T	Set Speed: 2.5	96.3 ± 29.0	101.0 ± 28.4	Not significant, p>.05.	5
Davis, Bowser and Mullineaux, 2016	249	INJ: 144♀ CON: 105♀	Run ≥20 miles/week	2 years	O	Set Speed: 3.5	85.2 ± 22.7	81.1 ± 20.4	Not significant, p>.05.	-5
	32	Never INJ= 20 Medically diagnosed with first injury= 11					73.1 ± 15.9	88.0 ± 13.9	Greater VILR among INJ group, p=.014.	21
Dudley *et al.*, 2017	32	INJ: 4♂, 8♀ CON: 11♂, 8♀	Collegiate Runners, cross country	14 weeks	T	Self-selected: CON: 3.86 INJ: 3.84	109.5	123.4	Not significant, p>.05.	13
Gerlach *et al.*, 2005	87	87♀	Run ≥20miles/week	1 year	O	Self-Selected 5km Race Pace: 2.7 - 4.5	117.4 ± 0.4	124.8 ± 5.8	Not significant, p>.05.	6
Kuhman *et al.*, 2016	19	INJ: 4♂, 6♀ CON: 7♂, 2♀	Cross-country runners	Cross country season	O	Set Speed ♂: 4.5 ±5% ♀: 4.0 ±5%	100.3 ± 19.9	93.5 ± 30.3	Not significant, p>.05.	-7
Napier *et al.*, 2018	65	INJ: 22♀ CON: 33♀	Recreational	15 weeks	T	Self-selected: 2.47 ± 0.33	N/R	N/R	Not significant, p>.05.	–

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, VILR= vertical instantaneous loading rate. Black shading indicates that greater VILR was associated with injuries. Grey shading indicates that lower VILR was associated with injuries. White shading indicates that no association was found.

Table 36 Prospective studies investigating the association between vertical instantaneous loading rate during running and specific RRIs.

Authors	*n*	*Population*	*Runner type*	*Injury*	*Surface*	*Running Pace (m/s)*	*Study Design*	*CON Mean ± SD (BW/s)*	*INJ Mean ± SD (BW/s)*	*Findings*	*Percentage Difference (%)*
Retrospective											
Hreljac, Marshall and Hume, 2000	40	INJ: 12♂, 8♀ CON: 12♂, 8♀	Runners and triathletes	Knee/below knee RRIs	O	Set Speed: 4	Previously of INJ vs CON	76.6 ± 19.5	93.1 ± 23.8	Greater VILR among INJ runners, p=.001.	22
Pohl, Hamill and Davis, 2009	50	INJ: 25♀ CON: 25♀	Run ≥20 miles/week	Plantar Fasciitis	O	Set Speed: 3.7 ± 5%	Previously of INJ vs CON	82.9 ± 18.7	100.5 ± 36.0	Greater VILR among INJ runners, p=.037.	21
Zifchock, Davis and Hamill, 2006- Peak Instantaneous load rate	49	INJ: 25♀ Never INJ: 24♀	Minimum 20 miles/week	TSF	O	Set speed: 3.7	Previously of INJ vs CON	15.0 ± 10.4	12.6 ± 9.4	Not significant, p>.05.	-16

Milner, Davis and Hamill, 2006	40	INJ: 20♀ CON: 20♀	Runners	TSF	O	Set Speed: 3.7 ± 5	Previously of INJ vs CON	79.7 ± 18.8	92.6 ± 24.7	Not significant, p>.05.	16
Duffey *et al.*, 2000	169	INJ: 68♂, 31♀ CON: 48♂, 22♀	Runners	AKP	O	Self-selected: 3.35 ± 0.1	Currently INJ vs CON	54.9 ± 1.8	50.0 ± 1.7	Significantly lower peak VILR among INJ group, p<.005.	-9
Dixon, Creaby and Allsopp, 2006	20	INJ: 10 CON:10,	Military Recruits	SF	O	Set Speed: 3.58	Previously of INJ vs CON	156 ± 54	178 ± 49	Not significant, p>.05.	14
Messier *et al.*, 1991	36	INJ: 12♂, 4♀ CON: 14♂, 6♀	Run ≥4 days/week for 1 year	AKP	O	Self-selected: CON: 3.28 ± 0.22; INJ: 3.59 ± 0.16	Currently INJ vs CON	53.9 ± 3.1	56.5 ± 4.5	Not significant, p>.05.	5
Azevedo *et al.*, 2008	42	INJ: 16♂, 5♀ CON: 16♂, 5♀	Run ≥15km/week for 3 years	AT	O	Self-Selected: CON: 3.00 ± 0.41; INJ: 2.97 ± 0.37	Currently INJ vs CON	42.9 ± 9.3	44.8 ± 11.3	Not significant, p>.05.	5
McCrory *et al.*, 1999	89	N/R	Run ≥10 miles/week for 1 year	AT	O	Average training pace ± 3.5%	Currently INJ vs CON	54.9 ± 1.7	55.5 ± 2.7	Not significant, p>.05.	1
Esculier, Roy and Bouyer, 2015	41	INJ: 16♀, 5♂ CON: 15♀, 6♂	Run ≥15 km/week	PFPS	T	Self-Selected: INJ: 9 ± 0.8; CON: 9.2 ± 0.8	Previously of INJ vs CON	83.1 ± 15.1	81.4 ± 15.0	Not significant, p>.05.	-2
Johnson *et al.*, 2020	190	INJ: 125 CON: 65		PFPS	T	Self-selected: CON: 2.6 ± 0.2; INJ: 2.5 ± 0.3	Currently INJ vs CON	63.5 ± 20.5	80.5 ± 19.7	VILR >67.1 increased OR of 5.9 of injury, p<.001.	27
				TSF				*63.5 ± 20.5*	70.8 ± 21.6	No significant association between VILR and injury, p>.05.	12
				Plantar fasciitis				*63.5 ± 20.5*	75.7 ± 16.3	VILR >58.0 increased risk of INJ, OR=9.1, p=*.006*, .	19
				AT				*63.5 ± 20.5*	72.5 ± 19.4	Not significant, p>.05.	14
				ITBS				*63.5 ± 20.5*	70.9 ± 18.2	Not significant, p>.05.	11

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, VILR= vertical instantaneous loading rate, ITBS= iliotibial pain syndrome, TSF= tibial stress fracture, PFPS= patellofemoral pain syndrome, AT= Achilles tendon injury, AKP=anterior knee pain. Black shading indicates that greater VILR was associated with injuries. Grey shading indicates that lower VILR was associated with injuries. White shading indicates that no association was found.

To summarise, it is widely debated in the literature if the various components of vertical GRF relate to injury. There does not appear to be a clear link between higher vertical impact peaks and RRIs mong runners. This is in line with two systematic reviews finding insufficient evidence to suggest that there is a link between these measures and general RRIs (Van Der Worp, Vrielink and Bredeweg, 2016) or stress fractures (Zadpoor and Nikooyan, 2011). However, some evidence exists to suggest that injured runners have greater VALR and VIRL particularly those with plantar fascia pain. It is important to highlight that studies finding significance examined runners symptomatic at time of testing, making it unclear if loading rates are reflective of previous injury or causative of future RRIs.

Although theory suggests that a relationship may exist, the association between vertical GRF and RRIs in general is, as of yet, unclear owing to a lack of prospective trials and conflicting findings from current research. Prospective data analysis of subgroups, such as by injury type, may better examine this relationship. A potential limitation of the widely used GRF in quantifying loading is that it measures net forces acting on the body as a whole (through its centre of mass) (Van Der Worp, Vrielink and Bredeweg, 2016). Given that relative loading will not be equally distributed across the body segments (Shorten and Winslow, 1992), and that this distribution will vary across runners, analysis of GRFs fails to assess loading on individual body segments, which could be an important factor in injury research. As such, it may not be sufficiently sensitive in detecting potential differences between injured and uninjured participants. Further research investigating localised loading may help in exploring the aetiology of RRIs. Accelerometery presents a potential avenue for this exploration on a segment by segment basis (Sheerin, Reid and Besier, 2019).

2.5.2. The association between accelerometery and RRI.

Accelerometers are micro-electric-mechanical systems, which are often are used to examine the impact acceleration produced during running as the leg advances forward and rapidly decelerates while making contact with the ground (Sheerin *et al.*, 2018). Impact accelerations act as a surrogate measure of loading of biological tissues within the body (Sheerin, Reid and Besier, 2019). The use of accelerometers in research is becoming increasingly popular due to their small size and low power, making them convenient for attachment onto limbs and for the collection of data of long duration. Although accelerometers can be placed on multiple areas of the body, tibia-mounted sensors are often utilised in RRI research to detect tibial accelerations, which act as a proxy measurement for the forces experienced at the tibia during movement. Knowledge of the forces experienced at the tibia is thought to be important as it is a common site of lower limb injury (Mulvad *et al.*, 2018). Although the link between GRF and tibial (also known as shank) acceleration has been established, the exact relationship between bone strain and tibial acceleration is not known due to the interactions of local muscle forces and the impracticality and invasive nature associated with their measurement (Rueterbories *et al.*, 2010).

No prospective studies have examined the association between shank impact accelerations and either general or specific RRIs. One retrospective study (Zifchock *et al.*, 2008) examined the association between shank accelerations and general RRIs, finding no difference between injured and never injured runners as a whole. However, when examining injured and uninjured sides among the injured runners, injured limbs demonstrated significantly greater impact accelerations (Table 37). This highlights the importance of considering the side of injury in future research.

The association between peak shank impact accelerations and specific RRIs was examined in four retrospective studies (Table 38). Two studies found significantly greater peak shank accelerations to be associated with RRIs of MTSS (Milner *et al.*, 2006b) and tibial stress fractures (Zifchock, Davis and Hamill, 2006). Zifchock *et al.* (2006) (n=24) did not examine the difference between injured and uninjured runners but noted significantly greater peak accelerations on the injured (14.6%) compared to uninjured side. Similarly, Milner *et al.* (2006) found a similar result with an increase of 32.5 % in the MTSS group compared to the control. Binary regression analysis included in this latter study also indicated that the peak acceleration could determine whether a person belonged to the injured or injured group in 70% of cases. As both of these studies are retrospective, they are limited in their ability to determine the causative factors associated with injuries, but the presence of higher loading in injured participants and injured limbs that have been thought to have 'recovered' may account for the repeated succession of stress fracture injuries often noted in the research (Zifchock, Davis and Hamill, 2006) and the common recurrence of MTSS (Bliekendaal *et al.*, 2018). No significant differences in peak accelerations between injured and uninjured runners were found in the remaining studies investigating exercise related lower leg pain (Koldenhoven *et al.*, 2020) or MTSS (Schütte *et al.*, 2018).

Two studies additionally examined peak accelerations at the pelvis (Schütte *et al.*, 2018) and lower back (Winter *et al.*, 2020) in general RRIs. Winter *et al.*, (2020) found that runners with and without prospective injury (n=76) over one year tracking period did not have a significant difference in baseline lower back impact accelerations. Schutte *et al.* (2018) retrospectively investigated peak acceleration at the level of L3-L5, finding no significant difference in runners with and without MTSS. A possible explanation non-significant findings is the small sample size, as well as the fact that the lower back may be too distal from the most common sites of RRIs to detect excessive forces. However, given the relatively high proportion of injuries that occur proximal to the tibia (Francis *et al.*, 2019), it would seem pertinent to more thoroughly investigate impact accelerations at the lower back.

In summary, peak shank accelerations have been largely under-investigated and there is inconsistent evidence to suggest that they are associated with RRIs. The limited number of studies investigating peak shank impact accelerations and the fact that they are all retrospective in nature, limits the ability to draw definitive conclusions regarding their role in the aetiology of injury. The limited evidence regarding accelerations at the lower back also prompts further investigation, with just one study prospectively investigating this (Winter *et al.*, 2020). As accelerometery has the potential for mass screening of runners, it could present many opportunities for injury surveillance, although more prospective trials are needed.

As acceleration is a proxy measure for loading, *rate* of acceleration should also be examined (along with peak acceleration). Animal studies have found greater cell matrix damage in response to high rates of loading when compared to low rates of loading, despite no significant difference in the peak load applied among the groups (Ewers *et al.*, 2001). Furthermore, GRF loading rate is more closely related to stress fracture injury than peak loading (Zadpoor and Nikooyan, 2011). However, to date, rate of acceleration has not been previously researched in relation to RRI, signalling the need for more research in this area.

Table 37 Studies investigating the association between impact accelerations and general RRIs.

Authors	*n*	*Population*	*Type of Runner*	*Accelerometer Placement*	*Surface*	*Running Pace (m/s)*	*Groups Analysed*	*CON Mean ± SD (g)*	*INJ Mean ± SD (g)*	*Finding*	*Percentage Difference (%)*
Prospective											
Winter *et al.*, 2020	76	INJ: 22♂, 17♀ CON: 23♂, 14♀	Recreational/competitive	L5/S1	O	Self-selected	INJ vs CON	4.27 ± 1.07	4.19 ± 0.83	Not significant, p>.05.	N/R
Retrospective											
Zifchock *et al.*, 2008	20	INJ: 9♂, 11♀ CON: 11♂, 9♀	Run ≥20 miles/week	Distal, anterior-medial aspect of both tibiae	O	Set Speed: 3.7	INJ vs Never INJ- Side to side differences	4.8 ± 1.6	5.5 ± 2.2	Greater impact accelerations on INJ side, p=.05	15

Abbreviated Terms n= number of participants, CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported. Black shading indicates that greater acceleration was associated with injuries. Grey shading indicates that lower acceleration was associated with injuries. White shading indicates that no association was found.

Table 38 Studies investigating impact accelerations and specific RRIs.

Authors	*n*	*Population*	*Type of Runner*	*Accelerometer Placement*	*Injury*	*Surface*	*Running Pace (m/s)*	*Variable*	*Groups Analysed*	*CON Mean ± SD*	*INJ Mean ± SD*	*Finding*	*Percentage Difference (%)*
Retrospective													
Milner *et al.*, 2006	40	INJ: 20♀ CON: 20♀	Run ≥32 km/week minimum	Anteromedial portion of the distal tibia	Tibial Stress Fracture	O	Set Speed: 3.7 ± 5%	Peak positive acceleration (g)	Previous TSF and no previous TSF	5.81 ± 1.66	7.70 ± 3.21	Greater impact accelerations in INJ group, p=.014	33
Zifchock, Davis and Hamill, 2006	24	INJ: 24♀ CON: 25♀	Run ≥20 miles per week	Medial, inferior aspect of the tibia	Tibial Stress Fracture	O	Set Speed: 3.7 ± 5%	Peak positive acceleration (g)	Previous TSF vs Never INJ Side to side differences	N/R	N/R	Greater impact accelerations of injured leg, p=.02	16
Koldenhoven *et al.*, 2020	32	INJ: 16; CON: 16	Run >10 miles/week	Shoe mounted	Exercise related lower leg pain	O	Self-selected	Shoe mounted peak impact (g)	Currently INJ s CON	N/R	N/R	Not significant, p>.05.	N/R
Schütte *et al.*, 2018	30	INJ: 8♂; 6♀ CON: 10♂, 6♀	Recreational	Trunk	MTSS	O	Self-selected	Peak positive acceleration (g)	Previously INJ vs CON	1.96 ± 1.14	2.21 ± 0.98	Not significant, p>.05.	13
				Anteromedial portion of the distal tibia	MTSS	O	Self-selected	Peak positive acceleration (g)		6.43 ± 1.51	6.62 ± 1.20	Not significant, p>.05.	3

Abbreviated Terms: n= number of participants CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, MTSS= medial tibial stress syndrome. Black shading indicates that greater acceleration was associated with injuries. Grey shading indicates that lower acceleration was associated with injuries. White shading indicates that no association was found.

2.6. The association between running technique and RRI

The stance phase is the most commonly investigated part of the gait cycle, given that this is the point at which loading is applied and as such, technique during stance may govern the distribution of this load (Novacheck, 1998). In light of this, this literature review will examine stance phase running technique and its association with RRI.

2.6.1. The association between foot strike during running and RRI

This section is a summary of a published systematic review paper:

Burke, A., **Dillon, S.,** O'Connor, S., Whyte, E. F., Gore, S., & Moran, K. A. (2021). Risk Factors for Injuries in Runners: A Systematic Review of Foot Strike Technique and Its Classification at Impact. *Orthopaedic journal of sports medicine*, *9*(9). doi:10.1177/23259671211020283

Due to the proposed role of the foot in load absorption and due to the potential effects of its motion on proximal kinematics (Kulmala *et al.*, 2013; Goss *et al.*, 2015), considerable attention has been given to movement of the foot on the sagittal plane during running, particularly at initial contact. Foot strike pattern is primarily defined using two methods; (1) nominal means using foot strike pattern classification and (2) continuous measures. Nominal classifications are subdivided into three categories: rearfoot strike (RFS), in which contact is initiated by the heel, forefoot strike (FFS), in which the ball of the foot makes initial contact, and mid foot strike (MFS), in which there is simultaneous ground contact with the heel and the ball of foot (Daoud *et al.*, 2012). Additionally, some studies group MFS and FFS patterns together as non-RFS (Warr *et al.*, 2015; Ruder *et al.*, 2019). RFS is considered to be the most frequent strike pattern, with one observational study finding 95% were rearfoot strikers, 4.1% were mid foot strikers and just 0.8% forefoot strikers (de Almeida *et al.*, 2015). Previous research studies have determined foot strike pattern of participants using either visual analysis of a sagittal plane video camera (Daoud *et al.*, 2012; Warr *et al.*, 2015; Sugimoto *et al.*, 2019; Fukusawa, Stoddard and Lopes, 2020; Hollander, Johnson, *et al.*, 2021), categorization of continuous measures (foot and ankle contact angles and strike index) (Donoghue, A. Harrison, *et al.*, 2008; Mann, L. Malisoux, *et al.*, 2015; Dudley *et al.*, 2017; Paquette, Milner and Melcher, 2017; Messier *et al.*, 2018; Dingenen *et al.*, 2019), or using self-reporting methods (Goss and Gross, 2012). For the purpose of this review, due to the low number of prospective studies, retrospective research was included.

Four studies examined nominal foot strike pattern (Daoud *et al.*, 2012; Sugimoto *et al.*, 2019; Fukusawa, Stoddard and Lopes, 2020; Hollander, Johnson, *et al.*, 2021). No prospective study investigated this. Of the retrospective studies, just one examined general RRIs, finding significantly greater injury prevalence among RFS runners compared to non-RFS runners

Table 39 The studies investigating the association between foot strike and general RRIs.

Authors	*n*	*Population*	*No. of FS*	*Type of Runner*	*Tracking period*	*Surface*	*Running Pace (m/s)*	*Method of classifying FS*	*Instrumentation*	*Groups analysed*	*CON Mean ± SD*	*INJ Mean ± SD*	*Finding*	*Percentage Difference (%)*
Prospective														
Kuhman *et al.*, 2016	19	INJ: 7♂, 2♀; CON: 4♂, 6♀	10	Cross Country Collegiate	Season	O	4.5 ±5% (♂) 4.0 ±5% (♀)	SI	3D Motion Capture and Force Plate	INJ vs CON	55.8 ± 48.7 %	44.8 ± 50.0 %	Not significant, p>.05.	-20
Dudley *et al.*, 2017	31	INJ: 4♂, 8♀; CON: 11♂, 8♀	5	Cross Country Collegiate	14 weeks	O	Self-selected	FCA (degrees)	3D Motion Capture and Force Plate	INJ vs CON	10.95 (6.46, 15.44) degrees	11.21 (7.03, 15.39) degrees	Not significant, p>.05.	2
Messier *et al.*, 2018	300	INJ: 145♀, 54♂ CON: 63♀, 38♂	3	Recreational	2 years	O	Self-selected: INJ: 2.94 ± 1.2 CON: 3.01 ± 1.2	SI	3D Motion Capture and Force Plate	INJ vs CON	14 ± 20 %	12 ± 18 %	Not significant, p>.05.	-14
Retrospective														
Daoud *et al.*, 2012	52	INJ: 23♀, 29♂	3	Endurance cross country	N/A	T and O	3.5	FSP	2D Capture	Previous INJ vs CON	N/R	N/R	Rate of mild and moderate repetitive stress RRIs (but not severe) were 2.5 times higher in RFS than in FFS runners, p=.05.	
											N/R	N/R	Rate of combined moderate and severe repetitive injuries is 1.7 times more frequent in RFS runners than in FFS runners, p=.04.	
											N/R	N/R	Traumatic injury rates do not differ in a significant or consistent pattern between RFS and FFS runners, p=.7.	
Mann *et al.*, 2014	90	INJ: 44; CON: 46	161 ± 12	Recreational	N/A	O	Self -selected	SI	Pressure Insoles	Previous INJ vs CON	23.7 ± 10.3%	25.1 ± 9.4%	Not significant, p>.05.	6
Paquette, Milner and Melcher, 2017	44	INJ: 33♂, 11♀ CON: 33♂, 13♀;	5	Recreational	N/A	O	75% of their self-reported 10 km personal best	FCA (degrees)	3D Motion Capture	Previous INJ vs CON	4.6 ± 6.2	5.1 ± 6.3	Not significant, p>.05.	11

Abbreviated Terms: ♂= males, ♀= females, SD= standard deviation, INJ= injured group, CON= control group, N/R= not reported, RRI= running related injury, FS= foot strike, FSP= foot strike pattern, SI= Strike index, FCA- Foot contact angle, O= overground, T= treadmill, N/A= not applicable, RFS= rearfoot strike, FFS= forefoot strike. Grey shading indicates that a significant association was found between foot strike and injury. White shading indicates that no association was found.

Table 40 Studies investigating the association between foot strike pattern and specific RRIs.

Authors	***n***	***Population***	***No. of foot strikes***	***Type of Runner***	***Injury***	***Sur face***	***Runnin g Pace***	***Method of classifying foot strike***	***Instrumentation***	***Study Design***	***CON Mean ± SD***	***INJ Mean ± SD***	***Finding***	***Percentage Difference (%)***
Retrospective														
Dingenen *et al.*, 2019	42	INJ: 5♂, 13♀ CON: 7♂, 17♀	7	Recreation al	Knee injuries	T	Self-selected	FCA: video camera (continuou s)	2D analysis	Current INJ vs CON	9.7 ± 6.0	6.8 ± 5.1	Significantly smaller foot inclination at initial contact among INJ runners (p= .031).	-35
Hollander *et al.*, 2019	550	277♂, 273♀ All INJ	10	Recreation al	RRI: Subdivided	T	Self-selected: 2.6 ± 0.3	Visual observatio n using video	2 D analysis	Currently INJ-comparison of runners with difference INJ locations	N/R	N/R	MFS runners were at 2.27 times greater odds of sustaining an Achilles tendon injury. FFS runners at increased the risk of posterior lower leg injuries (OR=2.60, p<.05).	N/R
Donoghue *et al.*, 2008	22	INJ: 10♂, 1♀ CON: 10♂, 1♀	5	Recreation al	AT	T	Self-selected	Ankle flexion angle at initial contact	3 D analysis	Previously INJ vs CON	2.9 ± 4.9	3.3 ± 5.5	Not significant, p>.05.	14
Fukusawa, Stoddard and Lopes, 2020	122	INJ: 44♂, 17♀ CON: 42♂, 21♀	5	Recreation al	AKP	O	Self-selected	FSA	2D video analysis	Currently INJ vs CON	3.4 ± 5.6	3.1 ± 5.2	Not significant, p>.05.	9
Sugimoto *et al.*, 2019	75	INJ: 12♂, 23♀ CON: 12♂, 23♀	Data over 10-20 secon ds	Recreation al	Hamstring pain	T	Self-selected: 4–5 mph (6.44–8.05 km/h)	Visual observatio n using video	2 D analysis	Currently INJ vs CON	N/R	N/R	INJ runners had greater proportion of RFS, CON runners had greater proportion of FFS (p= 0.004**).**	N/R
Bramah *et al.*, 2021	30	INJ: 15♂; CON: 15♂	10	NS	Calf muscle injury	Y	Set speed: 3.2m/s	Ankle dorsiflexio n at initial contact	3 D analysis	Previously INJ vs CON	9.6 ± 64.5	11.3 ± 6.5	Not significant, p>.05.	18
								Foot inclination	3 D analysis	Previously INJ vs CON	20.4 ± 6.0	23.8 ± 6.8	Not significant, p>.05.	-17

Abbreviated Terms: ♂= males, ♀= females, SD= standard deviation, INJ= injured group, CON= control group, N/R= not reported, RRI= running related injury, FS= foot strike, FSP= foot strike pattern, SI= Strike index, FCA- Foot contact angle, O= overground, T= treadmill, N/A= not applicable, RFS= rearfoot strike, FFS= forefoot strike, MFS= mid foot strike, AT= Achilles tendon injury, AKP= anterior knee pain. Grey shading indicates that a significant association was found between foot strike and injury. White shading indicates that no association was found.

(Daoud *et al.*, 2012) (Table 39). Three retrospective studies investigated the association between nominal foot strike pattern and specific injuries (Sugimoto *et al.*, 2019; Fukusawa, Stoddard and Lopes, 2020; Hollander *et al.*, 2020) with two studies (66%) reporting a significant association (Sugimoto *et al.*, 2019; Hollander *et al.*, 2020) (Table 40). Sugimoto et al. (2019) found hamstring injury rates to be significantly greater in RFS runners in comparison to FFS runners. Although Hollander et al. (2020) reported there to be no relationship between RFS and RRI, strong associations were found between non-RFS patterns and RRI, with MFS runners more than twice as likely to have sustained an Achilles tendon injury (OR= 2.3), and FFS runners more than twice as likely to have sustained a posterior lower leg injury (OR= 2.6) in comparison to RFS runners. The final study investigating the association between foot strike pattern and anterior knee pain found no association to exist (Fukusawa, Stoddard and Lopes, 2020). Overall, there is inconsistent and primarily retrospective evidence relating foot strike pattern to RRI. This signals the need to prospectively investigate foot strike pattern and its association to general RRIs as well as specific RRIs.

Eight studies examined foot strike using two continuous scales: (1) initial ground contact angles (foot contact angle, ankle flexion angle) (Donoghue *et al.*, 2008; Dudley *et al.*, 2017; Dingenen *et al.*, 2019; Bramah *et al.*, 2021) and (2) location of initial point of contact relative to foot length [strike index (SI)] using pressure sensitive insoles (Mann, Malisoux, *et al.*, 2015) and force plate analysis (Kuhman, Melcher and Paquette, 2016; Messier *et al.*, 2018). Of these, three prospective (Kuhman, Melcher and Paquette, 2016; Dudley *et al.*, 2017; Messier *et al.*, 2018) and two retrospective studies investigated general RRIs (Mann, L. Malisoux, *et al.*, 2015; Paquette, Milner and Melcher, 2017), with no study finding an association between foot strike and RRI (Table 39).

No prospective studies have examined the association between continuous foot strike pattern classification and specific RRIs. Three retrospective studies investigated the association between foot strike and specific RRIs (Dingenen *et al.*, 2019; Fukusawa, Stoddard and Lopes, 2020; Bramah *et al.*, 2021) (Table 40), with just one study finding lower foot contact angle among recreational runners with a current knee injury compared to healthy controls (Dingenen *et al.*, 2019). It was hypothesised that the lower values observed in the injured group could be attributed to a potential compensatory pattern to reduce knee loading (Dingenen *et al.*, 2019).

Four primary mechanisms may explain the possible association between foot strike and RRIs. Firstly, running with a midfoot or forefoot strike changes the vertical ground reaction force curve such that the vertical impact peak is visually substantially minimised or absent (Hamill and Gruber, 2017). As such, it is proposed that manipulation of foot strike from rearfoot to mid or forefoot strike may lead to decreases in vertical impact peak and loading rate, thus potentially reducing the risk of injuries. Secondly, impact loading may be different between runners of differing strike patterns, with some evidence to suggest that rearfoot and midfoot strikers exhibit greater tibial accelerations compared to forefoot strikers (Ruder *et al.*, 2019). Thirdly, previous research has found increases in knee joint specific factors among rearfoot strikers compared to forefoot strikers, namely, patellofemoral stress (Kulmala *et al.*, 2013; Vannatta and Kernozek, 2015) and tibiofemoral joint vertical loading rate (Bowersock *et al.*, 2017). Finally, Achilles tendon force has been found to be reduced among rearfoot strikers compared to forefoot strikers (Kulmala *et al.*, 2013; Hashizume and Yanagiya, 2017). The latter two points signal a need for more prospective investigations regarding foot strike in relation to specific RRIs, given that differences in the force distributions may lead to overloading of specific structures.

In summary, there is inconsistent findings in relation to the association between footstrike pattern and both general and specific RRIs. Uncertainty persists due to contrasting definitions of foot strike pattern, measurement methods and analyses. Future research should explore foot strike not only as a categorical measure, but also as a continuous measure. As well as this, there may be value in investigating prospective footstrike and its relationship to both general and specific RRIs.

2.6.2. The association between knee kinematics during running and RRI

Knee flexion aids in shock absorption at initial contact (Dugan and Bhat, 2005). Perhaps one of the most well know and influential studies investigating knee kinematics was that of McMahon, Valiant and Frederick (1987) who investigated Groucho running, a running technique involving flexion of the knees. This study found that running in this manner resulted in significantly lower impact forces, compared to typical running. Similarly, a simulation study estimated that increasing knee flexion at initial contact during running would decrease the peak impact force by approximately 68 N per degree of flexion (Gerritsen, van den Bogert and Nigg, 1995). In a study of extended knee landing, it was found that greater knee extension at contact may result in extremely high forces with potential deformation of the meniscus and cartilage (Makinejad *et al.*, 2013). In contrast, excessive knee flexion may predispose the patella to increased lateral tilt and displacement, which can increase joint stress at the knee (Luginick *et al.*, 2018). However, despite these proposed explanations, evidence relating knee kinematics to loading is somewhat mixed. In a study of sagittal plane kinematic variables, knee flexion angle at initial contact was not included in any of the final models to predict loading (Wille *et al.*, 2014). The research regarding knee flexion and RRI is similarly inconsistent.

2.6.2.1. The association between peak knee flexion angle during and RRI.

Two prospective studies investigated the association between peak knee flexion angle and general RRIs, finding no relationship to exist (Messier *et al.*, 2018; Jungmalm *et al.*, 2020).

Two prospective studies have investigated the association between peak knee flexion and specific RRIs (Table 41). Of these, Shen et al (2019) found no association between peak knee flexion and ITBS. Conversely, Hein *et al.* (2014) found less peak knee flexion among runners who later developed Achilles tendon pain. This decrease in knee flexion was accompanied by decreased knee flexor strength. As such, it was proposed that the reduced flexion may have been a compensatory mechanism to improve stability around the knee, which may have consequently placed more tension on the gastrocnemius-soleus complex and the Achilles tendon, leading to tendonitis. However, it must be noted that Hein et al (2014) investigated a small sample size, with just 10 participants in the injured group.

2.6.2.1. The association between knee flexion excursion angle during running and RRI

Two prospective studies investigated knee flexion excursion in general RRIs (Jungmalm *et al.*, 2020) and AT pain (Hein *et al.*, 2014) (Table 43), with neither finding an association to exist.

2.6.2.2. The association between knee flexion at initial contact and RRI

One prospective investigated knee flexion at initial contact and specific RRIs finding no association with ITBS (Noehren, Davis and Hamill, 2007) (Table 43).

Table 41 Prospective studies investigating the association between peak knee flexion during running and RRI.

Authors	***n***	***Population***	***Surface***	***Number of foot strikes***	***Tracking Duration***	***Injury***	***Speed (m/s)***	***CON Mean ± SD (°)***	***INJ Mean ± SD (°)***	***Findings***	***Percentage Difference (%)***
Messier *et al.*, 2018	300	INJ: 145♀, 54 ♂ CON: 63♀, 38♂	O	3	12 months	General RRI	Self-selected: INJ: 2.94 ± 1.2; CON: 3.01 ± 1.2	40.1 ± 4.7	40.0 ± 5.3	Not significant, p>.05.	-0.2

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

Table 42 Prospective studies investigating the association peak knee flexion during running and specific RRI.

Authors	***n***	***Population***	***Surface***	***Number of foot strikes***	***Tracking Duration***	***Injury***	***Speed (m/s)***	***CON Mean ± SD (°)***	***INJ Mean ± SD (°)***	***Findings***	***Percentage Difference (%)***
Hein *et al.*, 2014- stance	142	INJ: 8♂, 2♀ CON: 8♂, 2♀	O	10	1 year	AT	Set speed: 3.3	41.0 ± 4.0	37.0 ± 7.0	Lower peak knee flexion among INJ group, no p value reported,	-10
Shen *et al.*, 2021- entire gait cycle	30	INJ: 15♂ CON: 15♂	O	5	8 weeks	ITBS	Set speed: 3.8	N/R	N/R	Not significant, p>.05.	N/R

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, ITBS= iliotibial pain syndrome, AT= Achilles tendon pain. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found**.**

Table 43 Prospective studies investigating the association between knee flexion excursion and knee flexion at initial contact during running and RRI.

Authors	n	Population	Surface	Number of foot strikes	Tracking Duration	Injury	Speed (m/s)	CON Mean ± SD (°)	INJ Mean ± SD (°)	Findings	Percentage Difference (%)
Knee flexion excursion											
Jungmalm *et al.*, 2020	224	CON: 55, INJ: 179	O	10	1 year	General RRIs	Set speed: 3.33	N/R	N/R	Not significant, p>.05.	N/R
Hein *et al.*, 2014	142	INJ: 8♂, 2♀ CON: 8♂, 2♀	O	10	1 year	AT	Set speed: 3.33	26.0 ± 3.0	26.0 ± 4.0	Not significant, p>.05.	0
Knee flexion at initial contact											
Noehren, Davis and Hamill, 2007	36	INJ: 18♀; CON: 18♀	O	5	2 years	ITBS	Set speed: 3.7 ± 5%	14.4 ± 6.03	11.8 ± 4.78	Not significant, p>.05.	-18

Abbreviated Terms: n=number, CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, ITBS= iliotibial pain syndrome, AT= Achilles tendon pain. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

2.6.2.3. The association between peak knee adduction angle during stance and RRI

Knee adduction and knee abduction have been suggested to be associated with RRIs, primarily due to their correlation with increased force on the medial and lateral condyles (Bruns, Volkmer and Luessenhop, 1993). Chronically high patellofemoral stress may lead to overloading of the articular cartilage and subchondral bone, ultimately resulting in pain (Farrokhi, Keyak and Powers, 2011).

No studies have examined peak knee adduction general RRIs. Furthermore, no studies have examined this association prospectively in relation to specific RRIs. Therefore, retrospective studies were reviewed. The association between peak knee adduction angle and specific RRIs has been investigated in seven retrospective studies, with six of these studies comparing between injured and uninjured groups (Table 44). One additional study by Pohl et al (2008) performed a logistic regression to evaluate the relationship between developing a tibial stress fracture and peak knee adduction, finding that the inclusion of peak knee adduction did not improve the predictive ability of the model. Among the remaining six retrospective studies, three (50%) found a significantly greater peak knee adduction angle among runners with ITBS (Noehren *et al.*, 2014b; Baker *et al.*, 2018) and PFPS (Willy *et al.*, 2012). Interestingly, two studies investigating the same injury, PFPS, found differing results (Willy *et al.*, 2012; Luz *et al.*, 2018). This may be explained by the consideration of sex in the analysis employed by Willy *et al.* (2012), who found greater knee adduction to only be observable in male runners. In contrast, Luz et al (2018) did not sub analyse by sex. As such, it is possible that analysing without consideration of sex may mask differences in groups. In relation to the association between knee adduction and ITBS found in the two studies, it was proposed that the anatomical attachment sites of the ITBS to the lateral knee may make it particularly vulnerable to potential increases in strain caused by increases in frontal plane motion (Noehren *et al.*, 2014b).

2.6.2.1. The association between peak knee abduction angle during stance and RRI

Peak knee abduction has been studied in one prospective study investigating general RRIs and two studies investigating specific injuries (PFPS) (Table 45). No association between peak knee abduction and general RRI was found (Dudley *et al.*, 2017). However, interestingly the two studies examining PFPS found conflicting results, with one finding no association (Noehren, Pohl, *et al.*, 2012) and one finding greater knee abduction among the injured group (Bazett-Jones *et al.*, 2013). Notably, both studies involved currently symptomatic runners with PFPS, therefore, changes in technique may be a compensatory response to injury. It is unclear if runners in these studies had comparable severity of PFPS, which may have helped to explain the results. This highlights the difficulty in determining the cause or effect relationship of factors related to injury in retrospective research.

Table 44 Studies investigating peak knee adduction during running and specific RRIs.

Authors	***n***	***Population***	***Surface***	***Number of foot strikes***	***Tracking Duration***	***Injury***	***Group Comparison***	***Speed (m/s)***	***CON Mean ± SD (°)***	***INJ Mean ± SD (°)***	***Finding***	***Mean difference (°)***
Retrospective												
Noehren *et al.*, 2014- early stance	34	INJ: 17♂ CON: 17♂	T	5	N/A	ITBS	Currently INJ vs CON	Set speed: 3.3	3.7 ± 3.6	7.3 ± 2.8	Greater peak knee adduction among INJ runners, p=.01	3.7
Baker and Fredericson, 2016- stance	30	INJ: 7♀; 8♂; CON: 7♀, 8♂	T	13-15	N/A	ITBS	Currently INJ vs CON	Set speed: 2.74	−1.5	3.7	Greater peak knee adduction among INJ runners, p<.01	6.2
Willy *et al.*, 2012- stance	72	INJ: 18♀, 18♂ CON: 18♀, 18♂	O	3	N/A	PFPS	Currently INJ vs CON= ♂	Set speed: 3.35	2.7 ± 3.2	5.7 ± 1.0	Greater peak knee adduction among INJ runners, p=.03	3.0
							Currently INJ vs CON= ♀		2.7 ± 3.2	2.2 ± 4.0	Not significant, p>.05.	-0.5
Luz *et al.*, 2018- stance	54	INJ: 16♂, 11♀ CON: 16♂, 11♀	T	10	N/A	PFPS	Currently INJ vs CON	Self-selected	5.3 ± 2.2	5.9 ± 2.0	Not significant, p>.05.	0.5
Bramah *et al.*, 2018- midstance	108	INJ: 28♂, 44♀; CON: 15♂, 21♀	T	10	N/A	PFP, ITBS, MTSS, AT	Currently INJ vs CON	Set speed: 3.2	–1.9 ± 3.1	–2.0 ± 3.5	Not significant, p>.05.	-0.01
Milner, Hamill and Davis, 2010- stance	60	INJ: 30♀; CON: 30♀	O	5	N/A	TSF	Previously INJ vs CON	3.7 ± 5%	2.2 ± 5.2	1.4 ± 4.0	Not significant, p>.05.	3.6
Pohl *et al.*, 2008- stance	60	INJ: 30♀; CON: 30♀	O	5	N/A	TSF	Previously INJ vs CON	Set speed: 3.7	2.5 ± 5.0	2.0 ± 5.0	Not significant, p>.05.	-0.5

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, MTSS= medial tibial stress syndrome, PFPS=patellofemoral pain syndrome, ITBS= iliotibial pain syndrome, AT= Achilles tendinopathy, TSF= tibial stress fracture, TSF= tibial stress fracture. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

Table 45 Studies examining the association between peak knee abduction and RRI.

Authors	n	Population	Surface	Number of foot strikes	Tracking Duration	Injury	Group Comparison	Speed (m/s)	CON Mean ± SD (°)	INJ Mean ± SD (°)	Finding	Mean difference (°)
General RRI												
Prospective												
Dudley *et al.*, 2017 Stance	31	INJ: 4♂, 8♀; CON: 11♂, 8♀	O	5	Season	General RRI	INJ vs CON	Self-reported training pace INJ vs CON	4.3	3.5	Not significant, p>.05.	0.8
Specific RRI												
Retrospective												
Bazett-Jones *et al.*, 2013- stance	38	INJ: 10♂, 9♀; CON: 10♂, 9♀	O	5	N/A	PFPS	Currently INJ vs CON	Set speed: 4.0	1.6 ± 2.7	3.4 ± 2.6	Greater peak knee abduction among INJ runners, P= 0.029	1.8
Noehren *et al.*, 2012- first 75% of stance	30	INJ: 15♀; CON: 15♀	O	5	N/A	PFPS	Currently INJ vs CON	Self-selected	4.4 ± 3.3	4.1 ± 4.1	Not significant, p>.05.	-0.3

Abbreviated terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, N/A= not applicable, RRI= running related injury, PFPS= patellofemoral pain syndrome, m/s= metres per second. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

The association between peak knee internal rotation angle during stance and RRI

No studies have examined the association between peak knee internal rotation and general RRIs. Peak knee internal rotation angle and its association to specific RRIs was investigated in two prospective studies (Table 46). Of these, one study investigating participants with ITBS (Noehren, Davis and Hamill, 2007) found significantly greater peak knee internal rotation angles among injured participants compared to uninjured controls. This may be due to increases in torsional load on the insertion of the ITB (Ferber *et al.*, 2009) and may indicate that this mechanism is injury-specific. The remaining prospective study found no association between this measure and Achilles tendon injury (Hein *et al.*, 2014).

2.6.2.2. The association between knee external-internal rotation excursion and RRI

No studies have examined the association between knee external-internal rotation and general RRIs. Knee internal rotation excursion was not found to be different between those with and without prospective Achilles tendon injuries (Hein *et al.*, 2014) (Table 47).

In summary, knee kinematics have been the subject of some research, largely retrospective in nature and predominantly investigating specific injuries. Despite the proposed mechanisms underpinning the suggestion that sagittal plane knee kinematics are associated with reduced risk of prospective RRI, there is very limited evidence investigating this, especially in relation to general RRIs, with the limited research available suggesting that no association exists. Furthermore, evidence linking sagittal plane motion and specific RRIs is inconsistent. With reference to frontal knee plane motion, there is moderate evidence to suggest that greater knee adduction is present in runners with ITBS and inconsistent evidence for an association between knee adduction or abduction and PFPS. The lack of prospective research investigating general or specific RRIs limits the ability to infer causality. Similarly, with respect to transverse-plane knee kinematics, little prospective research has been done, particularly in relation to general RRIs. Very limited evidence suggests that greater peak knee internal rotation is associated with ITBS, however, further studies would be needed to confirm this. Evidently, more prospective research examining stance phase knee kinematics and their association to general and specific RRIs are needed.

Table 46 Studies investigating peak knee internal rotation during running and RRI.

Prospective											
Authors	***n***	***Population***	***Surface***	***Number of foot strikes***	***Speed (m/s)***	***Tracking Duration***	***Injury***	***Group Comparison***	***CON Mean ± SD (°)***	***INJ Mean ± SD (°)***	***Findings***
Noehren, Davis and Hamill, 2007	36	INJ: 18♀ CON: 18♀	O	5	Set speed: 3.7 ± 5%	2 years	ITBS	INJ vs CON	0.0 ± 4.6	3.9 ± 3.7	Greater rotation among INJ runners, p=.01
Hein *et al.*, 2014	142	INJ: 8♂, 2♀ CON: 8♂, 2♀	O	10	3.2	1 year	AT	INJ vs CON AT	N/R	N/R	Not significant, p>.05.

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, MTSS= medial tibial stress syndrome, PFPS=patellofemoral pain syndrome, ITBS= iliotibial pain syndrome, AT= Achilles tendinopathy, TSF= tibial stress fracture, TSF= tibial stress fracture. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

Table 47 Studies investigating knee rotation excursion and specific RRIs

Authors	***n***	***Population***	***Surface***	***Number of foot strikes***	***Speed (m/s)***	***Tracking Duration***	***Injury***	***Group Comparison***	***CON Mean ± SD (°)***	***INJ Mean ± SD (°)***	***Findings***
Prospective											
Hein *et al.*, 2014	142	INJ: 8♂, 2♀ CON: 8♂, 2♀	O	10	3.2	1 year	AT	INJ vs CON	N/R	N/R	Not significant, p>.05..

Abbreviations: INJ= injured, CON= control, SD= standard deviation, O= over ground, ♂= males, ♀= females, AT= Achilles tendon injury, N/R= not reported. White shading indicates that no association was found.

2.6.3. The association between hip kinematics during running and RRI

2.6.3.1. The association between peak hip flexion angle during running and RRI

During weight bearing activities, the ability of the gluteus maximus and gluteus medius to generate torque decreases with increasing hip flexion (Ward, Winters and Blemker, 2010). Consequently, there may be an impaired ability to stabilise at the hip and pelvis with increasing hip flexion. No studies have prospectively examined peak hip flexion and general RRIs. However, of the two prospective studies examining the association between peak hip flexion angle and Achilles tendon injuries or ITBS, neither found a significant association to exist (Table 49).

2.6.3.2. The association between hip flexion angle at initial contact and RRI

No studies have examined hip flexion angle at initial contact and general RRIs. Just one retrospective study investigated the association between hip flexion angle at initial contact retrospectively investigating calf muscle injuries, finding greater values among injured runners (Bramah *et al.*, 2021) (Table 48). This was hypothesised to be related to their greater stride length. This, in turn, was suggested to be related to a shift in the centre of mass under the foot, necessitating increased ankle power during propulsion.

2.6.3.3. The association between hip flexion excursion and RRI

No studies have examined the association between hip flexion excursion and general RRIs. Hip flexion excursion has been investigated in a limited capacity in three studies, with no study finding an association between this metric and prospective Achilles tendon injuries (Hein *et al.*, 2014) or retrospective ITBS (Grau *et al.*, 2011) or retrospective Achilles tendinopathy (Creaby *et al.*, 2017) (Table 50).

Table 48 Studies investigating the association between hip flexion at initial contact and RRI.

Authors	Sample Size	Population	Surface	Number of foot strikes	Speed (m/s)	Tracking Duration	Injury	Group Comparison	CON Mean ± SD (°)	INJ Mean ± SD (°)	Finding	Percentage Difference (%)
Retrospective												
Bramah *et al.*, 2021 (midstance)	30	INJ: 15♂; CON: 15♂	T	10	Set speed: 3.2m/s	N/A	Calf muscle injury	Previously INJ vs CON	21.8 ± 3.5	26.3 ± 3.9	Greater hip flexion among INJ runners, p ≤.01.	21

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

Table 49 Studies investigating peak hip flexion angle during running and specific RRIs.

Authors	n	Population	Surface	Number of foot strikes	Speed (m/s)	Tracking Duration	Injury	Group Comparison	CON Mean ± SD (°)	INJ Mean ± SD (°)	Finding
Prospective											
Hein *et al.*, 2014- stance	142	INJ: 8♂, 2♀ CON: 8♂, 2♀	O	10	1 year	AT	INJ vs CON	Set speed: 3.3	N/R	N/R	No difference between injured runners and controls.
Shen *et al.*, 2021- entire gait cycle	30	INJ: 15♂ CON: 15♂	O	5	Set speed: 3.8	8 weeks	ITBS	INJ vs CON	N/R	N/R	No significant association between peak hip flexion angle and RRI, p>.05

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, MTSS= medial tibial stress syndrome, PFPS=patellofemoral pain syndrome, ITBS= iliotibial pain syndrome, AT= Achilles tendinopathy, TSF= tibial stress fracture, TSF= tibial stress fracture. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries.White shading indicates that no association was found.

Table 50 Studies investigating hip flexion excursion during running and RRI.

Authors	*n*	*Population*	*Surface*	*Number of foot strikes*	*Speed (m/s)*	*Tracking Duration*	*Injury*	*Group Comparison*	*CON Mean ± SD (°)*	*INJ Mean ± SD (°)*	*Findings*	*Percentage Difference (%)*
Prospective												
Hein *et al.*, 2014 - stance	142	INJ: 8♂, 2♀ CON: 8♂, 2♀	O	10	Set speed: 3.3	1 year	AT	INJ vs CON	N/R	N/R	Not significant, p>.05.	N/R
Retrospective												
Grau *et al.*, 2011- stance	36	INJ: 13♂, 5♀; CON: 13♂, 5♀	O	5	Set speed: 3.3	N/A	ITBS	Currently INJ vs CON	45.0 ± 5.0	44.0 ± 3.0	Not significant, p>.05.	2
Creaby *et al.*, 2017-change from foot strike to peak angle	25	INJ: 14♂; CON: 11♂	O	5	Set speed: 4.0	N/A	AT	Currently INJ vs CON	2.0 ± 3.1	0.7 ± 1.0	Not significant, p>.05.	65.0

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, ITBS= iliotibial pain syndrome, AT= Achilles tendinopathy. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

2.6.3.4. The association between peak hip adduction angle during running and RRI

The prevailing theory associating hip adduction to RRIs is that greater hip adduction may contribute to a sequelae of events including increased knee valgus, lateral patellar tracking and increased lateral knee contact pressure (Dudley *et al.*, 2017). Hip adduction may be related to impact loading. In a study of ten runners with PFPS, when provided real time feedback to reduce hip adduction, authors noted an 18% and 20% reduction in instantaneous and average vertical load rates, respectively (Noehren, Scholz and Davis, 2011).

One prospective study investigated the association between peak hip adduction angle and general RRIs among cross country runners, finding no association to exist (Dudley *et al.*, 2017) (Table 51). Three prospective studies investigated peak hip adduction angle during running and specific RRIs (Table 52). Of these, evidence is inconsistent. Noehren *et al.* (2007) found significantly greater hip adduction angles among female runners with ITBS compared to uninjured controls. While the exact mechanisms are not well understood, increases in hip adduction among injured participants may be a symptom of an impairment of the ITB in its function as a lateral stabiliser and resister of hip adduction (Milner, Hamill and Davis, 2007), however the link between hip abductor weakness and ITBS has been debated (Fredericson *et al.*, 2000; Grau *et al.*, 2008) and the decrease in gluteus medius activity among runners with previous ITBS has been refuted experimentally (Foch, Aubol and Milner, 2020). Furthermore, although also investigating ITBS, Shen *et al.* (2019) did not find a significant difference in peak hip adduction. Differences in findings may suggest that sex could be an important consideration in relation to ITBS given that Shen et al. (2019) investigated males only. In relation to Achilles tendon pain, Hein *et al.* (2014) found no difference between controls and injured runners.

2.6.3.1. The association between hip adduction excursion during running and RRI

Hip adduction excursion has been examined in two prospective studies in relation to general RRIs (Jungmalm *et al.*, 2020) and Achilles tendon injuries (Hein *et al.*, 2014), with neither finding an association to RRI (Table 53).

2.6.3.2. The association between hip adduction at toe off and RRI

No studies have examined the association between hip adduction at toe off and general RRIs. Hip adduction at toe off has been examined in one retrospective study, finding significantly greater hip adduction at toe off among runners with PFPS compared to uninjured runners (Esculier, Roy and Bouyer, 2015) (Table 54). This was hypothesised to be as a result of delayed activation of the gluteus medius muscle, however as a retrospective study it is unclear if this is causative of injury.

2.6.3.3. The association between peak hip internal rotation during running and RRI

Peak hip internal rotation angle and its association with general RRIs has been studied in one prospective study (Dudley *et al.*, 2017), finding no association to exist (Table 55). However, authors noted that a moderate effect size was found and that the study may not have been adequately powered to detect a significant difference between groups.

Twelve retrospective studies have examined the association between peak hip internal rotation and specific injuries (

Table **49**). No prospective studies have examined this. While three (25%) studies found an increase in peak hip internal rotation among runners with ITBS (Noehren *et al.*, 2014b) and PFPS (Souza and Powers, 2009; Noehren, Pohl, *et al.*, 2012), evidence is generally inconsistent, with no association found in the remaining ten studies (8.3%) for ITBS (Brown *et al.*, 2016), PFPS (Dierks *et al.*, 2011; Willy *et al.*, 2012; Bazett-Jones *et al.*, 2013; Esculier, Roy and Bouyer, 2015; Luz *et al.*, 2018), tibial stress fractures (Milner, Hamill and Davis, 2010), lower leg injuries (Bramah *et al.*, 2018) and medial shin pain (Loudon and Reiman, 2012). Where an association was found for PFPS, it may be explained by greater tension on the quadriceps tendon and increased patellofemoral contact pressure caused by this motion (Lee *et al.*, 1994).

2.6.3.4. The association between hip internal rotation excursion and RRI

No study has examined the association between hip internal rotation excursion and general RRIs. Just one retrospective study examined the association between hip internal rotation excursion and specific RRIs, finding no significant difference in late stance hip excursion between runners with and without PFPS (Esculier, Roy and Bouyer, 2015).

2.6.3.5. The association between hip internal rotation at toe off and RRI

No study has examined the association between hip internal rotation at toe-off and general RRIs. Just one retrospective study examined the association between internal rotation at toe off and RRIs, finding no significant difference in tis measure between runners with and without PFPS (Esculier, Roy and Bouyer, 2015).

In summary, it appears that there is no clear link between any measure of hip kinematics (adduction, flexion, internal rotation) during running and general or specific RRIs. Conclusions are limited due to a limited number of prospective studies and very little research examining general RRIs.

Table 51 Prospective studies investigating peak hip adduction angle during running and general RRIs.

Authors	*n*	*Population*	*Surface*	*Number of foot strikes*	*Speed (m/s)*	*Tracking Duration*	*Injury*	*Findings*	*CON Mean ± SD (°)*	*INJ Mean ± SD (°)*	*Percentage Difference (%)*
Dudley *et al.*, 2017- stance	31	INJ: 4♂, 8♀; CON: 11♂, 8♀	O	5	Self-reported training pace	Season	General RRI	Not significant, p>.05.	12.7 (11.1, 14.2) ±	14.0 (11.4, 16.5)	−10

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

Table 52 Prospective studies investigating peak hip adduction angle during running and specific RRIs.

Authors	*n*	*Population*	*Surface*	*Number of foot strikes*	*Speed (♂/s)*	*Tracking Duration*	*Injury*	*Findings*	*CON Mean ± SD (°)*	*INJ Mean ± SD (°)*	*Percentage Difference (%)*
Noehren, Davis and Hamill, 2007- stance	36	INJ: 18♀; CON: 18♀	O	5	Set speed: 3.7 ± 5%	2 years	ITBS	Greater peak hip adduction angle among INJ runners, p=.01	10.6 ± 5.1	14.1 ± 2.5	33
Shen *et al.*, 2021- entire cycle	30	CON: 15♂; INJ: 15♂	O	5	Set speed: 3.8	8 weeks	ITBS	Not significant, p>.05.	N/R	N/R	N/R
Hein *et al.*, 2014- stance	142	INJ: 8♂, 2♀ CON: 8♂, 2♀	O	10	Set speed: 3.3	1 year	AT	Not significant, p>.05.	N/R	N/R	N/R

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, , ITBS= iliotibial pain syndrome, AT= Achilles tendon injuries,. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

Table 53 Prospective studies investigating hip adduction excursion during running and specific and general RRIs.

Authors	*n*	*Population*	*Surface*	*Number of foot strikes*	*Speed*	*Tracking Duration*	*Injury*	*CON Mean ± SD (°)*	*INJ Mean ± SD (°)*	*Finding*
Jungmalm *et al.*, 2020	224	CON: 55, INJ: 179; 135♂, 89♀	O	10	Set speed: 3.3	1 year	General RRI	N/R	N/R	Not significant, p>.05.

Hein *et al.*, 2014 (stance)	142	INJ: 8♂, 2♀ CON: 8♂, 2♀	O	10	Set speed: 3.3	1 year	AT	N/R	N/R	Not significant, p>.05.	

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries.

Table 54 Studies investigating the association between hip adduction at toe off and RRI.

Authors	***n***	***Population***	***Surface***	***Number of foot strikes***	***Speed (m/s)***	***Tracking Duration***	***Injury***	***Group Comparison***	***CON Mean ± SD (°)***	***INJ Mean ± SD (°)***	***Finding***	***Percentage Difference***
Retrospective												
Esculier *et al.*, 2015	41	INJ: 5♂, 16♀; CON: 5♂, 15♀	T	50	Self-selected	N/A	PFPS	Currently INJ vs CON			Greater hip adduction at toe off among runners with PFPS, p<.01.	93

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, PFPS= patellofemoral pain syndrome, Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries.

Table 55 Studies investigating peak hip internal rotation during running and RRIs.

Authors	***n***	***Population***	***Surface***	***Number of foot strikes***	***Speed (m/s)***	***Tracking Duration***	***Injury***	***Groupings***	***CON Mean ± SD (°)***	***INJ Mean ± SD (°)***	***Finding***	***Percentage Difference (%)***
Prospective												
Dudley *et al.*, 2017- stance	31	INJ: 4♂, 8♀ CON: 11♂, 8♀	O	5	Self-reported training pace	Season	General RRI	INJ vs CON	4.8 (1.2, 8.4)	7.5 (5.0, 10.1)	Not significant, p>.05.	56
Retrospective												
Luginick *et al.*, 2018- stance	60	INJ: 15♂, 15♀; CON: 15♂; 15♀	O	4	Self-selected speed	N/A	ITBS	Currently INJ vs CON	9.7 ± 10.4	3.8 ± 7.8	Lower hip internal rotation angle among INJ groups, p<.05.	61
Noehren *et al.*, 2014- early stance	34	INJ: 17♂ CON: 17♂	T	5	Set speed: 3.3	N/A	ITBS	Currently INJ vs CON	9.6 ± 5.2	13.3 ± 6.6	Greater hip internal rotation angle among INJ groups, p=.03	-39
Noehren *et al.*, 2012- stance	32	INJ: 16♀ CON: 16♀	O	5	Self-selected	N/A	PFPS	Currently INJ vs CON	5.2 ± 3.3	9.8 ± 4.2	Greater hip internal rotation angle among INJ groups, p=.002	-89
Souza and Powers, 2009	38	INJ: 19♀ CON: 19♀	O	3	Set speed	N/A	PFPS	Currently INJ vs CON	4.2 ± 3.4	11.8 ± 6.9	Greater hip internal rotation angle among INJ groups, p=.001	-181
Bramah *et al.*, 2018- stance	108	CONJ: 28♂, 44♀; CON: 15♂, 21♀	T	10	Set speed: 3.2	N/A	PFP, ITBS, MTSS, AT	Currently INJ vs CON	4.4 ± 6.8	4.2 ± 8.0	Not significant, p>.05.	5

Loudon and Reiman, 2012- stance	28	INJ: 6♂, 8♀; CON: 6♂, 8♀	T	5	Self-selected	N/A	Medial shin pain	Previously INJ vs CON	8.3 ± 4.9	11.5 ± 5.2	Not significant, p>.05.	-39
Willy *et al.*, 2012 stance	72	INJ: 18♀, 18♂; CON: 18♀, 18♂	O	3	Set speed: 3.4	N/A	PFPS	Currently INJ vs CON males	6.0 ± 3.8	6.9 ± 4.6	Not significant, p>.05.	-15
								Currently INJ vs CON females	6.0 ± 3.8	9.0 ± 4.8		-50
Luz *et al.*, 2018- first 60% of stance	54	INJ: 27; CON: 27	T	10	Self-selected speed	N/A	PFPS	Currently INJ vs CON	11.1 ± 4.4	10.3 ± 3.7	Not significant, p>.05.	11
Dierks *et al.*, 2008- stance	40	INJ: 5♂; 15♀; CONINJ: 5♂, 15♀	T	20	Self-selected	N/A	PFPS	Currently INJ vs CON	6.0 ± 5.4	5.1 ± 6.8	Not significant, p>.05.	15
Milner, Hamill and Davis, 2010	60	INJ: 30 CON: 30	O	5	Set speed: 3.7 ± 5%	N/A	TSF	Previously INJ vs CON	8.5 ± 6.1	6.6 ± 5.0	Not significant, p>.05.	2
Bazett-Jones *et al.*, 2013	38	INJ: 10♂, 9♀; CON: 10♂, 9♀	O	5	Set speed: 4.0	N/A	PFPS	Previously INJ vs CON	6.3 ± 4.5	3.0 ± 4.2	Not significant, p>.05.	52
Brown *et al.*, 2008- stance	32	INJ: 12♀; CON: 20♀	O	5	3D motion analyses (120 Hz)	N/A	ITBS	Currently INJ vs CON	5.6 ± 8.3	3.6 ± 6.9	Not significant, p>.05.	36
Esculier, Roy and Bouyer, 2015- stance	41	INJ: 5♂, 16♀; CON: 5♂. 15♀	T	50	Self-selected	N/A	PFPS	Currently INJ vs CON	8.2 ± 5.5	7.9 ± 5.5	Not significant, p>.05.	4

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, MTSS= medial tibial stress syndrome, PFPS=patellofemoral pain syndrome, ITBS= iliotibial pain syndrome, AT= Achilles tendinopathy, TSF= tibial stress fracture, TSF= tibial stress fracture. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

2.6.4. The association between pelvic kinematics during running and RRI

The pelvis acts to transmit loads from the lower limbs to the spine. In addition, the pelvis serves as an insertion site for the gluteal and hamstring muscles which act to both attenuate forces during impact (Schache *et al.*, 2002) and propel the body during propulsion (Geraci and Brown, 2005). Furthermore, pelvis motion may govern movements at distal joint such as the hip and knee (Loudon and Reiman, 2012). It has been hypothesised that excessive pelvic motion, particularly contralateral pelvic drop may cause low back pain in runners (Schache, Blanch and Murphy, 2000), however, relatively few studies have explored the association between pelvic kinematics and RRIs. Due to the low number of studies investigating pelvis drop and RRI, retrospective studies were included.

2.6.4.1. The association between peak anterior pelvic tilt during running and RRI

No study has examined the association between peak anterior pelvic tilt and general RRIs. The association between anterior pelvic tilt and specific RRIs was examined prospectively in one study (Shen *et al.*, 2019) and retrospectively in six studies (Table 57). Just two studies (29%) found a significant link between RRI and pelvic tilt (Bramah *et al.*, 2021; Shen *et al.*, 2021). In the retrospective arm of their investigation, Shen et al (2019) found that when tested 8 weeks after enrolment in a running programme, runners that had developed ITBS had significantly greater peak anterior pelvic tilt when compared to uninjured controls. This difference was not present at enrolment into the study, indicating that changes may have occurred in response to the injury. Similarly, retrospectively, Bramah et al. (2021) found an association between greater pelvis anterior tilt and calf muscle injury, indicating that this may be as a result of neuromuscular deficits in the gluteal muscles in controlling sagittal plane pelvic motion, with consequently altered calf muscle action. No association was found between this metric and grouped injuries of ITBS, MTSS, Achilles tendinopathy and PFPS (Bramah *et al.,* 2018), medial shin pain (Loudon and Reiman, 2012b) or PFPS (Bazett-Jones *et al.,* 2013).

2.6.4.2. The association between anterior pelvic tilt at initial contact and RRI

No study has examined the association between anterior pelvis tilt at initial contact and general RRIs. One retrospective study investigated the association between anterior pelvic tilt at initial contact and RRI, finding greater anterior pelvic tilt among runners with previous calf muscle injury (Bramah *et al.*, 2021). This was explained via the reasoning outlined above.

2.6.4.3. The association between contralateral pelvic drop during running and RRI

No study has investigated the association between peak contralateral pelvic drop and general RRIs. Peak contralateral pelvic drop and its association with specific RRI has been studied in one prospective and nine retrospective studies (Table 56). Of these, only three retrospective studies found a significant relationship between greater contralateral pelvic drop and medial shin pain (Loudon and Reiman, 2012), PFPS, ITBS, MTSS, AT injuries grouped (Bramah *et al.*, 2018) and muscular calf injuries (Bramah *et al.*, 2021). Greater contralateral drop may result in a medial shift of the ground reaction force centre of mass relative to the knee (Loudon and Reiman, 2012), potentially altering force distribution through the lower limb with a simultaneous increase in knee valgus moment and subtalar pronation, both factors previously hypothesised to be associated with lower limb injury (Loudon and Reiman, 2012). Pelvic contralateral drop is theorised to be associated with weakness of the glute medius, which controls frontal plane pelvic and hip kinematics (Loudon and Reiman, 2012; Bramah *et al.*, 2018). However, none of the three studies with significant findings concurrently collected muscle strength data to support this suggestion. There was moderate evidence to suggest that PFPS (Noehren, Pohl, *et al.*, 2012; Esculier, Roy and Bouyer, 2015) and ITBS (as an individual injury) (Foch and Milner, 2014; Foch *et al.*, 2015; Shen *et al.*, 2021) were not associated with pelvic drop.

Table 56 Studies investigating contralateral peak pelvic drop during running and RRI.

Authors	*n*	*Population*	*Surface*	*Number of foot strikes*	*Speed (♂/s)*	*Tracking Duration*	*Injury*	*Grouping*	*CON Mean ± SD (◦)*	*INJ Mean ± SD (◦)*	*Findings*	*Percentage Difference (%)*
Prospective												
Shen *et al.*, 2021- entire gait cycle	30	INJ: 15♂; CON: 15♂	O	5	Set speed: 3.8m/s	8 weeks	ITBS	INJ vs CON	N/R	N/R	Not significant, p>.05.	N/R
Retrospective												
Bramah *et al.*, 2021- midstance	30	INJ: 15♂; CON: 15♂	T	10	Set speed: 3.2m/s	N/A	Calf muscle injury	Previously INJ vs CON	3.5 ± 2.6	5.7 ± 1.9	Greater contralateral pelvic drop among INJ group, p≤.01.	63
Bramah *et al.*, 2018- midstance	108	INJ: 28♂, 44♀; CON: 15♂, 21♀	T	10	Set speed: 3.2 m/s	N/A	PFP, ITBS, MTSS, AT	Currently INJ vs CON	3.7 ± 1.9	6.4 ± 2.1	Greater contralateral pelvic drop among INJ group, p<.01	-81
Loudon and Reiman, 2012- stance	28	INJ: 6♂, 8♀; CON: 6♂, 8♀	T	5	Self-selected	N/A	Medial shin pain	Previously INJ vs CON	5.9 ± 1.9	8.6 ± 2.2	Greater contralateral pelvic drop among INJ group, p=.002	-46
Noehren, Sanchez, *et al.*, 2012- first 75% of stance	30	INJ: 15♀; CON: 15♀	O	5	Self-selected	N/A	PFPS	Currently INJ vs CON	−6.6 ± 2.1	−8.0 ± 2.7	Not significant, p>.05.	21
Shen *et al.*, 2021- entire gait cycle	30	INJ: 15♂; CON: 15♂	O	5	Set speed: 3.8m/s	N/A	ITBS	Unclear	N/R	N/R	Not significant, p>.05.	N/R
Foch *et al.*, 2015- stance	27	INJ: 18; CON: 9	O	5	Set speed: 3.5 ± 0.18m/s.	N/A	ITBS	Currently INJ vs CON	−6.1 ± 1.7	−6.7 ± 2.8	Not significant, p>.05.	10
Foch and Milner, 2014- stance	34	INJ: 17♀ CON: 17♀	O	5	Set speed: 3.5 ± 0.18 m/s	N/A	ITBS	Previously INJ vs CON	–4.7 ± 2.2	–3.9 ± 1.9	Not significant, p>.05.	17
Bazett-Jones *et al.*, 2013- stance	38	INJ: 10♂, 9♀; CON: 10♂, 9♀	O	5	Set speed: 4.0 .5 m/s	N/A	PFPS	Previously INJ vs CON	4.2 ± 1.9	4.7 ± 2.0-	Not significant, p>.05.	-12
Esculier, Roy and Bouyer, 2015- stance	41	INJ: 5♂, 16♀; CON: 5♂, 15♀	T	50	Self-selected	N/A	PFPS	Currently INJ vs CON	−3.5 ± 1.8	−3.7 ± 1.4	Not significant, p>.05.	-6

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, MTSS= medial tibial stress syndrome, PFPS=patellofemoral pain syndrome, ITBS= iliotibial pain syndrome, AT= Achilles tendinopathy, TSF= tibial stress fracture, TSF= tibial stress fracture. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

Table 57 Studies investigating the association between anterior pelvic tilt during running and RRI.

Authors	***n***	***Population***	***Surface***	***Number of foot strikes***	***Speed (m/s)***	***Tracking Duration***	***Injury***	***Group Comparison***	***CON Mean ± SD (°)***	***INJ Mean ± SD (°)***	***Finding***	***Percentage Difference (%)***
Peak During stance												
Prospective												
Shen *et al.*, 2021- entire gait cycle	30	INJ: 15♂ CON: 15♂	O	5	Set speed: 3.8	8 weeks	ITBS	INJ vs CON	N/R	N/R	Not significant, p>.05.	N/R
Retrospective												
Shen *et al.*, 2021- entire gait cycle	30	INJ: 15♂ CON: 15♂	O	5	Set speed: 3.8	N/A	ITBS	Currently INJ vs CON	N/R	N/R	Greater anterior pelvic tilt among INJ group, p<.001	N/R
Bramah *et al.*, 2021- midstance	30	INJ: 15♂; CON: 15♂	T	10	Set speed: 3.2m/s	N/A	Calf muscle injury	Previously INJ vs CON	6.0 ± 9.1	9.1 ± 3.8	Greater anterior pelvic tilt among INJ group, p=.03	52
Luginick *et al.*, 2018	60	INJ: 15♂, 15♀; CON: 15♂; 15♀	O	4	Self-selected speed	N/A	ITBS	Currently INJ vs CON	19.3 ± 5.2	22.6 ± 4.0	Greater contralateral pelvic drop among INJ group, p≤.01.	17
Loudon and Reiman, 2012- stance	28	INJ: 6♂, 8♀ CON: 6♂, 8♀	T	5	Self-selected	N/A	Medial shin pain	Previously INJ vs CON	7.8 ± 2.4	9.6 ± 1.8	Not significant, p>.05.	-23
Bramah *et al.*, 2018- midstance	108	INJ: 28♂, 44♀ CON: 15♂, 21♀	T	10	Set speed: 3.2	N/A	PFP, ITBS, MTSS, AT	Currently INJ vs CON	5.0 ± 2.9	5.7 ± 3.8	Not significant, p>.05.	-14
Bazett-Jones *et al.*, 2013- stance	38	INJ: 10♂, 9♀ CON: 10♂, 9♀	O	5	Set speed: 4.0	N/A	PFPS	Previously INJ vs CON	10.2 ± 5.5	7.2 ± 5.1	Not significant, p>.05.	24
At initial contact												
Retrospective												
Bramah *et al.*, 2021	30	INJ: 15♂; CON: 15♂	T	10	Set speed: 3.2m/s	N/A	Calf muscle injury	Previously INJ vs CON	6.2 ± 9.9	9.9 ± 3.7	Greater anterior	4

										pelvic tilt among INJ group, p≤.01	

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, MTSS= medial tibial stress syndrome, PFPS=patellofemoral pain syndrome, ITBS= iliotibial pain syndrome, AT= Achilles tendinopathy, TSF= tibial stress fracture, Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

Table 58 Studies investigating the association between pelvis anterior tilt at initial contact and general RRI.

Authors	***n***	***Population***	***Surface***	***Number of foot strikes***	***Speed (m/s)***	***Injury***	***Group Comparison***	***CON Mean ± SD (◦)***	***INJ Mean ± SD (◦)***	***Finding***	***Percentage Difference (%)***
Retrospective											
Bramah *et al.*, 2021- midstance	30	INJ: 15♂; CON: 15♂	T	10	Set speed: 3.2 m/s	Calf muscle injury	Previously INJ vs CON	6.2 ± 3.5	9.9 ± 3.7	Greater pelvis anterior tilt among INJ runners, p≤.01.	60

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries.White shading indicates that no association was found.

2.6.4.4. The association between transverse plane rotation of the pelvis and RRI

Axial rotation, the rotation of the pelvis on the transverse plane (Figure 6), may be important in maintaining the balance between the upper and lower body angular momentum required for straight lined running (Willwacher *et al.*, 2016). Ipsilateral rotation of the pelvis at initial contact is suggested to aid in reducing the horizontal braking forces at initial contact and thus avoiding potential loss of speed (Novacheck, 1998; Schache *et al.*, 2002). Although transverse plane rotation of the pelvis is clearly important during the running movement, its relevance to RRIs has not been studied previously.

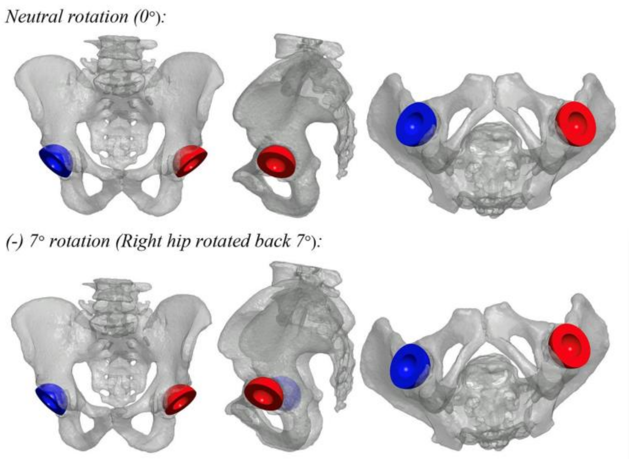

Figure 6 Transverse plane rotation of the pelvis. (Premkumar *et al.*, 2021).

In summary, there is moderate evidence to suggest that contralateral pelvic drop is not associated with retrospective ITBS. There is very limited research to support any conclusions with regard to the association between RRI and pelvic tilt. There is no evidence to date examining axial rotation of the pelvis in relation to RRIs. This should be explored in future studies. Conclusions are limited by the predominance of retrospective research, with just one study exploring pelvis motion and prospective ITBS injuries (Shen *et al.*, 2019).

2.6.5. The association between trunk kinematics during running and RRI

The trunk, head, arms and pelvis accounts for approximately 60% of a person's total body mass (Ford *et al.*, 2013), therefore trunk motion has been proposed to have an effect on factors which may precipitate injury, such as loading (Simic *et al.*, 2011). A study of recreational runners found that running with increased trunk flexion reduced energy absorption and generation of the knee extensors, and increased energy generation of the hip extensors (Teng and Powers, 2014). In another study of recreational runners, an inverse relationship existed between mean trunk flexion angle and peak patellofemoral joint stress during running (Teng and Powers, 2014).

2.6.5.1. The association between trunk forward flexion during running and RRI

Due to the low number of prospective studies retrospective research was included. No studies investigated the association between trunk forward flexion and general RRIs. One prospective (Shen *et al.*, 2021) and three retrospective (Bazett-Jones *et al.*, 2013; Bramah *et al.*, 2018; Shen *et al.*, 2021) studies investigated peak trunk forward flexion during running and specific RRIs (Table 59). Evidence is conflicting, with one retrospective (Bazett-Jones *et al.*, 2013) and one prospective study (Shen *et al.*, 2021) reporting no significant association between trunk forward flexion and RRI, while two studies (50%) found greater trunk flexion among injured runners (Bramah *et al.*, 2018; Shen *et al.*, 2021). Interestingly, although they did not find any difference in trunk flexion between uninjured runners and those who went on to develop ITBS in the prospective arm of their study, Shen et al (2019) found that after development of the injury, injured runners displayed significantly increased trunk flexion compared to their baseline. Similarly in their retrospective research Bramah et al. (2018) found that runners with lower limb injuries such as PFPS, ITBS, MTSS, and Achilles tendon injury had significantly greater trunk forward flexion than uninjured controls. Increases in trunk forward flexion has been found to decrease patellofemoral stress during running (Teng and Powers, 2014). Therefore, it is somewhat surprising that both Bramah *et al.* (2018) and Shen *et al.* (2021) found significant increases in forward flexion among the injured group. This may be as a result of a compensatory mechanism to decrease joint stress as the participants were currently symptomatic. Overall, there is inconsistent evidence to support the association between greater trunk flexion and specific RRIs, necessitating future prospective research.

Table 59 Studies investigating peak trunk flexion during running and RRI.

Authors	***n***	***Population***	***Surface***	***Number of foot strikes***	***Speed (m/s)***	***Tracking Duration***	***Injury***	***Group Comparison***	***CON Mean ± SD (◦)***	***INJ Mean ± SD (◦)***	***Findings***	***Percentage Difference (%)***
Prospective												
Shen *et al.*, 2021- entire gait cycle	30	INJ: 15 ♂ CON: 15 ♂	O	5	Set speed: 3.8	8 weeks	ITBS	INJ vs CON	19.9 ± 13.5	14.9 ± 4.8	Not significant, p>.05.	25
Retrospective												
Shen *et al.*, 2021- entire gait cycle	30	INJ: 15 ♂ CON: 15 ♂	O	5	Set speed: 3.8	N/A	ITBS	Pre and post injury	21.1 ± 17.9	20.9 ± 5.2	Greater trunk flexion among runners when injured with ITBS compared to when they did not have injury, p=.023.	11
Bramah *et al.*, 2018- midstance	108	INJ: 28♂, 44♀; CON: 15♂, 21♀	T	10	Set speed: 3.2	N/A	PFP, ITBS, MTSS, AT	Currently INJ vs CON	9.5 ± 2.9	12.0 ± 4.9	Greater trunk flexion among INJ group, p<.001	-70
Bazett-Jones *et al.*, 2013- stance	38	INJ: 10♂, 9♀ CON: 10♂, 9♀	O	5	Set speed: 4.0	N/A	PFPS	Previously INJ vs CON	13.9 ± 4.7	13.1 ± 6.2	Not significant, p>.05.	6

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, MTSS= medial tibial stress syndrome, PFPS=patellofemoral pain syndrome, ITBS= iliotibial pain syndrome, AT= Achilles tendinopathy, tibial stress fracture, TSF= tibial stress fracture. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

Table 60 Studies investigating contralateral trunk flexion during running and RRI.

Authors	***n***	***Population***	***Surface***	***Number of foot strikes***	***Speed (m/s)***	***Tracking Duration***	***Injury***	***Group Comparison***	***CON Mean ± SD (◦)***	***INJ Mean ± SD (◦)***	***Findings***	***Difference in means (◦)***
Retrospective												
Noehren, Sanchez, *et al.*, 2012- first 75% of stance	30	INJ: 15♀; CON: 15♀	O	5	Self-selected	N/A	PFPS	Currently INJ vs CON	3.5 ± 3.0	5.0 ± 1.3	Not significant, p>.05.	1.5
Foch and Milner, 2014- stance	34	IN: 17♀; CON: 17♀	O	5	Set speed: 3.5 ± 0.18	N/A	ITBS	Previously INJ vs CON	0.1 ±2.1	0.4 ± 2.2	Not significant, p>.05.	0.3
Bazett-Jones *et al.*, 2013- stance	38	INJ: 10♂, 9♀; CON: 10♂, 9♀	O	5	Set speed: 4.0 .5 ♂/s	N/A	PFPS	Previously INJ vs CON	2.5 ± 2.2	2.7 ± 4.1	Not significant, p>.05.	0.2

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, MTSS= medial tibial stress syndrome, PFPS=patellofemoral pain syndrome, ITBS= iliotibial pain syndrome, AT= Achilles tendinopathy, TSF= tibial stress fracture, TSF= tibial stress fracture. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

Table 61 Studies investigating ipsilateral trunk flexion during running and RRI

Authors	***n***	***Population***	***T/O***	***Number of foot strikes***	***Speed (m/s)***	***Tracking Duration***	***Injury***	***Group Comparison***	***CON Mean ± SD (◦)***	***INJ Mean ± SD (◦)***	***Finding***	***Percentage Difference (%)***
Prospective												
Shen *et al.*, 2021- entire gait cycle	30	INJ: 15♂; CON: 15♂	O	5	Set speed: 3.8 m/s	8 weeks	ITBS	INJ vs CON	9.8 ± 5.3	9.0 ± 2.4	Not significant, p>.05.	8
Retrospective												
Foch *et al.*, 2015- stance	34	IN: 17♀; CON: 17♀	O	5	Set speed: 3.5 ± 0.18 m/s.	N/A	ITBS	Current INJ vs CON	3.3 ± 1.6	5.6 ± 1.5	Greater trunk flexion among INJ runners, p=.01.	-70
Bramah *et al.*, 2018- midstance	108	INJ: 28♂, 44♀; CON: 15♂, 2 ♀	T	10	Set speed: 3.2 m/s	N/A	PFP, ITBS, MTSS, AT	Currently INJ vs CON	3.6 ± 1.8	4.3 ± 2.6	Not significant, p>.05.	-25
Shen *et al.*, 2021- entire gait cycle	30	CON: 15♂; INJ: 15♂	O	5	Set speed: 3.8 m/s	N/A	ITBS	Unclear	12.4 ± 16.9	10.5 ± 3.2	Not significant, p>.05.	15
Bazett-Jones *et al.*, 2013- stance	38	INJ: 10♂, 9♀; CON: 10♂, 9♀	O	5	Set speed: 4.0 .5 m/s	N/A	PFPS	Currently INJ vs CON	13.9 ± 4.7	13.1 ± 6.2	Not significant, p>.05.	-6
Foch and Milner, 2014- stance	34	IN: 17♀; CON: 17♀	O	5	Set speed: 3.5 ± 0.18	N/A	ITBS	Previously INJ vs CON	3.4 ± 2.2	3.7 ± 1.8	Not significant, p>.05.	-9

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, MTSS= medial tibial stress syndrome, PFPS=patellofemoral pain syndrome, ITBS= iliotibial pain syndrome, AT= Achilles tendinopathy, TSF= tibial stress fracture, TSF= tibial stress fracture. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

2.6.5.2. The association between peak thorax rotation and injury

No study has investigated peak thorax rotation and RRIs.

2.6.5.3. The association between peak ipsilateral trunk flexion during running and RRI

No studies have examined the association between peak ipsilateral trunk flexion and general RRIs. Peak ipsilateral trunk flexion and its association with specific RRIs was examined in one prospective study and five retrospective studies (Table 61). Of these, one retrospective study found significantly higher peak ipsilateral trunk flexion among runners with current ITBS (Foch *et al.*, 2015). However, also studying ITBS, Shen et al (2019) and Foch and Milner (2014) did not find a significant difference between groups. The study finding significance, differ in examining currently injured female participants (Foch *et al.*, 2015). Therefore, sex and timepoint from injury may affect findings. Increases in ipsilateral flexion may be a compensatory mechanism to decrease the demands on the typically weak trunk stabilisers seen in injured populations by leaning to the side of the stance leg (Leetun *et al.*, 2004), although lack of concurrent muscle strength data lessens the ability to draw a definite conclusion. No other study found an association between RRIs and peak ipsilateral flexion, resulting in inconsistent findings.

2.6.5.4. The association between peak contralateral trunk flexion during running and RRI

No studies have examined the association between contralateral trunk flexion and RRI. Four retrospective studies have investigated contralateral trunk flexion and specific RRIs (Noehren, Pohl, *et al.*, 2012; Foch and Milner, 2014; Bramah *et al.*, 2018) (Table 60). Of these, two investigated PFPS (Noehren, Michael B. Pohl, *et al.*, 2012), one investigated ITBS, Achilles tendon injuries, and PFPS (Bramah *et al.*, 2018), and one investigated ITBS (Foch and Milner, 2014). No study found a significant difference between injured and uninjured groups.

In summary, the association between trunk kinematics and RRI is generally inconsistent, hampered by the relatively low number of studies investigating it and the lack of prospective research.

2.7. Asymmetry and Injury

Imbalances between sides is classified as asymmetry, with various calculations being used to quantify this (Bishop *et al.*, 2016). It is commonly hypothesised that side to side asymmetry may precipitate injury and also persist following injury (Zifchock, Davis and Hamill, 2006). Asymmetry is proposed to be associated with RRIs for two primary reasons. Firstly, asymmetry may place excess loading on one side of the body, potentially relating to overload (Bredeweg, Buist and Kluitenberg, 2013). Secondly, some research has found that asymmetries induced by injury may persist after returning to sport (Ithurburn *et al.*, 2015), precipitating future injury, which may explain the high risk of reinjury among those with a history of previous injury (Desai *et al.*, 2021). However, asymmetry has not been heavily investigated in relation to RRIs. This review will focus on examining the association between asymmetry of clinical measures and RRI, in light of the potential ease of using this measure in clinical practice as a risk factor for injury.

One retrospective study investigated the association between hip internal rotation strength asymmetry and general RRIs (Zifchock *et al.*, 2008), finding no association to exist. Similarly, no association was found between asymmetry of hip abduction strength and PFPS (Plastaras *et al.*, 2016) (Table 62). In terms of range of motion, no significant difference in symmetry of hip internal rotation ROM existed between previously injured and never injured runners in relation to general RRI (Zifchock *et al.*, 2008). In relation to foot position, asymmetry between retrospectively injured and never injured runners in terms of Arch Height Index was found not to be related to general RRI (Zifchock *et al.*, 2008).

Evidently, although relatively easy to calculate and potentially useful in a clinical setting, asymmetry has only been the subject of a small number of studies (n=2), with low sample sizes (the largest being n=49), prompting further investigation.

Table 62 Studies investigating the association between asymmetry and RRI.

Authors	*Measure*	*n*	*Population*	*Injury*	*Calculation*	*Groupings*	*CON Mean ± SD (◦)*	*INJ Mean ± SD (◦)*	*Finding*
Retrospective									
Zifchock *et al.*, 2008	Hip external rotation strength	40	CON: 11♂, 9♀; INJ: 9♂, 11♀	General overuse RRI	Symmetry angle= (45◦-arctan (Left/Xright))/90◦* 100%	INJ vs never INJ runners	7.0 ± 5.3	6.5 ± 5.3	Not significant, p>.05.
Plastaras *et al.*, 2016	Hip abduction strength asymmetry in neutral	47	INJ: 21♀; CON: 36♀	Early stages of PFPS	Hip Strength Asymmetry Index (HSAI)= (weaker hip strength/ stronger hip) X 100	Currently INJ vs CON runners	87.0 ± 8.3	83.5 ± 10.2	Not significant, p>.05.
	Hip abduction strength asymmetry in extension	47	INJ: 21♀; CON: 36♀	Early stages of PFPS	Hip Strength Asymmetry Index (HSAI)= (weaker hip strength/ stronger hip) X 100	Currently INJ vs CON runners	87.0 ± 8.3	96.3 ± 21.9	Not significant, p>.05.
ROM									
Zifchock *et al.*, 2008	Hip IR ROM	40	CON: 11♂, 9♀; INJ: 9♂, 11♀	General overuse RRI	Symmetry angle= (45◦-arctan (Left/Xright))/90◦* 100%	Previously INJ vs never INJ runners	8.2 ± 5.3	6.4 ± 5.9	Not significant, p>.05.
Foot Position									
Zifchock *et al.*, 2008	Deviation from average arch height index	40	CON: 11♂, 9♀; INJ: 9♂, 11♀	General overuse RRI	Symmetry angle= (45◦-arctan (Xleft/Xright))/90◦ *100%	Previously INJ vs never INJ runners	1.4 ± 1.0	1.7 ± 1.2	Not significant, p>.05.

Abbreviated Terms: CON= control, INJ= injured, ♂= males, ♀= females, SD= standard deviation, T= treadmill, O= over ground, N/R= not reported, PFPS= patellofemoral pain syndrome. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries.White shading indicates that no association was found.

2.8. The association between the spatiotemporal parameters of running gait and RRI

Spatiotemporal parameters of running are measures that capture the running movement with regard to the variables of space and time, such as cadence (step rate), step length or flight time (Brindle *et al.*, 2020). Spatiotemporal parameters of running are relatively easily measured and have been postulated to be related to RRI. A common suggestion is that manipulation of these factors can reduce injury risk (Schubert, Kempf and Heiderscheit, 2014; Willson *et al.*, 2015). However, to date the majority of research centres around the relationship of these factors to potentially injurious running technique and loading and not injury itself. Many of the spatiotemporal parameters of gait are interdependent, for example stride length and step rate combine to directly determine running speed (Lohman, Balan Sackiriyas and Swen, 2011). An inverse relationship between these parameters exists when running speed is constant (Schubert, Kempf and Heiderscheit, 2014). Due to the limited prospective research, this section will include both retrospective and prospective research.

2.8.1. The association between flight time and RRI

Flight time is the duration between toe off and initial contact of the same foot (Dugan and Bhat, 2005). Flight time has not received much attention in relation to RRIs. Just one prospective study has investigated its association with general RRIs (Winter *et al.*, 2020), reporting significantly greater flight time among injured compared to uninjured female runners. This was suggested to be explained by lower step rates and a subsequent increase in GRFs, lower limb loading, and energy absorption at the hip and knee joints (Winter *et al.*, 2020). In relation to specific injuries, no difference in flight time was found between runners with previous calf muscle injuries and uninjured controls (Bramah *et al.*, 2021).

2.8.2. The association between step rate and RRI

Step rate is defined as the number of steps per unit time (typically per minute) (Futrell *et al.*, 2018). Greater step rate is associated with reduced loading parameters (Adams *et al.*, 2018) and a reduction in mechanical energy absorption at the knee and hip via decreases in the centre of mass excursion (Heiderscheit *et al.*, 2011). Four prospective studies have investigated the association between step rate and general RRIs (Table 63). Of these, just one study (33%) found a relationship between lower preferred running step rate and increased risk of injury (Winter *et al.*, 2020). One study prospectively examined the association between step rate and specific injuries, finding an association between lower step rate and prospective shin injuries (Luedke *et al.*, 2016).

Table 63 Studies investigating the association between step rate and general RRIs.

Authors	*n*	*Population*	*Tracking Time*	*CON Mean ± SD*	*INJ Mean ± SD*	*Percentage Difference (%)*	*Finding*
Prospective							
Winter *et al.*, 2020	76	INJ: 39, CON: 37	1 year	176 steps/min	168 steps/min	5	Lower step frequency among INJ, p< .05.
Szymanek *et al.*, 2020	381	INJ: 25, CON: 356	9 months	172 steps/min	173 steps/min	6	Not significant, p>.05.
Payne and D'Errico 2019	16	INJ: 6; CON: 10	Cross country season	172 steps/min ±10.9	173 ± 12.3 steps/min	6	Not significant, p>.05.
Bredeweg *et al.*, 2013	210	INJ: 34; CON: 176	9 weeks	2.70 ± 0.17 Hz	2.73 ± 0.17 1.84	11	Not significant, p>.05.

Abbreviated terms: RRIs= running related injuries, INJ= injured group, CON= control group, N/R= not reported, N/A = not applicable. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

Table 64 Prospective studies investigating the association between step rate and specific RRIs.

Author	*n*	*Population*	*Injury*	*Tracking Time*	*Groupings*	*CON Mean (steps/min)*	*INJ Mean (steps/min)*	*Percentage Difference (%)*	*Finding*
Luedke *et al.*, 2016	68	INJ: 13 CON: 55	AKP and shin injuries	School Season	INJ vs CON	N/R	N/R	N/R	Runners in the lowest tertile (≤166 steps per minute) (OR=5.85; $CI_{95\%}$= 1.1-32.1, p< 0.04) were more likely to experience a shin injury than runners in the highest tertile (≥178 steps per minute). AKP incidence was not significantly influenced by step rate.

Abbreviated terms: RRIs= running related injuries, INJ= injured group, CON= control group, N/R= not reported, N/A = not applicable, ♂=male, AKP= anterior knee pain. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

2.8.3. The association between step length and RRIs

Stride length is defined as the distance between successive ground contacts of the same foot (Dugan and Bhat, 2005). It has been found that L5-S1, T12-L1 vertical reaction forces at impact and during the early support phase increased significantly with increasing stride length (Seay, Van Emmerik and Hamill, 2014) and that GRF increases with greater stride length (Stergiou, Bates and Kurz, 2003). Similarly, Derrick et al (1998) found a significantly increased impact accelerations among runners with increased stride length. Although some evidence exists to support the suggestion that step/stride length may have an effect on kinetic risk factors related to RRIs, just three studies have investigated the association between step length and RRIs. All of these studies were retrospective, with two studies examining general RRIs and one examining specific RRIs (PFPS) (Table 65). No study found an association between step length and RRIs, although there is a clear need for prospective investigations. The lack of prospective studies warrants further investigation, given this is a relatively easily accessible measure.

2.8.4. The association between contact time and RRI

The time during which the foot maintains contact with the ground during stance is known as contact time (Brindle *et al.*, 2020). Of the two prospective studies investigating the association between contact time and general RRIs (Table 66), Bredeweg et al. (2013) found no significant difference between injured and uninjured runners with males and females grouped as a whole. However, they found that a sub-group analysis indicated that male runners (n=11) who became injured had a shorter contact time than uninjured male runners. However, this was not the case for Winter et al. (2020), who also subdivided by sex. Furthermore, given the small sample size, this finding should be interpreted with caution. No studies investigated contact time in relation to specific RRIs.

2.8.5. The association between RRI and running pace

Increased running pace has been shown to increase ground reaction force, with this effect plateauing at approximately 60% of an individual's maximum running speed and remaining constant at approximately 2.5 times body weight (Keller *et al.*, 1996). Step rate and step length are altered with changes in speed. Increases in running speed causes shorter contact time, and increases in step length, flight time and step rate (Roche-Seruendo *et al.*, 2018). Increased running speed is also associated with increases in peak sagittal plane hip flexion, knee flexion at mid stance, ankle dorsiflexion at initial contact and peak plantarflexion in early swing, which may predispose runners to different distributions of forces (Orendurff *et al.*, 2018).

Table 65 The association between stride length and RRI.

Authors	n	Population	Injury	Comparison	INJ ± SD (m)	Mean ± SD (m)	Findings	Percentage Difference (%)
Retrospective								
Heiderscheit, Hammill and Van Emmerik, 2002- (step length)	16	INJ: 8, CON: 8	PFPS	Currently INJ vs CON	0.74 ± 0.034	0.73 ± 04	Not significant, p>.05.	1
Peng *et al.*, 2015	100	INJ: 50, CON: 50	General RRI	Previously INJ vs CON	1.53 ± 0.52	1.47 ± 0.62	Not significant, p>.05.	4
Mann *et al.*, 2015	90	INJ: 11♂, 33♀ CON: 13♂, 33♀	General RRI	Previously INJ vs CON	N/R	N/R	Not significant, p>.05.	N/R

Abbreviation: INJ= injured, CON= control, SD= standard deviation, IQR= interquartile range, ♂= male, ♀= female, N/A= not applicable, N/R= not reported, RRI= running related injury, PFPS= Patellofemoral pain syndrome. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

Table 66 Studies investigating the association between contact time during running and RRI.

Authors	n	Population	Type of runner	Tracking period	Injury	Speed	O/T	Unit	Grouping	CON Mean ± SD (ms)	INJ Mean ± SD (ms)	Finding	Percentage difference (%)
Prospective													
Winter *et al.*, 2020	*76*	INJ: 22♂, 17♀; CON: 23♂, 14♀	Recreational and competitive	1 year	General RRI	Self-selected: 12.81m/s (INJ) 13.14 m/s (CON)	O	Milliseconds	INJ vs CON	227.13 ± 22.46	232.42 ± 16.89	Not significant, p>.05.	*2*
Bredeweg *et al.*, 2013	210	INJ: 10♂, 23♀; CON: 66♂, 110♀	Novice	9 weeks	General RRI	Set speed: 9km/hr	T	Milliseconds	INJ vs CON	228.41 ± 27.83	224.32 ± 35.62	Not significant, p>.05.	-2
									INJ vs CON ♂	237.0 ± 26.3	213.0 ± 39.5	Male injured runners had a significant shorter contact time compared to the noninjured male runners, p>.05.	-11
Retrospective													
Koldenhoven *et al.*, 2020	32	INJ: 16; CON: 16	Recreational	N/A	ERLLP	Self-selected	O	Milliseconds	Currently INJ vs CON	277.6 ± 19.5	292.9 ± 24.5	The ERLLP group had a longer contact time during the stance phase of running, p<.05.	5
Luginick et al., 2018 stance	60	INJ: 15♂, 15♀; CON: 15♂; 15♀	Recreational	N/A	ITBS	Self-selected	O	Seconds	Currently INJ vs CON	280 ± 30	270 ± 30	Greater contact time among runners with ITBS, p<.05.	
Hreljac *et al.*, 2000	40	INJ: 12♂, 8♀, CON: 12♂, 8♀	Runners and triathletes	N/A	Knee/below knee RRIs	Set Speed: 4 m/s	O	Seconds	Previous INJ vs CON	220 ± 21	216 ± 21	Not significant, p>.05.	2

Duffey *et al.*, 2000	169	INJ: 68 ♂, 31; CON: 53 ♂, 17 ♀	Distance runners	N/A	AKP	Self-selected	O	Seconds	Currently INJ vs CON	252 ± 30	258 ± 30	Greater time univariately associated with anterior knee pain, p<.05.	24
Messier *et al.*, 1991	36	INJ: 29, CON: 16	Recreational Runners	N/A	PFPS	Set speed: 12 km/h ±5%km/h	O	Seconds	Currently INJ vs CON	242 ± 20	248 ± 30	Not significant, p>.05.	2.4
Ribeiro *et al.*, 2015	75 (Subgroup)	CON: 30; INJ: 46	Long distance runners	N/A	Acute and chronic plantar fascia pain	Set Speed: 3.33 m/s	O	Seconds	Currently INJ vs CON	230 ± 21	203 ± 30 (acute) 240 ± 28 (chronic)	Not significant, p>.05.	0

Abbreviation: INJ= injured, CON= control, SD= standard deviation, IQR= interquartile range, ♂= male, ♀= female, N/A= not applicable, N/R= not reported, O= over ground, T= treadmill, RRI= running related injury, ERLLP= exercise related lower leg pain, ITBS= iliotibial band syndrome, AKP= anterior knee pain, PFPS= patellofemoral pain syndrome. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

Table 67 Studies investigating the association between running pace and general RRI.

Authors	***n***	***Population***	***Tracking Period***	***Runner Type***	***Variable Type***	***CON Mean ± SD/ Median (IQR)***	***INJ Mean ± SD/ Median (IQR)***	***Finding***	***Percentage Difference (%)***
Prospective									
Messier *et al.*, 2018	300	INJ: 145♀, 54♂; CON: 63♀, 38♂	2 years	Recreational	Continuous (min/mile)	8.9 ± 1.2	9.1 ± 1.2	Not significant, p>.05.	2
Walter *et al.*, 1989	1288	303♀,985♂; INJ: 637, CON: 628	1 year	Recreational	N/R	N/R	N/R	Not significant, p>.05.	N/R
Dudley *et al.*, 2017	31	INJ: 4♂, 8♀; CON: 11♂, 8♀	14 weeks	Collegiate cross country	Continuous (min/mile)	3.87 (3.74, 4.02)	3.85 (3.68, 4.03)	Not significant, p>.05.	1

Abbreviation: INJ= injured, CON= control, SD= standard deviation, IQR= interquartile range, ♂= male, ♀= female, N/A= not applicable, N/R= not reported, RRI= running related injury. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

Table 68 Studies investigating the association between running pace and specific RRI.

Authors	*n*	*Population*	*Tracking Period*	*Runner Type*	*Injury*	*Groupings*	*CON Mean ± SD*	*INJ Mean ± SD*	*Finding*	*Percentage Difference (%)*
Prospective										
McCrory *et al.*, 1999	1288	303♀,985♂; INJ: 637, CON: 628	1 year	Recreational	AT	INJ vs CON	4.64 ± 0.08 min/mile	4.87 ± 0.07 min/mile	INJ runners ran significantly slower, p<.05.	5
Retrospective										
Benca *et al.*, 2020	196	99♀, 79♂; INJ: 178, CON:18	N/A	Mixed levels	RRI subdivided by location	Previously INJ vs CON	N/R	N/R	Not significant, p>.05.	N/R
Messier *et al.*, 1995	118	CON: 53♂, 17♀ IN: 33♂, 23♀	N/A	Recreational	ITBS	Currently INJ vs CON	7.47 ± 0.16 min/mile	8.17 ± 0.22 min/mile	Not significant, p>.05.	9

Abbreviation: INJ= injured, CON= control, SD= standard deviation, IQR= interquartile range, ♂= male, ♀= female, N/A= not applicable, N/R= not reported, RRI= running related injury, AT= Achilles tendon injury, ITBS= iliotibial band syndrome. Black shading indicates that greater values were associated with injuries. Grey shading indicates that lower values associated with injuries. White shading indicates that no association was found.

The association between general RRIs and running pace has been investigated in three prospective studies (Table 67), with no study finding a significant association to exist. Of the three retrospective studies examining the association between running pace and specific injuries (Messier *et al.*, 1995; McCrory *et al.*, 1999; Benca *et al.*, 2020), Benca *et al.* (2020) and McCrory *et al.*, (1999) found that higher running pace was significantly associated with lower leg and Achilles tendon injuries, respectively (Table 68). It has been hypothesised that Achilles tendons may be particularly vulnerable to microtears with increasing pace due to the increased frequency of change in muscular tension as the tibia rotates as the limb prepares for impact. No association was found between self-selected pace and iliotibial band syndrome (Messier *et al.*, 1995).

Overall, findings are inconsistent with respect to the association between RRI and spatiotemporal parameters of gait. Adding credence to the largely non-significant findings found in the present review, is a systematic review by Brindle et al. (2019) which found no difference in these measures between uninjured and injured runners. In relation to running pace, there is limited evidence to suggest that greater running pace may be associated with lower leg injuries, with moderate evidence to suggest that there is no association between reported running pace and general RRIs. More prospective research is required.

2.9. Literature Review- Conclusion

The high prevalence of RRIs of between 19-92% (Lun *et al.*, 2004; Cahanin *et al.*, 2019) prompts further investigation into the factors associated with injury. Evidently, a wide range of modifiable and non-modifiable factors have been suggested to be associated with RRIs. However, despite the numerous suggested risk factors, no clear consensus exists regarding factors associated with RRIs. Three key issues exist within the current research, which have been explored below.

Firstly, the predominance of retrospective research makes it difficult to ascertain whether factors precede or are as a result of RRI. There is a clear lack of large-scale prospective studies, particularly those undertaking a multifactorial approach, despite most injury aetiology models stating that injury is caused by an interaction of multiple factors (Meeuwisse *et al.*, 2007a; Bertelsen *et al.*, 2017; Kalkhoven, Watsford and Impellizzeri, 2020). Potentially of interest in this multifactorial approach is the quantification of loading via impact accelerations, which has been the subject of just one prospective study (Winter *et al.*, 2020). Previous research has primarily measured overall loading via GRF, with inconsistent results (Davis, Bowser and Mullineaux, 2010; Messier *et al.*, 2018). However, impact accelerations may be advantageous in measuring *segmental* loading. This should be measured at the lower back as well as the shank, given that RRIs occur throughout the lower limb. As well as this, limited large-scale prospective research has investigated running technique throughout the stance phase. Considering the inconsistent research findings relating technique to RRIs, prospectively exploring joint angles, in multiple planes, during stance may be relevant to injury development (e.g. excursion, peak, minimum, initial contact, toe off). Furthermore, examinations of running technique have, in particular, omitted the analysis of the trunk and pelvis, which may also be relevant in the aetiology of RRIs. Finally, clinical measures should be considered in this multifactorial approach due to their ease of use in clinical practice and generally modifiable nature.

Secondly, much retrospective research has compared currently injured runners to those who are uninjured. This presents an issue with potential differences being due to the acute nature of the injury. Alternatively, other retrospective research has compared previously injured runners to those with no previous injury, and it is often unclear if the control group have never been injured, or, if they have had previous injuries outside a certain time frame. Therefore, more careful consideration of the methodology of retrospective injury studies is needed, as well as a nuanced approach to the interpretation of results. A potential line of investigation could be to examine never injured runners and explore the factors that may contribute to injury resistance, given the promising research in this area (Zifchock, Davis and Hamill, 2006; Davis, Bowser and Mullineaux, 2010)

Finally, although useful for understanding the aetiology of general RRIs, and potentially informing general RRI prevention practices, the grouping of injuries may lead to overlooking injury-specific risk factors. Despite some research investigating specific RRIs and their associated factors, injury-specific research is largely retrospective in nature and also limited by a lack of multifactorial design. Given the relatively high rate of knee and lower leg injuries, this may be an appropriate target for analysis.

This thesis aims to address these gaps in the literature.

3. *Chapter 3: Do Injury-Resistant Runners Have Distinct Differences in Clinical Measures Compared with Recently Injured Runners?*

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Dillon, S., Burke, A., Whyte, E., O'Connor, S., Gore, S. and Moran, K., 2021. Do injury resistant runners have distinct differences in clinical measures compared to recently injured runners?. *Medicine & Science in Sports & Exercise*, *53*(9), pp.1807-1817.

This is presented in full, with only minor formatting changes.

Abstract:

Introduction: Although lower extremity muscle strength, joint motion and functional foot alignment are commonly used, time-efficient clinical measures that have been proposed as risk factors for running related injuries (RRIs), it is unclear if these factors can distinguish injury-resistance in runners.

Purpose: This study compares clinical measures, with consideration of sex, between recently injured runners (3 months to 1 year prior), those with a high level of injury resistance who have been uninjured for at least 2 years, and never-injured runners.

Methods: Averaged bilateral values and between-limb symmetry angles of lower limb isometric muscle strength, joint motion, navicular drop and Foot Posture Index (FPI) were assessed in a cohort of recreational runners and their injury history was recorded. Differences in clinical measures between injury groupings were examined, with consideration of sex.

Results*:* Of the 223 runners tested, 116 had been recently injured, 61 had been injured >2 years ago and were deemed to have acquired re-injury resistance, and 46 were never injured. Plantar flexion was greater in both recently injured (P = .001) and acquired re-injury resistance runners (P = .001). compared to never-injured runners. Recently injured runners displayed higher hip abduction strength compared to never-injured runners (P = .019, η^2 = .038, small effect size). There were no statistically significant differences in the remaining measures between the injury groupings. With the exception of FPI, there was no interaction between sex and injury grouping for any of the measures.

Conclusion*:* Commonly employed clinical measures of strength, joint motion and functional foot alignment were not superior in injury-resistant runners compared to recently injured runners, questioning their relevance in identifying future injury resistance of runners.

Key words**:** Running injuries, strength, pronation, joint motion.

Introduction

Runners are subject to a high incidence of lower extremity injury of between approximately 20% to 80% (Van Gent *et al.*, 2007). The pervasive biomechanical model of injury identifies excessive loading to tissues to be causative of injuries (Kalkhoven, Watsford and Impellizzeri, 2020). Running is a cyclical movement that exposes the body to repetitive loads of up to 2.8 times body weight with each step (Cavanagh and Lafortune, 1980). Clinical measures of muscle strength, functional foot alignment and joint motion have been suggested to be related to loading (Ferenczi *et al.*, 2014; Mason-Mackay, Whatman and Reid, 2017) and, although evidence is mixed, may be related to injury itself (Becker *et al.*, 2017; Mucha *et al.*, 2017; Pérez-Morcillo *et al.*, 2019). Furthermore, studies involving asymmetry of these factors have demonstrated a similarly mixed relationship to injury (Fredericson *et al.*, 2000; Zifchock *et al.*, 2008; Ithurburn *et al.*, 2015). Imbalances in factors such as tissue strength and joint motion may be a precursor to injury. Additionally, at return to sport, asymmetry in factors such as tissue strength acquired as a result of injury-induced tissue damage may persist (Ithurburn *et al.*, 2015), potentially causing reinjury. These clinical measures are advantageous in being time-efficient, low cost and readily available to most clinicians, making their potential use in managing running related injuries (RRIs) particularly valuable.

Due to cost and time constraints, retrospective studies are the predominant methodology in examining factors associated with RRIs. One group of runners frequently studied are those who have relatively recently recovered from injury and returned to play (e.g. less than 12 months post injury). This group is of interest because they are thought to no longer retain the acute effects of injury itself, but may still maintain factors related to injury given the high risk of re-injury during this period (Saragiotto *et al.*, 2014). A second group of runners worth studying are those who have recovered from injury but have not experienced a reinjury (e.g. > 2 years since injury). This acquired re-injury resistance group may logically be less likely to retain the risk factors associated with injury/re-injury, or at least have a reduced weighting. A third and final group worth examining, and perhaps the most interesting, would be those who have never been injured. Given the high lifetime incidence of RRIs (~92 %) (Lun *et al.*, 2004) this group would potentially have no or significantly reduced levels of risk factors. A comparison of these three groups may provide novel and important insight into the three clinical-based factors possibly related to RRIs: muscle strength, functional foot alignment and joint motion. To the authors' knowledge, no previous study has undertaken such a three-way comparison for any factors related to RRIs. Zifchock and colleagues (2008) (Zifchock *et al.*, 2008) examined differences in hip motion and arch height between never-injured (n=20) and previously injured recreational runners (n=20), reporting both to be greater in the previously injured group. However, results of the study should be interpreted with caution as this was a small study and it did not take into account the possibly confounding effect of sex, a potentially important factor given that males are reported to be at an increased risk of RRIs (Buist, Bredeweg, Lemmink, *et al.*, 2010) and sex-specific differences in injury risk profiles have been suggested to exist (de Wijer *et al.*, 2015). In addition, Zifchock *et al.*, (2008) (Zifchock *et al.*, 2008) did not examine muscle strength as a primary factor, which may be important because of its relationship to both tissue loading (through movement technique) and tissue integrity, whose balance is central to the occurrence of musculoskeletal injuries (Kalkhoven, Watsford and Impellizzeri, 2020). The examination of clinical measures may provide greater insight into the potentially distinct characteristics of runners who have either acquired re-injury resistance or have never been injured in comparison to those who have been recently injured, and the results may inform injury prevention and rehabilitation strategies.

This study therefore aimed to examine the effect of injury status and sex on values of strength, functional foot alignment and joint motion using three distinct injury status groups: those who have recently returned from injury (injured 3 months - 1 year previously), those who have acquired re-injury resistance (remained uninjured for >2 years), and those who have never been injured (never injured). It was hypothesised that those with a high level of injury resistance (ie. never-injured runners and those who had not been injured for over two years) may have advantageous clinical measures of strength, functional foot alignment and joint motion compared with a recently injured group. A secondary aim was to investigate whether asymmetry values would be distinctive among groups, with injury resistant runners hypothesised to have less asymmetry. It was also hypothesised that sex-specific differences may exist between groups.

Methodology

Participants

As part of a more extensive study, male and female recreational runners from Dublin and its surrounding areas were recruited between the period of January to August 2018. Recreational runners between 18-65 years with no injury within the last three months were included in this study (Buist, Bredeweg, Lemmink, *et al.*, 2010). Three participant groups were later constructed: those injured 3-12 months prior (‘recently injured’), those whose most recent injury was over two years ago (‘acquired re-injury resistance’), and those who had never been injured (‘never injured’). A history of injury in the preceding year is cited as a main risk factor for future injury (Saragiotto *et al.*, 2014). Therefore, it was hypothesised that participants with a longer duration since injury would be less likely to retain the effects of injury and may demonstrate clinical factors that can contribute to their ‘injury resistance’. The exclusion of participants injured 1-2 years previously was done to ensure clear demarcation between ‘recently injured’ and ‘acquired re-injury resistance’ groups. To limit the effects of injuries related to non-running activities, participants were excluded if they participated in team, contact or high impact sports. A recreational runner was defined as a person who runs a minimum of 10km per week, for at least six months prior to their inclusion in the study (Saragiotto *et al.*, 2014).

Sample Size

Sample size was determined *a priori (*alpha probability = 0.05, with a power of $1 - \beta = 0.80$, effect size (f) = 0.25) for a Two Way Analysis of Variance (ANOVA) using a power analysis program, G*Power 3.1.9.7 (Faul *et al.*, 2007). Due to the presence of multiple variables and difficulty ascertaining which variable to base the power analysis on, the effect size was determined using a standardised medium effect size value (small = 0.1, medium = 0.25, large = 0.40) (Faul *et al.*, 2007). A total sample size of 158 was reached.

Ethical Approval

Ethical approval was sought from and granted by the Dublin City University Ethics Committee (DCUREC/2017/186).

Procedures

Eligible participants completed an informed consent form to partake in this study and then completed an online survey regarding their injury and training history (Section 8.1, Appendix A). Participants then attended a single baseline testing session in which isometric strength, joint motion, navicular drop and foot posture index (FPI) were assessed following the completion of the Par-Q questionnaire. Their survey information was verbally reviewed for accuracy and completeness. Height (m) and body mass (kg) were recorded using a portable stadiometer and electronic weighing scales, respectively (Seca, UK). A Certified Athletic Therapist (AB) and a Chartered Physiotherapist with experience in musculoskeletal therapy (SD) completed all testing components. Both testers practiced all aspects of the protocol prior to testing under the instruction and supervision of a senior researcher and clinician. Due to the presence of multiple and bilateral injuries and potential recall bias in remembering the side of injury, the average value of the sum of both sides were used for each measure.

Isometric muscle strength

Isometric hip abduction, hip extension, knee flexion, knee extension and ankle plantar flexion strength were measured using a dynamometer (J-Tech Commander Echo Wireless Muscle Testing Starter Kit, J-Tech Medical Industries, Midvale, UT, USA) (Thorborg *et al.*, 2010;

Mentiplay *et al.*, 2015) (Table 69). Knee flexion and extension and plantar flexion strength were tested using a stabilisation belt (Mentiplay *et al.*, 2015). Participants were directed to use maximum effort, whilst gently holding onto the side of the plinth for stabilisation (Thorborg *et al.*, 2010). Three repetitions were completed with 15 second rest intervals. The command: "Go ahead-push-push-push-push-push and relax", was given for each contraction (Thorborg *et al.*, 2010). The maximum value of three repetitions was documented and analysed for each muscle group and was multiplied by the length of the resistance moment arm (m) and normalized to body mass (kg) (Luedke *et al.*, 2015).

Navicular drop

The navicular drop test was conducted as previously described (Buist, Bredeweg, Lemmink, *et al.*, 2010). The medial and lateral aspects of the talus were palpated whilst sitting, and the foot was placed in a subtalar neutral position. The navicular tuberosity was palpated, marked and the distance from the mark on the navicular to the floor was measured. A second measurement was recorded in the upright standing position. The average of three measurements of the difference between the sitting and standing heights was calculated for both feet. Additionally, participants were categorised into two groups using the summed average navicular drop of >10mm and <10mm, as measurements exceeding 10mm have previously been found to be related to injury (Bennett, Reinking and Rauh, 2012).

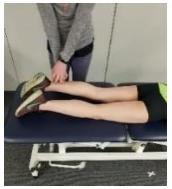
The foot posture index (FPI)

The FPI was assessed with participants standing in a relaxed barefoot stance. Participants were instructed to remain as still as possible and were scored in accordance to the FPI-6 scale (Redmond, Crosbie and Ouvrier, 2006) and subsequently divided into foot type categories: highly supinated (-5 to -12), supinated (0 to -4), neutral (+1 to +5), pronated (+6 to +9), highly pronated (+10 to +12) (Teyhen *et al.*, 2009).

Joint Motion

Ankle dorsiflexion, hip extension, hip internal and external rotation joint motion were assessed with the use of a smartphone application (Table 70) (Plaincode "clinometer", V2.4 on a Samsung S8+ (https://play.google.com/store/apps)).

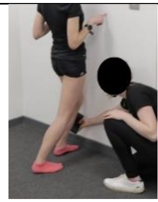
Table 69 Portable dynamometry manual muscle strength testing protocols.

Movement Tested	*Stabilisation Belt*	*Patient Position*	*Dynamometer Position Protocol*	*Image of testing*
Hip Abduction	N/A	Supine, knees in extension, hips in neutral	Positioned 5cm proximal to the lateral malleolus (Mentiplay *et al.*, 2015).	
Hip Extension	N/A	Prone, knee extended, hips in neutral.	Positioned on the posterior calf complex, in line with a mark that is 5cm proximal to the medial malleolus (Mentiplay *et al.*, 2015).	
Plantar Flexion	Around the plinth and the sole of the subject's shoe.	Prone, knees bent to 90 degrees of flexion and foot in plantar grade.	Positioned between the belt and the metatarsal heads of the sole of the foot.	
Knee Extension	A suction plug was used to fix the stabilisation belt to a concrete wall structure, allowing the tester to fasten the stabilisation belt around the anterior aspect of the shank, proximal to the ankle joint (Thorborg *et al.*, 2010).	Seated position with hips and knees flexed to 90 degrees.	Positioned between the anterior shank and the belt, and participants was instructed to kick out against it.	

Knee Flexion	A suction plug was used to fix the stabilisation belt to a concrete wall structure, allowing the tester to fasten the stabilisation belt around the anterior aspect of the shank, proximal to the ankle joint.	Seated position, again with hips and knees flexed to 90 degrees. Note: For the purpose of clear visibility the other leg was staggered behind the testing leg. This was done in practice with both feet in parallel.	Positioned between the posterior shank and the belt, posterior aspect of the shank, proximal to the ankle joint (Thorborg *et al.*, 2010).	

Abbreviations: N/A: not applicable.

Table 70 Joint motion testing protocols.

Movement Tested	***Patient Starting Position***	***Test Movement***	***Smartphone Placement***	***Image of Testing***
Dorsiflexion motion	Standing in a split stance facing a wall, with both heels in contact with the ground (Konor *et al.*, 2012).	Knee actively advanced forward over second toe (Konor *et al.*, 2012; Becker *et al.*, 2017).	Tibial tuberosity.	
Hip extension motion	Sitting on the edge of a firm plinth.	Participant guided into supine lying with legs over the edge of the plinth with the bio-feedback pressure cuff stabilize placed proximal to the posterior superior iliac spines of the lower back.	Midline of the femur, 5cm proximal to the superior surface of the patella (Vigotsky *et al.*, 2016).	 
Hip internal and external rotation motion	Sitting with arms folded on the edge of a plinth.	The hip was then passively maximally rotated on the frontal plane, with care taken to minimise compensatory movements (Bierma-Zeinstra *et al.*, 1998).	Lateral fibula, 5cm proximal to the lateral malleolus.	  

A knee to wall test was used to determine ankle dorsiflexion motion (Konor *et al.*, 2012). Reduced ankle dorsiflexion motion has previously been suggested to be associated with compensatory pronation during running in order to achieve forefoot contact (Becker *et al.*, 2017). This may consequently increase forces on surrounding structures. To perform this test, unshod participants faced a wall in a split stance. With one knee contacting the wall and the ipsilateral heel on the ground, participants gradually moved their foot as far away from the wall as possible, with their anterior knee maintaining contact with the wall. Participants were instructed to direct their knee anteriorly over the second toe. No additional effort was made for them to maintain a subtalar neutral position throughout the test. A smartphone was placed at the tibial tuberosity to measure the tibia angle relative to the ground. This was repeated 3 times and the average was recorded.

Hip motion has been suggested to be potentially related to injuries for two main reasons; (i) reduced motion may be reflective of shortened and therefore functionally limited hip muscles, and (ii) increased motion may signal potentially increased demands on musculature to control for excessive hip motion (Cannon, Finn and Yan, 2018). Hip extension motion was assessed using the Modified Thomas Test (Vigotsky *et al.*, 2016). A resting measure of thigh position was recorded by placing a smartphone along the midline of the femur, 5cm proximal to the superior surface of the patella, whilst the participant sat with their thighs supported on a firm plinth. The participant was then instructed to move to the edge of the plinth before being guided into a supine position by the tester. To control for lumbopelvic motion, a bio-feedback pressure cuff stabilizer was placed proximal to the posterior superior iliac spines of the lower back. The smartphone was again placed in the previous measurement position and a reading was taken. The resting femur measure was subtracted from this reading to determine extension.

Hip internal and external rotation motion were measured with participants sitting with arms folded on the edge of a plinth (Bierma-Zeinstra *et al.*, 1998). A smartphone was held against the fibula, 5cm proximal over to the lateral malleolus, and a resting value was obtained. The hip was then passively maximally rotated on the frontal plane, with care taken to minimise compensatory movements. The smartphone was repositioned, and a reading was taken. The resting value was subtracted from this reading and a resultant internal rotation measure was documented. This was repeated three times on each leg and averaged. The same procedure was repeated in the opposite direction to assess external rotation.

Each measure was performed by one tester. Good to excellent intraclass correlation coefficient values were found intrarater reliability of each of the above measures (Section 8.2, Appendix B).

Asymmetry:

Asymmetry was calculated for each measure using symmetry angle (Zifchock *et al.*, 2008), using the following equation:

$$Symmetry\ Angle= [(45^{\circ} - \arctan (X_{dominant}/X_{non\text{-}dominant}))/90^{\circ}] *100\%$$

with a symmetry angle of 0% representing perfect symmetry.

Running related injury (RRI) defined

Injury history was collected via an online questionnaire, which was completed prior to testing and reviewed (by SD or AB) with each participant for accuracy, at the time of testing. An RRI was defined as "any (training or competition) musculoskeletal pain in the lower limbs that causes a restriction/stoppage of running (distance, speed, duration, or training) for at least 7 days or 3 consecutive scheduled training sessions, or that requires the runner to consult a physician or other health professional" (Yamato *et al.*, 2015). Recently injured participants, who had been uninjured for 3 months to 1 year prior to enrolment in the study, detailed the location of previous injuries and whether they had completed a rehabilitation programme.

Statistical Analysis:

All data were analysed with SPSS (version 23; IBM Corp, Armonk, NY). Participants were divided into three groups: recently injured (history of injury between 3 months and one year, n=116), acquired re-injury resistance (history of injury > 2 years, n=61) and never-injured runners (n=46). Differences in demographics between injury groups were assessed using one-way ANOVAs. Two-way ANOVAs (3 x 2) (group x sex) were used to evaluate differences in average bilateral and symmetry angle values for strength, navicular drop, FPI and joint motion. Post hoc testing for significant interactions was performed using Gabriel's Test to accommodate for the uneven group sample size distribution. To further investigate any interaction effects a simple slopes analysis was conducted. Data violating the assumption of homogeneity of variance were analysed using separate Kruskal Wallace Tests to evaluate differences between injury group and sex. Effect sizes were reported using partial eta squared (η^2) with 0.01, 0.06 and 0.14 representing small, medium and large effect sizes (Tomczak and Tomczak, 2014). A chi-square test of independence was used to examine the relationship between FPI categories and the different injury groups. A separate chi-square test of independence was used to examine the relationship between navicular drop </> 10mm and the different levels of injury. Due to equipment malfunction, the sample size for each variable sometimes varied slightly and is detailed below.

Results

Demographics

Two hundred and seventy-four (171 males, 103 females) recreational runners participated in this study. Of these, 116 (77 males, 39 females, 42%) had been injured 3 months to 12 months prior, 61 (38 males, 23 females, 22%) had been injured over 2 years ago and 46 (29 males, 17 female, 17%) had never been injured. Fifty-one participants (38 males, 23 females, 19%) were injured in the 1- 2 years prior to participating in the study and were excluded from analysis. This was done to ensure a clear demarcation between those who were theorised to have 'acquired re-injury resistance' (injured > 2 years ago) and those that were recently injured (injured 3 months- 1 year previously). Of the runners in the recently injured group, 87 % had participated in a rehabilitation programme. A breakdown of the proportion of injuries for each injury location is detailed in (Table 71).

Table 71 The location of injuries among the recently injured group.

Injury Location	***Number of injuries at this location***	***Percentage of injuries at this location (%)***
Calf	30	20.4
Knee	19	12.9
Posterior thigh	18	12.2
Shin	12	8.2
Foot	11	7.5
Lateral thigh	10	6.8
Ankle	7	4.8
Lower Back	9	6.1
Hip	9	6.1
Buttock	7	4.8
Medial thigh	5	3.4
Heel	5	3.4
Anterior thigh	2	1.4
Toes	2	1.4
Sacroiliac Joint	1	0.7

Table 72 Participant demographics

		Recently Injured				Acquired Re-injury Resistance				Never-injured				p value
	Total n	***Males, females***	***Group***	***Males***	***Females***	***Males, females***	***Group***	***Males***	***Females***	***Males, females***	***Group***	***Males***	***Females***	
			(Mean ± SD)	(Mean ± SD)	(Mean ± SD)		(Mean ± SD)	(Mean ± SD)	(Mean ± SD)		(Mean ± SD)	(Mean ± SD)	(Mean ± SD)	
Age (years)	223	77 M, 39 F	43.11 ± 8.67	43.34 ± 9.16	42.67 ± 7.72	38 M, 23 F	44.70 ± 8.64	45.58 ± 8.13	43.26 ± 9.43	29 M, 17 F	41.76 ± 10.41	43.34 ± 11.41	39.06 ± 8.06	.989
Mass (kg)	223	77 M, 39 F	72.93 ± 11.78	78.30 ± 9.26	62.34 ± 8.65	38 M, 23 F	72.63 ± 13.15	79.56 ± 10.55	61.19 ± 8.03	29 M, 17 F	72.90 ± 14.05	80.81 ± 10.69	59.41 ± 7.02	.494
Height (m)	223	77 M, 39 F	1.73 ± 0.09	1.77 ± 0.06	1.64 ± 0.07	38 M, 23 F	1.74 ± 0.10	1.79 ± 0.07	1.66 ± 0.08	29 M, 17 F	1.72 ± 0.10	1.77 ± 0.08	1.63 ± 0.07	.243

Abbreviated Terms: n- number of participants, SD- standard deviation.

No significant differences were found for any of the demographic variables of height, mass and age between the three groups (*P* > .05, Table 72).

Normalised Strength Values (Table 73, Table 74)

No interaction effect was found between injury status and sex for the strength values. A simple main effect between injury groups existed for hip abduction strength (*P* = .019, η^2 = .038, small effect size) and plantar flexion strength (*P* = .002, η^2 = .057, small effect size). Post-hoc analyses revealed that recently injured (*P* = .001) and acquired re-injury resistance runners (*P* = .010) had significantly greater plantar flexion strength than never injured runners. Recently injured runners had significantly greater hip abduction strength compared with never-injured runners (*P* = .001). A trend towards significance existed for greater strength among recently injured compared to those with acquired re-injury resistance, although this did not reach significance (*P* = .067). A significant main effect was found for sex for all strength values with significantly greater values among males when compared to females (*P* < .05, Table 74), with the exception of plantar flexion strength, which only approached statistical significance (*P* = .078).

Joint Motion (Table 73, Table 74)

No interaction effect was found between injury status and sex for the joint motion values. No significant main effect was found for injury status. Males displayed significantly lower hip internal rotation motion (*P* = .038, η^2 = 0.02, small effect size) and significantly greater ankle dorsiflexion motion (*P* = .019, η^2 = 0.027, small effect size) compared to females.

Navicular Drop (Table 73, Table 74)

No interaction effects between injury status and sex or main effects for injury status was found for navicular drop. A significant main effect was found for sex, with males displaying significantly greater navicular drop compared to females (*P* = .000, η^2 = 0.062, moderate effect size, Table 5). A chi-square test of independence showed that there was no significant association between injury status and navicular drop > 10 mm, X^2 (2, N = 209) = 1.644, *P* = .440.

Foot Posture Index (Table 73, Table 74, Table 75)

Thera was a significant interaction effect between sex and injury status for FPI (*P* = .023, η^2 = .036, small effect size). Females with acquired re-injury resistance had significantly lower values of FPI (*P* = .007, [+4 (+1, +6)]) compared to recently injured females (+7 [+4, +8]). The median score for the acquired re-injury resistance group placed them in the “neutral” (+1 to +5) category. The median score of recently injured runners classified them as “pronated” (+6 to +11). A chi-square test of independence showed that there was no significant association between Foot Posture Index classification groups and RRI, X^2 (8, N = 212) = 3.363, P = .910 (Table 75).

Symmetry Angle (Table 76, Table 77)

No interaction effects between injury status and sex or main effects for injury status were found for symmetry angle of any variable. Females displayed greater asymmetry of knee flexion strength compared to males (P = .037, η^2= .021, small effect size).

Table 73 Descriptive statistics for each clinical measure.

			Recently Injured				Acquired Re-injury Resistance				Never-injured		
Clinical Test	***Total n***	***Males, females***	***Group***	***Males***	***Females***	***Males, females***	***Group***	***Males***	***Females***	***Males, females***	***Group***	***Males***	***Females***
			Mean ± SD*	Mean ± SD*	Mean ± SD*		Mean ± SD*	Mean ± SD*	Mean ± SD*		Mean ± SD*	Mean ± SD*	Mean ± SD*
Hip abduction strength (Nm/kg)	211	73 M, 34 F	1.75 ± 0.33	1.84 ± 0.30	1.56 ± 0.30	37 M, 22 F	1.64 ± 0.28	1.70 ± 0.27	1.54 ± 0.27	28 M, 17 F	1.56 ± 0.29	1.59 ± 0.31	1.51 ± 0.25
Hip extension strength (Nm/kg)	211	73 M, 34 F	1.98 ± 0.50	2.07 ± 0.50	1.80 ± 0.46	37 M, 22 F	1.90 ± 0.41	1.95 ± 0.42	1.82 ± 0.38	28 M, 17 F	1.82 ± 0.44	1.88 ± 0.47	1.72 ± 0.39
Plantar flexion strength (Nm/kg)	211	73 M, 34 F	0.61 ± 0.23	0.64 ± 0.22	0.57 ± 0.23	37 M, 22 F	0.60 ± 0.20	0.61 ± 0.19	0.59 ± 0.23	28 M, 17 F	0.48 ± 0.17	0.51 ± 0.15	0.44 ± 0.19
Knee flexion strength (Nm/kg)	209	72 M, 34 F	1.40 ± 0.33	1.50 ± 0.32	1.19 ± 0.26	37 M, 22 F	1.37 ± 0.31	1.47 ± 0.32	1.23 ± 0.24	28 M, 16 F	1.31 ± 0.74	1.39 ± 0.38	1.16 ± 0.30
Knee extension strength (Nm/kg)	210	73 M, 34 F	1.37 ± 0.39	1.49 ± 0.35	1.10 ± 0.34	37 M, 22 F	1.35 ± 0.43	1.47 ± 0.45	1.15 ± 0.30	28 M, 16 F	1.23 ± 0.47	1.35 ± 0.49	1.03 ± 0.36
Navicular drop (mm)	206	68 M, 37 F	8.4 ± 2.8	8.7 ± 2.7	7.8 ± 2.8	35 M, 20 F	8.6 ± 3.3	9.6 ± 3.4	6.7 ± 1.9	29 M, 17 F	8.8 ± 3.1	9.5 ± 3.3	7.5 ± 2.6
Foot Posture Index	212	70 M, 37 F	7 (4. 8)	6 (4, 8)	7 (4, 8)	36 M, 23 F	5 (3, 7)	6 (4, 8)	4 (1, 6)	29 M, 17 F	6 (4, 8)	6 (5, 8)	5 (3, 8)
Hip IR motion (degrees)	210	70 M, 38 F	39.1 ± 6.0	38.1 ± 6.3	41.0 ± 5.2	36 M, 20 F	40.5 ± 5.8	40.5 ± 5.6	40.7 ± 6.2	29 M, 17 F	40.1 ± 6.8	39.9 ± 6.6	42.7 ± 7.0
Hip ER motion (degrees)	210	70 M, 38 F	36.9 ± 6.2	35.5 ± 5.7	39.4 ± 6.4	36 M, 20 F	36.2 ± 6.18	36.2 ± 6.5	36.3 ± 5.7	29 M, 17 F	35.0 ± 5.2	34.8 ± 5.2	35.3 ± 5.2
Hip extension motion (degrees)	210	70 M, 38 F	12.1 ± 7.7	11.7 ± 8.1	12.8 ± 7.0	36 M, 20 F	12.6 ± 7.7	11.7 ± 8.9	14.2 ± 4.5	29 M, 17 F	12.3 ± 7.1	12.8 ± 6.4	11.5 ± 8.3
Ankle DF motion (degrees)	210	70 M, 38 F	40.4 ± 3.4	40.4 ± 3.3	40.3 ± 3.6	36 M, 20 F	40.0 ± 3.9	41.0 ± 4.7	38.2 ± 4.9	29 M, 17 F	39.5 ± 3.4	39.8 ± 3.3	38.8 ± 3.7

Abbreviated Terms: n- number of participants, M- males, F- females, SD- standard deviation, IR- internal rotation, ER- external rotation, DF- dorsiflexion. * Denotes that median (first quartile, third quartile) was reported.

Table 74 Results of the Two Way ANOVA investigating the differences in means between the different injury groups and sex for each clinical measure

Clinical Measure	***P value- injury status***	***Effect size- injury status***	***P value- sex***	***Effect size- sex***	***P value- injury status*sex***	***Effect size- injury status* sex***
Hip abduction strength	.019*	.038	.000*	.069	.143	.019
Hip extension strength	.285	.012	.008*	.034	.660	.004
Plantar flexion strength	.002*	.057	.078	.015	.794	.003
Knee flexion strength	.471	.007	.000*	.125	.678	.004
Knee extension strength	.257	.013	.000*	.141	.826	.002
Navicular drop	.836	.002	.000*	.089	.126	.002
Foot Posture Index	.179	.017	.065	.016	.023*	.036
Hip extension mobility	.839	.002	.484	.021	.472	.007
Hip IR mobility	.270	.013	.038*	.024	.477	.008
Hip ER mobility	.076	.025	.095	.014	.102	.022
Ankle DF mobility	.215	.015	.019*	.027	.148	.019
Hip abduction strength SA	.467	.007	.805	.000	.085	.024
Hip extension strength SA	.422	.008	.196	.008	.527	.006
Plantar flexion strength SA	.422	.008	.629	.001	.492	.007
Knee flexion strength SA	.572	.005	.037*	.021	.950	.001
Knee extension strength SA	.240	.014	.574	.002	.736	.003
Navicular drop SA	.861	.001	.632	.001	.338	.011
Foot Posture Index SA	.343	.004	.311	.011	.943	.001
Hip IR mobility SA	.497	0.007	.578	.002	.206	.015
Ankle DF SA	0.636	0.004	.753	.003	.411	.003

Abbreviation: SA- symmetry angle, IR- internal rotation, ER- external rotation, DF- dorsiflexion. *Indicates a significant difference between groups.

Table 75 Foot Posture Index breakdown of the injury groups.

	Recently Injured		***Acquired Re-injury Resistance***		***Never Injured***	
	n	%	n	%	n	%
Neutral	26	29	38	51	17	37
Pronated	53	58	22	29	20	43
Highly Pronated	7	8	6	8	5	11
Supinated	3	3	6	8	2	4
Highly Supinated	3	3	2	3	2	4

Abbreviation: n- number of participants

Table 76 Descriptive statistics of symmetry angle values for each clinical measure.

		Recently Injured				Acquired Re-injury Resistance				Never-injured			
Clinical Measure	Total n	Males, Females	Group	Males	Females	Males, Females	Group	Males	Females	Males, Females	Group	Males	Females
			Mean ± SD	Mean ± SD	Mean ± SD		Mean ± SD	Mean ± SD	Mean ± SD		Mean ± SD	Mean ± SD	Mean ± SD
Hip abduction strength SA	211	73 M, 34 F	2.53 ± 2.07	2.52 ± 2.16	2.54 ± 1.90	37 M, 22 F	2.56 ± 2.35	2.97 ± 2.44	1.88 ± 2.06	28 M, 17 F	2.84 ± 2.04	2.53 ± 1.64	3.35 ± 2.53
Hip extension strength SA	211	73 M, 34 F	2.66 ± 2.32	2.65 ± 2.52	2.68 ± 1.83	36 M, 20 F	3.30 ± 2.70	3.62 ± 2.85	2.77 ± 2.39	28 M, 17 F	2.73 ± 2.57	3.01 ± 2.46	2.35 ± 2.76
Plantar flexion strength SA	211	73 M, 34 F	6.98 ± 4.82	7.24 ± 4.47	6.41 ± 5.54	37 M, 22 F	7.61 ± 5.74	7.38 ± 5.26	8.01 ± 6.60	28 M, 17 F	7.85 ± 6.19	7.32 ± 6.01	8.72 ± 6.57
Knee flexion strength SA	209	72 M, 34 F	17.38 ± 5.31	16.77 ± 5.61	18.65 ± 4.41	37 M, 22 F	16.71 ± 5.71	15.91 ± 5.03	18.04 ± 6.60	28 M, 16 F	17.96 ± 6.14	17.45 ± 6.05	18.85 ± 6.40
Knee extension strength SA	210	73 M, 34 F	4.03 ± 3.18	3.78 ± 2.90	4.58 ± 3.70	37 M, 22 F	5.13 ± 3.43	5.12 ± 3.05	5.15 ± 4.07	28 M, 16 F	4.41 ± 3.56	4.39 ± 3.24	4.43 ± 4.16
Navicular drop SA	206	68 M, 37 F	6.12 ± 5.07	5.54 ± 4.28	7.19 ± 6.20	35 M, 20 F	6.33 ± 4.32	6.15 ± 4.68	6.66 ± 3.70	29 M, 17 F	6.04 ± 5.68	6.43 ± 5.51	5.37 ± 6.05
Foot Posture Index SA	212	70 M, 37 F	4.04 ± 13.12	3.63 ± 12.28	4.80 ± 14.73	36 M, 23 F	1.59 ± 4.56	0.75 ± 1.92	2.91 ± 6.78	29 M, 17 F	2.29 ± 4.56	1.94 ± 3.59	2.89 ± 5.95
Hip IR motion SA	210	70 M, 38 F	3.79 ± 2.81	3.63 ± 2.90	4.09 ± 2.63	36 M, 20 F	3.86 ± 3.58	4.35 ± 3.88	2.98 ± 2.84	29 M, 17 F	3.19 ± 2.69	3.14 ± 2.86	3.27 ± 2.45
Hip ER motion SA	210	70 M, 38 F	4.24 ± 3.40	4.85 ± 3.80	3.12 ± 2.13	36 M, 20 F	4.12 ± 4.65	4.50 ± 5.21	3.43 ± 3.45	29 M, 17 F	4.29 ± 3.65	4.49 ± 3.89	3.95 ± 3.29
Ankle DF motion SA	210	70 M, 38 F	1.95 ± 1.91	1.88 ± 1.67	2.07 ± 2.32	36 M, 20 F	1.85 ± 1.41	1.67 ± 1.28	2.16 ± 1.59	29 M, 17 F	2.23 ± 1.48	2.25 ± 1.57	2.21 ± 1.35
Hip extension motion SA	210	70 M, 38 F	17.18 ± 26.34	19.02 ± 28.61	13.79 ± 21.51	37 M, 22 F	16.63 ± 25.71	20.09 ± 30.84	10.42 ± 9.93	29 M, 17 F	17.18 ± 29.63	10.58 ± 17.74	28.42 ± 41.29

Abbreviation: n- number of participants, SD- standard deviation, SA- symmetry angle, M- males, F- females, IR- internal rotation, ER- external rotation, DF- dorsiflexion.

Table 77 Results of non-parametric tests investigating the differences in means between the different injury groups and sex for each clinical measure.

Clinical Measure	***P* value- injury status**	**Effect size- injury status**	***P* value- sex**	**Effect size- sex**
Hip ER mobility SA	.508	.003	.064	.011
Hip extension mobility SA	.960	.009	.160	.005

Abbreviation: n- number of participants, SD- standard deviation, M- males, F- females, ER- external rotation, SA- symmetry angle.

Discussion

This study investigated the effects of injury status (recently injured, acquired re-injury resistance, never injured) and sex on lower limb strength, joint motion and functional foot alignment, as well as the between-leg asymmetry of these clinical measures. Our findings largely did not support our hypothesis that injury resistant and never injured runners would have potentially distinctive clinical features, and differences between injury groupings were mostly non-significant. However, this is with the exception of both plantar flexion and hip abduction strength. Plantar flexion strength was greater among both recently injured and acquired re-injury resistance runners compared to never-injured runners, while hip abduction strength was greater among recently injured runners compared to never injured runners only. With regard to the effect of sex, with the exception of FPI, sex had no influence on the magnitude of the between group differences, though some main effects for sex were observed. Males exhibited significantly greater strength for all muscle groups except the plantar flexor group, in addition to greater navicular drop measurements and ankle dorsiflexion motion, and significantly less hip internal rotation motion.

Contrary to our hypothesis, knee flexion, knee extension and hip extension strength were not significantly different between injury groups, suggesting that greater strength of these muscle groups is not a characteristic of acquired re-injury resistance or never injured runners. It has been suggested that increased strength may be protective against injuries due to the impact absorption properties of muscle (Ferenczi *et al.*, 2014), but findings to date have been mixed (Luedke *et al.*, 2015; Mucha *et al.*, 2017). Our findings have been supported by previous prospective research that found no link between hip extension, knee flexion and knee extension strength and RRI (Torp *et al.*, 2018). However, lower knee flexion and extension strength have been found to specifically predict a higher incidence of anterior knee pain (AKP) (Luedke *et al.*, 2015) potentially indicating that strength may be related to specific injuries, which was not examined in this study.

Counterintuitively, hip abduction and plantar flexion strength were significantly greater among recently injured runners when compared to those who had never sustained an RRI. Previous studies of isometric hip abduction strength have found lower (Becker, Nakajima and Wu, 2018), higher (Plastaras *et al.*, 2016) and no difference (Esculier, Roy and Bouyer, 2015) in strength values among injured compared to uninjured runners. Although hip abduction strength of never-injured runners has been studied previously (Zifchock *et al.*, 2008), data were not analysed statistically, thus limiting the potential for comparison. Plantar flexion strength was also greater in the acquired re-injury resistance group compared to never injured runners. Plantar flexion strength measured via portable dynamometry does not appear to have been studied previously for any injury grouping, possibly due to difficulty with positioning posed by the large forces generated by this muscle group, which was mitigated in this study by use of a stabilisation belt. Results of wider research involving isokinetic testing of plantar flexion strength has also been mixed, finding no difference between uninjured athletes and those with current medial tibial stress syndrome (MTSS) (Saeki *et al.*, 2017), higher strength in athletes with a history of MTSS (Gehlsen and Seger, 1980) and lower muscle strength in symptomatic athletes with plantar fasciitis (Kibler, Goldberg and Chandler, 1991). Two possible explanations for the greater hip abduction strength and plantar flexion among recently injured runners observed in our study are the relatively recent participation in rehabilitation, and possible compensation as a result of injury. Firstly, gluteal and plantar flexor (Mascaró *et al.*, 2018) strengthening (Ferber, Kendall and Farr, 2011) are frequent components in the rehabilitation of common RRIs, such as knee and Achilles tendon injuries. In our study, 87 % of the recently injured runners participated in a rehabilitation programme, which could have induced increases in both plantar flexion and hip abduction strength. Secondly, greater plantar flexion and hip abduction strength may be a compensatory mechanism in response to injury. Increased frontal plane hip and knee motion have been found among runners with common injuries such as patellofemoral pain syndrome (PFPS) (Noehren, Pohl, *et al.*, 2012) and iliotibial band syndrome (Noehren, Davis and Hamill, 2007). Therefore, for a time after injury, there may be increased muscle activity of the gluteal muscles, potentially increasing their strength in order to control for this increase in motion. A similar reasoning may hold for compensatory increases in plantar flexor strength. Interestingly, plantar flexion strength was also greater in the acquired re-injury resistance group compared to the never injured group. This may indicate that compensations as a result of previous injury may persist in excess of two years after the initial injury.

Although hypermobility and hypomobility have both been proposed to be related to musculoskeletal injury, a definitive link has not been established for RRIs (Kendall *et al.*, 2005; Becker *et al.*, 2017; Cannon, Finn and Yan, 2018). This is further confirmed in a recent systematic review that concluded that there was limited and low quality evidence suggesting range of motion as a risk factor for RRIs (Christopher *et al.*, 2019). Our research support this as acquired injury resistance runners and never injured runners did not display distinctive differences in dorsiflexion, hip external rotation and hip extension motion compared to recently injured runners. Notably, in relation to hip internal rotation, this finding conflicts with previous results, which found significantly higher hip internal range of motion among injured participants compared to never-injured runners (Zifchock *et al.*, 2008), although different test positioning may account for the differences in results and their study had a smaller sample size (n= 40).

It is hypothesised that large amounts of joint motion may potentially increase demands on stabilising muscles (Cannon, Finn and Yan, 2018). Adaptive shortening or lengthening of muscles may also place muscles at non-optimal lengths, limiting their functional ability (Kendall *et al.*, 2005). This is a marked limitation of traditional clinic-based strength tests performed in a stationary position, which typically do not account for the interaction between joint motion and muscle action. This study found no association between general injuries and joint motion. While this is a commonly used measure in clinical practice, joint motion alone may not be able to differentiate between injury resistant and recently injured runners. The lack of association calls into question its use in the management of general RRIs, although it may be appropriate for screening for specific injuries (Winkelmann *et al.*, 2016) or used in combination with more dynamic muscle strength testing.

Foot alignment has been associated with changes in lower limb kinematics and loading during running (Williams, Tierney and Butler, 2014), although the association between functional foot alignment and RRIs have been conflicting (Nohr *et al.*, 2013; Pérez-Morcillo *et al.*, 2019). Contrary to our hypothesis, our study found no significant differences in either navicular drop means, the proportion of runners with navicular drop >10mm, or FPI categories, suggesting that functional foot alignment largely does not appear to be protective against general RRIs. An interaction effect between injury status and sex was found for FPI. Further analysis revealed that females with acquired re-injury resistance had significantly lower values of FPI compared to recently injured runners. It is unclear why this is, but it would suggest that females injured > 2 years ago have a more neutral foot type compared to female runners recently returned to play following injury, who had feet classified as "pronated". We had hypothesised that navicular drop > 10 mm would be associated with injury, however, assessing by cut-off point did not yield significant differences between groups in our study. This contrasts with a previous prospective study, which found this to be a risk factor for exercise related leg pain among high school runners (Bennett, Reinking and Rauh, 2012). Discrepancies in results may possibly be due to our inclusion of more experienced recreational runners, a difference in age or a variation in definition of injury. Notably, our findings conflict with those of Zifchock et al. (Zifchock *et al.*, 2008) who found significantly reduced Arch Height Index deviation from normal among never-injured runners,; however, our study used a larger sample size and different measurement of functional foot alignment.

No differences in asymmetry were found between different injury groupings. This is in line with previous research which found that asymmetry was not significantly different between never-injured and previously injured runners for hip strength and motion (Zifchock *et al.*, 2008) or for strength values between uninjured runners and those in the early stages of PFPS (Plastaras *et al.*, 2016). Limited research has found that asymmetries after injury may persist after return to play (Ithurburn *et al.*, 2015), despite the recommendation that asymmetries are minimised at this time point. However, for our cohort it appears that similar levels of asymmetry existed across all groups, indicating that some level of asymmetry is normal. A finding of particular interest is that greater asymmetry was not found among those injured in the past year. Another explanation could be that studies which show high levels of asymmetry are generally related to acute, traumatic injuries, such as ACL ruptures (Ithurburn *et al.*, 2015), which may require greater rest than typical RRIs. Our findings indicate to clinicians that some level of motion, isometric strength, FPI and navicular drop asymmetry are to be expected among runners, regardless of their injury history.

Owing to the differences in RRI risk profiles that have been noted to exist between males and females (de Wijer *et al.*, 2015), both the interaction effect of injury status on sex and the main effect of sex were investigated in this study. No interaction effects were found between injury status and sex for the clinical tests, with the exception of FPI. Sex may not have been a frequent interactive factor in our study as the majority of previous research finding sex-specific differences between injured and uninjured runners subdivided injury by diagnosis or location (Plastaras *et al.*, 2016; Becker *et al.*, 2017), which was not within the scope of this study. We found that compared to females, males displayed significantly greater knee flexion strength asymmetry, dorsiflexion motion, muscle strength normalised to body mass (with the exception of plantar flexion strength, which only approached significance) and navicular drop values, in addition to lower hip internal rotation. Previous research support these findings with regard to strength (Bishop, Cureton and Collins, 1987), navicular drop (Van Der Worp *et al.*, 2014) and hip internal rotation (Czuppon *et al.*, 2017). Little previous information is available investigating the between-sex differences in knee flexion strength asymmetry. However, force production asymmetry has been found to be greater in females during jumping movements (Bailey *et al.*, 2015). Males displayed significantly greater dorsiflexion motion than females, contrasting with previous findings for healthy runners (Van Der Worp *et al.*, 2014), although it is unclear why this difference exists.

A relatively unique component of this study was the examination of never injured runners. It was hypothesised that investigating this group may have been useful in determining if common, easily assessible measures could identify potential differences in their clinical factors that may be protective of injury. Of the two hundred and twenty three participants analysed in this study, 116 (77 males, 39 females, 42%) had been recently injured (<1 year prior), 61 (38 males, 23 females, 22%) had been injured over 2 years ago were deemed to have acquired re-injury resistance and 46 (29 males, 17 female, 17%) had never been injured. The most common location of injury was the calf, followed by the knee (Table 2), which is largely similar to what has been reported in previous literature (Francis *et al.*, 2019).

Limitations

Despite being chosen for their suitability for use in clinical practice and potential association with common RRIs, the clinical factors examined may have limitations. This study measured isometric contraction in a fixed position. Running also requires concentric and eccentric muscle action (Novacheck, 1998). Therefore, the muscle strength values measured within our study may not represent the typical values or contraction types produced during running. Similarly, quasi-static measures of navicular drop and FPI may not accurately reflect the dynamic motion of the foot during running. However, as these measures were considered to be more accessible in clinical practice, they were selected for this study.

The retrospective design of this study limits the ability to definitively ascertain whether differences between groups (recently injured, acquired re-injury resistance, never injured) are as a result of injury or causative in nature. Compensation and post-injury rehabilitation may mask our understanding of the factors associated with injury and whilst this information was collected for the recently injured runners, this was not gathered in the acquired injury resistance group. Additionally, the injury history relied on accurate reporting from participants, meaning that it may be subject to recall bias. In an effort to minimise recall bias and due to the presence of multiple injuries, data were analysed by grouping injuries together and averaging values from both sides. This method is advantageous in assessing whether there are factors protective from general RRIs, and not specific to a particular injury. However, this limited our ability to compare side to side differences, to examine injury-specific differences in clinical measures or to delineate between overuse and acute injuries. Future studies should prospectively track injuries to minimise the effect of recall bias, whilst allowing collection of a detailed injury history at the time of injury.

Conclusion

This study found that, in general, isometric muscle strength, joint motion, functional foot alignment, and side to side asymmetry values of these measures were not significantly different between runners who were recently injured, had acquired re-injury resistance or runners who were never injured. These findings suggest that injury resistant runners cannot be distinguished from previously injured runners using popular clinical tests, likely due to high engagement with rehabilitation. While these clinical factors may be important in the assessment and rehabilitation of injured athletes, the results of this study indicate that they have limited value in identifying future injury resistance of runners.

Link Section: Chapter 3 to 4

Chapter 3 addressed the gap in the literature with regard to the association between commonly used clinical tests and injury status. This study is the first to explore a myriad of clinical tests among these distinct injury groups. Although it was hypothesised that muscle strength, range of motion and foot position may reflect the ability of the body to distribute and attenuate load, as well as the strength of the tissues experiencing the load, these factors largely did not appear to be different between the injury groups. Therefore, other factors remain outstanding that may explain the injury resistance of the never injured/injured > 2 years group, or indeed the greater likelihood of injury faced by runners injured in the past year (Saragiotto *et al.*, 2014; Van Der Worp *et al.*, 2015). A variable that may be of particular relevance is impact loading, given that injuries are caused by high loading to tissue strength (Kalkhoven, Watsford and Impellizzeri, 2020). Therefore, there may be a need to quantify loading itself. Impact accelerometery is a low-cost method of measurement of segmental loading that has the potential to be used on a more widespread basis than typical measures of impact loading such as ground reaction force. Impact accelerations have previously been found to be significantly greater among female injured runners compared to never injured runners (Milner *et al.*, 2006b; Zifchock *et al.*, 2008). However, research is limited, both by sample size and number of studies, necessitating further investigation regarding whether this measure may explain injury resistance. Therefore, Chapter 4 presents an investigation of impact accelerations between three distinct injury groups (never injured, injured > 2 years and recently injured runners).

Note: Given the high proportion of runners who run over ground (Running USA, 2017), yet the difficulty in collecting biomechanical data on this surface, it is important determine if impact accelerations collected on a treadmill surface are representative of those produced over ground. Moreover, it is also important to ascertain whether we can interchange data collected on different treadmills. Section 8.3 (Appendix C) is a methodological chapter which examines if impact accelerations captured whilst treadmill running are "representative" of those produced overground. This section found that there was a moderate to excellent relative reliability of impact accelerations across treadmill and over ground surfaces, making this suitable for prospective study designs involving measurement of impact accelerations across the same surface for all participants. However, impact acceleration values derived from Chapter 5 and 6 should not be used for research where absolute values are important (e.g. setting target running retraining values) due to the significant differences in impact loading noted between surfaces and low absolute agreement of these values.

4. *Chapter 4: An investigation of the association between previous running related injuries and impact accelerations among recreational runners.*

This study is under review:

Dillon, S., Burke, A., O'Connor, S., Whyte, E., Gore, S., Moran, K., 2022. Are there differences in impact accelerations between recently injured and injury resistant runners? Sports Biomechanics (Awaiting decision).

This is presented in full, with only minor formatting changes.

Abstract

Background/aims: Running-related injuries (RRIs) are highly prevalent, yet some runners appear more resistant to injury than others. The purpose of this study was to investigate the effect of injury status [recently injured (injury 3 months- 1 year prior), injury resistant (injured > 2 years) and never injured runners] and sex on segmental impact accelerations/loading. While impact loading during running has been postulated to be related to RRIs, no studies have explored if impact loading varies across these distinct groups.

Methodology: This cross-sectional study included 193 recreational runners: 102 recently injured (69 males, 33 females), 53 injury resistant runners (33 males and 20 females), 38 never injured runners (23 males and 15 females). Peak and rate of acceleration were measured at the shank and lower back during running at a self-selected pace. Two-way ANCOVAs were used to investigate the effect of injury status and sex on these measures, with average weekly mileage as a covariate.

Results/conclusion: No interaction effect for injury status and sex was evident for any of the acceleration/loading variables. However, peak and rate impact accelerations at the lower back were significantly higher among recently injured runners compared to injury resistant runners, which may help explain the high rate of reinjury typically experienced by this group. Females displayed greater peak and rate of acceleration at both the lower back and shank, which may explain sex-related differences in RRIs.

Key words*:* running injury, recreational runners, biomechanics, impact acceleration, loading

Introduction

The high prevalence (Messier *et al.*, 2018) and burden (Hespanhol Junior, van Mechelen, *et al.*, 2016) of running related injuries (RRIs) has instigated much investigation into the factors associated with injury (Zifchock *et al.*, 2008; Messier *et al.*, 2018). A biomechanical model of injury stipulates that loading in excess of the tissue capabilities is causative of injury (Kalkhoven, Watsford and Impellizzeri, 2020). In light of the numerous, cyclic loads during running, loading metrics are increasingly of interest in understanding the aetiology of RRIs (Hreljac, 2004; Bredeweg *et al.*, 2013; Bigouette *et al.*, 2016; Davis, Bowser and Mullineaux, 2016). However, contradictory findings are evident across these studies (Davis, Bowser and Mullineaux, 2016; Messier *et al.*, 2018). This may in part be explained by the predominant use of force plates to assess loading (Bredeweg *et al.*, 2013; Bigouette *et al.*, 2016; Davis, Bowser and Mullineaux, 2016), with vertical ground reaction force (vGRF) only measuring whole-body loading, failing to account for more body segment-specific loading, because loading is not proportionately equal across all body segments. Impact accelerometery using small, wearable sensors presents accessible opportunities for measuring segmental-based loading compared to the traditional ground reaction force approach using force plates (Horsley *et al.*, 2021). Given that the whole-body GRF loading is the sum of all segmental loading, with the latter being the product of each segments' mass times acceleration (Equation 1), direct measurement of segmental acceleration is an appropriate proxy measure of segmental loading (Sheerin, Reid and Besier, 2019).

Equation 1

$$\boldsymbol{GRF} = \Sigma(\boldsymbol{m_i} * \boldsymbol{a_i})$$

where m_i is the mass of segment *i*, a_i is the acceleration of segment *i*, and equation 1 is calculated for all body segments.

Segmental acceleration has been used to examine the relationship between loading and running related injuries (Milner *et al.*, 2006a; Zifchock, Davis and Hamill, 2006), and loading and running technique (Mercer *et al.*, 2002), and has been found to be both valid (Van den Berghe *et al.*, 2019; Alcantara *et al.*, 2021) and reliable (Sheerin *et al.*, 2018).

The association between loading and RRIs can be explored at a general or injury specific level. The advantage of examining at the general injury level is that global factors associated with injury may be identified (Zifchock *et al.*, 2008), which is useful given that we cannot anticipate which injury a runner may develop. The shank is a common attachment site of accelerometers due to the high reports of injuries at the tibia among runners (Mulvad *et al.*, 2018; Francis *et al.*, 2019). In terms of the association between shank peak accelerations ($peak_{accel}$) and general

RRIs, research to date has been somewhat limited, with only one study examining this, reporting a trend for significantly higher peak accelerations of the injured limb compared to the uninjured limb within a group of female runners (Zifchock *et al.*, 2008). Similarly, despite the occurrence of RRIs at the lower back and hips (Ellapen *et al.*, 2013; Van Der Worp *et al.*, 2016), relatively few studies have examined the association between loading at the lower back and RRI (Winter *et al.*, 2020).

The research methodology is a key consideration when approaching the identification of factors related to RRIs. The predominance of retrospective methodologies is cited as a weakness in the RRI research domain, mainly due to the difficulty in identifying whether differences between the injured and non-injured groups preceded or followed the injury. However, we propose examining the association between injury status and loading using three distinct injury groupings which offers more insight. Previous injury history is one of the strongest risk factors for RRIs, particularly in relation to injury in the past year (Buist, Bredeweg, Lemmink, *et al.*, 2010; Winter *et al.*, 2020). Recently injured runners (reporting an injury less than 1 year prior), who have returned to running may have measurable loading factors that explain their heightened risk of re-injury (Saragiotto *et al.*, 2014). Furthermore, examining the differences between these recently injured runners and those with a previous injury, yet who have not sustained a reinjury in this high risk 1 year period, may be insightful in understanding why this group do not succumb to this typically high rate of injury. A third group of runners that are of particular interest are those who have never been injured. Although they may be a minority, with lifetime RRI prevalence ranging across studies between 54 (Vitez *et al.*, 2017) and 92% (Lun *et al.*, 2004), these runners may display advantageous factors that lead them to being injury-free. Previous research has examined impact accelerations among never injured runners in a limited capacity (Zifchock, Davis and Hamill, 2006; Zifchock *et al.*, 2008; Davis, Bowser and Mullineaux, 2016) most notably by Zifchock *et al.*(Zifchock, Davis and Hamill, 2006), who found greater loading among runners with previous tibial stress fracture compared to never injured runners. However, this study did not explore a number of potentially important factors in understanding RRIs: lower back loading/accelerations, rate of loading/acceleration, or the influence of sex. In addition, no studies have examined loading across the proposed three groups.

This study, therefore, aims to examine if impact accelerations differ across injury status and sex using three distinct injury status groups: those who have recently returned from injury (injured 3 months - 1 year previously), those who have acquired re-injury resistance (remained uninjured for >2 years), and those who have never been injured (never injured). We hypothesised that those with a high level of injury resistance (i.e., never-injured runners; runners who had remained uninjured for >2 years) would have lower impact accelerations/loading compared with the recently injured group. We also hypothesised that females would have greater impact acceleration/loading than males.

Methodology

Participants

From January 2018 to August 2019, male and female recreational runners between the ages of 18-65 were recruited. Recreational runners were defined as running a minimum of 10km/week, for at least six months immediately prior to the study (Saragiotto, Yamato and Lopes, 2014). Participants injured in the last three months were excluded to limit the effect of the acute effects of injury on running technique (Buist, Bredeweg, Lemmink, *et al.*, 2010). Runners participating in a team, contact or high impact sport were also excluded because it is not possible to associate the injury solely with running. Three participant groups were later constructed: those injured 3-12 months prior ('recently injured'), those whose most recent injury was >2 years ago ('acquired re-injury resistance'), and those who had never been injured ('never injured'). The exclusion of participants injured 1-2 years previously was done to ensure clear demarcation between 'recently injured' and 'acquired re-injury resistance' groups. Two hundred and forty-four runners participated in this study. Fifty-one participants (38 males, 23 females) were injured in the 1- 2 years prior to participating in the study and were therefore excluded from analysis.

Sample Size

We determined sample size *a priori* for the two-way Analysis of Variance (ANOVA) using a power analysis program, G*Power 3.1.9.7 (alpha probability = 0.05, with a power of $1 - \beta = 0.80$, effect size (f) = 0.25). The effect size was determined using a standardised medium effect size value (small = 0.1, medium = 0.25, large = 0.40), reaching a total sample size requirement of 158 participants.

Ethical Approval

Ethical approval was sought from and granted Dublin City University Ethics Committee (DCUREC/2017/186).

Procedures

Prior to baseline testing, eligible participants completed an online survey (Appendix A, page 278) detailing their training and injury history. At a single baseline session, participants completed a Par-Q clearance questionnaire and height (m) and body mass (kg) measurements as well as age (years) were recorded. $Peak_{accel}$ and $rate_{accel}$ were measured using three inertial measurement units (IMUs). Two IMUs (dimensions: 65 mm x 32 mm x 12 mm, mass: 31 gm, acceleration range: ± 16 g) (Shimmer, Ireland) were attached tightly bilaterally to the shank, 5 cm proximal to the medial malleolus, using Hypafix tape, aligned along the long-axis of the shank. A single IMU (dimensions: 51 mm x 34 mm x 14 mm, mass: 23.6 gm, acceleration range: ± 16 g) was secured tightly with a custom-made belt which was adhered to the skin using double sided sticky tape, with the y axis aligned along the vertical midline of the S2 spinous process. This was further secured with an elastic waistband (Johnson, Outerleys, *et al.*, 2020). These sensors have previously been used in running research (Moran *et al.*, 2015). The sensors were calibrated using the Shimmer 9DOF Calibration Application. The triaxial accelerometer data were captured at 512 Hz. Following a dynamic warmup, participants performed a run on a treadmill (Flow Fitness, Runner DTM3500i, The Netherlands), whilst wearing their own shoes. Participants ran for 9 km/hr for a period of six minutes, followed by three minutes at a pace that represented their self-selected typical running speed (Heiderscheit *et al.*, 2011). Data from the accelerometers during the second minute of the self-selected speed run was processed using custom-written software (MATLAB R2018a). Following a residual analysis and visual inspection of the data, the accelerometer data were filtered using a 4th-order zero lag Butterworth filter (60 Hz). Dropped packets were filled using a cubic spline, and the time series data were time-aligned to ensure functionally equivalent values were extracted from the shank and lower back sensors. Foot strike was identified using the shank mounted accelerometer as the local maxima preceding the peak negative acceleration. $Peak_{accel}$ and $rate_{accel}$ were extracted for 10 consecutive foot-strikes which were normalised to gravity and an average was calculated (Figure 7). $Rate_{accel}$ was calculated as the slope of the $peak_{accel}$. $Rate_{accel}$ was assessed because rate of loading has been found to be more closely related to stress fractures than peak loading when assessing vGRF (Zadpoor and Nikooyan, 2011), and animal studies show greater cell matrix damage in response to high rates of loading when compared to low rates, despite no significant difference in the peak load applied between the groups (Ewers *et al.*, 2001).

Running related injury (RRI) defined

Injury history was collected via an online questionnaire and was verbally reviewed for accuracy and completeness on the day of testing. A RRI was defined in line with a consensus statement by Yamato *et al.*(Yamato *et al.*, 2015) as “any (training or competition) musculoskeletal pain in the lower limbs that causes a restriction/stoppage of running (distance, speed, duration, or training) for at least 7 days or 3 consecutive scheduled training sessions, or that requires the runner to consult a physician or other health professional”. This definition was adapted to include lower back injuries and was restricted to overuse injuries. Due to the presence of multiple and bilateral injuries and potential recall bias in remembering the side of injury, the average $peak_{accel}$ and $rate_{accel}$ values of the sum of both sides was used.

Statistical Analysis:

Data were analysed using SPSS (version 27; IBM Corp, Armonk, NY). Participants were divided into three groups: recently injured (history of injury between 3 months and one year), acquired re-injury resistance (history of injury >2 years) and never-injured runners. Differences in demographics (sex, age, height, mass) between injury groups were assessed using one-way ANOVAs. Differences in running experience (6 months -5 years, 6-10 years, 11-15 years and 16+ years' experience) between injury groups were assessed using Chi Square tests. Two-way ANCOVAs (3 x 2) (group x sex) were used to evaluate difference between injury groups in measures of $peak_{accel}$ and $rate_{accel}$ at both the shank and lower back. Due to the proposed association between volume of loading and RRI (Bertelsen *et al.*, 2017), average weekly mileage (kilometers) over the preceding 3 months was included as a covariate. A two-way ANOVA (group x sex) was conducted to evaluate any differences in running speed. Effect sizes were reported using partial eta squared (η^2) with 0.01, 0.06 and 0.14 representing small, medium and large effect sizes (Tomczak and Tomczak, 2014). Pairwise post hoc testing for significant differences between injury groups was performed using a Bonferroni correction, with the $P < .05$ considered significant. Data violating the assumption of homogeneity of variance via Levene's test were log-transformed and parametrically analysed. Due to occasional equipment malfunction, the sample size for each variable sometimes varied slightly and is detailed below.

Results

Demographics

Of the 193 runners included in this analysis, 53% (n=102, 69 males, 33 females) were recently injured, 27% (n= 53, 33 males and 20 females) were injured over 2 years prior to inclusion and were deemed to be injury resistant, and 20% had never been injured (n= 38, 23 males and 15 females). A breakdown of the proportion of injuries for each injury location is detailed in Table 78. The demographics of those included in the study are detailed in (Table 79). No significant differences were found for any of the demographic variables of height, mass and age between the three groups ($P > .05$, Table 2). No significant difference in running experience of runners was found between injury history groups ($X^2 (6) = 3.868$, $P = .695$). No interaction effect between injury status and sex was found for running speed, nor was there a main effect for injury status. There was a significant main effect for sex on running speed, with male runners running significantly faster (Table 81).

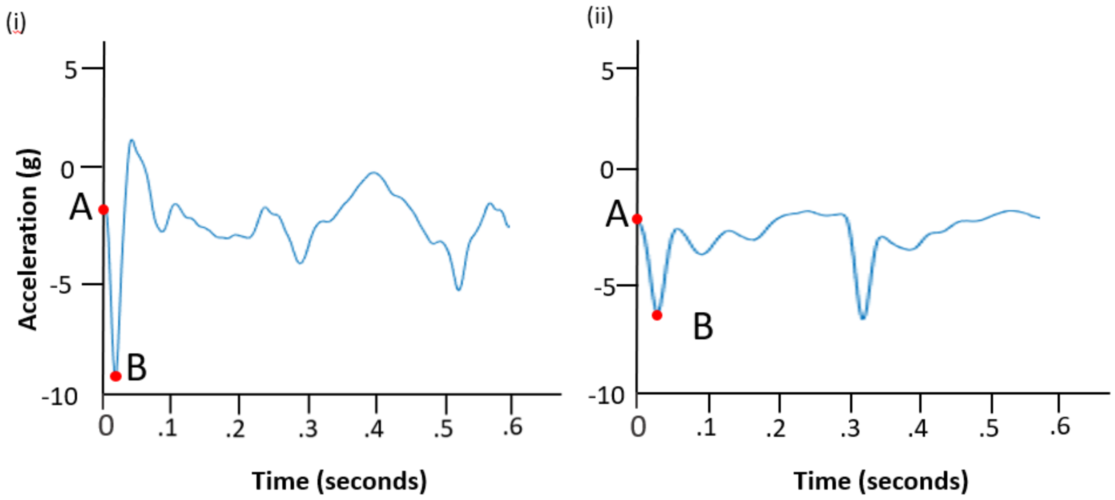


Figure 7 Example acceleration traces for treadmill running for the (i) shank and (ii) lower back. $Peak_{accel}$ (B) and the preceding point (A) were used to calculate the slope of the $peak_{accel}$ ($rate_{accel}$). More negative values are indicative of greater loading.

Table 78 The Location of Injuries Among the Recently Injured Group

Injury Location	***Number of injuries at this location***	***Percentage of injuries at this location (%)***	***Number of injuries at this location- males***	***Percentage of injuries at this location (%)- males***	***Number of injuries at this location- females***	***Percentage of injuries at this location (%)- females***
Calf	28	21%	21	23%	7	18%
Knee	18	14%	12	13%	6	15%
Posterior thigh	15	11%	11	12%	4	10%
Shin	12	9%	7	8%	5	13%
Foot	9	7%	5	6%	3	8%
Lower Back	9	7%	7	8%	1	3%
Lateral thigh	8	6%	5	6%	3	8%
Hip	8	6%	5	6%	4	12%
Buttock	7	5%	4	4%	3	8%
Ankle	5	4%	1	1%	3	8%
Heel	5	4%	5	6%	0	0%
Medial thigh	4	3%	4	4%	0	0%
Toes	2	2%	2	2%	0	0%
Anterior thigh	1	1%	0	0%	1	3%
Sacroiliac Joint	1	1%	1	1%	0	0%

Table 79 Participant demographics.

		Recently Injured				Acquired Re-injury Resistance				Never-injured				P value	Effect size
	Total n	***Males, females***	***Group*** Mean ± SD	***Males*** Mean ± SD	***Females*** Mean ± SD	***Males, females***	***Group*** Mean ± SD	***Males*** Mean ± SD	***Females*** Mean ± SD	***Males, females***	***Group*** Mean ± SD	***Males*** Mean ± SD	***Females*** Mean ± SD		
Age (years)	193	69 M, 33 F	44.7 ± 7.8	43.0 ± 8.8	43.1 ± 7.7	33 M, 20 F	44.7 ± 7.8	45.0 ± 7.8	44.4 ± 7.9	23 M, 15 F	42.0 ± 19.1	44.2 ± 10.6	38.6 ± 8.5	.306	.012
Mass (kg)	193	69 M, 33 F	73.4 ± 11.8	78.5 ± 9.6	62.9 ± 8.6	33 M, 20 F	73.4 ± 11.8	78.5 ± 9.6	62.9 ± 8.6	23 M, 15 F	73.3 ± 14.3	82.1 ± 10.0	59.6 ± 7.1	.816	.002
Height (m)	193	69 M, 33 F	1.73 ± 0.09	1.78 ± 0.06	1.64 ± 0.07	33 M, 20 F	1.74 ± 0.10	1.79 ± 0.07	1.66 ± 0.08	23 M, 15 F	1.72 ± 0.10	1.78 ± 0.07	1.63 ± 0.08	.735	.003

Abbreviations: n- number of participants, SD- standard deviation, M= male, F= female, $peak_{accel}$ = peak accelerations, $rate_{accel}$ = rate of accelerations.

Table 80 Descriptive Statistics of Running Speed and Average Weekly Running Distance of Participants.

			Recently Injured				**Acquired Re-injury Resistance**				**Never-injured**		
	Total n	***Males, females***	***Mean ± SD Group***	***Mean ± SD Males***	***Mean ± SD Females***	***Males, females***	***Mean ± SD Group***	***Mean ± SD Males***	***Mean ± SD Females***	***Males, females***	***Mean ± SD Group***	***Mean ± SD Males***	***Mean ± SD Females***
Average distance/week (km/week)	193	69 M, 33 F	32.2 ± 17.2	33.2 ± 16.2	30.1 ± 19.4	33 M, 20 F	43.6 ± 29.3	47.4 ± 34.5	37.3 ± 16.9	23 M, 15 F	36.7 ± 22.7	36.4 ± 19.6	37.3 ± 27.7
Running speed (km/hr)	193	69 M, 33 F	11.2 ± 1.5	11.6 ± 1.4	10.3 ± 1.3	33 M, 20 F	11.2 ± 1.6	11.8 ± 1.3	10.3 ± 1.6	23 M, 15 F	11.3 ± 1.4	11.7 ± 1.5	10.7 ± 1.1

Abbreviations: n- number of participants, SD- standard deviation, M= male, F= female.

Table 81 Results of a Two-way ANOVA Investigating the Difference Between Groups with Reference to Running Speed and Injury Status and Sex.

	P value injury status*sex	Effect size	P value injury status	Effect size	P value sex	Effect size
Running speed	.539	.007	.872	.002	.000[1]	.132

[1] Indicates that this was significant, P < .001.

Lower back peak accelerations (Table 82, Table 83)

There was no significant interaction effect between injury status and sex (P = .432, η_p^2 = 0.010). A simple main effect for injury status was found (P = .018, η_p^2 = 0.046). Pairwise comparisons revealed greater impact accelerations among recently injured runners, compared to those injured over one year ago (P = .014, mean difference = 0.86 g, $CI_{95\%}$= 0.14-1.58). A significant main effect for sex was found, with females displaying greater $peak_{accel}$ than males (P = .029, η_p^2 = 0.027).

Shank peak accelerations (Table 82, Table 83)

There was no significant interaction effect between injury status and sex (P = 0.065, η_p^2 = 0.032). No simple main effect for injury status was found (P = 0.084, η_p^2 = 0.029). A significant main effect for sex was found, with females displaying greater $peak_{accel}$ than males (P = 0.027, η_p^2 = 0.028).

Lower back rate of acceleration (Table 82, Table 83)

There was no significant interaction effect between injury status and sex (P = .301, η_p^2 = 0.014). A significant main effect for injury status was found (P = .016, η_p^2 = 0.047), with pairwise post hoc analyses revealing significantly greater $rate_{accel}$ among recently injured compared to injury resistant runners (P = .016, mean difference= 72.71 g/s, $CI_{95\%}$ = 10.7-134.8). A significant main effect for sex was found (P = .002, η_p^2 = 0.052), with greater lower back $rate_{accel}$ among females.

Shank rate of acceleration (Table 82, Table 83)

There was no interaction effect between injury status and sex (P = .935, η_p^2 = 0.001). No statistically significant simple main effect was found for injury grouping (P = .164, η_p^2 = 0.021). A significant main effect for sex was observed (P = .005, η_p^2 = 0.045), with females demonstrating greater $rate_{accel}$ than males.

Table 82 Descriptive Statistics for Impact Loading at Each Segment.

		Recently Injured				***Acquired Re-injury Resistance***				***Never-injured***			
Loading measure	***Total n***	***M/F***	***Group***	***Males***	***Females***	***M/F***	***Group***	***Males***	***Females***	***M/F***	***Group***	***Males***	***Females***
			Mean ± SD	***Mean ± SD***	***Mean ± SD***		***Mean ± SD***	***Mean ± SD***	***Mean ± SD***		***Mean ± SD***	***Mean ± SD***	***Mean ± SD***
Lower back $peak_{accel}$ (g)	179	64 M, 279 F	-5.99 ± 1.64	-5.68 ± 1.36	-6.67 ± 2.00	33 M, 19 F	-5.41 ± 1.62	-5.34 ± 1.54	-5.54 ± 1.79	21 M, 13 F	-5.79 ± 1.69	-5.59 ± 1.76	-6.11 ± 1.58
Shank $peak_{accel}$ (g)	182	63 M, 30 F	-7.32 ± 1.93	-7.08 ± 1.64	-7.83 ± 2.39	32 M, 20 F	-8.06 ± 3.09	-7.33 ± 2.22	-9.22 ± 3.91	22 M, 15 F	-7.19 ± 2.36	-6.69 ± 1.61	-7.93 ± 3.07
Lower back $rate_{accel}$ (g/s)	178	63 M, 29 F	319 ± 148	282 ± 124	398 ± 168	33 M, 19 F	269 ± 134	254 ± 130	296 ± 140	21 M, 13 F	292 ± 142	272 ± 146	324 ± 135
Shank $rate_{accel}$ (g/s)	179	63 M, 30 F	612 ± 306	562 ± 252	715 ± 381	32 M, 17 F	612 ± 306	568 ± 318	716 ± 393	22 M, 15 F	546 ± 378	466 ± 257	662 ± 493

Abbreviations: n- number of participants, M- males, F- females, SD- standard deviation, $peak_{accel}$ = peak accelerations, $rate_{accel}$ = rate of accelerations.

Table 83 Differences in Impact Loading Among Differing Injury Groupings and Sex.

Loading Measure	***P value- injury status*sex***	***Effect size- injury status* sex***	***P value- injury status***	***Effect size- injury status***	***P value- sex***	***Effect size- sex***
Lower back $peak_{accel}$	.432	.010	.018[1]	.046	.029[1]	.027
Shank $peak_{accel}$	.065	.032	.084	.029	.027[1]	.028
Lower back $rate_{accel}$	.301	.014	.016[1]	.047	.002[1]	.052
Shank $rate_{accel}$	.935	.001	.164	.021	.005[1]	.045

Abbreviations: [1] Indicates a significant difference between groups, $peak_{accel}$ = peak accelerations, $rate_{accel}$ = rate of accelerations.

Discussion

The aim of this study was to examine if impact accelerations ($peak_{accel}$, $rate_{accel}$), which are a measure of localised loading, differ across runners with distinct injury histories, and whether sex influences this association. We found no interaction effect for sex and injury status for any of the loading variables. However, $peak_{accel}$ and $rate_{accel}$ at the lower back were significantly greater among recently injured runners, compared to those injured over two years ago. Furthermore, females displayed greater $peak_{accel}$ and greater $rate_{accel}$ at both the lower back and shank compared to males.

Runners with recent injury displayed greater $peak_{accel}$ and $rate_{accel}$ at the lower back compared to runners with acquired injury resistance, albeit with a small effect size. Previous injury in the past year has been identified as a strong risk for future injury in multiple studies (Buist, Bredeweg, Lemmink, *et al.*, 2010; Winter *et al.*, 2020). This suggests two related points. Firstly, injury resistant runners may have avoided reinjury within this high-risk period via the adoption of a lower impact technique. Secondly, greater impact loading among recently injured runners may explain the typically high reinjury rate among this cohort, as greater loading may exceed the strength of recently injured tissue (Kalkhoven, Watsford and Impellizzeri, 2020). Previous research has shown that lowering loading is readily possible via running retraining targeting a reduction in impact accelerations (Crowell *et al.*, 2010). In addition, an intervention study using vGRF to teach runners to run with reduced loading reduced prospective general RRIs by 62% compared to a control group (Chan *et al.*, 2018). Therefore, our findings suggest that interventions to reduce impact accelerations measured at the lower back among recently injured runners may be helpful in improving resistance to injury; however, direct examination of this is required. The present study's significant finding was confined to loading at the lower back, indicating that impact accelerations at this segment may be more sensitive to general RRIs. Previous research examining impact accelerations at the lower back and RRIs have not found association to injury (Schütte *et al.*, 2018; Winter *et al.*, 2020) However, these studies have not directly examined differences in impact loading among these distinct injury history groups, explaining the difference in findings.

Rapid application of force has previously been suggested to be associated with injury (Ewers *et al.*, 2001; Zadpoor and Nikooyan, 2011), with greater loading rates suggested to concurrently increase the rate of strain on tissues. However, $rate_{accel}$ at the shank or the lower back has not been previously investigated in relation to RRI, making the findings of our study novel. The present study found that recently injured runners exhibited greater $rate_{accel}$ at the lower back compared to injury resistant runners. This signals the potential for $rate_{accel}$ to be targeted in RRI intervention studies. Previous research has assessed the association between loading rate measured via ground reaction force and general RRIs, finding mixed results (Davis, Bowser and Mullineaux, 2016; Napier *et al.*, 2018). Our significant findings indicate that that measurement of loading rate at a segmental level ($rate_{accel}$) may be more appropriate in RRI research, than measurement of overall whole-body loading via vGRF.

$Peak_{accel}$ and $rate_{accel}$ at the shank were not significantly different between the injury groups. To the best of our knowledge, just one study has previously investigated the association between impact accelerations at the shank and general RRIs (Zifchock *et al.*, 2008), also finding no significant differences between groups. This finding suggests that shank impact accelerations are not useful targets for runners in reinjury prevention interventions, with regard to general RRIs.

With regard to the never injured group, whilst it was hypothesised that never injured runners would have advantageous (i.e. lower) impact accelerations, this group did not exhibit significantly different peaks or rates of loading compared to other injury groups. Previous research comparing loading between never injured and injured runners has been somewhat conflicting (Zifchock, Davis and Hamill, 2006; Noehren, Davis and Hamill, 2007; Zifchock *et al.*, 2008), with our study adding to the evidence presented by Zifchock et al.(Zifchock *et al.*, 2008), who did not find significant differences in shank $peak_{accel}$ between runners with previous general RRIs and never injured runners. Given that injury is caused by high loads relative to tissue strength (Kalkhoven, Watsford and Impellizzeri, 2020), our finding is of particular importance as it indicates that loading alone may not explain the ability of these runners to remain injury-free. Therefore, studies may wish to examine this group for differences in tissue strength.

Some studies have previously found that factors associated with injury are different between males and females (de Wijer *et al.*, 2015), necessitating our investigation of the main and interaction effects of sex and injury status on loading. We found no interaction effect between sex and injury status for any of the loading variables in relation to general RRIs. A lack of significant interaction may be due to grouping all injuries, as males and females have, in some studies, been found to have similar prevalence of overall general injuries, but different proportions of specific injuries (Francis *et al.*, 2019). In relation to the main effect of sex, our study found females had significantly greater $peak_{accel}$ and $rate_{accel}$ at both the shank and lower back, compared to males, albeit with a low effect size. Greater $peak_{accel}$ at the lower back among females was also reported by Sinclair (Sinclair, 2016). Regarding rate of loading, while evidence suggests females may also have a greater rate of vGRF (Park *et al.*, 2018), no data exists exploring the effect of sex on $rate_{accel}$; therefore the present study adds important information to the general understanding of different loading rates across the sexes during running.

The greater $peak_{accel}$ and $rate_{accel}$ among females than males is likely to be even larger at a standardised speed, given that females ran at a lower self-selected speed, with lower speeds associated with reduced impact accelerations (Mercer *et al.*, 2002). The greater loading in females may be due to differences in running technique as females tend to have less knee flexion (Malinzak *et al.*, 2001), greater peak hip internal rotation and greater knee adduction during stance (Ferber, Davis and Williams, 2003). In addition, greater muscle thickness of the gastrocnemius and vastus lateralis in males may contribute to greater absorption of impact during stance (Connan *et al.*, 2019), although evidence to support this is limited. As well as this, low effect sizes were reported in relation to difference between sex and impact loading, meaning results should be interpreted with caution.

Limitations

This study has three primary limitations. Firstly, given the retrospective nature of the study, it is not known if recently injured runners, who were thought to be at increased risk of reinjury, went on to sustain a future RRI. Similarly, it is not known how many of the injury resistant group would go on to become injured. Secondly, grouping all injuries under one group of general injuries may result in the runners with different injuries *masking* each other's differences in site specific impact accelerations, thereby reducing the likelihood of finding a statistical difference. This is because runners with tibial based injuries have been found to exhibit greater accelerations at the tibia (Milner *et al.*, 2006b; Zifchock, Davis and Hamill, 2006), while those with more proximal injuries may exhibit greater accelerations at the lower back. Given that those with tibia-based injuries may not have elevated sacrum accelerations, and those with proximal injuries may not have elevated tibia accelerations, when looked at collectively site-specific differences will be harder to detect. To address this, future research should use the same division of injury status employed in the present study (recently injured, injury resistant, never injured runners), to explore specific injuries. Nevertheless, the advantage of grouping all RRIs together, as many research studies examining loading have done (Zifchock *et al.*, 2008; Messier *et al.*, 2018; Winter *et al.*, 2020), is that it potentially allows the identification of common factors associated with general RRIs, which would provide valuable information for developing injury prevention strategies for all. Finally, the collection of injury (Gabbe and Finch, 1999) and training history (Winter *et al.*, 2020) in this retrospective design may be subject to recall bias.

Conclusion

In conclusion, only $peak_{accel}$ and $rate_{accel}$ at the lower back were significantly greater among recently injured compared to injury resistant runners. Therefore, greater loading at the lower back may be associated with the high susceptibility to reinjury among recently injured runners compared to those who have acquired resistance to injury, and this may inform intervention studies which aim to reduce reinjury likelihood. However, at this time it appears that potentially advantageous impact loading measures that are protective of general RRIs are not evident among never injured runners, suggesting that other factors, such as tissue strength, may explain their resistance to injury. Furthermore, although there was no interaction effect between sex and RRI in relation to impact accelerations, females had significantly greater $peak_{accel}$ and $rate_{accel}$ at both the shank and lower back compared to males. Future research should explore if there are any differences between men and women in segmental loading at the tibia and sacrum associated with specific injuries.

Perspective:

The use of impact accelerometery in running injury research is growing, primarily because of the low-cost nature and clinical accessibility of these sensors to measure loading in real-time. It is generally accepted that injuries are a result of high load in excess of the tissue strength (Kalkhoven, Watsford and Impellizzeri, 2020). Research indicates that runners with a history of injury in the past year are at a high risk of re-injury (Mann, L. Malisoux, *et al.*, 2015; Winter *et al.*, 2020). Our findings of greater $peak_{accel}$ and $rate_{accel}$ at the lower back among recently injured runners compared to those with injury over 2 years ago, may explain the high risk of reinjury typically noted among this group. This suggests that interventions aimed at reducing $peak_{accel}$ and/or $rate_{accel}$ at the lower back (e.g. running re-education (Crowell *et al.*, 2010; Chan *et al.*, 2018)) could form part of a re-injury prevention programme in recently injured runners. This possibility should be experimentally examined. Greater loading exhibited by females in this study may explain the differences in the proportion of specific injuries commonly observed between the genders (Francis *et al.*, 2019) and should be explored further.

Link Section: Chapter 4 to 5

Retrospective research adds value in enabling exploration of factors associated with injury resistance and examining the response to, and perhaps the coping mechanisms associated with RRIs. Chapter 3 identified that hip abduction strength was significantly greater among recently injured runners compared to never injured runners and that plantarflexion strength was greater among recently injured runners compared to injury resistant runners and never injured runners. These differences are likely a reflection of as a result of engagement with rehabilitation or compensatory changes due to previous RRIs. Chapter 4 identified that recently injured runners have greater loading at the lower back compared to injury resistant runners, which may explain the typically high re-injury rate noted runners who have been injured in the past year. Notably, both the strength and impact acceleration differences found in these chapters are likely as a result of RRIs, rather than reflective of factors causing the initial injury. This highlights the primary limitation of retrospective research, in that that it is difficult to ascertain whether differences, if any, between groups are causative or as a result of injury. Therefore, prospective examination of factors associated with injury is important to add confidence to our assumption that factors are causative of injury. As such, Chapter 5 will prospectively explore multiple factors associated with general RRIs, including loading, technique and clinical measures.

5. *Chapter 5: A prospective multifactorial investigation of the factors associated with general running related injuries among recreational runners.*

This study is under review:

Dillon, S., Burke, A., O'Connor, S., Whyte, E., Gore, S., Moran, K., 2022. Running towards injury? A prospective investigation of running related injuries in recreational runners. *American Journal of Sports Medicine* (Awaiting decision).

This is presented in full, with only minor formatting changes.

Abstract

Background: Given the high incidence and heavy burden of running related injuries (RRIs), large-scale, prospective multifactorial investigations examining potential risk factors are warranted.

Hypothesis/Purpose: This study aimed to identify factors associated with RRI and to evaluate their potential in injury screening. It was hypothesised that factors associated with running injuries would be identified.

Study Design: Prospective cohort study

Methods: Two hundred and seventy-four recreational runners were recruited. Clinical measures (strength, range of motion, foot position), injury and training history (via questionnaire), impact loading (via accelerometery) and running technique measures were collected at baseline. Runners were tracked for injury for one year. A binary logistic regression, (injury versus no injury), was performed for each variable univariably, and then adjusting for age, sex and mileage. An exploratory multivariable regression was also performed to evaluate the model's discriminative ability.

Results: Of the 225 runners included in the final analysis 52% experienced an RRI. Injury history in the past year, less navicular drop, and measures of running technique (knee, hip, and pelvis kinematics) were associated with increased odds of injury ($p < .05$). The multivariable logistic regression model was statistically significant, $\chi^2(11) = 56.45$, $p < .001$, correctly classifying 74% of cases with a sensitivity and specificity of 72% and 76%, respectively. The area under the receiver operating characteristic curve was 0.79 ($CI_{95\%}$ = 0.73 - 0.85), demonstrating acceptable discriminative ability.

Conclusion: This study found a number of factors to be associated with prospective RRIs among recreational runners.

Clinical Relevance: With the exception of injury history, the factors identified as being significantly associated with RRIs may be modifiable and therefore, could form the basis of interventions. Range of motion, spatiotemporal parameters and strength measures were not associated with injury and thus their utilisation in injury prevention practices should be reconsidered.

Keywords: Injury, running, biomechanics, running technique, navicular drop.

What is known about the subject: Due to the high prevalence of RRIs, identification of risk factors is important. Given that RRIs are multifactorial and caused by relative excessive load, risk factors typically relate to (1) load (e.g. impact accelerations, ground reaction force), (2) factors affecting load (e.g. running technique analysis, BMI, sex, age), and/or (3) the ability of biological tissue to tolerate this load (e.g. previous injury history, clinical measures [strength measures, foot position, flexibility]). However, a limited number of prospective studies have examined these risk factors.

What this study adds to existing knowledge: This study is the first to prospectively examine the association between general RRIs and impact accelerations at the shank and lower back among recreational runners. In addition, it is one of the largest prospective studies to explore a wide range of injury risk factors. This study identified injury history in the past year, less navicular drop, and various measures of running technique (at the knee, pelvis and hip) to be associated with increased odds of injury. Given the modifiable nature of many of these factors, this information may form the basis of injury prevention interventions. However, these measures appear to have limited use in injury screening. This study calls for reconsideration of common clinically used tests of strength and range of motion in RRI prevention practices.

Introduction

The high incidence of running related injuries (RRIs) (Messier *et al.*, 2018; Winter *et al.*, 2020) and the their negative implications on both physical and mental health (Chan and Grossman, 2011) underscores the importance of understanding the associated risk factors. The challenge in identifying risk factors is that they are multifactorial in nature (Tonoli *et al.*, 2010; Messier *et al.*, 2018; Ceyssens *et al.*, 2019; Christopher *et al.*, 2019; Hollander *et al.*, 2019). Given that RRIs are caused by high load in excess of tissue capacity (Hreljac, Marshall and Hume, 2000; Bertelsen *et al.*, 2017; Kalkhoven, Watsford and Impellizzeri, 2020), risk factors generally relate to: (1) load (e.g. impact accelerations, ground reaction force), (2) factors affecting load (e.g. running technique analysis, BMI, sex, age), and/or (3) the ability of biological tissue to tolerate load (e.g. previous injury history, clinical measures [strength measures, foot position, range of motion]).

The most common method of indirectly quantifying loading during running has been by assessing ground reaction forces (GRFs) via force plates. However, there are mixed findings on their association with RRI (Gerlach *et al.*, 2005; S. W. Bredeweg, Buist and Kluitenberg, 2013; Davis, Bowser and Mullineaux, 2016; Messier *et al.*, 2018; Napier *et al.*, 2018). A limitation of GRF assessment is that it captures whole-body loading and therefore, does not assess segment-specific loading. Segmental measurement would be more appropriate because injuries are site-specific and because loading distribution throughout the body and across runners are not homogenous (Shorten and Winslow, 1992). Impact accelerometers, which indirectly assess segmental loading (F=ma), are low-cost and easy to use, making them potentially more appropriate to a clinic-based setting.

Factors that affect loading or the ability of the body to tolerate loading have also been the subject of RRI research. These range from high-resource, time-consuming measures of running technique using motion analysis systems (Messier *et al.*, 2018), to low-cost, easily-implementable clinical measures such as: range of motion (ROM) (Buist, Bredeweg, Lemmink, *et al.*, 2010; Jungmalm *et al.*, 2020), foot functional aligment (Buist, Bredeweg, Lemmink, *et al.*, 2010) and muscle strength (Torp *et al.*, 2018; Veras *et al.*, 2020). Furthermore, training history (Winter *et al.*, 2020), previous injury history (Winter *et al.*, 2020; Desai *et al.*, 2021), sex(Messier *et al.*, 2018), age (Taunton *et al.*, 2003) and BMI (Winter *et al.*, 2020) may also affect the load and tissue integrity.

Although studies have investigated RRIs, many have examined a small number of factors, potentially failing to account for important risk factors (Ramskov *et al.*, 2013; Davis, Bowser and Mullineaux, 2016; Becker *et al.*, 2018). Furthermore, many studies have utilised a retrospective approach comparing currently injured runners to healthy controls (Dierks *et al.*, 2011; Bramah *et al.*, 2018; Johnson, Tenforde, *et al.*, 2020; Koldenhoven *et al.*, 2020). Therefore, differences identified between injured and uninjured runners may be from alterations due to pain or a consequence of the injury, preventing appropriate conclusions from being made regarding the actual risk factors for RRIs. Few studies have examined multiple factors related to RRIs in a prospective manner. Perhaps the largest is that of Messier et al. (2018) (Messier *et al.*, 2018). However, they used GRFs to quantify loading, which do not reflect segmental loading (discussed above), and kinematic analysis was limited to the lower leg, despite kinematics further up the body being reported as potentially related to RRIs (Grau *et al.*, 2008; Dierks *et al.*, 2011; Noehren, Pohl, *et al.*, 2012; Foch *et al.*, 2015). Therefore, examinations involving impact accelerometery and kinematics of the thorax, hip and pelvis are required. This study aims to prospectively examine the association between RRIs and demographics, injury history and training history, clinical measures, impact accelerations and running technique in a large cohort. A further aim was to explore the potential of these factors in screening for RRIs. It was hypothesised that factors associated with RRIs would be identified.

Methodology

Two hundred and seventy-four recreational runners were recruited from Dublin and its surrounding areas (from January - December 2018) for participation in this prospective study via national radio, social media advertisement, phone calls to running clubs and leaflet distribution at running events. To be eligible for participation participants were required to be a recreational runner, between 18-65 years old, with no history of injury within the last three months (Hesar *et al.*, 2009; Buist, Bredeweg, Lemmink, *et al.*, 2010; Ramskov *et al.*, 2013). Participants were excluded if they participated in contact, team, or high impact sports, to limit the effects of injuries related to non-running activities (Lun *et al.*, 2004). A recreational runner was defined as a person who ran a minimum of 10km per week, for at least six months prior to inclusion in the study (Saragiotto *et al.*, 2014). Participants were excluded if they previously or currently participated at an international level.

This trial was registered prior to recruitment (ClinicalTrials.gov Identifier: NCT03671395). Ethical approval was granted by Dublin City University Ethics Committee (DCUREC/2017/186). Participants were provided with a plain language statement form and screened for inclusion and exclusion criteria via email prior to participation. Eligible participants completed an online survey (Section 8.1, Appendix A) regarding their injury and training history prior to attending a baseline testing session, lasting approximately two hours. The flow chart of participants is detailed in (Figure 8).

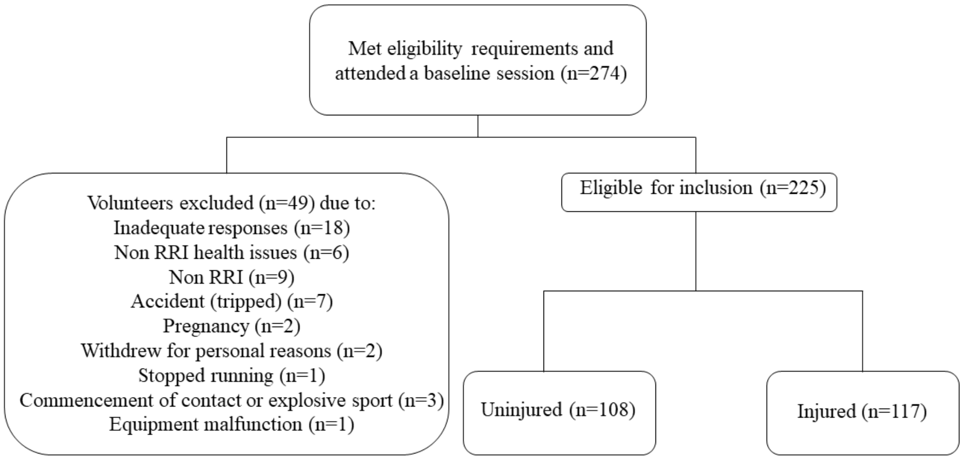


Figure 8 Flowchart of participants included in the study.

On the day of testing, participants completed a PAR-Q health clearance form and an informed consent form. The online survey responses were checked with the participant for accuracy. Anthropometric measurements and musculoskeletal clinical tests were performed for each participant by one tester in line with the protocol of Dillon *et al.* (2021) (Dillon *et al.*, 2021) (Chapter 3). Ankle dorsiflexion, hip extension, hip internal rotation, and external rotation range of motion were assessed for each leg and an average of three trials was used using a digital inclinometer a smartphone application (Plaincode "clinometer," V2.4 on a Samsung S8+, https://play.google.com/store/ apps). To assess foot functional alignment, navicular drop (Buist, Bredeweg, Lemmink, *et al.*, 2010) and foot posture index (FPI-6) (Redmond, Crosbie and Ouvrier, 2006) were measured on each foot. Manual isometric muscle testing was performed for the following actions using a portable dynamometer (J-Tech Commander Echo Wireless Muscle Testing Starter Kit; J-Tech Medical Industries, Midvale, UT): hip abduction, hip extension, plantarflexion, knee flexion and knee extension, with the maximum of three trials selected and normalised to moment arm and body mass. The same rater performed each test. Good to excellent intraclass correlation coefficient values were found intrarater reliability of each of the measures (Section 8.2, Appendix B).

Motion Analysis

Kinematic data were collected using a 17-camera, 3D motion analysis system (Vantage, Vicon, Oxford, United Kingdom). Thirty-two reflective markers, 14 mm in diameter, were placed by one investigator (SD) on bony landmarks of the trunk, pelvis and lower limbs according to a Plug in Gait model (Vicon), with additional markers on the anterior aspect of the mid-tibia and mid-thigh bilaterally. An image of the position of markers in available in Section 8.4, Appendix D).

Three inertial measurement units (IMUs) (Shimmer, Ireland) were used to capture peak acceleration ($peak_{accel}$) and rate of acceleration ($rate_{accel}$). Of these, two IMUs (dimensions: 65 mm x 32 mm x 12 mm, mass: 31 gm, acceleration range: ± 16 g) (Shimmer, Ireland) were attached tightly bilaterally to the shank, 5 cm proximal to the medial malleolus, using Hypafix tape, and aligned with the long-axis of the shank. A single IMU (dimensions: 51 mm x 34 mm x 14 mm, mass: 23.6 gm, acceleration range: ±8 g) was secured tightly with a custom-made belt adhered to the skin using double sided sticky tape and another belt overlaying it. The negative y-axis aligned superiorly along the vertical midline of the S2 spinous process. This was secured further by tape and an elastic waistband in line with recommendations that wrapping and taping is more representative of tibial accelerations than using a strap alone (Johnson, Outerleys, *et al.*, 2020). The IMU triaxial accelerometer data were captured at 512 Hz. Sensors were calibrated using the Shimmer 9DOF Calibration Application.

Running Protocol

Participants performed a dynamic warm up which targeted five main muscle groups (hip extensors, hip flexors, leg extensors, leg flexors and plantar flexors) (Yamaguchi, Takizawa and Shibata, 2015). Subsequently, participants performed a treadmill run (FlowFitness, Runner-DTM2500i, Netherlands) for 6 minutes at a speed of 9 km/hr for warm-up and treadmill familiarisation (Lavcanska, Taylor and Schache, 2005). Participants then ran for a further three minutes at a self-selected pace that best represents their typical training pace (Dierks *et al.*, 2011; Bazett-Jones *et al.*, 2013). To achieve this pace, speed was decreased and increased by the tester until the participant felt that they had achieved a speed that mirrored their typical training pace (Heiderscheit *et al.*, 2011).

Injury Tracking

After this testing session, participants were encouraged to train as normal and RRIs were tracked prospectively for one year. Participants were emailed every 2 weeks enquiring about injuries and were also encouraged to contact researchers at the time of any injury. An RRI was defined in line with a consensus statement (Yamato, Saragiotto and Lopes, 2015) as any muscle, bone, tendon or ligament pain in the lower back, hip, groin, thigh, leg, knee, foot, ankle and toe that caused the participant to stop or restrict their running. The pain must have persisted for at least 7 days or 3 consecutive scheduled training sessions or required the participant to consult a physician or other health care professional. All injuries were diagnosed by the researchers (SD (Chartered Physiotherapist) and AB (Certified Athletic Therapist)). Where this was not possible the diagnosis was confirmed via phone call. Injuries were logged by either of the main researchers (SD, AB) into a password protected Excel spreadsheet. Injury diagnosis, location, date of injury occurrence and date of return to running were inputted within this sheet. Severity was reported as minor, moderate, serious or long-term if 1-7 days, 8-28 days, 29 days-6 months or greater than 6 months was missed, respectively (Timpka *et al.*, 2014). Participants were removed if they did not respond to at least 80% of check ins (Webster *et al.*, 2019).

Data Management

Rigid body segments of the thorax, pelvis, thigh, shank and foot, and the joint angles between these segments in all three planes were defined by the Plug in Gait Model in Nexus 2 (Vicon, UK). Functional joints were calculated using the 'OSSCA' method in NEXUS 2 (Taylor *et al.*, 2010). Hip joint centre and the functional knee axes were calculated within Vicon Nexus 2 using the symmetrical centre of rotation estimation (SCoRE) (Ehrig *et al.*, 2006) and the symmetrical axis of rotation approach (SARA) (Ehrig *et al.*, 2007), respectively. Soft tissue artefact was minimized using the optimal common shape technique (OCST) (Taylor *et al.*, 2005), where an optimum rigid marker configuration for each segment is formed to reduce the effects of skin elasticity. Stance phase data were extracted at the time points outlined in Table 84.

Table 84 Extracted stance phase variables

Stance phase data extracted time points	***Definition***
Peak	Maximum angle achieved during stance.
Minimum	Minimum angle achieved during stance.
Excursion	Maximum-minimum angle during stance
Angle at initial contact	Angle when the foot contacts the ground.
Angle at toe off	Angle when the foot leaves the ground.

Statistical analysis:

Participants were first divided into prospectively injured and prospectively uninjured groups (Figure 8). Among injured runners, variables of interest were taken from the side of the body which was reported to have sustained the first injury. This was done for two reasons. Firstly, some participants experienced injuries on both sides of the body. Although values on both sides could have been averaged, it was hypothesised that the side of the first injury would most accurately reflect factors causative of injury. Secondly, it was hypothesised that subsequent injuries may be as a result of the first injury. To minimise the effects of limb dominance, the percentage of injuries sustained on the dominant and non-dominant sides was calculated. The same proportion of dominant and non-dominant sides were selected at random for the uninjured runners. Where first injuries were bilateral or central in nature (e.g. central low back pain), the dominant side was used. This was done because previous research has reported slightly more injuries to the dominant side, although this was non-significant (Niemuth *et al.*, 2005).

An independent T test was performed to assess the difference in mean running speed between the groups. The variables assessed are outlined in Table 85. To assess the primary aim, a univariable binomial regression for each variable was performed, with significance set at $p < .05$. Since sex (Messier *et al.*, 2018), age (Taunton *et al.*, 2003) and mileage (Winter *et al.*, 2020) may be associated with injury, these were included as covariates and both the adjusted and unadjusted results reported. To assess the secondary aim, variables with a p value < .25 were entered into a multivariable logistic regression (Bursac *et al.*, 2008). In relation to foot strike pattern, this was analysed as both a continuous and categorical variable. Categories were determined in line with previous recommendations, with foot flexion angle at initial contact over 8.0° representing rearfoot strike, less than -1.6° representing forefoot strike and between -1.6° to 8.0° indicating a midfoot strike (Altman and Davis, 2012). Linearity of the continuous variables with respect to the logit of the dependent variable was assessed via the Box-Tidwell procedure (Box and Tidwell, 1962). A Bonferroni correction was applied using all terms in the model resulting in statistical significance being accepted when $p < .00172$. Based on this assessment, all continuous independent variables were found to be linearly related to the logit of the dependent variable. Multicollinearity was assessed using Spearmon's Rho Correlations (Section 8.5, Appendix E). Where variables were correlated (>0.7) (Mukaka, 2012), the variable with the highest statistical significance was used (Van Der Worp *et al.*, 2016). Imputing missing variables was achieved by utilising the: clinical, kinematic, anthropometric and demographic variables, along with the training history (van Buuren and Groothuis-Oudshoorn, 2011). Numeric data were first scaled to unit variance and zero mean, while the categorical data were dummy encoded. Data were then imputed using multivariable imputation by chained equations and a Bayesian ridge regression approach (van Buuren and Groothuis-Oudshoorn, 2011). All variables with a univariate association $p < .25$ were included in a binomial regression using backward stepwise selection logistic regression (Field, 2005). Values in which $p < .05$ was considered to be statistically significant (IBM SPSS V27).

A receiver operating characteristic (ROC) curve was performed to determine the model's discriminatory ability. The area under the curve values were interpreted with: <0.5, >0.5 to 0.7, >0.7 to 0.8, > 0.8 to 0.9, > 0.9 representing no, poor, acceptable, excellent and outstanding discrimination, respectively (Hosmer, Lemeshow and Sturdivant, 2013).

To assess the usefulness of factors with high relevance to clinical practice, an additional multivariable binomial regression was run solely using factors considered cost and time efficient: clinical measures [foot functional alignment, muscle strength, range of motion], injury history, training history and demographics. This was undertaken using the same procedure outlined above.

Results

Of the 274 runners entering the study, 225 runners (82%) remained in the study to follow up. Reasons for exclusion are detailed in Figure 8. Over the 1-year period, 52% (n=117) reported at least one RRI. The location (Table 86*)*, diagnoses (Table 87) and severity (Table 88) of injury are reported, with injured runners missing an average of 56 days due to RRIs.

Table 85 Variables examined within this study and entered into a univariable analysis.

Factors that quantify the magnitude of this load	*Factors affecting load dissipation*	*Factors which capture the ability of tissue to tolerate load*
Peak shank accelerations (g)	Spatiotemporal Parameters:	Navicular drop (mm)
Peak lower back accelerations (g)	Foot strike pattern (FFS, MFS, RFS)	Navicular drop > 10 mm/< 10 mm
Shank rate of accelerations (g/s)	Flight time (milliseconds)	Foot Posture Index
Lower back rate of accelerations (g/s)	Stride length (metres)	Hip abduction strength (Nm/kg)
Stride frequency (stride/min)	Contact time (milliseconds)	Hip extension strength (Nm/kg)
Self-reported average running pace (km/hr)	Step time (milliseconds)	Plantarflexion strength (Nm/kg)
Self-reported 3 monthly mileage (km)	Stance phase foot, ankle*, knee, hip, pelvis, trunk angles (degrees) [sagittal, frontal, transverse plane] at:	Knee extension strength (Nm/kg)
Running experience (<10 years, 10+ years)	Initial contact	Knee flexion strength (Nm/kg)
	Toe-off	Knee to wall ROM (degrees)
	Peak	Hip extension ROM (degrees)
	Minimum	Hip internal rotation (degrees)
	Excursion	Hip external rotation (degrees)
	Age (years)	History of RRI < 1 year ago
	BMI (kg/m)	
	Sex	

*Examined solely on sagittal plane.

Abbreviations: FFS- forefoot strike, MFS- midfoot strike, RFS- rearfoot strike.

Table 86 Locations of first running related injury.

Location of injury	*Number of first injuries at this location (percentage)*	*Males*	*Females*
Calf	31 (26%)	18 (24%)	13 (30%)
Foot	23 (20%)	15 (20%)	8 (19%)
Knee	17 (15%)	13 (18%)	4 (9%)
Buttocks	12 (10%)	6 (8%)	6 (14%)
Thigh	11 (9%)	6 (8%)	5 (12%)
Lower back	9 (9%)	8 (11%)	1 (2%)
Shin	9 (8%)	5 (7%)	4 (9%)
Hip	5 (4%)	3 (4%)	2 (5%)

Table 87 Diagnoses of first running related injury.

Diagnosis of injury	*Number of first injuries with diagnosis (percentage)*	*Number of males with first injury (percentage)*	*Number of females with first injury (percentage)*	*Location of injury*
Achilles tendon pain	18 (15%)	8 (11%)	10 (23%)	Calf

Calf strain	13 (11%)	10 (14%)	3 (7%)	Calf
Plantar fasciopathy	11 (9%)	8 (11%)	3 (7%)	Foot
Lower limb stress fracture	10 (9%)	7 (9%)	3 (7%)	Various locations
Patellofemoral pain syndrome	9 (8%)	7 (9%)	2 (5%)	Knee
Piriformis syndrome	6 (5%)	4 (5%)	2 (5%)	Buttocks
Non-specific low back pain	4 (3%)	3 (4%)	1 (2%)	Low back
Medial tibial stress syndrome	5 (4%)	3 (4%)	2 (5%)	Shin
Hamstring strain	5 (4%)	5 (7%)	0 (0%)	Thigh
Gluteal strain	5 (4%)	2 (3%)	3 (7%)	Buttocks
Disc pain/referred low back pain	5 (4%)	5 (7 %)	0 (0%)	Low back
Hamstring tendinopathy	4 (3%)	1 (1%)	3 (7%)	Thigh
Hip flexor strain	2 (2%)	1 (1%)	1 (2%)	Hip
Iliotibial band syndrome	3 (3%)	2 (3%)	1 (2%)	Knee
Knee meniscus injury	3 (3%)	3 (4%)	0 (0%)	Knee
Flexor hallucis longus tendinopathy	2 (2%)	2 (3%)	0 (0%)	Foot
Patellar tendon pain	1 (1%)	0 (0%)	1 (2%)	Knee
Foot extensor tendinopathy	1 (1%)	0 (0%)	1 (2%)	Foot
Metatarsalgia	2 (2%)	2 (3%)	0 (0%)	Foot
Morton's Neuroma	1 (1%)	0 (0%)	1 (2%)	Foot
Quadriceps Tendon Pain	1 (1%)	1 (1%)	0 (0%)	Knee
Hip bursitis	1 (1%)	1 (1%)	0 (0%)	Hip
Exertional lower leg compartment syndrome	1 (1%)	0 (0%)	1 (2%)	Shin
Adductor magnus strain	1 (1%)	0 (0%)	1 (2%)	Thigh
Peroneal tendon pain	1 (1%)	0 (0%)	1 (2%)	Foot
Degenerative hip pain (OA)	1 (1%)	0 (0%)	1 (2%)	Hip

Abbreviations: N/A- not applicable.

Table 88 Severity of injury (Timpka *et al.*, 2014).

Severity of injury	***Number of first injuries of this severity (percentage)***
No days missed	12 (10%)
Minor (1-7 days missed)	12 (10%)
Moderate (8-28 days missed)	43 (37%)
Serious (29 days- 6 months missed)	44 (38%)
Long term (>6 months missed)	6 (5%)

Demographic characteristics of participants are detailed in Table 89. There were no differences in running speed between the injured (11.2 ± 1.5 km/hr) and uninjured runners (11.2 ± 1.5 km/hr) (mean difference = -0.006 km/hr, $CI_{95\%}$ = -0.40- 0.39, t (223) = -.029, p = .977). The univariable analysis (Table 90) revealed the following factors were significantly (p < .05) associated with the development of an RRI: clinical measures (less navicular drop), previous injury history < 1 year ago, and running technique (greater knee internal-external rotation excursion, less minimum knee valgus, less hip adduction at toe-off, less transverse plane peak pelvis contralateral rotation, less transverse plane pelvis contralateral rotation at toe-off, less knee valgus at initial contact, less peak knee valgus, less knee valgus at toe-off (Figure 9). After adjusting for age, weekly mileage and sex, the following were additionally statistically significant and associated with RRI: navicular drop <10 mm, greater transverse plane peak pelvis ipsilateral rotation, greater knee valgus-varus excursion, less minimum hip adduction. A complete report of the univariable analysis is available in Section 8.6, Appendix F. For clarity, when two significant variables were highly correlated (as evidenced in Section 8.5), terms were grouped for the discussion.

Regarding the multivariable analysis, only 11 variables remained in the final model, with eight being statistically significant (p < .05): previous injury history < 1 year ago, less navicular drop, lower BMI, less knee flexion strength, less knee valgus at initial contact, greater hip internal-external rotation excursion, greater thorax contralateral-ipsilateral side flexion excursion and less pelvis internal rotation at toe-off (Table 91). The multivariable logistic regression model was statistically significant, $\chi^2(11) = 56.45$, p < .001, correctly classifying 74% of cases. Sensitivity was 72% and specificity was 76%, the positive predictive value was 75% and the negative predictive value was 74%. The area under the ROC curve was 0.79 ($CI_{95\%}$ = 0.73 - 0.85), demonstrating acceptable discriminative ability between injured and uninjured runners.

A further analysis was conducted investigating the relationship between prospective RRIs and the factors considered relatively cost and time efficient to assess (clinical measures [functional foot alignment, muscle strength, range of motion], injury history, training history and demographics) (Table 92). Greater self-reported running pace, history of injury in the past year, less navicular drop, and lower hip abduction strength remained in the model, with the latter three variables significantly contributing to the model. The model was statistically significant, $\chi^2(5) = 21.38$, p = .001 and correctly classified 63% of cases. Sensitivity was 59%, specificity was 66%, positive predictive value was 64% and negative predictive value was 62%. The area under the ROC curve was 0.67 ($CI_{95\%}$ = 0.60 - 0.74), demonstrating poor discriminative ability between injured and uninjured runners.

Table 89 Results of the univariable regression for each demographic, training history and injury history variables.

Variable	***Uninjured***	***Injured***	***Unadjusted***				***Adjusted***			
	Mean ± SD	***Mean ± SD***	***Sig.***	***OR***	***95% C.I. for OR***		***Sig.***	***OR***	***95% C.I. for OR***	
Demographics					Lower	Upper			Lower	Upper
Age (years)	43.6 ± 9.3	43.4 ± 8.4	0.888	1.00	0.97	1.03				
BMI (kg/m2)	24.2 ± 2.9	23.7 ± 2.9	0.188	0.94	0.86	1.03	0.094	0.92	0.83	1.02
Female sex (reference is male)	41 females (38%)	43 females (37%)	0.851	0.95	0.55	1.63				
Training and injury history										
History of RRI < 1 year ago	38 (35%)	57 (49%)	0.041	1.75	1.02	2.99	0.05	1.72	1.00	2.95
Self-reported weekly mileage (km/week)	435 ± 255	410 ± 233	0.443	1.00	2.00	1.00				
Self-reported average running pace (km/hr)	11.3 ± 1.9	11.5 ± 1.6	0.289	1.09	0.93	1.27	0.222	1.11	0.94	1.31
Running experience > 10 years (reference is <10 years' experience)	27 (25%)	24 (21%)	0.422	0.77	0.41	1.45	0.383	0.76	0.40	1.42

Abbreviated terms: SD = standard deviation, C.I. = confidence interval, Sig = significance level, OR = odd ratio.

Table 90 Variables that were significantly associated with injury in the univariable regression.

Variable	*Uninjured*	*Injured*	*Unadjusted*				*Adjusted*			
	Mean ± SD	***Mean ± SD***	***Sig.***	***OR***	***95% C.I. for OR***		***Sig.***	***OR***	***95% C.I. for OR***	
Transverse plane pelvis contralateral rotation at toe-off (°)	3.6 ± 4.1	2.3 ± 3.9	0.018	0.92	0.86	0.99	0.014	0.92	0.85	0.98
Transverse plane peak pelvis contralateral rotation (°)	3.8 ± 3.7	2.8 ± 3.7	0.029	0.92	0.86	0.99	0.024	0.92	0.85	0.99
Transverse plane minimum pelvis contralateral rotation (°)	-5.3 ± 3.6	-6.4 ± 4.2	0.056	0.94	0.87	1.00	0.042	0.93	0.87	1.00
Hip adduction at toe-off (°)	1.1 ± 3.4	0.0 ± 3.7	0.022	0.92	0.85	0.99	0.024	0.92	0.85	0.99
Minimum hip adduction (°)	0.9 ± 3.4	-0.2 ± 3.7	0.057	0.94	0.88	1.00	0.023	0.91	0.85	0.99
Knee varus at initial contact (°)	-2.9 ± 2.8	-1.5 ± 3.1	0.001	1.19	1.08	1.32	0.001	1.20	1.08	1.33
Peak knee varus (°)	-2.1 ± 2.7	-0.8 ± 3.1	0.003	1.16	1.05	1.28	0.003	1.16	1.05	1.28
Knee varus at toe-off (°)	-3.9 ± 33.0	-2.7 ± 3.1	0.004	1.15	1.05	1.26	0.004	1.15	1.04	1.26
Minimum knee varus (°)	-5.9 ± 2.9	-5.0 ± 3.5	0.032	1.10	1.01	1.19	0.038	1.10	1.01	1.19
Knee varus valgus excursion (°)	3.9 ± 1.6	4.3 ± 1.7	0.060	1.17	0.99	1.38	0.049	1.18	1.00	1.40
Knee internal rotation external rotation excursion (°)	20.9 ± 4.5	22.4 ± 5.4	0.024	1.07	1.01	1.13	0.024	1.07	1.01	1.13

Navicular drop (mm)	9.0 ± 3.3	7.9 ± 2.9	0.005	0.88	0.81	0.96	0.004	0.87	0.80	0.96
Navicular Drop > 10 mm (Reference is navicular drop <10 mm)	40 (37%)	30 (26%)	0.066	0.59	0.33	1.04	0.05	0.56	0.31	1.00
History of RRI < 1 year ago (reference is injury > 1 year ago/never injured)	38 (35%)	57 (49%)	0.041	1.75	1.02	2.99	0.05	1.72	1.00	2.95

Abbreviated terms: SD = standard deviation, C.I. = confidence interval. The following denote the direction of the moment: knee varus (positive), knee valgus (negative), knee internal rotation (positive), knee external rotation (negative), hip adduction (positive), hip abduction (negative), pelvis anterior tilt (positive), pelvis rotation to contralateral side (positive), pelvis rotation to ipsilateral side (negative).

Table 91 Results of the multivariable regression.

Variable	***Uninjured***	***Injured***	***Sig.***	***OR***	***95% C.I. for OR***	
	Mean ± SD	***Mean ± SD***			***Lower***	***Upper***
Thorax contralateral-ipsilateral side flexion excursion (°)	5.1 ± 1.7	5.6 ± 2.2	0.04	1.18	1.01	1.39
Transverse plane pelvis contralateral drop at toe-off	2.2 ± 2.7	1.9 ± 2.3	0.00	0.86	0.79	0.94
Hip internal rotation external rotation excursion (°)	10.8 ± 3.8	11.7 ± 3.8	0.04	1.18	1.01	1.39
Hip adduction at initial contact (°)	10.1 ± 4.0	9.1 ± 3.8	0.09	0.92	0.83	1.01
Hip adduction at toe-off (°)	1.1 ± 3.4	0.0 ± 3.7	0.10	1.10	0.98	1.23
Knee varus at initial contact (°)	-2.9 ± 2.6	-1.5 ± 3.1	0.00	1.24	1.08	1.41
Navicular drop (mm)	9.0 ± 3.3	7.9 ± 2.9	0.00	0.84	0.76	0.93
Knee flexion strength (Nm/kg)	0.99 ± 0.28	0.93 ± 0.25	0.01	0.17	0.05	0.63
BMI (kg/m^2)	24.2 ± 2.9	23.7 ± 2.9	0.02	0.86	0.76	0.97
History of RRI < 1 year ago (reference is injured >1 year ago)	38 (35%)	57 (49%)	0.03	2.03	1.08	3.78
Female sex (reference is male)	41 females (38%)	43 females (37%)	0.09	0.50	0.22	1.13

Abbreviations: SD = standard deviation, CI = confidence interval, OR = odds ratio. The multivariable logistic regression model was statistically significant, $\chi^2(11) = 56.45$, $p < .001$. The model correctly classified 74% of cases. Sensitivity was 72%, specificity was 76%. The area under the ROC curve was 0.79 ($CI_{95\%}$ = 0.73 - 0.85).

Table 92 Results of the multivariable regression for clinical factors.

	Uninjured	***Injured***	***Sig.***	***OR***	***95% C. I. for OR***	
	Mean ± SD	***Mean ± SD***			***Lower***	***Upper***
Navicular drop (mm)	9.0 ± 3.3	7.9 ± 2.9	0.01	0.88	0.80	0.96
History of RRI < 1 year ago (reference is injured >1 year ago)	38 (35%)	57 (49%)	0.01	2.24	1.25	4.02
Hip abduction strength (Nm/kg)	1.70 ± 0.32	1.64 ± 0.30	0.01	0.28	0.10	0.76
BMI (kg/m^2)	24.2 ± 2.9	23.7 ± 2.9	0.05	0.90	0.80	1.00
Female sex (reference is male)	41 females (38%)	43 females (37%)	0.07	0.55	0.28	1.06

Abbreviations: SD = standard deviation, Sig = significant, CI = confidence interval, OR = odds ratio. The model was statistically significant, $\chi 2(5) = 21.38$, $p = .001$. The model correctly classified 63% of cases. Sensitivity was 59%, specificity was 66%. The area under the ROC curve was 0.67 ($CI_{95\%}$ = 0.60 - 0.74).

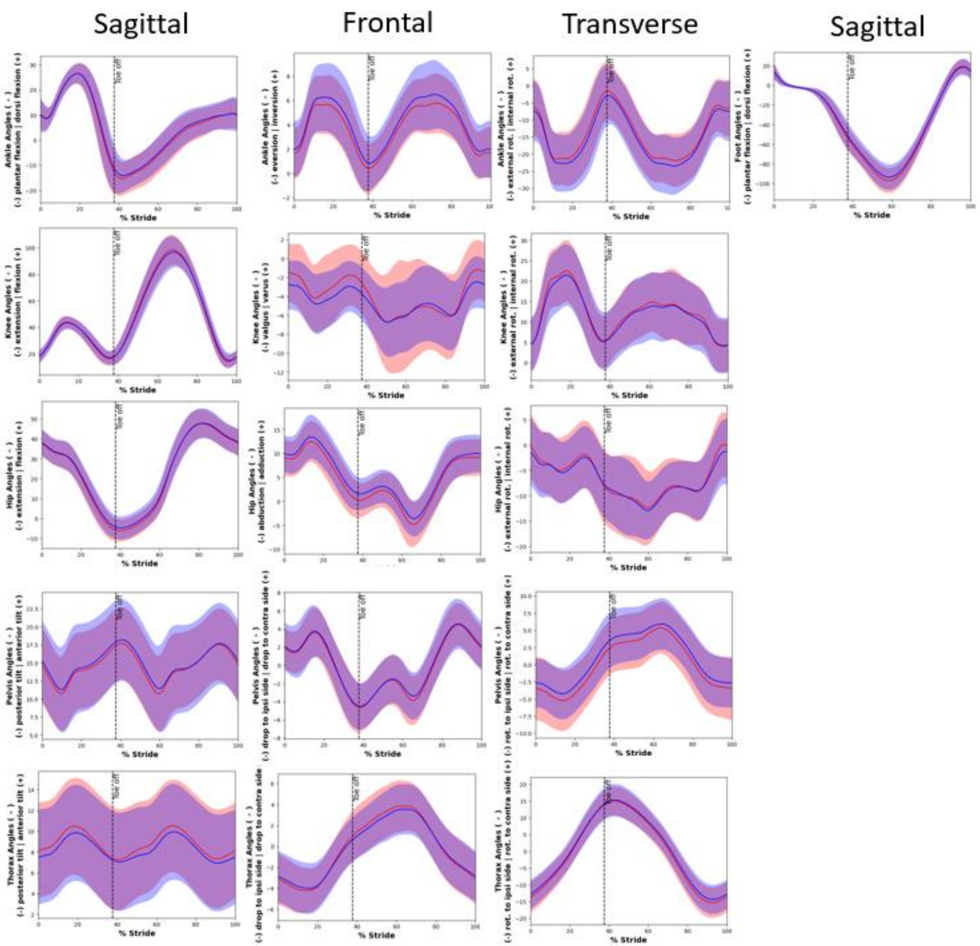


Figure 9 Graphical representation of kinematics during the entire gait cycle. The red line represents the injured group with the blue representing the uninjured group. The coloured bands represent the standard deviation of each group.

Discussion

Where possible, the findings of the present study were compared to previous prospective studies investigating general RRIs. This was done as the cause-effect response to injury is unclear in retrospective studies, with the possibility of injuries producing compensatory changes that are directly opposite to true causative factors.

Injury incidence

The one-year injury incidence of 52% is similar to other studies (Winter *et al.*, 2020; Desai *et al.*, 2021). The calf constituted the highest proportion of injuries, as found in previous research (Franke, Backx and Huisstede, 2019; Winter *et al.*, 2020). However, the knee was only the third most reported injury site, despite it being frequently cited as the most (Taunton *et al.*, 2003; McKean, Manson and Stanish, 2006; Leppe and Besomi, 2018; Francis *et al.*, 2019). In terms of injury diagnosis, calf strain (15%), followed by Achilles tendon injury (11%) and plantar fasciopathy (9%) constituted the largest proportion of injuries. In their study of injury diagnoses within a 24-week tracking period, Mulvad et al. (Mulvad *et al.*, 2018) found medial tibial stress syndrome, followed by Achilles tendon injury to be the most common diagnosis in recreational runners. The difference from our study may be explained by injuries being grouped differently. For example, what we classified as "calf injuries" were subdivided into "soleus injuries" and "gastrocnemius injuries" by Mulvad et al. (2018) (Mulvad *et al.*, 2018). Had these injuries been grouped, as in our study, calf injuries would have been the second most common injury, pointing to the need for standardised classification and reporting of RRIs. The comparatively small proportion of MTSS injuries may be reflective of the greater weighting of females in the study by Mulvad et al., (2018), as previous research suggests that female sex is a risk factor for this injury (Newman *et al.*, 2013). The majority of RRIs were classified as "serious", indicating that they lasted 28-6 months; the average number of missed days was similar to previous research (Mulvad *et al.*, 2018).

<u>*Univariable analysis*</u>

Demographic factors

The associations between RRI and demographic factors such as BMI, age and sex have been debated within the literature. Greater BMI has been theorised to be associated with increased risk of injury by placing increased load per step (Vadeboncoeur *et al.*, 2012); although its association to RRIs has been debated (Jungmalm *et al.*, 2020; Winter *et al.*, 2020; Desai *et al.*, 2021). Older age is suggested to be related to increased risk of RRI (Taunton *et al.*, 2003), possibly due to changes in running technique (Fukuchi *et al.*, 2013; Silvernail *et al.*, 2015), and decreased muscle strength (Goodpaster *et al.*, 2006; Fukuchi *et al.*, 2013). However, research is mixed (Taunton *et al.*, 2003; Desai *et al.*, 2021). In our study, age, BMI and sex were not found to be associated with RRI. A comparable proportion of males and females became injured during the one year tracking period, a finding echoed elsewhere (Dallinga *et al.*, 2019; Jungmalm *et al.*, 2020; Desai *et al.*, 2021).

Injury and training history

A running injury in the past year (injury history) was found to be associated with a prospective injury in both the multivariable and univariable analyses, increasing odds of injury by over two times. This is in line with two systematic reviews (Saragiotto *et al.*, 2014; Van Der Worp *et al.*, 2015). There are two primary explanations for this relationship. Firstly, previously injured tissues may not have adequately healed (Marti *et al.*, 1988; Iverson, 2007; Fulton *et al.*, 2014). Secondly, injury-related pain may lead to an alteration in running technique (Noehren, Sanchez, *et al.*, 2012; Fulton *et al.*, 2014), which may persist following return to sport. This alteration may overload biological structures, precipitating future injury. In our study, while an RRI in the previous year increased the odds of injury in the final multivariable model, a previous injury of greater than one year did not. This supports the suggestion that with a shorter time frame since injury, runners are more vulnerable to re-injury (Leppe and Besomi, 2018). This indicates that athletes, clinicians and coaches should be particularly cognisant of runners with an injury within the preceding year.

No association was found between RRIs and either measure of training history (self-reported pace, average weekly mileage in past three months). Regarding pace, our findings were in line with previous studies investigating RRIs (Dudley *et al.*, 2017; Messier *et al.*, 2018). However, the association between RRIs and weekly mileage has been conflicting (Messier *et al.*, 2018; Winter *et al.*, 2020). Our findings provide evidence to indicate that recall of weekly mileage may not provide clinicians with information useful for indicating who will sustain an RRI. However, given the theoretical link between increased load and RRIs (Bertelsen *et al.*, 2017; Kalkhoven, Watsford and Impellizzeri, 2020), other measures of capturing volume of loading, such as strides/session, should be explored.

Spatiotemporal parameters such as stride length, flight time, step time, stance time and stride rate were not associated with injury. Spatiotemporal parameters are relatively easily measurable and have been postulated to be related to RRI. A common suggestion is that manipulation of these factors can reduce injury risk via load reduction (Agresta and Brown, 2015). For example, increasing step length has been found to increase loading during running (Derrick, Hamill and Caldwell, 1998; Stergiou, Bates and Kurz, 2003; Seay, Selbie and Hamill, 2008). Most research investigating the association between RRIs and spatiotemporal parameters is retrospective, therefore, this study adds important information to this area. To our knowledge, just one prospective study has investigated the association between general RRIs and a number of spatiotemporal parameters during running (Winter *et al.*, 2020), finding significantly greater flight time and lower step rate among injured compared to uninjured runners. However, this was based on a sample size of 31 runners and this finding only pertained to females. Adding credence to our non-significant findings, a systematic review by Brindle *et al.* (Brindle *et al.*, 2020) found no difference in mean stride time, stance time, cadence, and stride length between uninjured and injured runners via a meta-analysis.

Clinical measures

Clinical measures such as strength (Veras *et al.*, 2020), range of motion (Buist, Bredeweg, Lemmink, *et al.*, 2010; Desai *et al.*, 2021) and functional foot alignment (Buist, Bredeweg, Lemmink, *et al.*, 2010; Nohr *et al.*, 2013) have widely been hypothesised to be associated with injury, with modification via strengthening, stretching and orthoses suggested in injury intervention methods (Mcmillan and Payne, 2008; Baltich *et al.*, 2017). The present study found just one clinical measure, the navicular drop test, to be associated with injury. With less navicular drop, the odds of future RRI increased. Our results also indicated that navicular drop < 10 mm, which is a previously used cut-off point (Plisky *et al.*, 2007; Bennett, Reinking and Rauh, 2012), increased odds of injury by two times. Largely, findings from studies investigating the relationship between general RRIs and navicular drop on a continuous level (Buist, Bredeweg, Lemmink, *et al.*, 2010; Dudley *et al.*, 2017) or using cut-off points (Plisky *et al.*, 2007; Bennett, Reinking and Rauh, 2012) have been mixed. It should be noted, that similar to our study, Dudley et al. (2017) (Dudley *et al.*, 2017) reported mean navicular drop of injured participants to be 17% less than that of uninjured runners, however, this did not reach significance. Lack of significance may have been related to the small sample size (n=31). Unlike static measures such as Foot Posture Index, which was not found to be univariately related to injury in our study, navicular drop captures the mobility of the foot. An explanation of our findings may be that uninjured runners have a more flexible foot (as reflected in the greater values of navicular drop), with increased capability in absorbing loads during stance (Chan and Rudins, 1994). However, the mean values of navicular drop test observed in our study would place the uninjured runners in the "pronated" category and the injured runners in the "neutral" category (Langley, Cramp and Morrison, 2016b). Therefore, although injured runners may not have as much arch collapse as the uninjured group, they do demonstrate some flexibility of the foot. Secondly, a minimal detectable change of 1.70– 2.22 mm has previously been reported (Zuil-Escobar *et al.*, 2018) and differences between our groups do not exceed this. Therefore, from a clinical perspective this finding should be interpreted cautiously.

Lower strength has been suggested to be associated with RRIs, with strengthening a target of injury prevention interventions (Snyder *et al.*, 2009; Baltich *et al.*, 2017). However, research surrounding the association between prospective RRIs and strength has largely been inconsistent (Torp *et al.*, 2018; Veras *et al.*, 2020). The present study indicates that isometric strength in a fixed position is not associated with RRIs. Similarly, ROM has been inconsistently linked to RRI (Buist, Bredeweg, Lemmink, *et al.*, 2010; Jungmalm *et al.*, 2020), with some authors suggesting that low ROM places excessive stress on joint (Buist, Bredeweg, Lemmink, *et al.*, 2010) and others suggesting that high ROM increases demands on muscles to stabilise during movement (Cannon, Finn and Yan, 2018). Our large-scale study indicates that ROM values have very limited value in understanding the aetiology of RRI. This may be because the ranges of motion exhibited in these clinical tests are greater than those utilised during running, indicating that running is unlikely to produce strain-related injuries.

Running technique

Significant associations between the risk of RRIs and pelvis, hip and knee kinematics were found. Stance phase transverse plane pelvis rotation was found to be associated with RRI (Figure 9). During running, the pelvis rotates contralaterally and ipsilaterally in the transverse plane (whereby the anterior aspect of the pelvis rotates towards the swing and stance legs, respectively). Although the important role of transverse plane pelvic rotation in running for performance is well recognised (Schache *et al.*, 1999), to the best of our knowledge, it has not been previously studied, either prospectively or retrospectively, in relation to RRIs. At initial contact the pelvis is in slight ipsilateral transverse plane rotation and this increases until midway through stance (Figure 9, Figure 10) (Schache *et al.*, 1999). During terminal stance and approaching toe-off the pelvis begins to contralaterally rotate. In our study, less peak pelvic contralateral rotation during stance was associated with increased odds of injury. During straight-line running, the balance of the angular momentum between the upper and lower body about the vertical axis must be maintained (Willwacher *et al.*, 2016; Mohr *et al.*, 2021). This is controlled by the interaction of movements of the head, arms, trunk, pelvis and legs in the transverse plane and the vertical free moment produced at the foot (Mohr *et al.*, 2021). The vertical free moment is the moment of force produced due to the friction between the foot and the ground during stance (Milner, Davis and Hamill, 2006). While it is not clear which is cause and which is effect, less pelvic contralateral rotation is reflective of higher vertical free moments at the foot, which are related to an increase in lower limb tortional stress (Willwacher *et al.*, 2016). An increase in torsional stress has been linked to injuries such as tibial stress fractures (Milner, Davis and Hamill, 2006) and PFPS (Willwacher *et al.*, 2016).

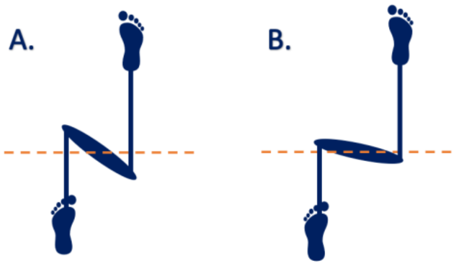


Figure 10 Transverse plane rotation of the pelvis at toe-off. The left leg is the stance leg at toe-off. A. demonstrates greater contralateral pelvic rotation as seen in the uninjured runners, with B. demonstrating less peak contralateral pelvic rotation, as seen in the injured runners.

In the frontal plane, less hip adduction was found to be associated with injury. To our knowledge, frontal plane hip motion has only been examined in one prospective study with respect to general RRI, finding no association to exist (Dudley *et al.*, 2017). However, Dudley *et al.* (Dudley *et al.*, 2017) investigated collegiate cross-country runners who may have distinctive injury risk factors. Our finding is in line with some previous retrospective studies examining specific injuries (Dierks *et al.*, 2008; Grau *et al.*, 2011; Foch *et al.*, 2015). Primarily, explanations connecting less peak adduction to injury have focused on iliotibial band syndrome, suggesting that this may result in decreased strain on the iliotibial band and consequently increased friction against the lateral condyle(Grau *et al.*, 2011). However, this proposed mechanism is injury-specific, and does not fully account for the association between less hip adduction at toe-off and *general* RRIs. Two possible reasons for decreased hip adduction are the less transverse plane contralateral pelvic rotation (discussed above) and/or increased trunk lateral flexion over the stance limb as a result of weak hip stabilisers (Dierks *et al.*, 2008; Foch *et al.*, 2015). This latter suggestion, is in part, suggested by our data which found greater side flexion excursion and less hip abduction strength among injured runners.

At the knee, less knee valgus and greater valgus-varus excursion were found to be univariately associated with increased odds of RRIs. The prevailing theory relating knee motion to injury suggests that extreme varus and valgus knee positions increase load bearing on the knee medially and laterally, respectively (Bruns, Volkmer and Luessenhop, 1993; Sharma *et al.*, 2001). Over time, high patellofemoral stress overload the articular cartilage and subchondral bone, resulting in injury (Farrokhi, Keyak and Powers, 2011). However, previous research investigating peak knee varus during the stance phase of running has been limited, finding no difference between those with and without general prospective RRIs (Dudley *et al.*, 2017). Similarly, the association between peak valgus and specific RRIs is mixed (Willy *et al.*, 2012; Noehren *et al.*, 2014b). In our study, it is in fact *less* peak valgus and *less* valgus at initial contact that is associated with injury. However, when considering the entire stance phase, injured runners displayed greater frontal excursion at the knee. Therefore, it is possible that greater frontal plane motion at the knee during stance signifies a lack of control of the knee, potentially causing increased force on both the medial and lateral knee. Greater knee excursion during stance, despite the similar stance time between injured and uninjured runners, may indicate that the rate of loading on knee structures during stance was greater among injured runners. Although this has not been previously investigated during running in relation to general RRIs, in a study of team sport athletes, those displaying large frontal knee motion angles during a single leg squat were 2.7 times more likely to sustain a lower extremity injury (Räisänen *et al.*, 2018). This indicates that frontal joint excursion, rather than peak angles, is important in relation to RRIs.

In the transverse plane, our study found that greater knee internal-external rotation excursion was univariately associated with increased odds of RRIs. Only one RRI study has previously investigated knee rotation excursion, finding no association in their retrospective cohort study involving currently injured runners with PFPS (Luz *et al.*, 2018). Greater knee rotation excursion may have lead to increased torsional loads on knee and thigh structures such as the iliotibial band (ITB) (Foch *et al.*, 2015) and greater patellofemoral contact pressures on facets of the patella (Lee, Morris and Csintalan, 2003).

Our study found no sagittal plane running technique factors to be associated with prospective injury. This is very important given the preponderance of research studies and clinical examinations that focus predominantly or exclusively on sagittal plane motion. Notably, rearfoot striking has frequently been theorised to relate to RRI via greater impact loading magnitudes (Kulmala *et al.*, 2013; Mercer and Horsch, 2015; Thompson *et al.*, 2015) and loading rates (Almeida, Davis and Lopes, 2015). However, even the results from this research is conflicting (Nunns *et al.*, 2013; Sun *et al.*, 2018). This area is also limited by the dominance of retrospective research (Daoud *et al.*, 2012; Goss *et al.*, 2015; Warr *et al.*, 2015; Sugimoto *et al.*, 2019; Fukusawa, Stoddard and Lopes, 2020; Hollander *et al.*, 2020). The present study was unique in examining both continuous and categorical classifications of foot strike and its association with prospective injury. Our research indicates that no association existed between foot strike and injury, in line with a recent systematic review (Burke *et al.*, 2021). However, its relationship to specific injuries should be considered further due to the associations between foot strike patterns and structure specific loading, such as between rearfoot strike pattern and increase in knee joint stress (Kulmala *et al.*, 2013) and between forefoot strike pattern and increase in Achilles tendon force (Kulmala *et al.*, 2013).

Similarly, knee flexion has been hypothesised to be a cause of general RRIs, due to increase in contact forces with knee extension (Dugan and Bhat, 2005); but few studies have examined this (Messier *et al.*, 2018; Jungmalm *et al.*, 2020). During gait, knee flexion aids in shock absorption at initial contact and throughout stance (Dugan and Bhat, 2005). Our findings add weight to the existing evidence that there is no association between general prospective RRIs and either peak knee flexion (Messier *et al.*, 2018), knee flexion-extension excursion (Jungmalm *et al.*, 2020) or knee flexion at initial contact.

Loading during running

Neither peak nor rate of impact acceleration at the shank and sacrum were associated with injury in this study. Previous research investigating impact accelerations and RRIs has been limited and conflicting, with just one prospective study examining impact accelerations at the back among 76 runners (Winter *et al.*, 2020). Therefore, the present prospective study provides the strongest evidence to date that impact accelerations assessed at a single time point when tested on a treadmill do not significantly affect the odds of sustaining an RRI. Although there are a number of reasons to inform the hypothesis that loading in excess of tissues capabilities would be related to injury (Nigg, 1985; Musumeci, 2016; Kalkhoven, Watsford and Impellizzeri, 2020), our study may have found no such relationship to exist for three reasons. Firstly, the magnitude of impact accelerations may not in isolation distinguish between injured and uninjured runners, but a combination of loading and accurate collection of training volume could be necessary to determine cumulative loading (Bertelsen *et al.*, 2017). Secondly, impact accelerations were captured on a treadmill and therefore may not be representative of typical running surfaces (Milner, Hawkins and Aubol, 2020). Finally, it may not be excess loading, but decreased tissue strength among injured runners that make them susceptible to injury. This was not directly measured in this study due to the potentially invasive and costly nature of this process.

Multivariable analysis

The aim of multivariable analysis to act as a preliminary step in identifying the potential of these factors to be used for RRI screening. The multivariate analysis identified a significant model containing eight features. Less navicular drop, injury history <1 year ago, lower knee flexion strength and stance phase variables (i.e. greater thorax contralateral-ipsilateral side flexion, greater hip internal-external rotation excursion, greater knee varus valgus excursion, less pelvic contralateral rotation at toe-off and less knee valgus at initial contact) all significantly contributed to greater odds of RRIs. While the area under the ROC curve indicates an acceptable level of discrimination (74% accuracy), making this exploratory examination of the use of these variables for a screening tool somewhat promising, the use of this information to screen for RRIs has a number of practical limitations. Firstly, given the large number of factors which contribute to the model and the time and effort that would be required to identify these factors, using this as a screening tool may not be feasible. Secondly, almost 30% of runners who would become injured would not be identified and therefore would not receive an intervention. Issues with sensitivity of screening tools has been highlighted as a challenge in injury screening programmes *per se* previously(Bahr, 2016). Thirdly, cut-off points would need to be established to make this viable as an injury screening approach. Finally, the multivariable assessment of factors associated with RRI was exploratory in nature and was not developed and tested within different samples, as is recommended in previous research (Collins *et al.*, 2015).However, although these three points suggest challenges in relation to injury *screening*, the identified risk factors of RRIs provide the foundation for the design of intervention programmes that can be undertaken by all runners. Effective programmes are currently lacking for running, but should be implemented and tested for efficacy, as has been done in in other sports (e.g. soccer (Sadigursky *et al.*, 2017) and rugby (Barden, Stokes and Mckay, 2022)).

Similarly, the additional analysis undertaken to determine the association between RRI and factors easily measurable by clinicians (clinical measures, training history and demographics), showed limited discriminative ability.

Clinical Implications of Research

This study found a number of factors to be associated with increased odds of general RRIs, the strongest of which was previous injury < 1 year ago. This may indicate that, following injury, some runners have not regained original tissue strength or that they have alterations in technique that increase their vulnerability to injury. We also found that running technique is related to RRI. Running technique is amenable to change via running retraining protocols, with moderate to large treatment effects found from previous trials (Tate and Milner, 2010; Chan *et al.*, 2018). For example, real-time feedback has facilitated runners with PFPS to reduce both hip adduction and contralateral pelvic drop while running (Noehren, Scholz and Davis, 2011). Recent research has also demonstrated the long-term efficacy of running retraining (Teran-Yengle, Cole and Yack, 2016). Intervention strategies targeting neuromuscular and technique-based interventions should be developed and tested for efficacy in the same way that FIFA 11 (Sadigursky *et al.*, 2017) and similar approaches (Barden, Stokes and Mckay, 2022) have been developed in other sports to address injury. Our study provides important information for general RRI prevention strategies for runners. Although the developed model could correctly classify 74% of cases and showed acceptable discrimination between injured and uninjured runners, given the large number of variables that contributed to this model and the time-consuming nature of measuring each of these variables, the feasibility of using all of these measures in practice is questionable.

Limitations

This study has three main limitations. Firstly, all risk factors for RRI were measured at a single time point. However, it is not known whether these factors remained consistent between the initial baseline testing and the point of injury. Secondly, while there is a clear and significant value in identifying risk factors for *general* RRIs as a whole, it is possible that specific RRIs may have different, or perhaps, conflicting injury risk factors. Future studies should employ a similar deign as the present study, but with analysis of specific RRIs. Pooling of data across research centres may facilitate this, as large numbers of runners would be required to appropriately analyse specific injuries. Thirdly, the running technique and impact loading analysis was performed on a treadmill. Although this was advantageous for simultaneous collection of running technique and impact loading, and increasing the number of strides examined, both measures may be affected by surface. Therefore these results may not be ecologically valid for runners who typically do not train on a treadmill (Riley *et al.*, 2008; Milner, Hawkins and Aubol, 2020). However, a systematic review and metanalysis found that most biomechanical measures are largely comparable across surfaces (Van Hooren *et al.*, 2020).

Conclusion

This large-scale prospective study investigated the association between general RRIs and demographics, training history, injury history, clinical measures, impact accelerations and running technique. Of the clinical factors, history of injury in the past year and less navicular drop were univariately associated with increased odds of injury. In terms of stance-based measures of running technique, knee, pelvis and hip motion in the frontal and transverse planes were associated with increased odds of injury. Demographics, strength, ROM and measures of impact acceleration were not significantly associated with RRIs. This study emphasises the multifactorial nature of running related injuries and highlights that factors remain outstanding that contribute to RRI development. Although these factors had a 74% accuracy in discriminating between injured and uninjured; the use of these variables as screening tests may have limited value. However, these factors could form the basis for the design of much-needed intervention programmes, which should be subsequently investigated for efficacy. The identification of clinically accessible measures sufficiently able to identify risk factors remains challenging.

This paper has been quality checked via the STROBE framework (Section 8.9)

Link Section: Chapter 5 to 6

Chapter 5 identified a number of variables associated with general RRIs. Examining general RRIs has value given that, at present, we cannot anticipate what injuries runners will develop. Chapter 5 may also pave the way for informing general RRI prevention protocols which may be adapted by all recreational runners. However, a common take-home message in the review of literature (Chapter 2) is that risk factors for injuries may be injury-specific (Napier *et al.*, 2019; Burke *et al.*, 2021). In support of this hypothesis, are findings from previous studies finding an increase in structure-specific loading with changes in technique. For example, when examining foot strike pattern, some research indicates that forefoot strike leads to greater increases in Achilles tendon loading (Almonroeder, Willson and Kernozek, 2013), with some research finding associations between forefoot strike and posterior leg injuries (Hollander, Johnson, *et al.*, 2021). Therefore, Chapter 6 aims to identify factors associated with calf-complex RRIs and evaluate their potential for use in injury screening. Injuries of the calf-complex were examined for two main reasons; (1) they were the most common injury among our cohort (and indeed in other studies (Winter *et al.*, 2020)) and therefore would provide the highest sample size of any subdivision of injury and also be of relevance to a large proportion of recreational runners and (2) there has been very limited research examining calf-complex injuries using a prospective multifactorial approach.

6. Chapter 6: A multifactorial prospective investigation of the factors associated with calf-complex running related injuries among recreational runners.

This study is intended for submission to the British Journal of Sports Medicine:

Dillon, S., Burke, A., O'Connor, S., Whyte, E., Gore, S., Moran, K., 2022. Factors associated with calf-complex injuries in recreational runners: A prospective study. *British Journal of Sports Medicine* (Not yet submitted).

Abstract

Background: Calf-complex running related injuries (RRIs) are among the most common injuries experienced by recreational runners. Given the multifactorial nature of RRIs, prospective investigation into the factors associated with injury is warranted. This study aimed to identify factors associated with calf-complex injury and evaluate their potential for use in injury screening.

Methods: Recreational runners were recruited for this prospective study. During a baseline session, demographic factors, clinical measures (strength, range of motion, functional foot allignment), injury and training history (via questionnaire), impact loading (via accelerometery) and running technique (via 3 D motion analysis) measures were collected. RRI incidence was monitored over the course of one year. A binary logistic regression, with calf-complex injury as the dependent variable, was performed for each variable independently, and then adjusting for age, sex and mileage. Variables were then entered into a multivariable regression, with the aim of exploring its potential for use in the RRI screening domain.

Results: Of the 225 runners tracked for injury, 31 (14%) runners experienced a calf-complex injury, whilst 108 remained uninjured. Less navicular drop, as well as measures of running technique (at the thorax, pelvis, hip, knee and foot) were found to be associated with injury (p < .05). The final multivariable model included less navicular drop, less transverse plane pelvis contralateral rotation at toe-off and less knee valgus at initial contact ($\chi^2(3) = 27.25$, $p < .001$). The model correctly classified 84% of cases, with 39% sensitivity and 96% specificity.

Conclusion: A number of variables were identified as being significantly associated with calf-complex RRIs. However, the low sensitivity of the overall model suggests that we are currently not able to effectively pre-screen for these RRIs. The factors identified as significantly associated with calf-complex RRIs should be considered in the design of intervention programmes.

Keywords: Calf-complex injury, running injury, Achilles tendon, biomechanics

Introduction

The calf-complex is responsible for vertical support and forward propulsion of the body during running (Sasaki and Neptune, 2006; Hamner, Seth and Delp, 2010). Consisting of the gastrocnemius, plantaris and soleus muscles, this complex shares a common insertion site on the calcaneus via the Achilles tendon, producing ankle plantarflexion and knee flexion (gastrocnemius and plantaris). During running, these structures are exposed to high levels of repetitive loading and they comprise a large proportion of RRIs, of between 15% (Nielsen, Rønnow, *et al.*, 2014) and 26% (Desai *et al.*, 2021) per year. Therefore, identifying the risk factors for these injuries is important and may help in designing effective interventions, and identifying at-risk runners through screening.

Research examining calf-complex injuries has predominantly been retrospective. Just five studies appear to have examined the prospective association between risk factors for injury and calf-complex injuries, despite its advantage over retrospective research in providing insight regarding risk factors for injury. Previous prospective research has most frequently examined Achilles tendon (AT) injuries (Van Ginckel *et al.*, 2009; Hirschmüller *et al.*, 2012; Hein *et al.*, 2014; Lagas *et al.*, 2020), with just one study prospectively examining calf-complex injuries (Van Middelkoop, Kolkman, Van Ochten, Bierma-Zeinstra, *et al.*, 2008). This latter study, however, only examined demographics and training characteristics among male marathon runners and did not examine other potentially important factors among recreational runners. It is generally accepted that running related injuries (RRIs) are multifactorial in nature (Munteanu *et al.*, 2011; Messier *et al.*, 2018). Therefore, investigating a number of potential risk factors is important in understanding the aetiology of injury, designing injury prevention programmes, or indeed constructing injury screening protocols. Many of these risk factors are underpinned by the principle that excessive loading causes injury (Hreljac, Marshall and Hume, 2000). Therefore, proposed risk factors primarily aim to quantify load, capture how load may be dissipated (e.g running technique, foot position or range of motion), or capture the tolerance of the tissue to such load (e.g strength measures). However, to our knowledge, to date no studies have prospectively investigated all three elements in relation to calf-complex injuries.

With regard to the quantification of loading during running, mixed findings to date relate ground reaction forces (GRF) to either Achilles tendinopathy (McCrory *et al.*, 1999; Baur *et al.*, 2004; Azevedo *et al.*, 2009) or lower leg injury (Hreljac, Marshall and Hume, 2000). However, as a measure of overall whole-body loading, GRF does not take into account the uneven relative distribution of loading throughout the body, especially as it will vary between runners. Impact accelerometery, which assesses loading at a segmental level, may be more useful in investigating the loading-based risk factors associated with RRI (Sheerin, Reid and Besier, 2019), with some research associating greater impact loading to RRIs (Milner *et al.*, 2006b; Zifchock, Davis and Hamill, 2006). Although wearable accelerometers have the added benefit of being relatively low cost and user-friendly, no studies to date have used them to investigate the relationship between loading and injury of the calf-complex.

In addition, from a practical perspective, there is a need to identify a subset of measures associated with RRIs that can be used in a clinical environment. If effective, such an assessment would increase their utilisation. Therefore, the examination of a number of variables that can be easily and inexpensively assessed, such as strength (Hein *et al.*, 2014; Andere *et al.*, 2021), functional foot alignment (Clement, Taunton and Smart, 1984), and range of motion (Becker *et al.*, 2017; Andere *et al.*, 2021) is important. Although some research has demonstrated differences in these measures between runners with and without calf-complex injuries (Haglund-Åkerlind and Eriksson, 1993; Annuar *et al.*, 2021), these studies have largely been retrospective.

Therefore, this study aimed to both identify factors associated with calf-complex RRIs and to explore their ability to be used for injury screening. We hypothesised that clinical factors, loading and running technique variables would be associated with injuries in runners and have the potential to be used in injury screening.

Methodology

This study is a sub-analysis of a longitudinal study spanning over a period between January 2018 and April 2020 which examined all RRIs (ClinicalTrials.gov Identifier: NCT03671395). Recreational runners, who ran a minimum of 10km/week over the previous 6 months (Saragiotto *et al.*, 2014) were recruited via radio, social media, advertisements to running clubs and leaflets distributed at running events. Runners between the ages of 18-65 years old, with no history of injury within the last three months (Hesar *et al.*, 2009; Buist, Bredeweg, Lemmink, *et al.*, 2010; Ramskov *et al.*, 2013), who did not participate in contact, team or high impact sports (Lun *et al.*, 2004) were included. Participants were excluded if they previously or presently participated at an international level. The flow chart of participants is detailed in (Figure 11). Ethical approval was sought from and granted by the Dublin City University Ethics Committee (DCUREC/2017/186).

A plain language statement was provided to participants and each participant was evaluated for eligibility (outlined above) via email. Following this, participants completed an online survey regarding their injury and training history (Section 8.1, Appendix A). Participants attended a baseline session in which they completed a PAR-Q and the online questionnaire was verified for accuracy. Musculoskeletal clinical measures were assessed for each participant in line with the protocol described by Dillon *et al.* (2021) (Chapter 3). Each test was performed by the same rater. Intra-rater reliability of each of the measures ranged from good to excellent (Section 8.2, Appendix B). Functional foot alignment of both feet was measured using navicular drop (Buist, Bredeweg, Lemmink, *et al.*, 2010) and foot posture index (FPI) (Redmond, Crosbie and Ouvrier, 2006). An average of three values of bilateral joint motion values for ankle dorsiflexion, hip extension, hip internal rotation motion, and external rotation were assessed using a smartphone application (Plaincode "clinome-ter," V2.4 on a Samsung S8+, https://play.google.com/store/ apps). The maximum of three trials of the following strength tests was recorded using a hand-held dynamometer (J-Tech Commander Echo Wireless Muscle Testing Starter Kit; J-Tech Medical Industries, Midvale, UT): hip abduction, hip extension, plantarflexion, knee flexion and knee extension. This value was normalised to moment arm and body mass.

A dynamic warm-up targeting five muscle groups (hip extensors, hip flexors, leg extensors, leg flexors and plantar flexors) was performed on both lower extremities (Yamaguchi, Takizawa and Shibata, 2015). Following this, participants ran for 6 minutes on a treadmill (FlowFitness, Runner-DTM2500i, Netherlands) at a speed of 9 km/hr, to ensure treadmill familiarisation (Lavcanska, Taylor and Schache, 2005), with three further minutes at a self-selected pace (Dierks *et al.*, 2011; Bazett-Jones *et al.*, 2013). To achieve this, the tester decreased and increased the treadmill speed until the participant felt that they had achieved a similar speed to their typical training pace (Heiderscheit *et al.*, 2011). Running technique data were recorded using a 17-camera 3D motion analysis system (Vantage, Vicon, Oxford, United Kingdom) consisting of 32, 14 mm in diameter, reflective markers. These were applied by one investigator (SD) to the following bony landmarks; C7, T10, sternum, clavicle, shoulder, anterior superior iliac spine, posterior superior iliac spine, pelvis, thigh, knee, lateral malleoli, heel and toe (Marshall *et al.*, 2014) (see Section 8.4., Appendix D for image). Whilst running, peak ($peak_{accel}$) and rate of impact accelerations ($rate_{accel}$) were measured using inertial measurement units (IMUs) (dimensions: 65 mm x 32 mm x 12 mm, mass: 31 g, acceleration range: ± 16 g) (Shimmer, Ireland). Two IMUs were attached tightly bilaterally to the shank, 5 cm proximal to the medial malleolus, using Hypafix tape aligned along the long axis of the shank. One IMU was also secured to the lower back with a custom-made elastic belt secured with additional elastic waistband and Hypafix tape; aligned along the vertical midline of the S2 spinous process. Tape and wrapping of sensors has previously been found to capture more accurate accelerometery data compared to manufacturer straps (Johnson, Outerleys, *et al.*, 2020). The triaxial accelerometer data were captured at 512 Hz (Hennig, Milani and Lafortune, 1993). Prior to the trial, calibration of sensors was performed using the Shimmer 9DOF Calibration Application.

Injury Tracking

Following the baseline session, participants were encouraged to train as normal and RRIs were tracked prospectively for a period of one year, via fortnightly emails. An RRI was defined in line with a modified version of a the consensus statement by Yamato, Saragiotto and Lopes (2015), and participants were classified as injured if they reported calf or Achilles pain that caused them to stop or restrict their running. The pain must have persisted for at least 7 days or 3 consecutive scheduled training sessions or required the participant to consult a physician or other health care professional (Yamato, Saragiotto and Lopes, 2015). Diagnosis of injuries was performed by the researchers (SD (Chartered Physiotherapist) and AB (Certified Athletic Therapist)). Where this was not possible, the diagnosis was confirmed via phone call. Only injured participants whose first injury was to the calf-complex were included in the analysis.

Data Management

The Vicon Plug in Gait model, with two additional markers were used to define the rigid body segments of the thorax, pelvis, thigh, shank and foot, and the joint angles between them. Functional joints were calculated using the 'OSSCA' method in NEXUS 2 (Taylor *et al.*, 2010). Hip joint centre and the functional knee axes were also calculated within Vicon Nexus 2 using the symmetrical centre of rotation estimation (SCoRE) (Ehrig *et al.*, 2006) and the symmetrical axis of rotation approach (SARA) (Ehrig *et al.*, 2007), respectively. Minimisation of soft tissue artefact was achieved using the optimal common shape technique (OCST) (Taylor *et al.*, 2005), where an optimum rigid marker configuration for each segment is formed to reduce the effects of skin elasticity. Trunk, pelvis, hip, knee, ankle on the sagittal, frontal and transverse planes were extracted for 30 strides, with foot angle on the sagittal plane also extracted. Visual inspection of the data was performed by three investigators (SD, SG, AB) (MATLAB R2018a). The extracted stance phase variables are outlined in (Table 93).

Table 93 Extracted stance phase variables

Stance phase data extracted time points	***Definition***
Peak	Maximum angle achieved during stance.
Minimum	Minimum angle achieved during stance.
Excursion	Maximum-minimum angle during stance.
Angle at initial contact	Angle of foot when contacting ground.
Angle at toe-off	Angle of foot when first leaving ground.

Statistical analysis:

Means and standard deviations were assessed for each continuous variable. An independent T test was run to explore differences in running speed between groups. To investigate the association between each variable and injury, a univariable regression analysis was employed, in which calf-complex injury was the dependent variable. The significance level was set at $p < .05$. The non-injury group consisted of all of the runners who did not experience any injury during the one-year tracking period. The side of the calf-complex injury was used for the injured runners. The percentage of injuries sustained on the dominant and non-dominant sides was calculated. The side of comparison for uninjured runners was selected at random to meet the same proportion of dominant and non-dominant sides. This univariable analysis was also performed with age (Marti *et al.*, 1988; Hollander *et al.*, 2020), weekly mileage (McCrory *et al.*, 1999) and sex (Satterthwaite *et al.*, 1999; Taunton *et al.*, 2002) included, to account for these variables due to their proposed link with injury.

In order to explore the potential of variables for use in injury screening a multivariable logistic regression was performed. Continuous variables were assessed for linearity using the Box-Tidwell procedure (Box and Tidwell, 1962; Tabachnick & Fidell, 2013). To assess for multicollinearity, strongly correlated variables were identified using Spearmon's Rho Correlations (Mukaka, 2012; Dormann *et al.*, 2013) (Section 8.7, Appendix G). Strongly correlated variables (>0.7) were identified and the variable with the highest statistical significance as per the univariable analysis was used (Van Der Worp *et al.*, 2016). Multivariable imputation by chained equations and a Bayesian ridge regression approach was used to impute missing data (van Buuren and Groothuis-Oudshoorn, 2011). To achieve this, numeric data were scaled to unit variance and zero mean, and dummy coding was used for categorical data. Variables with a univariable association of $p < 0.25$ (Bursac *et al.*, 2008) were included in a binomial regression using a backward stepwise selection method (Field, 2005), with statistical significance set to $p < .05$. Analyses were performed using IBM SPSS Statistics version 27.

A receiver operating characteristic (ROC) curve was used to investigate the discriminatory ability of the model. In line with previous suggestions (Hosmer, Lemeshow and Sturdivant, 2013), the area under the curve values were classified as <0.5 (no discrimination), >0.5 to 0.7 (poor discrimination), >0.7 to 0.8 (acceptable discrimination), > 0.8 to 0.9 (excellent discrimination), ≥ 0.9 (outstanding discrimination). The specificity, sensitivity, negative and positive prediction value were also calculated.

Results

Of the 274 recreational runners recruited and eligible to participate in the study, 49 (18%) of participants were excluded (Figure 11). Over the one-year tracking period, 117 of the 225 runners (52%) sustained an injury, with the calf-complex constituting 26% (n = 31) of first injuries. Of these, 18 (58%) involved the Achilles tendon and 13 (42%) involved muscles of the calf. Descriptive demographics of participants are detailed in Table 94. There was no significant difference in running speed between the injured (11.4 ± 1.8 km/hr) and uninjured (11.2 ± 1.5 km/hr) runners (mean difference = -0.23 km/hr, $CI_{95\%}$ = -0.86- 0.40, t(137)=-0.708, *p*= .480). The following variables were associated with increased odds of calf-complex RRI: less navicular drop, greater running pace, greater thorax flexion-extension excursion, greater peak hip abduction, greater hip abduction at toe-off, greater knee internal-external rotation excursion, less transverse plane pelvic contralateral rotation at toe-off, less peak transverse plane pelvic contralateral rotation, less peak knee valgus, less knee valgus at initial contact, less minimum knee valgus, less knee valgus at toe-off, less knee flexion at toe-off and less minimum knee flexion (Table 95). The following additional variables were significant when age, sex and mileage was adjusted for; greater peak transverse plane pelvis rotation to contralateral side, greater peak hip internal rotation, greater ankle dorsiflexion at toe-off and greater peak plantar flexion. The remaining univariable regression analysis findings are detailed in (Section 8.8, Appendix H). To minimise repetition and for clarity, when two significant variables were highly correlated (as per Section 8.7, Appendix G), terms were grouped for the discussion.

Three variables were included in the final multivariable model (Table 96), which was statistically significant, $\chi^2(3) = 27.25$, $p < .001$. The model correctly classified 84% of cases. Sensitivity was 39%, specificity was 96%, positive prediction was 75% and negative prediction was 85%. The area under the ROC curve was 0.79 ($CI_{95\%}$ = 0.70 to 0.88), which is an acceptable level of discrimination (Hosmer, Lemeshow and Sturdivant, 2013).

A further analysis was performed investigating the relationship between calf-complex RRIs and easily measurable, inexpensive variables including: clinical measures of functional foot alignment, muscle strength, range of motion, RRI history, training history and demographics (Table 97). The model contained three terms (navicular drop, self reported running pace and self-reported weekly mileage) and was statistically significant, $\chi^2(3) = 13.83$, $p = .003$ and correctly classified 79% of cases. Sensitivity was 10%, specificity was 99%, positive prediction was 75% and negative prediction was 79%. The area under the ROC curve was 0.70 ($CI_{95\%}$ = 0.60 to 0.80), which is an acceptable level of discrimination (Hosmer, Lemeshow and Sturdivant, 2013).

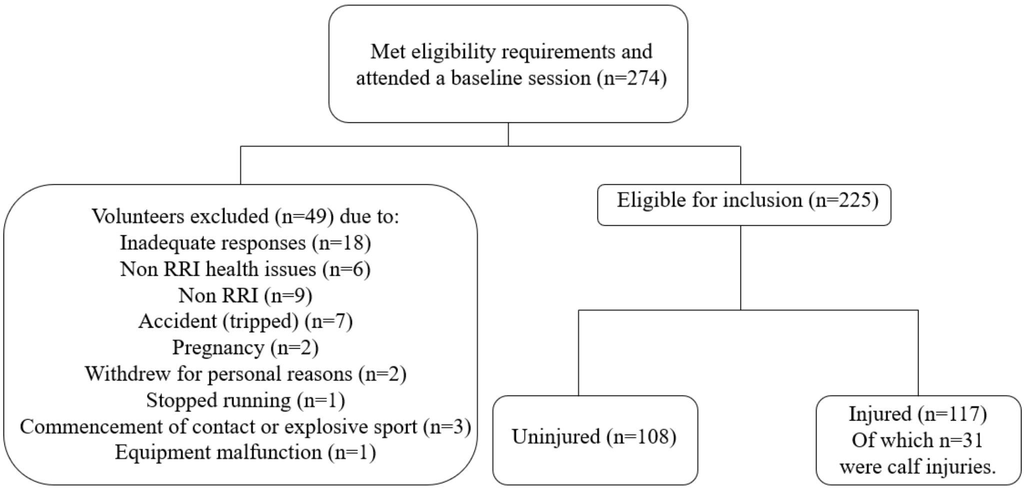


Figure 11 Flowchart of participants in the study.

Table 94 Descriptive demographics of participants.

Variable	*Uninjured*	*Injured*	*Unadjusted*				*Adjusted**			
	Mean ± SD	***Mean ± SD***	***Sig.***	***OR***	***95% C.I. for OR***		***Sig.***	***OR***	***95% C.I. for OR***	
Demographics					Lower	Upper			Lower	Upper
Age (years)	43.6 ± 9.3	44.1 ± 6.3	0.794	1.01	0.96	1.05				
BMI (kg/m^2)	24.2 ± 3.0	23.4 ± 2.7	0.167	0.90	0.78	1.04	0.074	0.86	0.72	1.02
Female sex (reference is male)	41 (38%)	13 (42%)	0.689	1.18	0.52	2.66				
Training and injury history										
History of RRI < 1 year ago	38 (35%)	14 (45%)	0.313	1.52	0.68	3.41	0.142	2.61	0.72	9.38
Self-reported weekly mileage (km/week)	36.4 ± 21.2	30.7 ± 18.1	0.191	1.00	1.00	1.00				
Self-reported average running pace (km/hr)	11.2 ± 1.9	11.9 ± 2.0	0.124	1.18	0.96	1.45	0.035	1.29	1.02	1.63

Abbreviated terms: SD = standard deviation, hr = hour.

Table 95 Variables significantly related to injury in the univariable regression analysis.

Variable			***Unadjusted***				***Adjusted****			
	Uninjured	***Injured***	***Sig.***	***OR***	***95% C.I. for OR***		***Sig.***	***OR***	***95% C.I. for OR***	
	Mean ± SD	Mean ± SD			Lower	Upper			Lower	Upper
Thorax flexion-extension excursion (°)	3.7 ± 1.34	4.2 ± 1.3	0.071	1.32	0.98	1.77	0.041	1.42	1.02	2.00
Transverse plane pelvis contralateral rotation at toe-off (°)	3.6 ± 4.1	1.2 ± 4.5	0.008	0.88	0.79	0.97	0.004	0.86	0.77	0.95
Peak transverse plane pelvis contralateral rotation (°)	3.8 ± 3.7	1.9 ± 4.1	0.015	0.87	0.78	0.98	0.008	0.85	0.76	0.96
Minimum transverse plane pelvis contralateral rotation (°)	-5.4 ± 3.6	-6.8 ± 4.6	0.063	0.90	0.81	1.01	0.04	0.89	0.80	1.00
Hip adduction at toe-off (°)	1.1 ± 3.4	-1.4 ± 3.6	0.001	0.81	0.71	0.92	0.001	0.80	0.70	0.91
Minimum hip adduction (°)	0.9 ± 3.4	-1.5 ± 3.7	0.001	0.81	0.72	0.92	0.001	0.80	0.70	0.92

Peak hip internal rotation (°)	0.9 ± 6.2	3.2 ± 6.6	0.085	1.06	0.99	1.13	0.043	1.08	1.00	1.16
Knee flexion at toe-off (°)	16.0 ± 5	13.0 ± 5.4	0.017	0.91	0.85	0.98	0.011	0.90	0.83	0.98
Minimum knee flexion (°)	13.5 ± 4.7	11.3 ± 4.7	0.026	0.91	0.83	0.99	0.029	0.90	0.82	0.99
Minimum knee varus (°)	-5.9 ± 2.9	-4.1 ± 3.3	0.006	1.22	1.06	1.40	0.006	1.23	1.06	1.42
Knee varus at initial contact (°)	-2.9 ± 2.6	-0.8 ± 3.1	0.001	1.34	1.13	1.60	0.001	1.35	1.13	1.61
Knee varus at toe-off (°)	-3.9 ± 3.0	-1.7 ±2.7	0.001	1.32	1.12	1.55	0.001	1.32	1.12	1.56
Peak knee varus (°)	-2.1 ± 2.7	0.0 ± 3.0	0.001	1.31	1.11	1.54	0.001	1.32	1.12	1.56
Knee internal- external rotation excursion (°)	20.9 ± 4.5	23.8 ± 5.1	0.004	1.14	1.04	1.25	0.003	1.15	1.05	1.26
Ankle dorsiflexion at toe-off (°)	-14.5 ± 6.1	-16.7 ± 5.8	0.085	0.94	0.88	1.01	0.044	0.92	0.85	1.00
Minimum ankle dorsiflexion (°)	-14.5 ± 6.1	-16.7 ± 5.8	0.087	0.94	0.88	1.01	0.045	0.92	0.85	1.00
Navicular drop (mm)	9.04 ± 3.30	7.43 ± 3.11	0.018	0.84	0.73	0.97	0.013	0.83	0.71	0.96
Self-reported average running pace (km/hr)	11.2 ± 1.9	11.9 ± 2.0	0.124	1.18	0.96	1.45	0.035	1.29	1.02	1.63

Abbreviated terms: SD = standard deviation, OR = odds ratio, C.I.= confidence interval. *Adjusted for sex, age and mileage. Abbreviated terms: SD = standard deviation, OR = odds ratio, C.I.= confidence interval, ROM = range of motion. *Adjusted for sex, age and mileage. The following denote the direction of the moment: Ankle dorsiflexion (positive), plantar flexion (negative), knee flexion (positive), knee extension (negative), knee varus (positive), knee valgus (negative), knee internal rotation (positive), knee external rotation (negative), hip adduction (positive), hip abduction (negative), hip internal rotation (positive), hip external rotation (negative), thorax anterior tilt (positive), thorax posterior tilt (negative), pelvis rotation to contralateral side (positive), pelvis rotation to ipsilateral side (negative).

Table 96 Variables retained in the multivariable regression analysis.

Variable	*Uninjured*	*Injured*	*Sig.*	*OR*	*95% C.I. for OR*	
	Mean ± SD	*Mean ± SD*			*Lower*	*Upper*
Pelvis contralateral rotation at toe-off on the transverse plane (°)	3.6 ± 4.1	1.2 ± 4.5	0.012	0.87	0.79	0.97
Knee varus at initial contact (°)	-2.9 ± 2.6	-0.8 ± 3.1	0.001	1.34	1.12	1.60
Navicular drop (mm)	9.04 ± 3.30	7.43 ± 3.11	0.011	0.82	0.71	0.96

Abbreviated terms: SD = standard deviation, OR = odds ratio, C.I.= confidence interval. *Adjusted for sex, age and mileage.

The model correctly classified 84% of cases. Sensitivity was 39%, specificity was 96%.

Table 97 Variables retained in the multivariable regression for clinical variables.

Variables	***Mean ± SD***	***Mean ± SD***	***Sig.***	***OR***	***95% C.I. for OR***	
					Lower	Upper
Navicular drop (mm)	9.04 ± 3.30	7.43 ± 3.11	0.009	0.81	0.69	0.95
Self-reported weekly mileage (km/week)	36.42 ± 21.2	30.71 ± 18.1	0.046	0.98	0.95	1.00
Self-reported average running pace (km/hr)	11.2 ± 1.9	11.9 ± 2.01	0.031	1.30	1.02	1.64

Abbreviated terms: SD = standard deviation, OR = odds ratio, C.I.= confidence interval. *Adjusted for sex, age and mileage.

The model correctly classified 79% of cases. Sensitivity was 10%, specificity was 99%.

Discussion

The association between calf-complex injuries and runners' demographics, clinical measures, technique and loading were examined; both in a univariable analysis to identify variables associated with injury and also within a multivariable analysis, to establish the potential screening ability of these variables. Of the variables examined, less navicular drop, faster running pace, as well as aspects of running technique (in the sagittal, transverse and frontal planes), were found to be associated with increased odds of RRI. Of these, some were also identified as significant in the final multivariable analysis, strengthening our confidence in their association with injury. Over the one-year tracking period, the first injury of 31 of the 225 runners (26%) was a calf-complex injury, an incidence proportion similar to previous research (Desai *et al.*, 2021). For the purpose of this discussion, findings will be compared predominantly to previous prospective research. This is in light of the difficulty in ascertaining the cause-effect relationship of retrospective research, with the possibility that the effects of injury produce compensatory changes that are directly opposite to true causative factors.

<u>Univariable analysis:</u>

Demographic Variables

Although previously proposed to be associated with RRI (Satterthwaite *et al.*, 1999; Vadeboncoeur *et al.*, 2012; Fukuchi *et al.*, 2013) neither sex, age nor BMI were found to be associated with calf-complex injury, in line with most of the prospective research investigating AT and calf injuries (Van Middelkoop *et al.*, 2008a; Van Ginckel *et al.*, 2009; Lagas *et al.*, 2020),

Clinical measures

Only navicular drop was found to be independently associated with injury, with increases in navicular drop decreasing odds of injury. This was also significant in the multivariable analysis. This is in contrast with the commonly cited hypothesis that greater pronation may create a "whipping action" at the AT, precipitating injury (Clement, Taunton and Smart, 1984). As the first study to our knowledge to prospectively investigate navicular drop and calf-complex injuries, this provides important evidence to this area. Using standardised classifications (Langley, Cramp and Morrison, 2016b) based on means, uninjured runners in the present study fit into the "pronated" category and the injured runners fall into the "neutral" category. A possible explanation of our finding is that uninjured runners may have a more flexible foot (reflected in the larger values of navicular drop) which increases impact absorption capabilities (Chan and Rudins, 1994). Less navicular drop reflects decreased flexibility of the longitudinal arch of the foot and a higher arched foot. A higher arched foot may also result in more lateral rollover of the foot, which has been associated with prospective Achilles injury (Van Ginckel *et al.*, 2009). However, differences between the injured and uninjured groups do not exceed the minimal detectable change for this measure (Zuil-Escobar *et al.*, 2018), indicating it may be challenging to identify in a clinical setting.

Our study indicates that range of motion (hip extension, hip internal rotation, hip external rotation and ankle dorsiflexion) were not associated with calf-complex RRIs. This adds further support to the only other prospective study to our knowledge investigating range of motion and calf-complex injury, which found no association between these variables and Achilles tendon pain (Hein *et al.*, 2014). Our finding may be explained by the fact that the maximum ranges measured in the clinical tests exceed the range of motion utilised during running, therefore, this may not be a limiting factor contributing to RRI.

While muscle strength has been suggested to be associated with general RRIs (Finnoff *et al.*, 2011; Luedke *et al.*, 2015; Becker, Nakajima and Wu, 2018), just one prospective study has examined this among runners with Achilles tendon pain (Hein *et al.*, 2014). Our study found no association between calf-complex injury and hip abduction, hip extension, knee extension, knee flexion or ankle plantar flexion strength. This is in agreement with Hein et al (2014) who found no association between AT pain and hip abduction or knee extension strength. However, Hein *et al.* (2014) found decreased knee flexor strength to be prospectively associated with injury, which was not observed in our study. This may be attributed to different testing protocols, as Hein et al. (2014) measured knee flexion at a 30 degree angle. Given the role of the calf muscle in generating forward propulsion during running, plantar flexion strength was a variable of particular interest (Sasaki and Neptune, 2006; Hamner, Seth and Delp, 2010). However, no previous prospective research has investigated the association between plantar flexion strength and calf-complex injuries. Our study found no association between plantar flexion strength and injury. Given that retrospective research largely suggests that *lower* plantar flexion strength is associated with calf complex injuries (Haglund-Åkerlind and Eriksson, 1993; McCrory *et al.*, 1999; Ferreira *et al.*, 2020; Andere *et al.*, 2021; Annuar *et al.*, 2021), findings from previous retrospective studies may reflect a change in strength following injury rather than preceding it.

Running technique

In relation to running technique, a number of stance phase joint actions were found to be associated with injury. Just one prospective study appears to have explored if kinematic variables during running are associated with AT pain in runners (Hein *et al.*, 2014). Our study indicates that greater thorax flexion-extension excursion was associated with increased odds of injury. Accounting for approximately 60% of a person's total body mass (Ford *et al.*, 2013), upper body movement has a notable effect on the distribution of loading on the lower body (Simic *et al.*, 2011). In particular, previous research has found a trend towards greater ankle plantar flexor energy absorption (p = .06) among runners with high thorax flexion compared to low thorax flexion (Teng and Powers, 2014), indicating that calf muscle function is affected by thorax movement. Given that thorax flexion-extension has not been prospectively researched, the present study provides new evidence for an association between calf-complex injury and sagittal plane thorax motion.

Less transverse plane pelvis contralateral rotation increased the odds of calf-complex RRI. In order to maintain straight line running, angular momentum between the upper and lower body must be equal. To maintain this in the presence of lower angular rotation produced at the pelvis, as seen in our injured group (Figure *10*), greater vertical free moments are likely produced at the foot, as a result of friction between the foot and the ground (Willwacher *et al.*, 2016; Mohr *et al.*, 2021). Conversely, greater free moments at the foot may be driving less pelvis rotation. Irrespective of the cause, larger free moments likely produce higher torques on biological tissue, which has been linked to injuries such as tibial stress fractures (Milner, Davis and Hamill, 2006) and patellofemoral pain syndrome (Willwacher *et al.*, 2016). Transverse plane pelvis rotation has not been previously prospectively (or retrospectively) investigated in relation to calf-complex injuries, therefore, this study provides a potentially important and novel consideration for injury prevention programme design.

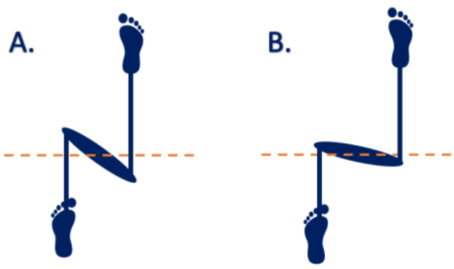


Figure 12 Axial rotation of the pelvis at toe-off. The left leg is the stance leg at toe-off. A. demonstrates greater contralateral pelvic rotation as seen in the uninjured runners, with B. demonstrating lesser peak contralateral pelvic rotation, as seen in the injured runners.

Injured runners ran with greater hip abduction at toe-off (which was also the peak value). Hein *et al*. (2014) also prospectively explored peak hip abduction, finding no differences between the control and their AT injury group. However, their study was limited by the small sample size of injured runners (n = 10) reducing the likelihood of detecting a statistical effect. Although no additional studies appear to have prospectively investigated peak hip abduction and calf-complex injury, retrospective studies have found an association between greater hip abduction and specific injuries (Dierks *et al.*, 2008; Grau *et al.*, 2011; Foch *et al.*, 2015). It is unclear how the greater hip adduction is related to calf-complex injury, however our findings may be linked to the reduced transverse plane contralateral pelvis rotation also observed in participants in the present study.

Greater peak hip internal rotation was also associated with calf-complex injury. To our knowledge this has not been previously prospectively investigated; however, Williams, Zambardino and Banning, (2008) suggest that a greater internal rotation may pull the lateral head of the gastrocnemius muscle anteriorly and the medial head posteriorly, resulting in shortening of the muscle on the medial side and increasing stress at the musculotendinous junction.

Similarly, our study found that greater knee internal-external rotation excursion increased odds of injury. Hein *et al.* (2014) also prospectively examined this, finding no differences between the control and AT group, however the small sample size (n=10) of the injured group reduces the likelihood of detecting a statistical difference. The majority of the remaining research focuses on the association between injury and *peak* knee internal rotation. Previous research has found that greater peak knee internal rotation to be related to a number of RRIs (Noehren, Davis and Hamill, 2007; Ferber *et al.*, 2009; Dudley *et al.*, 2017), with suggestions that excessive knee internal rotation increases torsional load of tissues around the knee, such as the iliotibial band (ITB) (Foch *et al.,* 2015). While the present study found no significant difference in peak or minimum knee internal rotation, the observed greater internal-external rotation excursion may reflect torsional loading of tissues in both the internal and external rotation directions. Similar to the ITB, the gastrocnemius also crosses the knee joint and therefore increased rotation at the knee may make it more vulnerable to rotational forces.

In the frontal plane, less knee valgus was associated with increased odds of injury. Frontal plane knee movement has not been previously investigated in relation to prospective calf-complex injuries, with most research relating frontal knee motion to altered forces on the knee joint (Bruns, Volkmer and Luessenhop, 1993; Sharma et al., 2001). The results of the current study may be explained, at least in part, by less navicular drop observed among runners who subsequently became injured. The present study found a pronated foot to be protective factor against injury. A pronated foot is indicative of a more mobile foot. Previous research has indicated that there association between less foot mobility and less frontal plane knee movement (Wyndow *et al.,* 2016). Therefore, less knee valgus may be as a result of the of the lower mobility of the arch of the foot among injured runners.

Our study found that less knee flexion at toe-off was associated with greater odds of injury. Similarly, Hein *et al.* (2014), the only other study to prospectively examine it, also found less knee flexion during stance to be associated with AT injury. As a biarticular muscle crossing both the knee and ankle joint, the gastrocnemius muscle's functions varies with the orientation of both joints (Landin, Thompson and Reid, 2015). The gastrocnemius has greater force generation capabilities in a less flexed knee position. Therefore, with less knee flexion at toe-off, the proximal portion of the gastrocnemius may be subject to greater stress.

Finally, greater ankle plantar flexion at toe-off was associated with greater odds of injury in the present study. To our knowledge, no study has investigated this association, with most choosing to investigate ankle angles solely at initial contact. The association between greater plantar flexion angle at toe-off and increased odds of injury may be because of increased compression between the Achilles tendon and the plantaris, which has been shown to increase at end range of plantarflexion (Stephen *et al.*, 2018). Interestingly, foot and ankle angle at *initial contact* was not associated with calf-complex injuries. Previous research has highlighted the necessity of investigating the association between foot strike and specific RRIs (Burke *et al.*, 2021), given that different foot strike patterns have resulted in different distribution of loading within the lower limb (Kulmala *et al.*, 2013; Hashizume and Yanagiya, 2017). However, prospective research remains limited with just three studies investigating this to date, with mixed results. In contrast to our findings, Hein *et al.* (2014) found less dorsiflexion angle at initial contact among prospectively injured runners with AT and Altman and Davis (2016) found barefoot runners (who typically forefoot strike) had a greater proportion of calf injuries compared to shod runners (who typically rearfoot strike). However, similar to our study, Lagas *et al.* (2010) found no association between self-reported foot strike pattern and AT injury. Therefore, more research is required before reaching a conclusion regarding foot strike pattern and calf-complex injuries.

Spatiotemporal parameters

Greater self-reported running pace was the sole spatiotemporal parameter found to be associated with increased odds of injury. No prospective studies appear to have directly investigated self-reported running pace and calf-complex injury. However, Achilles tendon force has been shown to increase as pace increases (Starbuck *et al.*, 2021), potentially due to larger associated rotations of the tibia giving rise to changes in muscular tension (McCrory *et al.*, 1999). In addition, retrospectively some studies have found that greater running pace is related to AT (McCrory *et al.*, 1999) and lower leg injuries (Benca *et al.*, 2020). As an easily modified variable, this is something that could potentially form the basis for an intervention programme, although there is the challenge that increased pace is directly related to increased performance and positive physiological adaptations.

Loading

This is the first study to investigate impact accelerations in calf-complex injuries. A recent systematic review (not limited to runners) found individuals with AT injuries did not run with higher GRFs (Sancho *et al.*, 2019). In line with this, the present study found that tibia and lower back impact accelerations, which are a proxy measure of loading (F=ma), were not significantly related to injury. While previous studies have found a relationship between increased impact accelerations and bone stress injuries (Milner *et al.*, 2006b; Zifchock, Davis and Hamill, 2006), these were retrospective, potentially reflecting the change in biomechanics as a result of injury. Given that injuries are caused by high load in excess of tissue strength (Kalkhoven, Watsford and Impellizzeri, 2020), other variables such as the internal strength of tissue may be more heavily contributing to injury.

Multivariable Analysis:

A preliminary exploration of the ability of these measures to predict RRI was performed. The multivariable model contained three significant variables (less navicular drop, less transverse plane contralateral pelvis rotation at toe-off and less knee valgus at initial contact) with an overall accuracy of 84%. In addition, the model, appears to be considerably more accurate in identifying uninjured runners, rather than identifying those who will suffer a calf-complex injury. The low sensitivity means that two thirds of runners who will become injured would not be identified and therefore would not receive and injury prevention intervention. Accurate targeting of appropriate individuals to receive the interventions has previously been highlighted as a significant challenge in injury screening programmes (Bahr, 2016). In terms of using only the more easily measurable clinical variables to screen for injury (clinical measures [functional foot alignment, muscle strength, range of motion], injury history, training history and demographics), overall accuracy decreased, and the poor sensitivity indicates that these measures have limited value in injury screening. Therefore, these variables do not appear to hold much value for the development of an injury screening tool, particularly in light of the fact that this model may overfit the data, given that it was developed and tested within the same sample (Collins *et al.*, 2015).

Limitations:

There are four primary limitations of this study. Firstly, the clinical, loading and technique variables were collected at just one time point. Whilst, like previous prospective studies (e.g. Hein *et al.*, 2014; Messier *et al.*, 2018), our methodology assumes that variables collected during the baseline session would remain constant over the year-long tracking period, it is possible that these variable changed over time. Secondly, although weekly mileage information was collected, more detailed concurrent collection of mileage data (such as strides per second) (Bertelsen *et al.*, 2017) or measurement of variables such as acute:chronic workload ratio (Kalkhoven *et al.*, 2021) should be explored. Thirdly, collection of information on a treadmill may not be ecologically valid for runners whose typical running surface was not a treadmill (Riley *et al.*, 2008; Milner, Hawkins and Aubol, 2020). Finally, in terms of grouping of injuries, the gastrocnemius, soleus, plantaris and Achilles injuries were grouped and termed the “calf-complex” for analysis due to their similar anatomical location, their shared role in propulsion and support, and the large proportion of RRIs they constitute. However, it is possible that different types of tissue (tendon, muscle) have specific predictors of injury.

Conclusion

This study prospectively investigated the association between calf-complex injury and demographics, clinical variables, running technique and loading. Running technique variables (in the sagittal, transverse and frontal plane), as well as less navicular drop and greater running pace were found to be associated with a calf-complex injury. These variables may be useful in designing intervention programmes due to the modifiable nature of many of them and the effectiveness of running retraining programmes to both alter running technique and to prospectively reduce the risk of injury (Chan *et al.*, 2018; Doyle *et al.*, 2022). In terms of injury screening, although less navicular drop, less pelvis contralateral rotation at toe-off and less knee valgus at initial contact were identified to have an overall accuracy of 84% in combination, the model appears to be considerably more sensitive than specific. This indicates that it is not very useful in screening for injury.

7. *Chapter 7: Overall Discussion*

Please note that take home messages are highlighted in **bold.**

This thesis is one of the largest bodies of evidence investigating multiple factors associated with RRIs among recreational runners. Chapter 2, the review of literature highlighted the high incidence of RRIs, something echoed in this thesis, with a high percentage of runners presenting with previous RRI (Chapters 3 and 4) and a high incidence of RRI over the 1-year tracking period (Chapters 5 and 6). Also outlined in the review of literature is the value in understanding the factors associated with RRIs to inform running injury prevention studies and practices, which was highlighted in the numerous previously proposed injury prevention models (van Mechelen, Hlobil and Kemper, 1992; Finch, 2006). Chapter 2 identified the need for prospective examinations of a multitude of risk factors, given the multifactorial nature of injury (Meeuwisse *et al.*, 2007a; Bertelsen *et al.*, 2017). A core underpinning of this thesis was the principle that injury results from high load in excess of tissue strength (Hreljac, Marshall and Hume, 2000; Kalkhoven, Watsford and Impellizzeri, 2020). Thus, a number of factors which (1) quantified loading, (2) measured the body's ability to distribute and attenuate loading or (3) measured the strength of body tissue to withstand loading, were investigated. These factors capture both the structure specific capacity and the structure specific load, outlined as key contributors to injury within the model of running injury aetiology by Bertelsen *et al.* (2017). In quantifying loading, this thesis investigated impact accelerations and therefore it represents one of only two (Winter *et al.*, 2020) studies investigating impact accelerations and prospective general RRIs. A unique aspect of this thesis was also the retrospective investigation of never injured, injury resistant and recently injured runners, groupings which have received limited attention in the RRI research domain. Retrospectively, this thesis found impact loading and strength differences between runners with differing injury histories (Chapters 3 and 4). Prospectively, running technique variables (such as transverse plane contralateral pelvis rotation, frontal plane hip abduction and frontal and transverse plane knee angles), as well as history of injury and less navicular drop were associated with general RRIs (Chapter 5). In relation to calf-complex injuries, less navicular drop and the aforementioned pelvis, hip and knee angles were associated with calf-complex injuries. Additionally, faster running pace and changes in sagittal plane knee and ankle angles, as well as to hip rotation on the frontal plane were associated with injury (Chapter 6). The following overall discussion will examine two major aspects of the thesis (1) an interpretation and comparison of retrospective and prospective findings and (2) differences and commonalities between specific and general RRIs.

(1) An interpretation of prospective versus retrospective findings

This thesis identified a number of factors associated with injury, both retrospectively and prospectively. This dual approach enabled a more nuanced interpretation regarding factors resulting from, and causative of, RRI, which is not possible with a solely retrospective design. Firstly, a primary focus of this research was to identify clinical measures associated with RRI. This was done in an attempt to find clinician-friendly and relatively low-cost measures that might be more amenable for use in clinical practice than resource-heavy measures such as those derived from motion analysis. **Neither retrospective nor prospective approaches found significant associations between range of motion and RRIs, which is in support of recent reviews on this topic** (Christopher *et al.*, 2019; Peterson *et al.*, 2022). In terms of strength measures, only the retrospective study (Chapter 3) found both plantar flexion and hip abduction strength were greater among runners with a history of injury, which was suggested to be as a result of rehabilitation rather than causative of injury. This explanation was strengthened by the findings of the prospective study (Chapter 5) which did not find an association between strength and general RRIs. Interestingly, plantar flexion strength has been previously associated with Achilles tendon injury, (Haglund-Åkerlind and Eriksson, 1993; McCrory *et al.*, 1999; Ferreira *et al.*, 2020; Andere *et al.*, 2021; Annuar *et al.*, 2021), but all research is retrospective in nature. Given that the present prospective examination of calf-complex injuries found no association between RRI and strength (Chapter 6), the previous retrospective studies may have been measuring factors that changed following injury, and not those causative of injury. This finding indicates that **retrospective research, especially that involving strength measures, should be interpreted with caution by clinicians when seeking information regarding factors that are *causative* of RRIs.**

With regard to the investigation of impact accelerations, differences between the retrospective and prospective findings were evident. This was a relatively novel aspect of this thesis, given that just one study to our knowledge has prospectively investigated impact accelerations among runners (Winter *et al.*, 2020). The retrospective approach revealed that recently injured runners exhibited greater loading at the lower back compared to those deemed injury resistant. This was not a finding echoed in the prospective study, which did not find impact loading to be associated with injury. **This may indicate that recently injured runners use a higher impact loading strategy as a result of injury, with this decreasing as time since injury elapses**. This may explain, at least in part, why previous injury in the past year is associated with future injury, as has been previously reported (Saragiotto *et al.*, 2014; Van Der Worp *et al.*, 2015) and as is evident from the prospective study (Chapter 5). Therefore, decreasing impact accelerations could be targeted as part of a rehabilitation programme and may be potentially useful in reducing the re-injury risk of recently injured runners. However, it is speculative to assert that impact loading decreases over time after initial recovery; a prospective study examining loading both pre- and post- injury would shed light on this.

Another relatively novel aspect of this thesis was the investigation into never injured runners, with findings from Chapter 3 and 4 indicating that **never injured runners do not appear to exhibit advantageous impact loading (i.e. lower loading) or clinical factors that could explain their resistance to injury.** Examining never injured runners is a relatively under-explored avenue of investigation in RRI research, despite the fact that avoiding RRIs is rare, given the high lifetime prevalence (Vitez *et al.*, 2017). Thus, even though the present thesis did not identify distinct differences in loading or clinical factors among never injured runners, future research may wish to examine other factors among this group, which may explain their resistance to injury. Given that injuries are caused by high loading relative to tissue strength (Kalkhoven, Watsford and Impellizzeri, 2020), future research may want explore whether injury resistant runners have stronger tissues.

(2) Differences and commonalities between general *and calf-complex RRIs*

The prospective studies (Chapters 5 and 6) examined a wide range of factors that may contribute to RRI, in line with the model of RRI outlined by Bertelsen *et al.,* (2017), with the inclusion of structure specific load capacity measures (e.g. injury and training history, age, sex strength) and structure specific loading measures (running technique, impact loading, mass, speed). Interestingly, some clinical and stance-phase factors were common to both general (Chapter 5) and calf-complex RRIs (Chapter 6), namely: less navicular drop, less transverse plane pelvis contralateral rotation at toe off, less knee valgus, greater peak hip abduction and greater knee internal-external rotation excursion. Risk factors being common to both general and calf-complex injuries may indicate two things: (1) that the common factors reflect the large proportion of calf-complex injuries among the injured runners in the general RRI study (26%), or (2) that these are global factors for RRI. If we assume the second explanation is true, then the **factors identified in Chapter 5 associated with general RRI could form the basis for the design of a general RRI prevention programme** and then be tested for efficacy, as has been done previously in other sports (Sadigursky *et al.*, 2017; Barden, Stokes and Mckay, 2022), and as has been outlined in injury prevention models (Finch, 2006).

This prevention programme could be multifaceted, with three main aspects. Firstly, education regarding a history of previous injury and its relationship with future injury could be implemented. Although we do not know if the association between previous RRI and increased odds of future RRI is related to factors such as training errors, compensatory technique or decreased strength of injured tissue, awareness of previous injury could be used to prompt runners to seek guidance regarding suitable return to running following RRI and appropriate tissue-healing time frames. Secondly, less navicular drop was associated with RRIs. Therefore, prevention programmes may target increasing flexibility of the foot. This is challenging in that this an area that has not been subject to much previous examination, however, foot stretching exercises may potentially achieve this (Manoli and Graham, 2005). However, as highlighted above due to the small differences in navicular drop between groups were within the minimal detectable change, this recommendation should be applied cautiously. Thirdly, the association between running technique and RRI found in this thesis could be targeted. This may be done via running-retraining, with limited, yet promising research to indicate that running retraining could be effective in reducing RRIs (Davis and Futrell, 2016; Doyle *et al.*, 2022). For example, the present thesis found less transverse plane contralateral rotation of the pelvis increased odds of RRI. Greater contralateral rotation of the pelvis is suggested to be associated with decreased step length (Preece, Mason and Bramah, 2016). Therefore, perhaps greater contralateral rotation could be encouraged by decreasing step length. This could be done by measuring step length via motion analysis software and providing real time feedback via audio or visual means (Agresta and Brown, 2015). Changes in kinematics may also be achieved through neuromuscular training exercises, as has been suggested for general sports injuries (Hübscher *et al.*, 2010). Following on from the pelvis rotation example, exercises which encourage pelvis transverse plane contralateral rotation, such as a forward lunge with rotation to the lunging leg may be an appropriate exercise to trial within this prevention programme.

Some differences in findings were evident between the general RRI and calf-complex RRIs analyses. Namely, calf-complex injures were associated with greater pace and more sagittal plane technique variables, such as: less knee flexion at toe off, greater plantar flexion at toe off, and greater thorax flexion-extension excursion. This points to the fact that **some factors associated with RRIs may be injury-specific,** a hypothesis formed in the literature review of Chapter 2. This information could be used as the basis for the design of a calf-complex injury prevention programme for runners. For example, an obvious and easily implementable prevention strategy for runners at risk of calf-complex injuries could be a reduction in running pace. Additionally, running-retraining may form part of the prevention programme, for example, real-time feedback could be used to encourage greater knee flexion during toe-off or to reduce flexion-extension excursion at the thorax. Similarly neuromuscular exercises could be considered to encourage greater knee flexion at toe off; for example, push off drills with cueing and emphasising greater knee flexion.

In terms of exploring the potential for screening for either general RRIs or calf-complex RRIs, the prospective studies (Chapters 5 and 6) found that, although an overall level of discrimination of 74 and 84%, respectively could be reached, the models only displayed an acceptable level of discrimination, with the calf-complex screening test in particular showing a low sensitivity (39%) in identifying injured runners. Given the relatively large number of injured participants in both arms of this study, **this thesis points to the challenge in identifying effective screening tests for RRI.** This challenge is not unique to running; it has been similarly identified in some of the most researched areas of musculoskeletal injury, namely anterior cruciate ligament tear (Krosshaug *et al.*, 2016) and hamstring injuries (Van Dyk *et al.*, 2017). Furthermore, Bahr (2016) concluded that overlap between high and low risk injury groups in screening test measurements mean that most screening tests are not sufficiently accurate. However, future research using more advanced data analytical approaches (e.g. machine learning) and more ecologically valid and frequent data collections (e.g. overground, run-by-run) may be more effective. Among the approaches that should be considered for future research in this area is the Complex Systems approach for sports injuries (Bittencourt *et al.*, 2016). This approach describes the development of risk injury profiles, as opposed to isolating risk factors for the prediction of injuries. This thesis was more grounded in the latter approach, adopting a prospective study design to examine the association of baseline characteristics on the development of an injury. However, the Complex Systems Approach describes the development of an injury as non-linear, with factors interacting in a complex manner to produce patterns that lead to adaptation or injury (Bittencourt *et al.*, 2016). This has been explored to a limited degree in the running research domain (Hulme *et al.*, 2017; Hulme *et al.*, 2019), with the results proving promising. The poor performance of the exploratory multivariable model in predicting injury within this these (Chapter 5, Chapter 6) also may indicate that examination of injury prediction through this Complex Systems approach may be necessary.

To summarise, this thesis found a number of injury and training history, clinical and running technique variables to be associated with RRIs. In the context of RRI prevention models, this thesis adds important information to the second step of the van Mechelen model (van Mechelen, 1992) which prompts investigation into the factors associated with injury. Therefore, ultimately this information could be implemented in RRI prevention programmes and then tested for efficacy by comparing levels of injury incidence. This has been successfully applied in other sports (Sadigursky *et al.*, 2017; Barden, Stokes and Mckay, 2022), but to date has not been applied in running. Whilst some of the factors identified to be associated with RRIs appear to relate to general RRIs, some factors appear to be injury-specific. Therefore, Chapter 5 may inform general RRI prevention practices and Chapter 6 may be most helpful for runners with specific recurring or early-stage calf-complex injuries. However, at present we are unable to accurately screen for RRIs. It is clear that some factors remain unidentified and should be explored in future research.

Future directions of research

This thesis prompts a number of future research ideas, which could add to the RRI research domain.

Firstly, one of the primary limitations of this thesis is the assumption that the single baseline data collection, using treadmill-based measures, remained unchanged throughout the prospective injury tracking period. It was assumed that these factors would be reflective of factors affecting future RRI, however, it is possible that these factors changed since the baseline data collection session. It has been outlined that predisposition to injury dynamically changes over time and therefore, single assessments of risk factors to injury may be limited in anticipating odds of RRI (Meeuwisse *et al.*, 2007). **As technology advances, a solution to this challenge is the use of more ecologically valid (e.g. overground) and frequent data collections (e,g. run-by-run) which may allow for more insight regarding the aetiology and prevention of RRIs**. A run by-run analysis would also allow for a more accurate record of volume of loading, that is not subject to recall bias. Real-time tracking of both the magnitude of loading and number of steps, would allow for quantification of real-time cumulative loading per run (Bertelsen *et al.*, 2017). This would also have the added advantage of enabling evaluation of training changes (e.g. acute:chronic workload), previously proposed to be important by other authors (Damsted *et al.*, 2018).

Secondly, previous RRI was found to be associated with future injury, both in Chapter 5 and in previous research (Desai *et al.*, 2021). This suggests that factors change following injury and therefore, govern re-injury (Meeuwisse *et al.*, 2007b). Therefore, **examining variables throughout the injury process (preinjury, during recovery, return to running) may help identify why such a high proportion of runners become injured during this time period and why some are resistant to re-injury**. This may be made more achievable with the use of technology described above.

The findings of Chapter 5 and 6 could form the basis of an injury prevention protocol for runners. With the exception of injury history, many of the factors identified as being associated with injury may be modifiable. For example, running technique changes may be amenable to gait retraining protocols (Chan *et al.*, 2018; Doyle *et al.*, 2022). However, more work would be needed to identify how to most effectively change these factors (e.g. via strengthening, running-retraining) and the ideal target running-retraining parameters. This should be done in consultation with runners, clinicians and domain experts, as has previously been done in other sports, such as soccer (Sadigursky *et al.*, 2017) and rugby (Barden, Stokes and Mckay, 2022). This will not only increase the likelihood of their effectiveness, but also increase the adoption by runners, in line with Translating Research into Injury Prevention Practice (TRIPP) framework (Finch, 2006).

It is apparent from Chapters 5 and 6 that some variables associated with RRIs were not examined in this thesis. Therefore, future studies may want to examine these variables. The biopsychosocial model of injury details that psychological and social factors may interact with biological factors to cause injury (Appaneal and Pernal, 2014). These are considered to be intrinsic factors within some models of injury aetiology and therefore, may interact with extrinsic factors to expose an athlete to a higher risk of injury (Meeuwisse *et al.*, 2007). **Among the variables that should be considered such as personality, sleep and stress** (Hackfort and Kleinert, 2007; Williams and Andersen, 1998), some of which have previously been related to RRIs (Mousavi *et al.*, 2021). As well as this, although this thesis quantified loading via the use of impact accelerometery, the biomechanical model of injury states that it is not just excessive loading, but inadequate tissue strength that precipitates injury (Kalkhoven, Watsford and Impellizzeri, 2020). Although isometric muscle strength was used in this study as a surrogate measure of muscle-tendon strength, **measures of intrinsic strength of biological tissue should be considered in future studie**s (e.g. quantitative ultrasound (Franchi *et al.*, 2018; Sahr, Sturnick and Nwawka, 2018) and quantitative CT scans (Donnelly, 2011)).

From Chapter 2 (the review of literature) and Chapter 6, it was clear that distinctive factors for injury were found in relation to calf-complex injuries. Therefore, **future studies may want to consider subdividing by RRI diagnoses or location.** Due to the low numbers of each injury that would typically be expected in a prospective study (e.g. knee patellofemoral pain injuries in the present thesis was 8%, n=9), the open sharing of data using standardised data collection protocols and pooling of similar research across centres would aid in achieving this research aim.

This thesis examined discrete data points in loading (peak and rate) and technique (e.g peak angle, angle at initial contact or toe off, minimum angle and excursion angle). However it is possible that **examination of continuous phases may provide greater insight into injury**, for example through the use of functional data analysis techniques (Richter *et al.*, 2014). Discrete and continuous data analysis methods could also be compared to examine what technique is most advantageous (if any), in light of the high resource and training needed to undertake functional data analysis. Furthermore, advances in technology may allow for alternative data analytical approaches (e.g. machine learning) (Rossi *et al.*, 2018; Xu *et al.*, 2022), which could allow for recognition of patterns in data that may not be identified within traditional statistical analyses. Advances in computational technology may also allow for an approach more in line with the Complex Systems approach to sports injuries (Bittencourt *et* *al.*, 2016), as has been done, although in a limited capacity, in previous RRI research (Hulme *et al.*, 2019).

Finally, further investigations using the dataset in this thesis could be explored. Research questions could include: (i) what technique leads to higher or lower impact acceleration (examinable by comparing technique in lowest and highest 25% percentile for impact accelerations), (ii) what technique distinguishes between rearfoot strike and non-RFS runners, (iii) how many strides are needed to produce consistent kinematics and impact accelerations and (iv) can clinicians visually identify extremes in technique using 2 D video data.

References

Adams, D., Pozzi, F., Willy, R.W., Carrol, A. and Zeni, J. (2018) 'Altering cadence or vertical osscillation during running: Effects on running injury factors.', *International Journal of Sports Physical Therapy,* 13(4), pp. 633–642. Available at: https://doi.org/10.26603/ijspt20180633.

Agresta, C. and Brown, A. (2015) 'Gait Retraining for Injured and Healthy Runners Using Augmented Feedback: A Systematic Literature Review', *Journal of Orthopaedic & Sports Physical Therapy,* 45(8), pp. 576–584. Available at: https://doi.org/10.2519/jospt.2015.5823.

Aicale, R., Tarantino, D. and Maffulli, N. (2018) 'Overuse injuries in sport: A comprehensive overview', *Journal of Orthopaedic Surgery and Research*. Available at: https://doi.org/10.1186/s13018-018-1017-5.

Akima, H., Kano, Y., Enomoto, Y., Ishizu, M., Okada, M., Oishi, Y., Katsuta, S. and Kuno, S.Y. (2001) 'Muscle function in 164 men and women aged 20-84 yr', *Medicine and Science in Sports and Exercise,* 33(2), pp. 220–226. Available at: https://doi.org/10.1097/00005768-200102000-00008.

Alcantara, R.S., Day, E.M., Hahn, M.E. and Grabowski, A.M. (2021) 'Sacral acceleration can predict whole-body kinetics and stride kinematics across running speeds', *SportRxiv,* 9. Available at: https://doi.org/10.7717/peerj.11199.

Almeida, M.O., Davis, I.S. and Lopes, A.D. (2015) 'Biomechanical differences of foot-strike patterns during running: A systematic review with meta-analysis', *Journal of Orthopaedic and Sports Physical Therapy,* pp. 738–755. Available at: https://doi.org/10.2519/jospt.2015.6019.

de Almeida, M.O., Saragiotto, B.T., Yamato, T.P. and Lopes, A.D. (2015) 'Is the rearfoot pattern the most frequently foot strike pattern among recreational shod distance runners?', *Physical Therapy in Sport,* 16(1), pp. 29–33. Available at: https://doi.org/10.1016/j.ptsp.2014.02.005.

Almonroeder, T., Willson, J.D. and Kernozek, T.W. (2013) 'The effect of foot strike pattern on achilles tendon load during running', *Annals of Biomedical Engineering*, 41(8), pp. 1758–1766. Available at: https://doi.org/10.1007/s10439-013-0819-1.

Altman, A.R. and Davis, I.S. (2012) 'A kinematic method for footstrike pattern detection in barefoot and shod runners', *Gait and Posture*, 35(2), pp. 298–300. Available at: https://doi.org/10.1016/j.gaitpost.2011.09.104.

Altman, A.R. and Davis, I.S. (2016) 'Prospective comparison of running injuries between shod and barefoot runners', *British Journal of Sports Medicine*, 50(8), pp. 476–480. Available at: https://doi.org/10.1136/bjsports-2014-094482.

Andere, N.F.B., Godoy, A.L., Mochizuki, L., Rodrigues, M.B., Fernandes, T.D., Soares-Júnior, J.M., Alonso, A.C., Luna, N.M.S., Brech, G.C. and Greve, J.M.D.A. (2021) 'Biomechanical evaluation in runners with Achilles tendinopathy', *Clinics (Sao Paulo, Brazil)*, 76, p. e2803. Available at: https://doi.org/10.6061/clinics/2021/e2803.

Annuar, A.S., Rahman, R.A., Munir, A., Murad, A., El-enshasy, H.A. and Illias, R. (2021) ‘Recreational runners with Achilles tendinopathy have clinically detectable impairments: A case-control study’, p. 118159. Available at: https://doi.org/10.1016/j.ptsp.2022.05.002.

Appaneal, R. and Pernal, F. (2014) *Biopsychosocial model of injury, Encyclopedia of Sport and Exercise Psychology*. Edited by R. Eklund and G. Tenenbaum. Thousand Oaks: SAGE Publications, Inc. Available at: https://doi.org/10.4135/9781483332222.n30.

Aquino, M.R.C., Avelar, B.S., Silva, P.L., Ocarino, J.M. and Resende, R.A. (2018) ‘Reliability of Foot Posture Index individual and total scores for adults and older adults’, *Musculoskeletal Science and Practice*, 36, pp. 92–95. Available at: https://doi.org/10.1016/j.msksp.2018.02.002.

Arnheim, D.D. and Klafs, C.E. (1985) *Modern principles of athletic training : the science of sports medicine : injury prevention, causation, and management*.

Atkinson, G. and Nevill, A.M. (1998) ‘Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine’, *Sports Medicine*, 26(4), pp. 217–238. Available at: https://doi.org/10.2165/00007256-199826040-00002.

Azevedo, L.B., Lambert, M.I., Vaughan, C.L., O’Connor, C.M. and Schwellnus, M.P. (2009) ‘Biomechanical variables associated with Achilles tendinopathy in runners’, *British Journal of Sports Medicine*, 43(4), pp. 288–292. Available at: https://doi.org/10.1136/bjsm.2008.053421.

Azevedo, L.B., Lambert, M.I., Vaughan, C.L., O’connor, C.M., Schwellnus, M.P. and Azevedo, L. (2008) ‘Biomechanical variables associated with Achilles tendinopathy in runners’. Available at: https://doi.org/10.1136/bjsm.2008.053421.

Baggaley, M., Noehren, B., Clasey, J.L., Shapiro, R. and Pohl, M.B. (2015) ‘Frontal plane kinematics of the hip during running: Are they related to hip anatomy and strength?’, *Gait & Posture*, 42(4), pp. 505–510. Available at: https://doi.org/10.1016/j.gaitpost.2015.07.064.

Bahr, R. (2016) ‘Why screening tests to predict injury do not work-and probably never will.: A critical review’, *British Journal of Sports Medicine*, 50(13), pp. 776–780. Available at: https://doi.org/10.1136/bjsports-2016-096256.

Bahr, R. and Krosshaug, T. (2005) ‘Understanding injury mechanisms: a key component of preventing injuries in sport’, *Br J Sports Med*, 39, pp. 324–329. Available at: https://doi.org/10.1136/bjsm.2005.018341.

Bailey, C.A., Sato, K., Burnett, A. and Stone, M.H. (2015) ‘Force-production asymmetry in male and female athletes of differing strength levels’, *International Journal of Sports Physiology and Performance*, 10(4), pp. 504–508. Available at: https://doi.org/10.1123/ijspp.2014-0379.

Baker, R.L. and Fredericson, M. (2016) ‘Iliotibial Band Syndrome in Runners. Biomechanical Implications and Exercise Interventions.’, *Physical Medicine and Rehabilitation Clinics of North America*, pp. 53–77. Available at: https://doi.org/10.1016/j.pmr.2015.08.001.

Baker, R.L., Souza, R.B., Rauh, M.J., Fredericson, M. and Rosenthal, M.D. (2018) 'Differences in Knee and Hip Adduction and Hip Muscle Activation in Runners With and Without Iliotibial Band Syndrome', *PM and R*, 10(10), pp. 1032–1039. Available at: https://doi.org/10.1016/j.pmrj.2018.04.004.

Baltich, J., Emery, C.A., Whittaker, J.L. and Nigg, B.M. (2017) 'Running injuries in novice runners enrolled in different training interventions: a pilot randomized controlled trial', *Scandinavian Journal of Medicine and Science in Sports*, 27(11), pp. 1372–1383. Available at: https://doi.org/10.1111/sms.12743.

Barden, C., Stokes, K.A. and Mckay, C.D. (2022) 'Effectiveness of the Activate injury prevention exercise programme to prevent injury in schoolboy rugby union', *British Journal of Sports Medicine*, 1(7). Available at: https://doi.org/10.1136/bjsports-2021-105170.

Barnes, A., Wheat, J. and Milner, C.E. (2011) 'Fore- and rearfoot kinematics in high- and low-arched individuals during running', *Foot and Ankle International*, 32(7), pp. 710–716. Available at: https://doi.org/10.3113/FAI.2011.0710.

Barrett, A. and Caulfield, B. (2008) 'Weight-bearing dorsiflexion is associated with sagittal plane kinematics during gait...Rehabilitation and Therapy Research Society Fourth Annual Conference', *Physical Therapy Reviews*, 13(3), pp. 200-200 1p. Available at: https://www.researchgate.net/publication/281481438_Weight-bearing_dorsiflexion_is_associated_with_sagittal_plane_kinematics_during_gait/citations (Accessed: 29 May 2022).

Batt, M.E. (2005) *Rehabilitation of sports injuries: scientific basis*, *British Journal of Sports Medicine*. Available at: https://doi.org/10.1136/bjsm.2003.008318.

Baur, H., Divert, C., Hirschmüller, A., Müller, S., Belli, A. and Mayer, F. (2004) 'Analysis of gait differences in healthy runners and runners with chronic Achilles tendon complaints', *Isokinetics and Exercise Science*, 12(2), pp. 111–116.

Bazett-Jones, D.M., Cobb, S.C., Huddleston, W.E., O'Connor, K.M., Armstrong, B.S.R. and Earl-Boehm, J.E. (2013) 'Effect of patellofemoral pain on strength and mechanics after an exhaustive run', *Medicine and Science in Sports and Exercise*, 45(7), pp. 1331–1339. Available at: https://doi.org/10.1249/MSS.0b013e3182880019.

Becker, J., James, S., Osternig, L. and Chou, L.S. (2018) 'Foot Kinematics Differ Between Runners With and Without a History of Navicular Stress Fractures', *Orthopaedic Journal of Sports Medicine*, 6(4), pp. 1–9. Available at: https://doi.org/10.1177/2325967118767363.

Becker, J., James, S., Wayner, R., Osternig, L. and Chou, L.S. (2017) 'Biomechanical Factors Associated with Achilles Tendinopathy and Medial Tibial Stress Syndrome in Runners', *American Journal of Sports Medicine*, 45(11), pp. 2614–2621. Available at: https://doi.org/10.1177/0363546517708193.

Becker, J., Nakajima, M. and Wu, W.F.W. (2018) 'Factors Contributing to Medial Tibial Stress Syndrome in Runners: A Prospective Study', *Medicine and Science in Sports and Exercise*, 50(10), pp. 2092–2100. Available at: https://doi.org/10.1249/MSS.0000000000001674.

Benca, E., Listabarth, S., Flock, F.K.J., Pablik, E., Fischer, C., Walzer, S.M., Dorotka, R., Windhager, R. and Ziai, P. (2020) 'Analysis of Running-Related Injuries: The Vienna Study', *Journal of Clinical Medicine*, 9(2), p. 438. Available at: https://doi.org/10.3390/jcm9020438.

Bennell, K., Crossley, K., Jayarajan, J., Walton, E., Warden, S., Kiss, Z.S. and Wrigley, T. (2004) 'Ground Reaction Forces and Bone Parameters in Females with Tibial Stress Fracture', *Medicine and Science in Sports and Exercise*, 36(3), pp. 397–404. Available at: https://doi.org/10.1249/01.MSS.0000117116.90297.E1.

Bennett, J., Seaton, M. and Killian, C. (2001) *Factors Contributing to the Development of Medial Tibial Stress Syndrome in High School Runners*, *Journal of Orthopaedic & Sports Physical Therapy*.

Bennett, J.E., Reinking, M.F. and Rauh, M.J. (2012) 'The relationship between isotonic plantar flexor endurance, navicular drop, and exercise-related leg pain in a cohort of collegiate cross-country runners.', *International journal of sports physical therapy*, 7(3), pp. 267–78. Available at: http://www.ncbi.nlm.nih.gov/pubmed/22666641%0Ahttp://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC3362985 (Accessed: 22 March 2019).

Van den Berghe, P., Six, J., Gerlo, J., Leman, M. and De Clercq, D. (2019) 'Validity and reliability of peak tibial accelerations as real-time measure of impact loading during over-ground rearfoot running at different speeds', *Journal of Biomechanics*, 86, pp. 238–242. Available at: https://doi.org/10.1016/j.jbiomech.2019.01.039.

Bertelsen, M.L., Hulme, A., Petersen, J., Brund, R.K., Sørensen, H., Finch, C.F., Parner, E.T. and Nielsen, R.O. (2017) 'A framework for the etiology of running-related injuries', *Scandinavian Journal of Medicine and Science in Sports*, 27(11), pp. 1170–1180. Available at: https://doi.org/10.1111/sms.12883.

Bierma-Zeinstra, S.M.A., Bohnen, A.M., Ramlal, R., Ridderikhoff, J., Verhaar, J.A.N. and Prins, A. (1998) 'Comparison between two devices for measuring hip joint motions', *Clinical Rehabilitation*, 12(6), pp. 497–505. Available at: https://doi.org/10.1191/026921598677459668.

Bigelow, E.M.R., Elvin, N.G., Elvin, A.A. and Arnoczky, S.P. (2013) 'Peak impact accelerations during track and treadmill running', *Journal of Applied Biomechanics*, 29(5), pp. 639–644. Available at: https://doi.org/10.1123/jab.29.5.639.

Bigouette, J., Simon, J., Liu, K. and Docherty, C.L. (2016) 'Altered vertical ground reaction forces in participants with chronic ankle instability while running', *Journal of Athletic Training*, 51(9), pp. 682–687. Available at: https://doi.org/10.4085/1062-6050-51.11.11.

Bischof, J.E., Abbey, A.N., Chuckpaiwong, B., Nunley, J.A. and Queen, R.M. (2010) 'Three-dimensional ankle kinematics and kinetics during running in women', *Gait & Posture*, 31(4), pp. 502–

505. Available at: https://doi.org/10.1016/j.gaitpost.2010.02.010.

Bishop, C., Read, P., Chavda, S. and Turner, A. (2016) ‘Asymmetries of the Lower Limb: The Calculation Conundrum in Strength Training and Conditioning’, *Strength and Conditioning Journal*, 38(6), pp. 27–32. Available at: https://doi.org/10.1519/SSC.0000000000000264.

Bishop, P., Cureton, K. and Collins, M. (1987) ‘Sex difference in muscular strength in equally-trained men and women’, *Ergonomics*, 30(4), pp. 675–687. Available at: https://doi.org/10.1080/00140138708969760.

Bittencourt, N.F.N., Meeuwisse, W.H., Mendonça, L.D., Nettel-Aguirre, A., Ocarino, J.M. and Fonseca, S.T. (2016) ‘Complex systems approach for sports injuries: Moving from risk factor identification to injury pattern recognition - Narrative review and new concept’, *British Journal of Sports Medicine*, 50(21), pp. 1309–1314. Available at: https://doi.org/10.1136/bjsports-2015-095850.

Bland M., J. and Altman G, D. (1999) *Measuring agreement in method comparison studies*, *Statistical Methods in medical Research*.

Bliekendaal, S., Moen, M., Fokker, Y., Stubbe, J.H. and Twisk, J. (2018) ‘Incidence and risk factors of medial tibial stress syndrome: a prospective study in Physical Education Teacher Education students’, *BMJ Open Sport Exerc Med*, 4, p. 421. Available at: https://doi.org/10.1136/bmjsem-2018-000421.

Bohannon, R.W. (2019) ‘Considerations and Practical Options for Measuring Muscle Strength: A Narrative Review’. Available at: https://doi.org/10.1155/2019/8194537.

Borg, G.A.V. (1954) ‘Psychophysical bases of perceived exertion’, *Plastic and Reconstructive Surgery*, 14(5), pp. 377–381. Available at: https://doi.org/10.1249/00005768-198205000-00012.

Bovens, A.M.P., Janssen, G.M.E., Vermeer, H.G.W., Hoeberigs, J.H., Janssen, M.P.E. and Verstappen, F.T.J. (1989) ‘Occurrence of running injuries in adults following a supervised training program’, *International Journal of Sports Medicine*, 10(SUPPL. 3), pp. S186–S190. Available at: https://doi.org/10.1055/s-2007-1024970.

Bowersock, C.D., Willy, R.W., DeVita, P. and Willson, J.D. (2017) ‘Independent effects of step length and foot strike pattern on tibiofemoral joint forces during running’, *Journal of Sports Sciences*, 35(20), pp. 2005–2013. Available at: https://doi.org/10.1080/02640414.2016.1249904.

Box, G. and Tidwell, P. (1962) ‘Transformation of the Independent Variables’, *Technometrics*, 4(4), pp. 531–550. Available at: https://doi.org/10.1080/00401706.1962.10490038.

Bramah, C., Preece, S., Gill, N. and Herrington, L. (2021) ‘Kinematic characteristics of male runners with a history of recurrent calf muscle strain injury’, *International Journal of Sports Physical Therapy*, 16(3), pp. 732–740. Available at: https://doi.org/10.26603/001c.22971.

Bramah, C., Preece, S.J., Gill, N. and Herrington, L. (2018) ‘Is There a Pathological Gait Associated With Common Soft Tissue Running Injuries?’, *American Journal of Sports Medicine*, 46(12), pp.

3023–3031. Available at: https://doi.org/10.1177/0363546518793657.

Bredeweg, S., Buist, I. and Kluitenberg, B. (2013) ‘Differences in kinetic asymmetry between injured and noninjured novice runners: A prospective cohort study’, *Gait and Posture*, 38(4), pp. 847–852. Available at: https://doi.org/10.1016/j.gaitpost.2013.04.014.

Bredeweg, S., Kluitenberg, B., Bessem, B. and Buist, I. (2013) ‘Differences in kinetic variables between injured and noninjured novice runners: A prospective cohort study’, *Journal of Science and Medicine in Sport*, 16(3), pp. 205–210. Available at: https://doi.org/10.1016/j.jsams.2012.08.002.

Bredeweg, S.W., Buist, I. and Kluitenberg, B. (2013) ‘Differences in kinetic asymmetry between injured and noninjured novice runners: A prospective cohort study’, *Gait and Posture*, 38(4), pp. 847–852. Available at: https://doi.org/10.1016/j.gaitpost.2013.04.014.

Brindle, R.A., Taylor, J.B., Rajek, C., Weisbrod, A. and Ford, K.R. (2020) ‘Association Between Temporal Spatial Parameters and Overuse Injury History in Runners: A Systematic Review and Meta-analysis’, *Sports Medicine*. Springer, pp. 331–342. Available at: https://doi.org/10.1007/s40279-019-01207-5.

Brody, D.M. (1982) ‘Techniques in the evaluation and treatment of the injured runner.’, *The Orthopedic Clinics of North America*, 13(3), pp. 541–558. Available at: https://doi.org/10.1016/s0030-5898(20)30252-2.

Brown, A.M., Zifchock, R.A., Hillstrom, H.J., Song, J. and Tucker, C.A. (2016) ‘The effects of fatigue on lower extremity kinematics, kinetics and joint coupling in symptomatic female runners with iliotibial band syndrome’, *Clinical Biomechanics*, 39, pp. 84–90. Available at: https://doi.org/10.1016/j.clinbiomech.2016.09.012.

Brown, C., Padua, D., Marshall, S.W. and Guskiewicz, K. (2008) ‘Individuals with mechanical ankle instability exhibit different motion patterns than those with functional ankle instability and ankle sprain copers’, *Clinical Biomechanics*, 23(6), pp. 822–831. Available at: https://doi.org/10.1016/j.clinbiomech.2008.02.013.

Brumitt, J. and Cuddeford, T. (2015) *Current Concepts of Muscle and Tendon Adaptation To Strength and Conditioning.*, *International journal of sports physical therapy*.

Bruns, J., Volkmer, M. and Luessenhop, S. (1993) ‘Pressure distribution at the knee joint - Influence of varus and valgus deviation without and with ligament dissection’, *Archives of Orthopaedic and Trauma Surgery*, 113(1), pp. 12–19. Available at: https://doi.org/10.1007/BF00440588.

Buist, I., Bredeweg, S., Bessem, B., Van Mechelen, W., Lemmink, K.A.P.M. and Diercks, R.L. (2010) ‘Incidence and risk factors of running-related injuries during preparation for a 4-mile recreational running event’, *British Journal of Sports Medicine*, 44(8), pp. 598–604. Available at: https://doi.org/10.1136/bjsm.2007.044677.

Buist, I., Bredeweg, S., Lemmink, K., Van Mechelen, W. and Diercks, R. (2010) ‘Predictors of running-related injuries in novice runners enrolled in a systematic training program: A prospective cohort study', *American Journal of Sports Medicine*, 38(2), pp. 273–280. Available at: https://doi.org/10.1177/0363546509347985.

Buist, I., Bredeweg, S.W., Lemmink, K.A., Pepping, G.J., Zwerver, J., Van Mechelen, W. and Diercks, R.L. (2007) 'The GRONORUN study: Is a graded training program for novice runners effective in preventing running related injuries? Design of a Randomized Controlled Trial', *BMC Musculoskeletal Disorders*, 8. Available at: https://doi.org/10.1186/1471-2474-8-24.

Buist, I., Bredeweg, S.W., Van Mechelen, W., Lemmink, K.A.P.M., Pepping, G.J. and Diercks, R.L. (2008) 'No effect of a graded training program on the number of running-related injuries in novice runners: A randomized controlled trial', *American Journal of Sports Medicine*, 36(1), pp. 33–39. Available at: https://doi.org/10.1177/0363546507307505.

Bujang, M.A. and Baharum, N. (2017) 'A simplified guide to determination of sample size requirements for estimating the value of intraclass correlation coefficient: A review', *Archives of Orofacial Sciences*, 12(1), pp. 1–11.

Burke, A., Dillon, S., O'Connor, S., Whyte, E.F., Gore, S. and Moran, K.A. (2021) 'Risk Factors for Injuries in Runners: A Systematic Review of Foot Strike Technique and Its Classification at Impact', *Orthopaedic Journal of Sports Medicine*, 9(9), pp. 1–11. Available at: https://doi.org/10.1177/23259671211020283.

Bursac, Z., Gauss, C.H., Williams, D.K. and Hosmer, D.W. (2008) 'Purposeful selection of variables in logistic regression', *Source Code for Biology and Medicine*, 3, pp. 1–8. Available at: https://doi.org/10.1186/1751-0473-3-17.

van Buuren, S. and Groothuis-Oudshoorn, K. (2011) 'mice: Multivariate imputation by chained equations in R', *Journal of Statistical Software*, 45(3), pp. 1–67. Available at: https://doi.org/10.18637/jss.v045.i03.

Cahanin, R.L., Jefferson, J.R., Flynn, T.W. and Goyeneche, N. (2019) 'Iliac Crest Height Difference and Other Running-Related Variables' Relationship With Running Injury', *International Journal of Sports Physical Therapy*, 14(6), pp. 957–966. Available at: https://doi.org/10.26603/ijspt20190957.

Cannon, A., Finn, K. and Yan, Z. (2018) 'Comparison of hip internal rotation and external rotation between intercolleagiate distance runners and non-running college students', *International Journal of Sports Physical Therapy*, 13(6), pp. 956–962. Available at: https://doi.org/10.26603/ijspt20180956.

Di Caprio, F., Buda, R., Mosca, M., Calabrò, A. and Giannini, S. (2010) 'Foot and lower limb diseases in runners: Assessment of risk factors', *Journal of Sports Science and Medicine*, 9(4), pp. 587–596.

Cavanagh, P.R. and Lafortune, M.A. (1980) 'Ground reaction forces in distance running', *Journal of Biomechanics*, 13(5), pp. 397–406. Available at: https://doi.org/10.1016/0021-9290(80)90033-0.

Centers for Disease Control and Prevention (2012) 'Principles of Epidemiology | Lesson 3 - Section 6', *May 18, 2012*, p. 1. Available at: https://www.cdc.gov/csels/dsepd/ss1978/lesson3/section2.html (Accessed: 2 April 2021).

Ceyssens, L., Vanelderen, R., Christian Barton, ·, Malliaras, · Peter and Dingenen, B. (2019) 'Biomechanical Risk Factors Associated with Running-Related Injuries: A Systematic Review', 49, pp. 1095–1115. Available at: https://doi.org/10.1007/s40279-019-01110-z.

Chan, C.S. and Grossman, H.Y. (2011) 'Psychological Effects of Running Loss on Consistent Runners', *Perceptual and Motor Skills*, 66(3), pp. 875–883. Available at: https://doi.org/10.2466/pms.1988.66.3.875.

Chan, C.W. and Rudins, A. (1994) *Subject Review Foot Biomechanics During Walking and Running*, *Mayo Clinic Proceedings*. Available at: https://doi.org/10.1016/S0025-6196(12)61642-5.

Chan, Z.Y., Zhang, J.H., Au, I.P., An, W.W., Shum, G.L., Ng, G.Y. and Cheung, R.T. (2018) 'Gait Retraining for the Reduction of Injury Occurrence in Novice Distance Runners: 1-Year Follow-up of a Randomized Controlled Trial', *American Journal of Sports Medicine*, 46(2), pp. 388–395. Available at: https://doi.org/10.1177/0363546517736277.

Chang, J.S., Kwon, Y.H., Kim, C.S., Ahn, S.-H. and Park, S.H. (2012) 'Differences of ground reaction forces and kinematics of lower extremity according to landing height between flat and normal feet', *Journal of Back and Musculoskeletal Rehabilitation*, 25(1), pp. 21–26. Available at: https://doi.org/10.3233/BMR-2012-0306.

Christopher, S.M., McCullough, J., Snodgrass, S.J. and Cook, C. (2019) 'Do alterations in muscle strength, flexibility, range of motion, and alignment predict lower extremity injury in runners: a systematic review', *Archives of Physiotherapy*, 9(1), p. 2. Available at: https://doi.org/10.1186/s40945-019-0054-7.

Chumanov, E.S., Heiderscheit, B.C. and Thelen, D.G. (2011) 'Hamstring musculotendon dynamics during stance and swing phases of high-speed running', *Medicine and Science in Sports and Exercise*, 43(3), pp. 525–532. Available at: https://doi.org/10.1249/MSS.0b013e3181f23fe8.

Chumanov, E.S., Wall-Scheffler, C. and Heiderscheit, B.C. (2008) 'Gender differences in walking and running on level and inclined surfaces', *Clinical biomechanics (Bristol, Avon)*, 23(10), pp. 1260–1268. Available at: https://doi.org/10.1016/j.clinbiomech.2008.07.011.

Chuter, V.H. and Janse de Jonge, X.A.K. (2012) 'Proximal and distal contributions to lower extremity injury: A review of the literature', *Gait and Posture*, 36(1), pp. 7–15. Available at: https://doi.org/10.1016/j.gaitpost.2012.02.001.

Clement, D.B., Taunton, J.E. and Smart, G.W. (1984) 'Achilles tendinitis and peritendinitis: Etiology and treatment', *The American Journal of Sports Medicine*, 12(3), pp. 179–184. Available at: https://doi.org/10.1177/036354658401200301.

Cohen, J. (1998) *Statistical Power Analysis for the Behavioral Sciences*. 2nd Editio, *Statistical Power Analysis for the Behavioral Science*. 2nd Editio. USA: Lawrence Erlbaum Associates. Available at: https://doi.org/10.2307/2529115.

Cohen, J. (2013) *Statistical Power Analysis for the Behavioral Sciences*. 2nd edn, *Statistical Power Analysis for the Behavioral Sciences*. 2nd edn. Hillsdale, NJ Lawrence Erlbaum Associates, Publishers. Available at: https://doi.org/10.4324/9780203771587.

Colino, E., Garcia-Unanue, J., Gallardo, L., Foster, C., Lucia, A. and Felipe, J.L. (2020) 'Mechanical properties of treadmill surfaces and their effects on endurance running', *International Journal of Sports Physiology and Performance*, 15(5), pp. 685–689. Available at: https://doi.org/10.1123/ijspp.2019-0539.

Collins, G.S., Reitsma, J.B., Altman, D.G. and Moons, K.G.M. (2015) 'Transparent reporting of a multivariable prediction model for individual prognosis or diagnosis (TRIPOD): The TRIPOD Statement', *BMC Medicine*, 13(1), pp. 1–10. Available at: https://doi.org/10.1186/s12916-014-0241-z.

Connan, P., Ravelojaona, M., Grémeaux, V., Rossi, J. and Edouard, P. (2019) 'Sex differences in thigh muscles characteristics: A systematic review', *Swiss Sports and Exercise Medicine*, 67(1), pp. 49–59. Available at: https://doi.org/10.34045/ssem/2019/7.

Corbin, C. and Noble, L. (1980) *Flexibility: A Major Component of Physical Fitness*, *Journal of Physical Education and Recreation*. Available at: https://www.tandfonline.com/doi/abs/10.1080/00971170.1980.10622349 (Accessed: 30 March 2020).

Coventry, E., O'Connor, K.M., Hart, B.A., Earl, J.E. and Ebersole, K.T. (2006) 'The effect of lower extremity fatigue on shock attenuation during single-leg landing', *Clinical Biomechanics*, 21(10), pp. 1090–1097. Available at: https://doi.org/10.1016/j.clinbiomech.2006.07.004.

Creaby, M. and Dixon, S. (2008) 'External Frontal Plane Loads May Be Associated with Tibial Stress Fracture', 40(9), pp. 1669–1674. Available at: https://doi.org/10.1249/MSS.0b013e31817571ae.

Creaby, M.W., Honeywill, C., Franettovich Smith, M.M., Schache, A.G. and Crossley, K.M. (2017) 'Hip Biomechanics Are Altered in Male Runners with Achilles Tendinopathy', *Medicine and Science in Sports and Exercise*, 49(3), pp. 549–554. Available at: https://doi.org/10.1249/MSS.0000000000001126.

Creighton, D.W., Shrier, I., Shultz, R., Meeuwisse, W.H. and Matheson, G.O. (2010) 'Return-to-Play in Sport: A Decision-based Model', *Clinical Journal of Sport Medicine*, 20(5), pp. 379–385. Available at: https://doi.org/10.1097/JSM.0b013e3181f3c0fe.

Crossley, K., Bennell, K.L., Wrigley, T. and Oakes, B.W. (1999) 'Ground reaction forces, bone characteristics, and tibial stress fracture in male runners', *Medicine and Science in Sports and Exercise*, 31(8), pp. 1088–1093. Available at: https://doi.org/10.1097/00005768-199908000-00002.

Crowell, H.P., Milnert, C.E., Hamill, J. and Davis, I.S. (2010) 'Reducing impact loading during running with the use of real-time visual feedback', *Journal of Orthopaedic and Sports Physical Therapy*, 40(4), pp. 206–213. Available at: https://doi.org/10.2519/jospt.2010.3166.

Czuppon, S., Prather, H., Hunt, D.M., Steger-May, K., Bloom, N.J., Clohisy, J.C., Larsen, R. and Harris-Hayes, M. (2017) 'Gender-Dependent Differences in Hip Range of Motion and Impingement Testing in Asymptomatic College Freshman Athletes', *PM and R*, 9(7), pp. 660–667. Available at: https://doi.org/10.1016/j.pmrj.2016.10.022.

Dallinga, J., Van Rijn, R., Stubbe, J. and Deutekom, M. (2019) 'Injury incidence and risk factors: A cohort study of 706 8-km or 16-km recreational runners', *BMJ Open Sport and Exercise Medicine*, 5(1), p. 489. Available at: https://doi.org/10.1136/bmjsem-2018-000489.

Damsted, C., Glad, S., Nielsen, R.O., Sørensen, H. and Malisoux, L. (2018) 'Is There Evidence for an Association Between Changes in Training Load and Running-Related Injuries? a Systematic Review', *International Journal of Sports Physical Therapy*, 13(6), pp. 931–942. Available at: https://doi.org/10.26603/ijspt20180931.

Damsted, C., Parner, E.T., Sørensen, H., Malisoux, L. and Nielsen, R.O. (2019a) 'ProjectRun21: Do running experience and running pace influence the risk of running injury—A 14-week prospective cohort study', *Journal of Science and Medicine in Sport*, 22(3), pp. 281–287. Available at: https://doi.org/10.1016/j.jsams.2018.08.014.

Damsted, C., Parner, E.T., Sørensen, H., Malisoux, L. and Nielsen, R.O. (2019b) 'ProjectRun21: Do running experience and running pace influence the risk of running injury—A 14-week prospective cohort study', *Journal of Science and Medicine in Sport*, 22(3), pp. 281–287. Available at: https://doi.org/10.1016/j.jsams.2018.08.014.

Daoud, A.I.A., Geissler, G.J., Wang, F., Saretsky, J., Daoud, Y.A., Lieberman, D.E., Daoud, A.I.A., Geissler, G.J., Wang, F., Saretsky, J., *et al.* (2012) 'Foot Strike and Injury Rates in Endurance Runners: A Retrospective Study', *Med. Sci. Sports Exerc*, 44(7), pp. 1325–1334. Available at: https://doi.org/10.1249/MSS.0b013e3182465115.

Davis, I., Bowser, B. and Mullineaux, D. (2010) 'Do Impacts Cause Running Injuries? A Prospective Investigation. ASB, 2010', *Asb*, pp. 1335–1230.

Davis, I.S., Bowser, B.J. and Mullineaux, D.R. (2016) 'Greater vertical impact loading in female runners with medically diagnosed injuries: a prospective investigation', 50(14). Available at: https://doi.org/10.1136/bjsports-2015-094579.

Davis, I.S. and Futrell, E. (2016) 'Gait Retraining: Altering the Fingerprint of Gait', *Physical Medicine and Rehabilitation Clinics of North America*, pp. 339–355. Available at: https://doi.org/10.1016/j.pmr.2015.09.002.

Deng, J. (2010) 'Reliability and validity of the sit-to-stand navicular drop test : Do static measures of navicular height relate to the dynamic navicular motion during gait ?', *Journal of student physical therapy research*, 2(1), pp. 21–28.

Department of Health (2016) *Obesity Policy and Action Plan*.

Derrick, T.R., Hamill, J. and Caldwell, G.E. (1998) 'Energy absorption of impacts during running at various stride lengths', *Medicine and Science in Sports and Exercise*, 30(1), pp. 128–135. Available at: https://doi.org/10.1097/00005768-199801000-00018.

Desai, P., Jungmalm, J., Börjesson, M., Karlsson, J. and Grau, S. (2021) 'Recreational Runners With a History of Injury Are Twice as Likely to Sustain a Running-Related Injury as Runners With No History of Injury: A 1-Year Prospective Cohort Study', *The Journal of orthopaedic and sports physical therapy*, 51(3), pp. 144–150. Available at: https://doi.org/10.2519/jospt.2021.9673.

DeVita, P., Fellin, R.E., Seay, J.F., Ip, E., Stavro, N. and Messier, S.P. (2016) 'The relationships between age and running biomechanics', *Medicine and Science in Sports and Exercise*, 48(1), pp. 98–106. Available at: https://doi.org/10.1249/MSS.0000000000000744.

Dierks, T., Manal, K., Hamill, J. and Davis, I. (2008) 'Proximal and Distal Influences on Hip and Knee Kinematics in Runners With Patellofemoral Pain During a Prolonged Run', *Journal of Orthopaedic & Sports Physical Therapy*, 38(8), pp. 448–456. Available at: https://doi.org/10.2519/jospt.2008.2490.

Dierks, T.A., Manal, K.T., Hamill, J. and Davis, I. (2011) 'Lower extremity kinematics in runners with patellofemoral pain during a prolonged run', *Medicine and Science in Sports and Exercise*, 43(4), pp. 693–700. Available at: https://doi.org/10.1249/MSS.0b013e3181f744f5.

Dillon, S., Burke, A., Whyte, E.F., O'Connor, S., Gore, S. and Moran, K.A. (2021) 'Do Injury-Resistant Runners Have Distinct Differences in Clinical Measures Compared with Recently Injured Runners?', *Medicine and Science in Sports and Exercise*, 53(9), pp. 1807–1817. Available at: https://doi.org/10.1249/MSS.0000000000002649.

Dingenen, B., Malliaras, P., Janssen, T., Ceyssens, L., Vanelderen, R. and Barton, C.J. (2019) 'Two-dimensional video analysis can discriminate differences in running kinematics between recreational runners with and without running-related knee injury', *Physical Therapy in Sport*, 38, pp. 184–191. Available at: https://doi.org/10.1016/j.ptsp.2019.05.008.

Dix, J., Marsh, S., Dingenen, B. and Malliaras, P. (2019) 'The relationship between hip muscle strength and dynamic knee valgus in asymptomatic females: A systematic review', *Physical Therapy in Sport*, pp. 197–209. Available at: https://doi.org/10.1016/j.ptsp.2018.05.015.

Dixon, S.J., Creaby, M.W. and Allsopp, A.J. (2006) 'Comparison of static and dynamic biomechanical measures in military recruits with and without a history of third metatarsal stress fracture', *Clinical Biomechanics*, 21(4), pp. 412–419. Available at: https://doi.org/10.1016/j.clinbiomech.2005.11.009.

Donnelly, E. (2011) 'Methods for assessing bone quality: A review', *Clinical Orthopaedics and Related Research*, 469(8), pp. 2128–2138. Available at: https://doi.org/10.1007/s11999-010-1702-0.

Donoghue, O., Harrison, A., Laxton, P. and Jones, R. (2008) ‘Lower limb kinematics of subjects with chronic Achilles tendon injury during running’, *Research in Sports Medicine*, 16(1), pp. 23–38. Available at: https://doi.org/10.1080/15438620701693231.

Donoghue, O., Harrison, A.J., Laxton &, P. and Jones, R.K. (2008) ‘Orthotic control of rear foot and lower limb motion during running in participants with chronic Achilles tendon injury’, *Sports Biomechanics*, 7(2), pp. 194–205. Available at: https://doi.org/10.1080/14763140701841407.

Dormann, C.F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carr é, G., Garc í Marqu é, J.R., Gruber, Bernd, Lafourcade, B., Leit ã, P.J., *et al.* (2013) ‘Collinearity: a review of methods to deal with it and a simulation study evaluating their performance’, *Ecography*, 36, pp. 27–046. Available at: https://doi.org/10.1111/j.1600-0587.2012.07348.x.

Doyle, E., Doyle, T.L.A., Bonacci, J. and Fuller, J.T. (2022) ‘The Effectiveness of Gait Retraining on Running Kinematics, Kinetics, Performance, Pain, and Injury in Distance Runners: A Systematic Review With Meta-analysis’, *Journal of Orthopaedic & Sports Physical Therapy*, 52(4), pp. 192-A5. Available at: https://doi.org/10.2519/jospt.2022.10585.

Dudley, R.I., Pamukoff, D.N., Lynn, S.K., Kersey, R.D. and Noffal, G.J. (2017) ‘A prospective comparison of lower extremity kinematics and kinetics between injured and non-injured collegiate cross country runners’, *Human Movement Science*, 52, pp. 197–202. Available at: https://doi.org/10.1016/j.humov.2017.02.007.

Duffey, M., Martin, D., Cannon, D., Craven, T. and Messier, S. (2000) ‘Etiologic factors associated with anterior knee pain in distance runners’, *Medicine and Science in Sports and Exercise*, 32(11), pp. 1825–1832. Available at: https://doi.org/10.1097/00005768-200011000-00003.

Dugan, S.A. and Bhat, K.P. (2005) ‘Biomechanics and analysis of running gait’, *Physical Medicine and Rehabilitation Clinics of North America*, pp. 603–621. Available at: https://doi.org/10.1016/j.pmr.2005.02.007.

Van Dyk, N., Bahr, R., Burnett, A.F., Whiteley, R., Bakken, A., Mosler, A., Farooq, A. and Witvrouw, E. (2017) ‘A comprehensive strength testing protocol offers no clinical value in predicting risk of hamstring injury: A prospective cohort study of 413 professional football players’, *British Journal of Sports Medicine*, 51(23), pp. 1695–1702. Available at: https://doi.org/10.1136/bjsports-2017-097754.

Eckard, T.G., Padua, D.A., Hearn, D.W., Pexa, B.S. and Frank, B.S. (2018) ‘The Relationship Between Training Load and Injury in Athletes: A Systematic Review’, *Sports Medicine*, pp. 1929–1961. Available at: https://doi.org/10.1007/s40279-018-0951-z.

Edwards, W.B. (2018) ‘Modeling Overuse Injuries in Sport as a Mechanical Fatigue Phenomenon’, *Exercise and Sport Sciences Reviews*, 46(4), pp. 224–231. Available at: https://doi.org/10.1249/JES.0000000000000163.

Ehrig, R.M., Taylor, W.R., Duda, G.N. and Heller, M.O. (2006) ‘A survey of formal methods for determining the centre of rotation of ball joints', *Journal of Biomechanics*, 39(15), pp. 2798–2809. Available at: https://doi.org/10.1016/j.jbiomech.2005.10.002.

Ehrig, R.M., Taylor, W.R., Duda, G.N. and Heller, M.O. (2007) 'A survey of formal methods for determining functional joint axes', *Journal of Biomechanics*, 40(10), pp. 2150–2157. Available at: https://doi.org/10.1016/j.jbiomech.2006.10.026.

Ellapen, T.J., Satyendra, S., Morris, J. and Van Heerden, H.J. (2013) 'Common running musculoskeletal injuries among recreational half-marathon runners in KwaZulu-Natal', *South African Journal of Sports Medicine*, 25(2), p. 39. Available at: https://doi.org/10.7196/sajsm.360.

Esculier, J.-F., Bouyer, L.J. and Roy, J.-S.B. (2016) *The Effects of a Multimodal Rehabilitation Program on Symptoms and Ground-Reaction Forces in Runners With Patellofemoral Pain Syndrome.*, *Journal of Sport Rehabilitation*. Available at: http://web.a.ebscohost.com.dcu.idm.oclc.org/ehost/pdfviewer/pdfviewer?vid=1&sid=147c132e-508f-49b7-a0b4-7abefa62e137%40sdc-v-sessmgr01 (Accessed: 11 December 2018).

Esculier, J., Roy, J.-S. and Bouyer, L. (2015) 'Lower limb control and strength in runners with and without patellofemoral pain syndrome', *Gait and Posture*, 41(3), pp. 813–819. Available at: https://doi.org/10.1016/j.gaitpost.2015.02.020.

Ethier, C.R. and Simmons, C.A. (2007) *Introductory Biomechanics: From Cells to Organisms*. Cambridge Texts in Biomedical Engineering.

Ewers, B.J., Driskna, D., Orth, M.W. and Haut, R.C. (2001) 'The extent of matrix damage and chondrocyte death in mechanically traumatized articular cartilage explants depends on rate of loading', *Journal of Orthopaedic Research*, 19.

Farrokhi, S., Keyak, J.H. and Powers, C.M. (2011) 'Individuals with patellofemoral pain exhibit greater patellofemoral joint stress: A finite element analysis study', *Osteoarthritis and Cartilage*, 19(3), pp. 287–294. Available at: https://doi.org/10.1016/j.joca.2010.12.001.

Faul, F., Erdfelder, E., Lang, A.G. and Buchner, A. (2007) 'G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences', *Behavior Research Methods*, 39(2), pp. 175–191. Available at: https://doi.org/10.3758/BF03193146.

Ferber, R., Davis, I.M., Hamill, J., Pollard, C.D. and McKeown, K.A. (2002) 'Kinetic Variables in Subjects With Previous Lower Extremity Stress Fractures', *Medicine & Science in Sports & Exercise*, 34(5), p. S5. Available at: https://doi.org/10.1007/s13296-012-4010-6.

Ferber, R., Davis, I.M.C. and Williams, D.S. (2003) 'Gender differences in lower extremity mechanics during running', *Clinical Biomechanics*, 18(4), pp. 350–357. Available at: https://doi.org/10.1016/S0268-0033(03)00025-1.

Ferber, R., Kendall, K.D. and Farr, L. (2011) 'Changes in knee biomechanics after a hip-abductor strengthening protocol for runners with patellofemoral pain syndrome', *Journal of Athletic Training*, 46(2), pp. 142–149. Available at: https://doi.org/10.4085/1062-6050-46.2.142.

Ferber, R., Noehren, B., Hamill, J. and Davis, I. (2009) ‘Competitive Female Runners With a History of Iliotibial Band Syndrome Demonstrate Atypical Hip and Knee Kinematics’, *Journal of Orthopaedic & Sports Physical Therapy*, 40(2), pp. 52–58. Available at: https://doi.org/10.2519/jospt.2010.3028.

Ferenczi, M.A., Bershitsky, S.Y., Koubassova, N.A., Kopylova, G. V., Fernandez, M., Narayanan, T. and Tsaturyan, A.K. (2014) ‘Why muscle is an efficient shock absorber’, *PLoS ONE*, 9(1). Available at: https://doi.org/10.1371/journal.pone.0085739.

Ferreira, V.M.L.M., Oliveira, R.R., Nazareno, T.S., Freitas, L. V. and Mendonça, L.D. (2020) ‘Interaction of foot and hip factors identifies Achilles tendinopathy occurrence in recreational runners’, *Physical Therapy in Sport*, 45, pp. 111–119. Available at: https://doi.org/10.1016/j.ptsp.2020.06.006.

Field, A. (2005) *Discovering Statistics using SPSS Statistics, SAGE Publications*.

Finch, C. (2006) ‘A new framework for research leading to sports injury prevention’, *Journal of Science and Medicine in Sport*, 9, pp. 3–9. Available at: https://doi.org/10.1016/j.jsams.2006.02.009.

Finnoff, J.T., Hall, M.M., Kyle, K., Krause, D.A., Lai, J. and Smith, J. (2011) ‘Hip Strength and Knee Pain in High School Runners: A Prospective Study’, *PM and R*, 3(9), pp. 792–801. Available at: https://doi.org/10.1016/j.pmrj.2011.04.007.

Foch, E., Aubol, K. and Milner, C.E. (2020) ‘Relationship between iliotibial band syndrome and hip neuromechanics in women runners’, *Gait and Posture*, 77, pp. 64–68. Available at: https://doi.org/10.1016/j.gaitpost.2019.12.021.

Foch, E. and Milner, C.E. (2014) ‘Frontal plane running biomechanics in female runners with previous iliotibial band syndrome’, *Journal of Applied Biomechanics*, 30(1), pp. 58–65. Available at: https://doi.org/10.1123/jab.2013-0051.

Foch, E., Reinbolt, J.A., Zhang, S., Fitzhugh, E.C. and Milner, C.E. (2015) ‘Associations between iliotibial band injury status and running biomechanics in women’, *Gait and Posture*, 41(2), pp. 706–710. Available at: https://doi.org/10.1016/j.gaitpost.2015.01.031.

Foch, E.H. (2013) ‘Association between Iliotibial Band Syndrome Status and Running Biomechanics in Women’, *Dissertation*, pp. 3–4.

Fong, C.M., Blackburn, J.T., Norcross, M.F., McGrath, M. and Padua, D.A. (2011) ‘Ankle-dorsiflexion range of motion and landing biomechanics’, *Journal of Athletic Training*, 46(1), pp. 5–10. Available at: https://doi.org/10.4085/1062-6050-46.1.5.

Ford, K.R., Taylor-Haas, J.A., Genthe, K. and Hugentobler, J. (2013) ‘Relationship between hip strength and trunk motion in college cross-country runners’, *Medicine and Science in Sports and Exercise*, 45(6), pp. 1125–1130. Available at: https://doi.org/10.1249/MSS.0b013e3182825aca.

Franchi, M. V., Raiteri, B.J., Longo, S., Sinha, S., Narici, M. V. and Csapo, R. (2018) 'Muscle Architecture Assessment: Strengths, Shortcomings and New Frontiers of in Vivo Imaging Techniques', *Ultrasound in Medicine and Biology*, 44(12), pp. 2492–2504. Available at: https://doi.org/10.1016/j.ultrasmedbio.2018.07.010.

Francis, P., Whatman, C., Sheerin, K., Hume, P. and Johnson, M.I. (2019) 'The proportion of lower limb running injuries by gender, anatomical location and specific pathology: A systematic review', *Journal of Sports Science and Medicine*, pp. 21–31. Available at: http://www.jssm.org (Accessed: 1 March 2019).

Franke, T.P.C., Backx, F.J.G. and Huisstede, B.M.A. (2019) 'Running themselves into the ground? Incidence, prevalence, and impact of injury and illness in runners preparing for a half or full marathon', *Journal of Orthopaedic and Sports Physical Therapy*, 49(7), pp. 518–528. Available at: https://doi.org/10.2519/jospt.2019.8473.

Franklyn, M. and Oakes, B. (2015) 'Aetiology and mechanisms of injury in medial tibial stress syndrome: Current and future developments'. Available at: https://doi.org/10.5312/wjo.v6.i8.577.

Fredericson, M., Cookingham, C.L., Chaudhari, A.M., Dowdell, B.C., Oestreicher, N. and Sahrmann, ‡shirley A (2000) 'Hip abductor weakness in distance runners with iliotibial band syndrome', *Clinical Journal of Sport Medicine*, 10(3), pp. 169–175. Available at: https://doi.org/10.1097/00042752-200007000-00004.

Fu, W., Fang, Y., Liu, D.M.S., Wang, L., Ren, S. and Liu, Y. (2015) 'Surface effects on in-shoe plantar pressure and tibial impact during running', *Journal of Sport and Health Science*, 4(4), pp. 384–390. Available at: https://doi.org/10.1016/j.jshs.2015.09.001.

Fukuchi, R., Stefanyshyn, D., Stirling, L., Duarte, M. and Ferber, R. (2013) 'Flexibility, muscle strength and running biomechanical adaptations in older runners'. Available at: https://doi.org/10.1016/j.clinbiomech.2013.12.007.

Fukusawa, L., Stoddard, R. and Lopes, A.D. (2020) 'There is no difference in footstrike pattern distribution in recreational runners with or without anterior knee pain', *Gait and Posture*, 79, pp. 16–20. Available at: https://doi.org/10.1016/j.gaitpost.2020.03.020.

Fulton, J., Wright, K., Kelly, M., Zebrosky, B., Zanis, M., Drvol, C. and Butler, R. (2014) 'Injury risk is altered by previous injury: a systematic review of the literature and presentation of causative neuromuscular factors.', *International journal of sports physical therapy*, 9(5), pp. 583–95.

Futrell, E.E., Jamison, S.T., Tenforde, A.S. and Davis, I.S. (2018) 'Relationships between Habitual Cadence, Footstrike, and Vertical Load Rates in Runners', *Medicine and Science in Sports and Exercise*, 50(9), pp. 1837–1841. Available at: https://doi.org/10.1249/MSS.0000000000001629.

Gabbe, B.J. and Finch, C.F. (1999) *How valid is a self reported 12 month sports injury history?, Br J Sports Med*. Available at: www.bjsportmed.com (Accessed: 10 March 2020).

Gabbett, T.J. (2016) ‘The training-injury prevention paradox: Should athletes be training smarter and harder?’, *British Journal of Sports Medicine*, pp. 273–280. Available at: https://doi.org/10.1136/bjsports-2015-095788.

García-Pérez, J.A., Pérez-Soriano, P., Llana Belloch, S., Lucas-Cuevas, Á.G. and Sánchez-Zuriaga, D. (2014) ‘Effects of treadmill running and fatigue on impact acceleration in distance running’, *Sports Biomechanics*, 13(3), pp. 259–266. Available at: https://doi.org/10.1080/14763141.2014.909527.

Gehlsen, G.M. and Seger, A. (1980) ‘Selected measures of angular displacement, strength, and flexibility in subjects with and without shinsplints’, *Research Quarterly for Exercise and Sport*, 51(3), pp. 478–485. Available at: https://doi.org/10.1080/02701367.1980.10608070.

Van Gent, R.N., Siem, D., Van Middelkoop, M., Van Os, A.G., Bierma-Zeinstra, S.M.A. and Koes, B.W. (2007) ‘Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review’, *Br J Sports Med*, 41, pp. 469–480. Available at: https://doi.org/10.1136/bjsm.2006.033548.

Geraci, M.C. and Brown, W. (2005) ‘Evidence-based treatment of hip and pelvic injuries in runners’, *Physical Medicine and Rehabilitation Clinics of North America*, pp. 711–747. Available at: https://doi.org/10.1016/j.pmr.2005.02.004.

Gerlach, K.E., White, S.C., Burton, H.W., Dorn, J.M., Leddy, J.J. and Horvath, P.J. (2005) ‘Kinetic changes with fatigue and relationship to injury in female runners’, *Medicine and Science in Sports and Exercise*, 37(4), pp. 657–663. Available at: https://doi.org/10.1249/01.MSS.0000158994.29358.71.

Gerritsen, K.G.M., van den Bogert, A.J. and Nigg, B.M. (1995) ‘Direct dynamics simulation of the impact phase in heel-toe running’, *Journal of Biomechanics*, 28(6examined), pp. 661–668. Available at: https://doi.org/10.1016/0021-9290(94)00127-P.

Van Ginckel, A., Thijs, Y., Hesar, N.G.Z., Mahieu, N., De Clercq, D., Roosen, P. and Witvrouw, E. (2009) ‘Intrinsic gait-related risk factors for Achilles tendinopathy in novice runners: A prospective study’, *Gait and Posture*, 29(3), pp. 387–391. Available at: https://doi.org/10.1016/j.gaitpost.2008.10.058.

Goodpaster, B.H., Park, S.W., Harris, T.B., Kritchevsky, S.B., Nevitt, M., Schwartz, A. V, Simonsick, E.M., Tylavsky, F.A., Visser, M. and Newman, A.B. (2006) *The Loss of Skeletal Muscle Strength, Mass, and Quality in Older Adults: The Health, Aging and Body Composition Study*.

Goss, D.L. and Gross, M.T. (2012) ‘Relationships among self-reported shoe type, footstrike pattern, and injury incidence.’, *U.S. Army Medical Department journal*, (December), pp. 25–30.

Goss, D.L., Lewek, M., Yu, B., Ware, W.B., Teyhen, D.S. and Gross, M.T. (2015) ‘Lower Extremity Biomechanics and Self-Reported Foot-Strike Patterns Among Runners in Traditional and Minimalist Shoes’, *Journal of Athletic Training*, 50(6), pp. 603–611. Available at: https://doi.org/10.4085/1062-6050.49.6.06.

Gottschalk, F., Kourosh, S. and Leveau, B. (1989) 'The functional anatomy of tensor fasciae latae and gluteus medius and minimus.', *Journal of anatomy*, 166, pp. 179–89.

Grau, S., Krauss, I., Maiwald, C., Axmann, D., Horstmann, T. and Best, R. (2011) 'Kinematic classification of iliotibial band syndrome in runners', *Scandinavian Journal of Medicine and Science in Sports*, 21(2), pp. 184–189. Available at: https://doi.org/10.1111/j.1600-0838.2009.01045.x.

Grau, S., Krauss, I., Maiwald, C., Best, R. and Horstmann, T. (2008) 'Hip abductor weakness is not the cause for iliotibial band syndrome', *International Journal of Sports Medicine*, 29(7), pp. 579–583. Available at: https://doi.org/10.1055/s-2007-989323.

Grimston, S.K., Engsberg, J.R., Kloiber, R. and Hanley, D.A. (2016) 'Bone Mass, External Loads, and Stress Fracture in Female Runners', *International Journal of Sport Biomechanics*, 7(3), pp. 293–302. Available at: https://doi.org/10.1123/ijsb.7.3.293.

Gruber, A.H., Boyer, K.A., Derrick, T.R. and Hamill, J. (2014) 'Impact shock frequency components and attenuation in rearfoot and forefoot running', *Journal of Sport and Health Science*, 3(2), pp. 113–121. Available at: https://doi.org/10.1016/j.jshs.2014.03.004.

Guy-Grand, B. (2014) 'Beyond body mass index', *Cahiers de Nutrition et de Dietetique*, 49(3), pp. 93–94. Available at: https://doi.org/10.1016/j.cnd.2014.05.002.

Hackfort, D. and Kleinert, J. (2007) 'Research on sport injury development: Former and future approaches from an action theory perspective', *International Journal of Sport and Exercise Psychology*, 5(4), pp. 324–339. Available at: https://doi.org/10.1080/1612197x.2007.9671839.

Haglund-Åkerlind, Y. and Eriksson, E. (1993) 'Range of motion, muscle torque and training habits in runners with and without Achilles tendon problems', *Knee Surgery, Sports Traumatology, Arthroscopy*, 1(3–4), pp. 195–199. Available at: https://doi.org/10.1007/BF01560205.

Haley, S.M. and Fragala-pinkham, M.A. (2006) 'Interpreting Change Scores of Tests', 86(5), pp. 735–743.

Hamill, J. and Gruber, A.H. (2017) 'Is changing footstrike pattern beneficial to runners?', *Journal of Sport and Health Science*, 6(2), pp. 146–153. Available at: https://doi.org/10.1016/j.jshs.2017.02.004.

Hamill, J., Lim, J. and van Emmerik, R. (2020) 'Locomotor coordination, visual perception and head stability during running', *Brain Sciences*, 10(3). Available at: https://doi.org/10.3390/brainsci10030174.

Hamner, S.R., Seth, A. and Delp, S.L. (2010) 'Muscle contributions to propulsion and support during running'. Available at: https://doi.org/10.1016/j.jbiomech.2010.06.025.

Hargrave, M.D., Carcia, C.R., Gansneder, B.M. and Shultz, S.J. (2003) 'Subtalar pronation does not influence impact forces or rate of loading during a single-leg landing', *Journal of Athletic Training*, 38(1), pp. 18–23.

Hashizume, S. and Yanagiya, T. (2017) 'A Forefoot Strike Requires the Highest Forces Applied to the Foot Among Foot Strike Patterns', *Sports Medicine International Open*, 01(02), pp. E37–E42. Available at: https://doi.org/10.1055/s-0042-122017.

Heiderscheit, B., Hammill, J. and Van Emmerik, R. (2002) 'Variability of Stride Characteristics and Joint Coordination Among Individuals with Unilateral Patellofemoral Pain.', *Journal of Applied Biomechanics*, 18, pp. 110–121.

Heiderscheit, B.C., Chumanov, E.S., Michalski, M.P., Wille, C.M. and Ryan, M.B. (2011) 'Effects of Step Rate Manipulation on Joint Mechanics during Running', *Med. Sci. Sports Exerc*, 43(2), pp. 296–302. Available at: https://doi.org/10.1249/MSS.0b013e3181ebedf4.

Hein, T., Janssen, P., Wagner-Fritz, U., Haupt, G. and Grau, S. (2014) 'Prospective analysis of intrinsic and extrinsic risk factors on the development of Achilles tendon pain in runners', *Scandinavian Journal of Medicine and Science in Sports*, 24(3), pp. 201–212. Available at: https://doi.org/10.1111/sms.12137.

Hendricks, C. and Phillips, J. (2013) 'Prevalence and incidence rate of injuries in runners at a local athletic club in Cape Town', *South African Journal of Physiotherapy*, 69(3), pp. 33–37. Available at: https://doi.org/10.4102/sajp.v69i3.31.

Hennig, E.M., Milani, T.L. and Lafortune, M.A. (1993) 'Use of Ground Reaction Force Parameters in Predicting Peak Tibial Accelerations in Running', *Journal of Applied Biomechanics*, 9(4), pp. 306–314. Available at: https://doi.org/10.1123/jab.9.4.306.

Hesar, N., Van Ginckel, A., Cools, A., Peersman, W., Roosen, P., De Clercq, D. and Witvrouw, E. (2009) 'A prospective study on gait-related intrinsic risk factors for lower leg overuse injuries', *British Journal of Sports Medicine*, 43(13), pp. 1057–1061. Available at: https://doi.org/10.1136/bjsm.2008.055723.

Hespanhol-Junior, L., van Mechelen, W., Postuma, E. and Verhagen, E. (2016) 'Health and economic burden of running-related injuries in runners training for an event: A prospective cohort study', *Scandinavian journal of medicine & science in sports*, 26(9), pp. 1091–1099. Available at: https://doi.org/10.1111/sms.12541.

Hespanhol Junior, L., de Carvalho, A.C.A., Costa, L.O.P. and Lopes, A.D. (2016) 'Lower limb alignment characteristics are not associated with running injuries in runners: Prospective cohort study', *European Journal of Sport Science*, 16(8), pp. 1137–1144. Available at: https://doi.org/10.1080/17461391.2016.1195878.

Hespanhol Junior, L., van Mechelen, W., Postuma, E. and Verhagen, E. (2016) 'Health and economic burden of running-related injuries in runners training for an event: A prospective cohort study', *Scandinavian journal of medicine & science in sports*, 26(9), pp. 1091–1099. Available at: https://doi.org/10.1111/sms.12541.

Hespanhol Junior, L.C., van Mechelen, W. and Verhagen, E. (2017) 'Health and Economic Burden of

Running-Related Injuries in Dutch Trailrunners: A Prospective Cohort Study', *Sports Medicine*, 47(2), pp. 367–377. Available at: https://doi.org/10.1007/s40279-016-0551-8.

Hespanhol Junior, Pena Costa, L. and Dias Lopes, A. (2013) 'Previous injuries and some training characteristics predict running-related injuries in recreational runners: a prospective cohort study', *Australian Journal of Physiotherapy*, 59, pp. 263–269. Available at: https://doi.org/10.1016/S1836-9553(13)70203-0.

Hirschmüller, A., Frey, V., Konstantinidis, L., Baur, H., Dickhuth, H.H., Südkamp, N.P. and Helwig, P. (2012) 'Prognostic value of achilles tendon doppler sonography in asymptomatic runners', *Medicine and Science in Sports and Exercise*, 44(2), pp. 199–205. Available at: https://doi.org/10.1249/MSS.0b013e31822b7318.

Hollander, K., Johnson, C.D., Outerleys, J. and Davis, I.S. (2020) 'Multifactorial Determinants of Running Injury Locations in 550 Injured Recreational Runners', *Medicine & Science in Sports & Exercise*, Publish Ah. Available at: https://doi.org/10.1249/mss.0000000000002455.

Hollander, K., Johnson, C.D., Outerleys, J. and Davis, I.S. (2021) 'Multifactorial Determinants of Running Injury Locations in 550 Injured Recreational Runners', *Medicine and Science in Sports and Exercise*, 53(1), pp. 102–107. Available at: https://doi.org/10.1249/MSS.0000000000002455.

Hollander, K., Rahlf, A.L., Wilke, J., Edler, C., Steib, S., Junge, A. and Zech, A. (2021) 'Sex-Specific Differences in Running Injuries: A Systematic Review with Meta-Analysis and Meta-Regression', *Sports Medicine*, pp. 1011–1039. Available at: https://doi.org/10.1007/s40279-020-01412-7.

Hollander, K., Zech, A., Rahlf, A.L., Orendurff, M.S., Stebbins, J. and Heidt, C. (2019) 'The relationship between static and dynamic foot posture and running biomechanics: A systematic review and meta-analysis', *Gait and Posture*, pp. 109–122. Available at: https://doi.org/10.1016/j.gaitpost.2019.05.031.

Van Hooren, B., Fuller, J.T., Buckley, J.D., Miller, J.R., Sewell, K., Rao, G., Barton, C., Bishop, C. and Willy, R.W. (2020) 'Is Motorized Treadmill Running Biomechanically Comparable to Overground Running? A Systematic Review and Meta-Analysis of Cross-Over Studies', *Sports Medicine*, pp. 785–813. Available at: https://doi.org/10.1007/s40279-019-01237-z.

Horsley, B.J., Tofari, P.J., Halson, S.L., Kemp, J.G., Dickson, J., Maniar, N. and Cormack, S.J. (2021) *Does Site Matter? Impact of Inertial Measurement Unit Placement on the Validity and Reliability of Stride Variables During Running: A Systematic Review and Meta-analysis*, *Sports Medicine*. Springer International Publishing. Available at: https://doi.org/10.1007/s40279-021-01443-8.

Hosmer, D.W., Lemeshow, S. and Sturdivant, R.X. (2013) *Applied Logistic Regression, 3rd Edition*. Wiley.

Hreljac, A. (2004) 'Impact and Overuse Injuries in Runners', *Med. Sci. Sports Exerc*, 36(5), pp. 845–849. Available at: https://doi.org/10.1249/01.MSS.0000126803.66636.DD.

Hreljac, A., Marshall, R. and Hume, P. (2000) ‘Evaluation of lower extremity overuse injury potential in runners’, *Medicine & Science in Sports & Exercise*, 32(9), pp. 1635–1641. Available at: https://doi.org/10.1097/00005768-200009000-00018.

Hubbard, T.J., Carpenter, E.M. and Cordova, M.L. (2009) ‘Contributing factors to medial tibial stress syndrome: A prospective investigation’, *Medicine and Science in Sports and Exercise*, 41(3), pp. 490–496. Available at: https://doi.org/10.1249/MSS.0b013e31818b98e6.

Hübscher, M., Zech, A., Pfeifer, K., Hänsel, F., Vogt, L. and Banzer, W. (2010) ‘Neuromuscular training for sports injury prevention: A systematic review’, *Medicine and Science in Sports and Exercise*, 42(3), pp. 413–421. Available at: https://doi.org/10.1249/MSS.0b013e3181b88d37.

Hulme, A., Rasmus, •, Nielsen, O., Toomas Timpka, •, Evert Verhagen, •, Finch, C., Nielsen, R.O., Timpka, T. and Verhagen, E. (2017) ‘Risk and Protective Factors for Middle- and Long-Distance Running-Related Injury’, *Sports Med*, 47, pp. 869–886. Available at: https://doi.org/10.1007/s40279-016-0636-4.

Hulme, A., Salmon, P., Nielsen, R.O., Read, G.J.M. and Finch, C.F. (2017) ‘From control to causation: Validating a “complex systems model” of running-related injury development and prevention’, *Applied Ergonomics*, 65, pp. 345–354. Available at: https://doi.org/10.1016/j.apergo.2017.07.005.

Hulme, A., Thompson, J., Nielsen, R., Read, G. and Salmon, P. (2019) ‘Towards a complex systems approach in sports injury research: Simulating running-related injury development with agent-based modelling’, *British Journal of Sports Medicine*, pp. 560–569. Available at: https://doi.org/10.1136/bjsports-2017-098871.

Ithurburn, M.P., Paterno, M. V., Ford, K.R., Hewett, T.E. and Schmitt, L.C. (2015) ‘Young athletes with quadriceps femoris strength asymmetry at return to sport after anterior cruciate ligament reconstruction demonstrate asymmetric single-leg drop-landing mechanics’, *American Journal of Sports Medicine*, 43(11), pp. 2727–2737. Available at: https://doi.org/10.1177/0363546515602016.

Iverson, G. (2007) ‘Predicting slow recovery from sport-related concussion: The new simple-complex distinction’, *Clinical Journal of Sport Medicine*, 17(1), pp. 31–37. Available at: https://doi.org/10.1097/JSM.0b013e3180305e4d.

Jakobsen, B.W., Króner, K., Schmidt, S.A. and Kjeldsen, A. (1994) ‘Prevention of injuries in long-distance runners’, *Knee Surgery, Sports Traumatology, Arthroscopy*, 2(4), pp. 245–249. Available at: https://doi.org/10.1007/BF01845597.

Jaric, S. (2002) ‘Muscle strength testing: Use of normalisation for body size’, *Sports Medicine*, 32(10), pp. 615–631. Available at: https://doi.org/10.2165/00007256-200232100-00002.

Johnson, C.D., Outerleys, J., Tenforde, A.S. and Davis, I.S. (2020) ‘A comparison of attachment methods of skin mounted inertial measurement units on tibial accelerations’, *Journal of Biomechanics*, 113, p. 110118. Available at: https://doi.org/10.1016/j.jbiomech.2020.110118.

Johnson, C.D., Tenforde, A.S., Outerleys, J., Reilly, J. and Davis, I.S. (2020) 'Impact-Related Ground Reaction Forces Are More Strongly Associated With Some Running Injuries Than Others', *American Journal of Sports Medicine*, 48(12), pp. 3072–3080. Available at: https://doi.org/10.1177/0363546520950731.

Juhler, C., Andersen, K.B., Nielsen, R.O. and Bertelsen, M.L. (2020) 'Knee injuries in normal-weight, overweight, and obese runners: Does body mass index matter?', *Journal of Orthopaedic and Sports Physical Therapy,* 50(7), pp. 397–401. Available at: https://doi.org/10.2519/jospt.2020.9233.

Jungmalm, J., Nielsen, R.Ø., Desai, P., Karlsson, J., Hein, T. and Grau, S. (2020) 'Associations between biomechanical and clinical/anthropometrical factors and running-related injuries among recreational runners: A 52-week prospective cohort study', *Injury Epidemiology,* 7(1). Available at: https://doi.org/10.1186/s40621-020-00237-2.

Kakouris, N., Yener, N. and Fong, D.T.P. (2021) 'A systematic review of running-related musculoskeletal injuries in runners', *Journal of Sport and Health Science*. Elsevier B.V., pp. 0–27. Available at: https://doi.org/10.1016/j.jshs.2021.04.001.

Kalkhoven, J.T., Watsford, M.L., Coutts, A.J., Edwards, W.B. and Impellizzeri, F.M. (2021) 'Training Load and Injury: Causal Pathways and Future Directions', *Sports Medicine,* 51(6), pp. 1137–1150. Available at: https://doi.org/10.1007/S40279-020-01413-6.

Kalkhoven, J.T., Watsford, M.L. and Impellizzeri, F.M. (2020) 'A conceptual model and detailed framework for stress-related, strain-related, and overuse athletic injury', *Journal of Science and Medicine in Sport,* 23, pp. 726–734. Available at: https://doi.org/10.1016/j.jsams.2020.02.002.

Keller, T.S., Weisberger, A.M., Ray, J.L., Hasan, S.S., Shiavi, R.G. and Spengler, D.M. (1996) 'Relationship between vertical ground reaction force and speed during walking, slow jogging, and running', *Clinical Biomechanics,* 11(5), pp. 253–259. Available at: https://doi.org/10.1016/0268-0033(95)00068-2.

Kelsey, J.L., Bachrach, L.K., Procter-Gray, E., Nieves, J., Greendale, G.A., Sowers, M., Brown, B.W., Matheson, K.A., Crawford, S.L. and Cobb, K.L. (2007) 'Risk factors for stress fracture among young female cross-country runners', *Medicine and Science in Sports and Exercise,* 39(9), pp. 1457–1463. Available at: https://doi.org/10.1249/mss.0b013e318074e54b.

Kemler, E., Blokland, D., Backx, F. and Huisstede, B. (2018) 'Differences in injury risk and characteristics of injuries between novice and experienced runners over a 4-year period', *Physician and Sportsmedicine,* 46(4), pp. 485–491. Available at: https://doi.org/10.1080/00913847.2018.1507410.

Kendall, F., Kendall McCreary, E., Geise Provance, P., McIntyre Rodgers, M. and Romani, W. (2005) *Muscles: Testing and Function with Posture and Pain.* 5th edn. Baltimore: Lippincott Williams & Wilkins.

Kibler, W. Ben, Goldberg, C. and Chandler, T.J. (1991) 'Functional biomechanical deficits in running athletes with plantar fasciitis', *American Journal of Sports Medicine*, 19(1), pp. 66–71. Available at: https://doi.org/10.1177/036354659101900111.

Kiernan, D., Hawkins, D.A., Manoukian, M.A.C., McKallip, M., Oelsner, L., Caskey, C.F. and Coolbaugh, C.L. (2018) 'Accelerometer-based prediction of running injury in National Collegiate Athletic Association track athletes', *Journal of Biomechanics*, 73, pp. 201–209. Available at: https://doi.org/10.1016/j.jbiomech.2018.04.001.

King, P.H. (2020) 'Biomechanics and Gait Analysis, 1st ed.', *IEEE Pulse*, 11(6), pp. 34–34. Available at: https://doi.org/10.1109/mpuls.2020.3036149.

Kline, P. and Williams, D. (2015) 'Effects of Normal Aging on Lower Extremity Loading and Coordination During Running in Males and Females.', *International journal of sports physical therapy*, 10(6), pp. 901–9.

Kluitenberg, B., van Middelkoop, M., Smits, D.W., Verhagen, E., Hartgens, F., Diercks, R. and van der Worp, H. (2015) 'The NLstart2run study: Incidence and risk factors of running-related injuries in novice runners', *Scandinavian Journal of Medicine and Science in Sports*, 25(5), pp. e515–e523. Available at: https://doi.org/10.1111/sms.12346.

Kluitenberg, B., van Middelkoop, M., Verhagen, E., Hartgens, F., Huisstede, B., Diercks, R. and van der Worp, H. (2016) 'The impact of injury definition on injury surveillance in novice runners', *Journal of Science and Medicine in Sport*, 19(6), pp. 470–475. Available at: https://doi.org/10.1016/j.jsams.2015.07.003.

Koldenhoven, R.M., Virostek, A., DeJong, A.F., Higgins, M. and Hertel, J. (2020) 'Increased Contact Time and Strength Deficits in Runners With Exercise-Related Lower Leg Pain', *Journal of Athletic Training*, 55(12), pp. 1247–1254. Available at: https://doi.org/10.4085/1062-6050-0514.19.

Kong, P.W., Koh, T.M.C., Tan, W.C.R. and Wang, Y.S. (2012) 'Unmatched perception of speed when running overground and on a treadmill', *Gait and Posture*, 36(1), pp. 46–48. Available at: https://doi.org/10.1016/j.gaitpost.2012.01.001.

Konor, M.M., Morton, S., Eckerson, J.M. and Grindstaff, T.L. (2012) 'Reliability of three measures of ankle dorsiflexion range of motion.', *International journal of sports physical therapy*, 7(3), pp. 279–87.

Koo, T.K. and Li, M.Y. (2016) 'A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research', *Journal of Chiropractic Medicine*, 15(2), pp. 155–163. Available at: https://doi.org/10.1016/j.jcm.2016.02.012.

Kozinc, Ž. and Šarabon, N. (2017) 'Common Running Overuse Injuries and Prevention', *J. Sports Sci. Med. UDC*, 64125(796).

Krosshaug, T., Steffen, K., Kristianslund, E., Nilstad, A., Mok, K.M., Myklebust, G., Andersen, T.E., Holme, I., Engebretsen, L. and Bahr, R. (2016) 'The Vertical Drop Jump Is a Poor Screening Test for

ACL Injuries in Female Elite Soccer and Handball Players’, *American Journal of Sports Medicine*, 44(4), pp. 874–883. Available at: https://doi.org/10.1177/0363546515625048.

Kuhman, D., Melcher, D. and Paquette, M.R. (2016) ‘Ankle and knee kinetics between strike patterns at common training speeds in competitive male runners’, *European Journal of Sport Science*, 16(4), pp. 433–440. Available at: https://doi.org/10.1080/17461391.2015.1086818.

Kuhman, D.J., Paquette, M.R., Peel, S.A. and Melcher, D.A. (2016) ‘Comparison of ankle kinematics and ground reaction forces between prospectively injured and uninjured collegiate cross country runners’, *Human Movement Science*, 47, pp. 9–15. Available at: https://doi.org/10.1016/j.humov.2016.01.013.

Kulmala, J., Avela, J., Pasanen, K. and Parkkari, J. (2013) ‘Forefoot strikers exhibit lower running-induced knee loading than rearfoot strikers’, *Medicine and Science in Sports and Exercise*, 45(12), pp. 2306–2313. Available at: https://doi.org/10.1249/MSS.0b013e31829efcf7.

Lagas, I.F., Fokkema, T., Verhaar, J.A.N., Bierma-Zeinstra, M.A., Van Middelkoop, M. and De Vos, R.-J. (2020) ‘Incidence of Achilles tendinopathy and associated risk factors in recreational runners: A large prospective cohort study’, *Journal of Science and Medicine in Sport*, 23, pp. 448–452. Available at: https://doi.org/10.1016/j.jsams.2019.12.013.

Landin, D., Thompson, M. and Reid, M. (2015) ‘Knee and Ankle Joint Angles Influence the Plantarflexion Torque of the Gastrocnemius’, *Journal of Clinical Medicine Research*, 7(8), pp. 602–606. Available at: https://doi.org/10.14740/jocmr2107w.

Langley, B., Cramp, M. and Morrison, S.C. (2016a) ‘Clinical measures of static foot posture do not agree’, *Journal of Foot and Ankle Research*, 9(1), pp. 1–6. Available at: https://doi.org/10.1186/s13047-016-0180-3.

Langley, B., Cramp, M. and Morrison, S.C. (2016b) ‘Clinical measures of static foot posture do not agree’, *Journal of Foot and Ankle Research*, 9(1). Available at: https://doi.org/10.1186/s13047-016-0180-3.

Lavcanska, V., Taylor, N.F. and Schache, A.G. (2005) ‘Familiarization to treadmill running in young unimpaired adults’, *Human Movement Science*, 24(4), pp. 544–557. Available at: https://doi.org/10.1016/j.humov.2005.08.001.

Lee, D., Brellenthin, A., Thompson, P., Sui, X., Lee, I.M. and Lavie, C.J. (2017) ‘Running as a Key Lifestyle Medicine for Longevity’, *Progress in Cardiovascular Diseases*, pp. 45–55. Available at: https://doi.org/10.1016/j.pcad.2017.03.005.

Lee, T.Q., Anzel, S.H., Bennett, K.A., Pang, D. and Kim, W.C. (1994) ‘The influence of fixed rotational deformities of the femur on the patellofemoral contact pressures in human cadaver knees’, in *Clinical Orthopaedics and Related Research*, pp. 69–74. Available at: https://doi.org/10.1097/00003086-199405000-00013.

Lee, T.Q., Morris, G. and Csintalan, R.P. (2003) ‘magnitude of random variation’, *Journal of Orthopaedic and Sports Physical Therapy*, 33(11), pp. 686–693. Available at: https://doi.org/10.2519/jospt.2003.33.11.686.

Lees, A., Lake, M. and Klenerman, L. (2005) ‘Shock absorption during forefoot running and its relationship to medial longitudinal arch height’, *Foot and Ankle International*, 26(12), pp. 1081–1088. Available at: https://doi.org/10.1177/107110070502601214.

Leetun, D.T., Ireland, M.L., Willson, J.D., Ballantyne, B.T. and Davis, I.M.C. (2004) ‘Core stability measures as risk factors for lower extremity injury in athletes’, *Medicine and Science in Sports and Exercise*, 36(6), pp. 926–934. Available at: https://doi.org/10.1249/01.MSS.0000128145.75199.C3.

Leppe, J. and Besomi, M. (2018) ‘Recent Versus Old Previous Injury and Its Association with Running-Related Injuries During Competition by SeRUN® Running Profiles: a Cross-sectional Study’, *Sports Medicine - Open*, 4(1). Available at: https://doi.org/10.1186/s40798-018-0164-x.

Lohman, E.B., Balan Sackiriyas, K.S. and Swen, R.W. (2011) ‘A comparison of the spatiotemporal parameters, kinematics, and biomechanics between shod, unshod, and minimally supported running as compared to walking’, *Physical Therapy in Sport*, pp. 151–163. Available at: https://doi.org/10.1016/j.ptsp.2011.09.004.

Lopes, A.D., Costa, L.O.P., Saragiotto, B.T., Yamato, T.P., Adami, F. and Verhagen, E. (2011) ‘Musculoskeletal pain is prevalent among recreational runners who are about to compete: An observational study of 1049 runners’, *Journal of Physiotherapy*, 57(3), pp. 179–182. Available at: https://doi.org/10.1016/S1836-9553(11)70039-X.

Lopes, A.D., Hespanhol, L.C., Yeung, S.S. and Costa, L.O.P. (2012) ‘What are the Main Running-Related Musculoskeletal Injuries?’, *Sports Medicine*, 42(10), pp. 891–905. Available at: https://doi.org/10.1007/bf03262301.

Loudon, J.K. and Reiman, M.P. (2012) ‘Lower extremity kinematics in running athletes with and without a history of medial shin pain.’, *International journal of sports physical therapy*, 7(4), pp. 356–64.

Luedke, L.E., Heiderscheit, B.C., Williams, D.S.B. and Rauh, M.J. (2015) ‘Association of Isometric Strength of Hip and Knee Muscles With Injury Risk in High School Cross Country Runners.’, *International journal of sports physical therapy*, 10(6), pp. 868–76.

Luedke, L.E., Heiderscheit, B.C., Williams, D.S.B. and Rauh, M.J. (2016) ‘Influence of Step Rate on Shin Injury and Anterior Knee Pain in High School Runners’, *Medicine and Science in Sports and Exercise*, 48(7), pp. 1244–1250. Available at: https://doi.org/10.1249/MSS.0000000000000890.

Luginick, B.S., Ojeda, J.R., García, C.C., Fernández, S.V. and Cabello, E.N. (2018) ‘Kinematics of recreational runners with iliotibial band injury’, *Journal of Human Sport and Exercise*, 13(3), pp. 698–709. Available at: https://doi.org/10.14198/jhse.2018.133.19.

Lun, V., Meeuwisse, W., Stergiou, P. and Stefanyshyn, D. (2004) ‘Relation between running injury and static lower limb alignment in recreational runners’, *British Journal of Sports Medicine*, 38(5), pp. 576–580. Available at: https://doi.org/10.1136/bjsm.2003.005488.

Luz, B.C., dos Santos, A.F., de Souza, M.C., de Oliveira Sato, T., Nawoczenski, D.A. and Serrão, F.V. (2018) ‘Relationship between rearfoot, tibia and femur kinematics in runners with and without patellofemoral pain’, *Gait and Posture*, 61, pp. 416–422. Available at: https://doi.org/10.1016/j.gaitpost.2018.02.008.

Macera, C.A., Pate, R.R., Powell, K.E., Jackson, K.L., Kendrick, J.S. and Craven, T.E. (1989) ‘Predicting lower-extremity injuries among habitual runners’, *Archives of Internal Medicine*, 149(11), pp. 2565–2568. Available at: https://doi.org/10.1001/archinte.149.11.2565.

Makinejad, M.D., Abu Osman, N.A., Wan Abas, W.A.B. and Bayat, M. (2013) ‘Preliminary analysis of knee stress in full extension landing’, *Clinics*, 68(9), pp. 1180–1188. Available at: https://doi.org/10.6061/clinics/2013(09)02.

Malinzak, R.A., Colby, S.M., Kirkendall, D.T., Yu, B. and Garrett, W.E. (2001) ‘A comparison of knee joint motion patterns between men and women in selected athletic tasks’, *Clinical Biomechanics*, 16(5), pp. 438–445. Available at: https://doi.org/10.1016/S0268-0033(01)00019-5.

Malisoux, L, Nielsen, R., Urhausen, A. and Theisen, D. (2015) ‘A step towards understanding the mechanisms of running-related injuries’, *Journal of Science and Medicine in Sport*, 18(5), pp. 523–528. Available at: https://doi.org/10.1016/j.jsams.2014.07.014.

Malisoux, L., Ramesh, J., Mann, R., Seil, R., Urhausen, A. and Theisen, D. (2015) ‘Can parallel use of different running shoes decrease running-related injury risk?’, *Scandinavian Journal of Medicine and Science in Sports*, 25(1), pp. 110–115. Available at: https://doi.org/10.1111/sms.12154.

Mann, R., Malisoux, L., Brunner, R., Gette, P., Urhausen, A., Statham, A., Meijer, K. and Theisen, D. (2014) ‘Reliability and validity of pressure and temporal parameters recorded using a pressure-sensitive insole during running’, *Gait & Posture*, 39(1), pp. 455–459. Available at: https://doi.org/10.1016/j.gaitpost.2013.08.026.

Mann, R., Malisoux, L., Nührenbörger, C., Urhausen, A., Meijer, K. and Theisen, D. (2015) ‘Association of previous injury and speed with running style and stride-to-stride fluctuations’, *Scandinavian Journal of Medicine and Science in Sports*, 25(6), pp. e638–e645. Available at: https://doi.org/10.1111/sms.12397.

Mann, R., Malisoux, L, Urhausen, A., Statham, A., Meijer, K. and Theisen, D. (2015) ‘The effect of shoe type and fatigue on strike index and spatiotemporal parameters of running’, *Gait and Posture*, 42(1), pp. 91–95. Available at: https://doi.org/10.1016/j.gaitpost.2015.04.013.

Manoli, A. and Graham, B. (2005) ‘The subtle cavus foot, “the underpronator,” a review’, *Foot and Ankle International*, pp. 256–263. Available at: https://doi.org/10.1177/107110070502600313.

Marti, B., Vader, J.P., Minder, C.E. and Abelin, T. (1988) 'On the epidemiology of running injuries. The 1984 Bern Grand-Prix study', *American Journal of Sports Medicine*, 16(3), pp. 285–294. Available at: https://doi.org/10.1177/036354658801600316.

Mascaró, A., Cos, M.À., Morral, A., Roig, A., Purdam, C. and Cook, J. (2018) 'Load management in tendinopathy: Clinical progression for Achilles and patellar tendinopath', *Apunts Medicina de l'Esport*, 53(197), pp. 19–27. Available at: https://doi.org/10.1016/j.apunts.2017.11.005.

Mason-Mackay, A.R., Whatman, C. and Reid, D. (2017) 'The effect of reduced ankle dorsiflexion on lower extremity mechanics during landing: A systematic review', *Journal of Science and Medicine in Sport*, 20, pp. 451–458. Available at: https://doi.org/10.1016/j.jsams.2015.06.006.

McCrory, J., Martin, D., Lowery, R., Curl, W., Wayne, D., Jr, H.M. and Monte, D. (1999) *Etiologic factors associated with Achilles tendinitis in runners.*, *Medicine & Science in Sports & Exercise Issue*.

McDowell, C.P., Dishman, R.K., Hallgren, M., MacDonncha, C. and Herring, M.P. (2018) 'Associations of physical activity and depression: Results from the Irish Longitudinal Study on Ageing', *Experimental Gerontology*, 112, pp. 68–75. Available at: https://doi.org/10.1016/j.exger.2018.09.004.

McIntosh, A.S. (2005) 'Risk compensation, motivation, injuries, and biomechanics in competitive sport', *British Journal of Sports Medicine*, 39(1), pp. 2–3. Available at: https://doi.org/10.1136/bjsm.2004.016188.

McKean, K.A., Manson, N.A. and Stanish, W.D. (2006) 'Musculoskeletal injury in the masters runners', *Clinical Journal of Sport Medicine*, 16(2), pp. 149–154. Available at: https://doi.org/10.1097/00042752-200603000-00011.

McMahon, T.A., Valiant, G. and Frederick, E.C. (1987) 'Groucho running', *Journal of Applied Physiology*, 62(6), pp. 2326–2337. Available at: https://doi.org/10.1152/jappl.1987.62.6.2326.

Mcmillan, A. and Payne, C. (2008) 'Effect of foot orthoses on lower extremity kinetics during running: a systematic literature review'. Available at: https://doi.org/10.1186/1757-1146-1-13.

McPoil, T.G. and Cornwall, M.W. (1996) 'The relationship between static lower extremity measurements and rearfoot motion during walking', *Journal of Orthopaedic and Sports Physical Therapy*, 24(5), pp. 309–314. Available at: https://doi.org/10.2519/jospt.1996.24.5.309.

Mcpoil, T.G., Cornwall, M.W., Medoff, L., Vicenzino, B., Forsberg, K. and Hilz, D. (2008) 'Arch height change during sit-to-stand: an alternative for the navicular drop test'. Available at: https://doi.org/10.1186/1757-1146-1-3.

van Mechelen, W. (1992) 'Running Injuries: A Review of the Epidemiological Literature', *Sports Medicine: An International Journal of Applied Medicine and Science in Sport and Exercise*, pp. 320–335. Available at: https://doi.org/10.2165/00007256-199214050-00004.

Van Mechelen, W., Hlobil, H., Kemper, H., Voorn, W.J. and De Jongh, H.R. (1993) 'Prevention of running injuries by warm-up, cool-down, and stretching exercises', *The American Journal of Sports Medicine*, 21(5), pp. 711–719. Available at: https://doi.org/10.1177/036354659302100513.

Van Mechelen, W., Hlobil, H., Kemper, H.C. g., Voorn, W.J. and De Jongh, H.R. (1993) 'Prevention of running injuries by warm-up, cool-down, and stretching exercises', *The American Journal of Sports Medicine*, 21(5), pp. 711–719. Available at: https://doi.org/10.1177/036354659302100513.

van Mechelen, W., Hlobil, H. and Kemper, H.C.G.C. (1992) 'Incidence, Severity, Aetiology and Prevention of Sports Injuries', *Sports Medicine*, 14(2), pp. 82–99. Available at: https://doi.org/10.2165/00007256-199214020-00002.

Meeuwisse, W.H., Tyreman, H., Hagel, B. and Emery, C. (2007a) 'A dynamic model of etiology in sport injury: The recursive nature of risk and causation', *Clinical Journal of Sport Medicine*, pp. 215–219. Available at: https://doi.org/10.1097/JSM.0b013e3180592a48.

Meeuwisse, W.H., Tyreman, H., Hagel, B. and Emery, C. (2007b) 'Dynamic model of etiology', 17(3), pp. 215–219.

Mei, Q., Gu, Y., Xiang, L., Baker, J.S. and Fernandez, J. (2019) 'Foot Pronation Contributes to Altered Lower Extremity Loading After Long Distance Running', *Frontiers in Physiology*, 10, p. 573. Available at: https://doi.org/10.3389/fphys.2019.00573.

Mentiplay, B.F., Perraton, L.G., Bower, K.J., Adair, B., Pua, Y.H., Williams, G.P., McGaw, R. and Clark, R.A. (2015) 'Assessment of lower limb muscle strength and power using hand-held and fixed dynamometry: A reliability and validity study', *PLoS ONE*, 10(10). Available at: https://doi.org/10.1371/journal.pone.0140822.

Mercer, J.A. and Horsch, S. (2015) 'Heel-toe running: A new look at the influence of foot strike pattern on impact force', *Journal of Exercise Science and Fitness*, 13(1), pp. 29–34. Available at: https://doi.org/10.1016/j.jesf.2014.12.001.

Mercer, J.A., Vance, J., Hreljac, A. and Hamill, J. (2002) 'Relationship between shock attenuation and stride length during running at different velocities', *European Journal of Applied Physiology*, 87(4–5), pp. 403–408. Available at: https://doi.org/10.1007/s00421-002-0646-9.

Messier, S., Davis, S., Curl, W.W., Lowery, R.B. and Pack, R.J. (1991) 'Etiologic factors associated with patellofemoral pain in runners', *Medicine and Science in Sports and Exercise*, pp. 1008–1015. Available at: https://doi.org/10.1249/00005768-199109000-00003.

Messier, S., Edwards, D., Martin, D., LOWERY, R., CANNON, D., JAMES, M., CURL, W., READ, H. and HUNTER, D. (1995) 'Etiology of iliotibial band friction syndrome in distance runners', *Medicine & Science in Sports & Exercise*, 27(7), pp. 951–960. Available at: https://doi.org/10.1249/00005768-199507000-00002.

Messier, S.P., Martin, D.F., Mihalko, S.L., Ip, E., DeVita, P., Cannon, D.W., Love, M., Beringer, D., Saldana, S., Fellin, R.E., *et al.* (2018) 'A 2-Year Prospective Cohort Study of Overuse Running

Injuries: The Runners and Injury Longitudinal Study (TRAILS)', *American Journal of Sports Medicine*, 46(9), pp. 2211–2221. Available at: https://doi.org/10.1177/0363546518773755.

Van Middelkoop, M., Kolkman, J., Van Ochten, J., Bierma-Zeinstra, S. and Koes, B. (2008a) 'Prevalence and incidence of lower extremity injuries in male marathon runners', *Scandinavian Journal of Medicine and Science in Sports*, 18(2), pp. 140–144. Available at: https://doi.org/10.1111/j.1600-0838.2007.00683.x.

Van Middelkoop, M., Kolkman, J., Van Ochten, J., Bierma-Zeinstra, S. and Koes, B. (2008b) 'Risk factors for lower extremity injuries among male marathon runners', *Scandinavian Journal of Medicine and Science in Sports*, 18(6), pp. 691–697. Available at: https://doi.org/10.1111/j.1600-0838.2007.00768.x.

Milner, C., Hamill, J. and Davis, I. (2010) 'Distinct hip and rearfoot kinematics in female runners with a history of tibial stress fracture', *Journal of Orthopaedic and Sports Physical Therapy*, 40(2), pp. 59–66. Available at: https://doi.org/10.2519/jospt.2010.3024.

Milner, C.E., Davis, I.S. and Hamill, J. (2006) 'Free moment as a predictor of tibial stress fracture in distance runners', *Journal of Biomechanics*, 39(15), pp. 2819–2825. Available at: https://doi.org/10.1016/j.jbiomech.2005.09.022.

Milner, C.E., Ferber, R., Pollard, C.D., Hamill, J. and Davis, I.S. (2006a) 'Biomechanical factors associated with tibial stress fracture in female runners', *Medicine and Science in Sports and Exercise*, 38(2), pp. 323–328. Available at: https://doi.org/10.1249/01.mss.0000183477.75808.92.

Milner, C.E., Ferber, R., Pollard, C.D., Hamill, J. and Davis, I.S. (2006b) 'Biomechanical Factors Associated with Tibial Stress Fracture in Female Runners', *Med. Sci. Sports Exerc*, 38(2), pp. 323–328. Available at: https://doi.org/10.1249/01.mss.0000183477.75808.92.

Milner, C.E., Hamill, J. and Davis, I. (2007) 'Are knee mechanics during early stance related to tibial stress fracture in runners?', *Clinical Biomechanics*, 22(6), pp. 697–703. Available at: https://doi.org/10.1016/j.clinbiomech.2007.03.003.

Milner, C.E., Hawkins, J.L. and Aubol, K.G. (2020) 'Tibial acceleration during running is higher in field testing than indoor testing', *Medicine and Science in Sports and Exercise*, 52(6), pp. 1361–1366. Available at: https://doi.org/10.1249/MSS.0000000000002261.

Mohr, M., Pieper, R., Löffler, S., Schmidt, A.R. and Federolf, P.A. (2021) 'Sex-Specific Hip Movement Is Correlated With Pelvis and Upper Body Rotation During Running', *Frontiers in Bioengineering and Biotechnology*, 9(June). Available at: https://doi.org/10.3389/fbioe.2021.657357.

Mohseni, M.M., Filmalter, S.E., Taylor, W.C., Vadeboncoeur, T.F. and Thomas, C.S. (2019) 'Factors Associated With Half- and Full-Marathon Race-Related Injuries : A 3-Year Review', 00(00).

Montgomery, G., Abt, G., Dobson, C., Smith, T. and Ditroilo, M. (2016) 'Tibial impacts and muscle activation during walking, jogging and running when performed overground, and on motorised and non-motorised treadmills', *Gait and Posture*, 49, pp. 120–126. Available at: https://doi.org/10.1016/j.gaitpost.2016.06.037.

Moran, K., Richter, C., Farrell, E., Mitchell, E., Ahmadi, A. and O'Connor, N.E. (2015) 'Detection of running asymmetry using a wearable sensor system', *Procedia Engineering*, 112, pp. 180–183. Available at: https://doi.org/10.1016/j.proeng.2015.07.196.

Mountjoy, M., Sundgot-Borgen, J., Burke, L., Carter, S., Constantini, N., Lebrun, C., Meyer, N., Sherman, R., Steffen, K., Budgett, R., *et al.* (2014) 'The IOC consensus statement: Beyond the Female Athlete Triad-Relative Energy Deficiency in Sport (RED-S)', *British Journal of Sports Medicine*, 48(7), pp. 491–497. Available at: https://doi.org/10.1136/bjsports-2014-093502.

Mousavi, S.H., Hijmans, J.M., Minoonejad, H., Rajabi, R. and Zwerver, J. (2021) 'Associated With Lower Limb Injuries in Recreational Runners: A Cross-Sectional Survey Including Mental Aspects and Sleep Quality', *©Journal of Sports Science and Medicine*, 20, pp. 204–215. Available at: https://doi.org/10.52082/jssm.2021.204.

Mucha, M.D., Caldwell, W., Schlueter, E.L., Walters, C. and Hassen, A. (2017) 'Hip abductor strength and lower extremity running related injury in distance runners: A systematic review', *Journal of Science and Medicine in Sport*, 20(4), pp. 349–355. Available at: https://doi.org/10.1016/j.jsams.2016.09.002.

Mukaka, M.M. (2012) 'Statistics corner: A guide to appropriate use of correlation coefficient in medical research', *Malawi Medical Journal*, 24(3), pp. 69–71. Available at: www.mmj.medcol.mw.

Mulvad, B., Nielsen, R., Lind, M. and Ramskov, D. (2018) 'Diagnoses and time to recovery among injured recreational runners in the RUN CLEVER trial', *PLoS ONE*, 13(10). Available at: https://doi.org/10.1371/journal.pone.0204742.

Munnangi, S. and Boktor, S.W. (2019) 'Epidemiology Of Study Design', *StatPearls* [Preprint]. Available at: http://www.ncbi.nlm.nih.gov/pubmed/29262004 (Accessed: 26 August 2022).

Munteanu, B., Journal, B., Munteanu, S.E. and Barton, C.J. (2011) *Lower limb biomechanics during running in individuals with achilles tendinopathy: a systematic review, Foot and Ankle Research*. Available at: https://doi.org/10.1186/1757-1146-4-15.

Murley, G.S., Landorf, K.B., Menz, H.B. and Bird, A.R. (2009) 'Effect of foot posture, foot orthoses and footwear on lower limb muscle activity during walking and running: A systematic review', *Gait and Posture*, pp. 172–187. Available at: https://doi.org/10.1016/j.gaitpost.2008.08.015.

Musumeci, G. (2016) 'The effect of mechanical loading on articular cartilage', *Journal of Functional Morphology and Kinesiology*, pp. 154–161. Available at: https://doi.org/10.3390/jfmk1020154.

Nachbauer, W. and Nigg, B.M. (1992) 'Effects of arch height of the foot on ground reaction forces in running', *Medicine and Science in Sports and Exercise*, 24(11), pp. 1264–1269. Available at: https://doi.org/10.1249/00005768-199211000-00011.

Napier, C., MacLean, C.L., Maurer, J., Taunton, J.E. and Hunt, M.A. (2018) ‘Kinetic risk factors of running-related injuries in female recreational runners’, *Scandinavian Journal of Medicine and Science in Sports*, 28(10), pp. 2164–2172. Available at: https://doi.org/10.1111/sms.13228.

Napier, C., MacLean, C.L., Maurer, J., Taunton, J.E. and Hunt, M.A. (2019) ‘Kinematic correlates of kinetic outcomes associated with running-related injury’, *Journal of Applied Biomechanics*, 35(2), pp. 123–130. Available at: https://doi.org/10.1123/jab.2018-0203.

Neal, B.S., Griffiths, I.B., Dowling, G.J., Murley, G.S., Munteanu, S.E., Franettovich Smith, M.M., Collins, N.J. and Barton, C.J. (2014) ‘Foot posture as a risk factor for lower limb overuse injury: a systematic review and meta-analysis’, *Journal of Foot and Ankle Research*, 7(1), p. 55. Available at: https://doi.org/10.1186/s13047-014-0055-4.

Neal, B.S., Lack, S.D., Lankhorst, N.E., Raye, A., Morrissey, D. and Van Middelkoop, M. (2019) ‘Risk factors for patellofemoral pain: A systematic review and meta-analysis’, *British Journal of Sports Medicine*, pp. 270–281. Available at: https://doi.org/10.1136/bjsports-2017-098890.

Newman, P., Witchalls, J., Waddington, G. and Adams, R. (2013) ‘Risk factors associated with medial tibial stress syndrome in runners: a systematic review and meta-analysis’, *Open Access Journal of Sports Medicine*, 2013, p. 229. Available at: https://doi.org/10.2147/oajsm.s39331.

Nielsen, R., Bertelsen, M., Parner, E., Sørensen, H., Lind, M. and Rasmussen, S. (2014) ‘Running more than three kilometers during the first week of a running regimen may be associated with increased risk of injury in obese novice runners.’, *International journal of sports physical therapy*, 9(3), pp. 338–45.

Nielsen, R., Buist, I., Parner, E.T., Nohr, E.A., Sørensen, H., Lind, M. and Rasmussen, S. (2013) ‘Predictors of running-related injuries among 930 novice runners: A 1-year prospective follow-up study’, *Orthopaedic Journal of Sports Medicine*, 1(1), pp. 1–7. Available at: https://doi.org/10.1177/2325967113487316.

Nielsen, R., Parner, E.T., Nohr, E.A., Sørensen, H., Lind, M. and Rasmussen, S. (2014) ‘Excessive progression in weekly running distance and risk of running-related injuries: An association which varies according to type of injury’, *Journal of Orthopaedic and Sports Physical Therapy*, 44(10), pp. 739–747. Available at: https://doi.org/10.2519/jospt.2014.5164.

Nielsen, R., Rønnow, L., Rasmussen, S. and Lind, M. (2014) ‘A prospective study on time to recovery in 254 injured novice runners’, *PLoS ONE*, 9(6), p. 99877. Available at: https://doi.org/10.1371/journal.pone.0099877.

Nielsen, R.O., Buist, I., Sørensen, H., Lind, M. and Rasmussen, S. (2012) ‘Training errors and running related injuries: a systematic review.’, *International journal of sports physical therapy*, 7(1), pp. 58–75.

Niemuth, P.E., Johnson, R.J., Myers, M.J. and Thieman, T.J. (2005) ‘Hip muscle weakness and overuse injuries in recreational runners’, *Clinical Journal of Sport Medicine*, 15(1), pp. 14–21.

Available at: https://doi.org/10.1097/00042752-200501000-00004.

Nigg, B.M. (1985) ‘Biomechanics, Load Analysis and Sports Injuries in the Lower Extremities’, *Sports Medicine: An International Journal of Applied Medicine and Science in Sport and Exercise*, pp. 367–379. Available at: https://doi.org/10.2165/00007256-198502050-00005.

Nillson, R. and Thorstensson, A. (1989) ‘Ground reaction forces at different speeds of human walking and running’, *Acta Physiologica Scandinavica*, 136(2), pp. 217–227. Available at: https://doi.org/10.1111/j.1748-1716.1989.tb08655.x.

Noehren, B., Davis, I. and Hamill, J. (2007) ‘ASB Clinical Biomechanics Award Winner 2006. Prospective study of the biomechanical factors associated with iliotibial band syndrome’, *Clinical Biomechanics*, 22(9), pp. 951–956. Available at: https://doi.org/10.1016/j.clinbiomech.2007.07.001.

Noehren, B., Pohl, M., Sanchez, Z., Cunningham, T. and Lattermann, C. (2012) ‘Proximal and distal kinematics in female runners with patellofemoral pain’, *Clinical Biomechanics*, 27Noehren,(4), pp. 366–371. Available at: https://doi.org/10.1016/j.clinbiomech.2011.10.005.

Noehren, B., Sanchez, Z., Cunningham, T. and McKeon, P.O. (2012) ‘The effect of pain on hip and knee kinematics during running in females with chronic patellofemoral pain’, *Gait and Posture*, 36(3), pp. 596–599. Available at: https://doi.org/10.1016/j.gaitpost.2012.05.023.

Noehren, B., Schmitz, A., Hempel, R., Westlake, C. and Black, W. (2014a) ‘Assessment of Strength, Flexibility, and Running Mechanics in Males with Iliotibial Band Syndrome’, *Journal of Orthopaedic & Sports Physical Therapy*, 78(2), pp. 711–716. Available at: https://doi.org/10.2519/jospt.2014.4991.Assessment.

Noehren, B., Schmitz, A., Hempel, R., Westlake, C. and Black, W. (2014b) ‘Assessment of Strength, Flexibility, and Running Mechanics in Men With Iliotibial Band Syndrome’, *Journal of Orthopaedic & Sports Physical Therapy*, 44(3), pp. 217–222. Available at: https://doi.org/10.2519/jospt.2014.4991.

Noehren, B., Scholz, J. and Davis, I. (2011) ‘The effect of real-time gait retraining on hip kinematics, pain and function in subjects with patellofemoral pain syndrome’, *British Journal of Sports Medicine*, 45(9), pp. 691–696. Available at: https://doi.org/10.1136/bjsm.2009.069112.

Nohr, E.A., Parner, E.T., Sørensen, H., Buist, I., Rasmussen, S., Lind, M. and Nielsen, R.O. (2013) ‘Foot pronation is not associated with increased injury risk in novice runners wearing a neutral shoe: a 1-year prospective cohort study’, *British Journal of Sports Medicine*, 48(6), pp. 440–447. Available at: https://doi.org/10.1136/bjsports-2013-092202.

Novacheck, T.F. (1998) ‘The biomechanics of running’, *Gait and Posture*, pp. 77–95. Available at: https://doi.org/10.1016/S0966-6362(97)00038-6.

Nunns, M., House, C., Fallowfield, J., Allsopp, A. and Dixon, S. (2013) ‘Biomechanical characteristics of barefoot footstrike modalities’, *Journal of Biomechanics*, 46(15), pp. 2603–2610. Available at: https://doi.org/10.1016/j.jbiomech.2013.08.009.

Ogon, M., Aleksiev, A.R., Pope, M.H., Wimmer, C. and Saltzman, C.L. (1999) 'Does arch height affect impact loading at the lower back level in running?', *Foot and Ankle International*, 20(4), pp. 263–266. Available at: https://doi.org/10.1177/107110079902000410.

Ogwumike, O.O. and Adeniyi, A.F. (2013) 'The SPLASH/ICPC integrity marathon in Ibadan, Nigeria: Incidence and management of injuries and marathon-related health problems', *BMC Sports Science, Medicine and Rehabilitation*, 5(1). Available at: https://doi.org/10.1186/2052-1847-5-6.

Oliveira, A.S., Gizzi, L., Ketabi, S., Farina, D. and Kersting, U.G. (2016) 'Modular Control of Treadmill vs Overground Running', *PLoS ONE*, 11(4), p. 153307. Available at: https://doi.org/10.1371/journal.pone.0153307.

Orendurff, M.S., Kobayashi, T., Tulchin-Francis, K., Tullock, A.M.H., Villarosa, C., Chan, C. and Strike, S. (2018) 'A little bit faster: Lower extremity joint kinematics and kinetics as recreational runners achieve faster speeds', *Journal of Biomechanics*, 71, pp. 167–175. Available at: https://doi.org/10.1016/j.jbiomech.2018.02.010.

Pamukoff, D.N. and Blackburn, J.T. (2015) 'Comparison of plantar flexor musculotendinous stiffness, geometry, and architecture in male runners with and without a history of tibial stress fracture', *Journal of Applied Biomechanics*, 31(1), pp. 41–47. Available at: https://doi.org/10.1123/JAB.2014-0127.

Paquette, M.R., Milner, C.E. and Melcher, D.A. (2017) 'Foot contact angle variability during a prolonged run with relation to injury history and habitual foot strike pattern', *Scandinavian Journal of Medicine and Science in Sports*, 27(2), pp. 217–222. Available at: https://doi.org/10.1111/sms.12647.

Park, S.-K., Koo, S., Yoon, S.-H., Park, S., Kim, Y. and Ryu, J.-S. (2018) 'Gender Differences in Ground Reaction Force Components', *Korean Journal of Sport Biomechanics*, 28(2), pp. 101–108. Available at: http://dx.doi.org/10.5103/KJSB.2018.28.2.101.

Peng, L., Seay, A.N., Montero, C., Barnes, L.L., Vincent, K.R., Conrad, B.P., Chen, C. and Vincent, H.K. (2015) 'Metabolic, cardiopulmonary, and gait profiles of recently injured and noninjured runners', *PM and R*, 7(1), pp. 26–33. Available at: https://doi.org/10.1016/j.pmrj.2014.06.013.

Pérez-Morcillo, A., Gómez-Bernal, A., Gil-Guillen, V.F., Alfaro-Santafé, J., Alfaro-Santafé, J.V., Quesada, J.A., Lopez-Pineda, A., Orozco-Beltran, D. and Carratalá-Munuera, C. (2019) 'Association between the Foot Posture Index and running related injuries: A case-control study', *Clinical Biomechanics*, 61, pp. 217–221. Available at: https://doi.org/10.1016/j.clinbiomech.2018.12.019.

Perry, J. and Burnfield, J.M. (1992) *Gait Analysis: Normal and Pathological Function*. 2nd Editio. Slack Incorporated.

Peterson, B., Hawke, F., Spink, M., Sadler, S., Hawes, M., Callister, R. and Chuter, V. (2022) 'Biomechanical and Musculoskeletal Measurements as Risk Factors for Running-Related Injury in Non-elite Runners: A Systematic Review and Meta-analysis of Prospective Studies', *Sports Medicine - Open*. Available at: https://doi.org/10.1186/s40798-022-00416-z.

Plastaras, C., McCormick, Z., Nguyen, C., Rho, M., Nack, S.H., Roth, D., Casey, E., Carneiro, K., Cucchiara, A., Press, J., *et al.* (2016) ‘Is Hip Abduction Strength Asymmetry Present in Female Runners in the Early Stages of Patellofemoral Pain Syndrome?’, *American Journal of Sports Medicine*, 44(1), pp. 105–112. Available at: https://doi.org/10.1177/0363546515611632.

Pless, I.B. and Hagel, B.E. (2005) ‘Injury prevention: A glossary of terms’, *Journal of Epidemiology and Community Health*, pp. 182–185. Available at: https://doi.org/10.1136/jech.2003.017715.

Plisky, M.S., Rauh, M.J., Heiderscheit, B., Underwood, F.B. and Tank, R.T. (2007) ‘Medial tibial stress syndrome in high school cross-country runners: Incidence and risk factors’, *Journal of Orthopaedic and Sports Physical Therapy*, 37(2), pp. 40–47. Available at: https://doi.org/10.2519/jospt.2007.2343.

Pohl, M.B., Hamill, J. and Davis, I.S. (2009) ‘Biomechanical and anatomic factors associated with a history of plantar fasciitis in female runners’, *Clinical Journal of Sport Medicine*, 19(5), pp. 372–376. Available at: https://doi.org/10.1097/JSM.0b013e3181b8c270.

Pohl, M.B., Mullineaux, D.R., Milner, C.E., Hamill, J. and Davis, I.S. (2008) ‘Biomechanical predictors of retrospective tibial stress fractures in runners’, *Journal of Biomechanics*, 41(6), pp. 1160–1165. Available at: https://doi.org/10.1016/j.jbiomech.2008.02.001.

van Poppel, D., Scholten-Peeters, G.G.M., van Middelkoop, M. and Verhagen, A.P. (2014) ‘Prevalence, incidence and course of lower extremity injuries in runners during a 12-month follow-up period’, *Scandinavian Journal of Medicine and Science in Sports*, 24(6), pp. 943–949. Available at: https://doi.org/10.1111/sms.12110.

Powden, C.J., Hoch, J.M. and Hoch, M.C. (2015) ‘Systematic review Reliability and minimal detectable change of the weight-bearing lunge test: A systematic review’. Available at: https://doi.org/10.1016/j.math.2015.01.004.

Powers, C.M. (2003) ‘The Influence of Altered Lower-Extremity Kinematics on Patellofemoral Joint Dysfunction: A Theoretical Perspective’, *Journal of Orthopaedic and Sports Physical Therapy*, pp. 639–646. Available at: https://doi.org/10.2519/jospt.2003.33.11.639.

Powers, C.M. (2010) ‘The Influence of Abnormal Hip Mechanics on Knee Injury: A Biomechanical Perspective’, *Journal of Orthopaedic & Sports Physical Therapy*, 40(2), pp. 42–51. Available at: https://doi.org/10.2519/jospt.2010.3337.

Preece, S.J., Mason, D. and Bramah, C. (2016) ‘The coordinated movement of the spine and pelvis during running’, *Human Movement Science*, 45, pp. 110–118. Available at: https://doi.org/10.1016/j.humov.2015.11.014.

Preiss, D. and Fisher, J. (2008) ‘A measure of confidence in Bland - Altman analysis for the interchangeability of two methods of measurement’, *Journal of Clinical Monitoring and Computing*, 22(4), pp. 257–259. Available at: https://doi.org/10.1007/s10877-008-9127-y.

Premkumar, A., Almeida, B., Ranawat, C.S., Jerabek, S.A., Esposito, C.I. and Mayman, D.J. (2021) 'Variability of pelvic axial rotation in patients undergoing total hip arthroplasty', *HIP International*, 31(2), pp. 215–222. Available at: https://doi.org/10.1177/1120700019889618.

Räisänen, A.M., Pasanen, K., Krosshaug, T., Vasankari, T., Kannus, P., Heinonen, A., Kujala, U.M., Avela, J., Perttunen, J. and Parkkari, J. (2018) 'Association between frontal plane knee control and lower extremity injuries: A prospective study on young team sport athletes', *BMJ Open Sport and Exercise Medicine*, 4(1). Available at: https://doi.org/10.1136/bmjsem-2017-000311.

Raissi, G.R.D., Cherati, A.D.S., Mansoori, K.D. and Razi, M.D. (2009) 'The relationship between lower extremity alignment and Medial Tibial Stress Syndrome among non-professional athletes', *BMC Sports Science, Medicine and Rehabilitation*, 1(1), p. 11. Available at: https://doi.org/10.1186/1758-2555-1-11.

Ramskov, D., Barton, C., Nielsen, R.O. and Rasmussen, S. (2015) 'High eccentric hip abduction strength reduces the risk of developing patellofemoral pain among novice runners initiating a self-structured running program: A 1-year observational study', *Journal of Orthopaedic and Sports Physical Therapy*, 45(3), pp. 153–161. Available at: https://doi.org/10.2519/jospt.2015.5091.

Ramskov, D., Jensen, M.L., Obling, K., Nielsen, R., Parner, E.T. and Rasmussen, S. (2013) 'No association between q-angle and foot posture with running-related injuries: a 10 week prospective follow-up study.', *International journal of sports physical therapy*, 8(4), pp. 407–15. Available at: http://www.ncbi.nlm.nih.gov/pubmed/24175127%5Cnhttp://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC3812840.

Ranganathan, P., Aggarwal, R. and Pramesh, C. (2015) 'Common pitfalls in statistical analysis: Odds versus risk', *Perspectives in Clinical Research*, 6(4), p. 222. Available at: https://doi.org/10.4103/2229-3485.167092.

Rasmussen, C.H., Nielsen, R.O., Juul, M.S. and Rasmussen, S. (2013) 'Weekly running volume and risk of running-related injuries among marathon runners.', *International journal of sports physical therapy*, 8(2), pp. 111–20. Available at: http://www.ncbi.nlm.nih.gov/pubmed/23593549%0Ahttp://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC3625790.

Redmond, A.C., Crosbie, J. and Ouvrier, R.A. (2006) 'Development and validation of a novel rating system for scoring standing foot posture: The Foot Posture Index', *Clinical Biomechanics*, 21(1), pp. 89–98. Available at: https://doi.org/10.1016/j.clinbiomech.2005.08.002.

Reinking, M.F., Austin, T.M. and Hayes, A.M. (2007) 'Exercise-related leg pain in collegiate cross-country athletes: Extrinsic and intrinsic risk factors', *Journal of Orthopaedic and Sports Physical Therapy*, 37(11), pp. 670–678. Available at: https://doi.org/10.2519/jospt.2007.2534.

Reinking, M.F., Austin, T.M. and Hayes, A.M. (2013) 'A survey of exercise-related leg pain in community runners.', *International journal of sports physical therapy*, 8(3), pp. 269–76. Available at:

http://www.ncbi.nlm.nih.gov/pubmed/23772343%0Ahttp://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC3679633 (Accessed: 23 June 2020).

Resende, R.A., Pinheiro, L.S.P. and Ocarino, J.M. (2019) 'Effects of foot pronation on the lower limb sagittal plane biomechanics during gait', *Gait and Posture*, 68, pp. 130–135. Available at: https://doi.org/10.1016/j.gaitpost.2018.10.025.

Ribeiro, A.P., Maria, S., João, A., Casanova Dinato, R., Tessutti, V.D., Camargo, I. and Sacco, N. (2015) *Dynamic Patterns of Forces and Loading Rate in Runners with Unilateral Plan...: EBSCOhost*, *PLoS ONE*. Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4574154/pdf/pone.0136971.pdf (Accessed: 9 April 2018).

Richter, C., O'Connor, N.E., Marshall, B. and Moran, K. (2014) 'Comparison of discrete-point vs. dimensionality-reduction techniques for describing performance-related aspects of maximal vertical jumping', *Journal of Biomechanics*, 47(12), pp. 3012–3017. Available at: https://doi.org/10.1016/j.jbiomech.2014.07.001.

Riley, P.O., Dicharry, J., Franz, J., Croce, U. Della, Wilder, R.P. and Kerrigan, D.C. (2008) 'A kinematics and kinetic comparison of overground and treadmill running', *Medicine and Science in Sports and Exercise*, 40(6), pp. 1093–1100. Available at: https://doi.org/10.1249/MSS.0b013e3181677530.

Roche-Seruendo, L.E., García-Pinillos, F., Haicaguerre, J., Bataller-Cervero, A. V., Soto-Hermoso, V.M. and Latorre-Román, P.Á. (2018) 'Lack of Influence of Muscular Performance Parameters on Spatiotemporal Adaptations With Increased Running Velocity', *Journal of Strength and Conditioning Research*, 32(2), pp. 409–415. Available at: https://doi.org/10.1519/JSC.0000000000001845.

Rossi, A., Pappalardo, L., Cintia, P., Iaia, F.M., Fernàndez, J. and Medina, D. (2018) 'Effective injury forecasting in soccer with GPS training data and machine learning'. Available at: https://doi.org/10.1371/journal.pone.0201264.

Ruder, M., Jamison, S.T., Tenforde, A., Mulloy, F. and Davis, I.S. (2019) 'Relationship of Foot Strike Pattern and Landing Impacts during a Marathon', *Medicine and Science in Sports and Exercise*, 51(10), pp. 2073–2079. Available at: https://doi.org/10.1249/MSS.0000000000002032.

Rueterbories, J., Spaich, E.G., Larsen, B. and Andersen, O.K. (2010) 'Methods for gait event detection and analysis in ambulatory systems', *Medical Engineering and Physics*, pp. 545–552. Available at: https://doi.org/10.1016/j.medengphy.2010.03.007.

Running USA (2017) *2017 National Runner Survey | Running USA*, *Running USA 2017 National Runner Survey*. Available at: http://www.runningusa.org/2015-national-runner-survey (Accessed: 25 January 2021).

Sadigursky, D., Braid, J.A., De Lira, D.N.L., Machado, B.A.B., Carneiro, R.J.F. and Colavolpe, P.O. (2017) 'The FIFA 11+ injury prevention program for soccer players: A systematic review', *BMC*

Sports Science, Medicine and Rehabilitation, 9(1), pp. 1–8. Available at: https://doi.org/10.1186/s13102-017-0083-z.

Saeki, J., Nakamura, M., Nakao, S., Fujita, K., Yanase, K., Morishita, K. and Ichihashi, N. (2017) ‘Ankle and toe muscle strength characteristics in runners with a history of medial tibial stress syndrome.’, *Journal of foot and ankle research*, 10, p. 16. Available at: https://doi.org/10.1186/s13047-017-0197-2.

Sahr, M., Sturnick, D.R. and Nwawka, O.K. (2018) ‘Quantitative Ultrasound Assessment of the Achilles Tendon Under Varied Loads’, *Journal of ultrasound in medicine : official journal of the American Institute of Ultrasound in Medicine*, 37(10), pp. 2413–2418. Available at: https://doi.org/10.1002/jum.14589.

Sancho, I., Malliaras, P., Barton, C., Willy, R.W. and Morrissey, D. (2019) ‘Biomechanical alterations in individuals with Achilles tendinopathy during running and hopping: A systematic review with meta-analysis’, *Gait and Posture*, 73(June), pp. 189–201. Available at: https://doi.org/10.1016/j.gaitpost.2019.07.121.

Saragiotto, B.T., Yamato, T.P., Hespanhol Junior, L.C., Rainbow, M.J., Davis, I.S. and Lopes, A.D. (2014) ‘What are the main risk factors for running-related injuries?’, *Sports Medicine*, 44(8), pp. 1153–1163. Available at: https://doi.org/10.1007/s40279-014-0194-6.

Saragiotto, B.T., Yamato, T.P. and Lopes, A.D. (2014) ‘What do recreational runners think about risk factors for running injuries? A descriptive study of their beliefs and opinions’, *Journal of Orthopaedic and Sports Physical Therapy*, 44(10), pp. 733–738. Available at: https://doi.org/10.2519/jospt.2014.5710.

Sasaki, K. and Neptune, R.R. (2006) ‘Differences in muscle function during walking and running at the same speed’, *Journal of Biomechanics*, 39(11), pp. 2005–2013. Available at: https://doi.org/10.1016/j.jbiomech.2005.06.019.

Satterthwaite, P., Norton, R., Larmer, P. and Robinson, E. (1999) ‘Risk factors for injuries and other health problems sustained in a marathon’, *British Journal of Sports Medicine*, 33(1), pp. 22–26. Available at: https://doi.org/10.1136/bjsm.33.1.22.

Schache, A.G., Bennell, K.L., Blanch, P.D. and Wrigley, T. V (1999) *The coordinated movement of the lumbo-pelvic-hip complex during running: a literature review, Gait and Posture*. Available at: www.elsevier.com/locate/gaitpos.

Schache, A.G., Blanch, P., Rath, D., Wrigley, T. and Bennell, K. (2002) ‘Three-dimensional angular kinematics of the lumbar spine and pelvis during running’, *Human Movement Science*, 21(2), pp. 273–293. Available at: https://doi.org/10.1016/S0167-9457(02)00080-5.

Schache, A.G., Blanch, P.D. and Murphy, A.T. (2000) ‘Relation of anterior pelvic tilt during running to clinical and kinematic measures of hip extension.’, *British journal of sports medicine*, 34(4), pp. 279–83. Available at: https://doi.org/10.1136/bjsm.34.4.279.

Schache, A.G., Blanch, P.D., Rath, D.A., Wrigley, T. V. and Bennell, K.L. (2005) ‘Are anthropometric and kinematic parameters of the lumbo-pelvic-hip complex related to running injuries?’, *Research in Sports Medicine*, 13(2), pp. 127–147. Available at: https://doi.org/10.1080/15438620590956133.

Schubert, A.G., Kempf, J. and Heiderscheit, B.C. (2014) ‘Influence of Stride Frequency and Length on Running Mechanics: A Systematic Review’, *Sports Health*, pp. 210–217. Available at: https://doi.org/10.1177/1941738113508544.

Schütte, K.H., Seerden, S., Venter, R. and Vanwanseele, B. (2018) ‘Influence of outdoor running fatigue and medial tibial stress syndrome on accelerometer-based loading and stability’, *Gait and Posture*, 59(October 2017), pp. 222–228. Available at: https://doi.org/10.1016/j.gaitpost.2017.10.021.

Seay, J., Selbie, W.S. and Hamill, J. (2008) ‘In vivo lumbo-sacral forces and moments during constant speed running at different stride lengths’, *Journal of Sports Sciences*, 26(14), pp. 1519–1529. Available at: https://doi.org/10.1080/02640410802298235.

Seay, J.F., Van Emmerik, R.E.A. and Hamill, J. (2014) ‘Trunk bend and twist coordination is affected by low back pain status during running’, *European journal of sport science*, 14(6), pp. 563–568. Available at: https://doi.org/10.1080/17461391.2013.866167.

Sharma, L., Song, J., Felson, D.T., Cahue, S., Shamiyeh, E. and Dunlop, D.D. (2001) ‘The role of knee alignment in disease progression and functional decline in knee osteoarthritis’, *Journal of the American Medical Association*, 286(2), pp. 188–195. Available at: https://doi.org/10.1001/jama.286.2.188.

Sheerin, K., Besier, T., Reid, D. and Hume, P. (2018) ‘The one-week and six-month reliability and variability of three-dimensional tibial acceleration in runners*’, *Sports Biomechanics*, 17(4), pp. 531–540. Available at: https://doi.org/10.1080/14763141.2017.1371214.

Sheerin, K., Reid, D. and Besier, T. (2019) ‘The measurement of tibial acceleration in runners—A review of the factors that can affect tibial acceleration during running and evidence-based guidelines for its use’, *Gait and Posture*, pp. 12–24. Available at: https://doi.org/10.1016/j.gaitpost.2018.09.017.

Shen, P., Mao, D., Zhang, C., Sun, W. and Song, Q. (2021) ‘Effects of running biomechanics on the occurrence of iliotibial band syndrome in male runners during an eight-week running programme—a prospective study’, *Sports Biomechanics*, 20(5), pp. 560–570. Available at: https://doi.org/10.1080/14763141.2019.1584235.

Shorten, M.R. and Winslow, D.S. (1992) *Spectral Analysis of impact Shock During Running*, *INTERNATIONAL JOURNAL OF SPORT BIOMECHANICS*. Available at: https://pdfs.semanticscholar.org/6388/c98b4826c7b1c5586637bf5c363dee0277fc.pdf (Accessed: 28 January 2019).

Silvernail, J.F., Boyer, K., Rohr, E., Brüggemann, G.P. and Hamill, J. (2015) ‘Running Mechanics and Variability with Aging’, *Medicine and Science in Sports and Exercise*, 47(10), pp. 2175–2180.

Available at: https://doi.org/10.1249/MSS.0000000000000633.

Simic, M., Hinman, R.S., Wrigley, T. V, Bennell, K.L. and Hunt, M.A. (2011) ‘Gait Modification Strategies for Altering Medial Knee Joint Load: A Systematic Review’. Available at: https://doi.org/10.1002/acr.20380.

Sinclair, J. (2016) ‘Sex Differences in Shock Attenuation during Running’, *Central European Journal of Sport Sciences and Medicine*, 15(3), pp. 37–42. Available at: https://doi.org/10.18276/cej.2016.3-04.

Smith, J.A.H., McKerrow, A.D. and Kohn, T.A. (2017) ‘Metabolic cost of running is greater on a treadmill with a stiffer running platform’, *Journal of Sports Sciences*, 35(16), pp. 1592–1597. Available at: https://doi.org/10.1080/02640414.2016.1225974.

Smits, D.W., Huisstede, B., Verhagen, E., Van Der Worp, H., Kluitenberg, B., Van Middelkoop, M., Hartgens, F. and Backx, F. (2016) ‘Short-Term Absenteeism and Health Care Utilization Due to Lower Extremity Injuries among Novice Runners: A Prospective Cohort Study’, *Clinical Journal of Sport Medicine*, 26(6), pp. 502–509. Available at: https://doi.org/10.1097/JSM.0000000000000287.

Snyder, K.R., Earl, J.E., O’Connor, K.M. and Ebersole, K.T. (2009) ‘Resistance training is accompanied by increases in hip strength and changes in lower extremity biomechanics during running’, *Clinical Biomechanics*, 24(1), pp. 26–34. Available at: https://doi.org/10.1016/j.clinbiomech.2008.09.009.

Soligard, T., Schwellnus, M., Alonso, J.-M., Bahr, R., Clarsen, B., Dijkstra, P., Gabbett, T., Gleeson, M., Hägglund, M., Hutchinson, M.R., *et al.* (2016) ‘How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury’, 50, pp. 1030–1041. Available at: https://doi.org/10.1136/bjsports-2016-096581.

Souza, R. and Powers, C. (2009) ‘Predictors of hip internal rotation during running: An evaluation of hip strength and femoral structure in women with and without patellofemoral pain’, *American Journal of Sports Medicine*, 37(3), pp. 579–587. Available at: https://doi.org/10.1177/0363546508326711.

Souza, R.B. and Powers, C.M. (2009) ‘Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain’, *Journal of Orthopaedic and Sports Physical Therapy*, 39(1), pp. 12–19. Available at: https://doi.org/10.2519/jospt.2009.2885.

Spörndly-Nees, S., Dåsberg, B., Nielsen, R.O., Boesen, M.I. and Langberg, H. (2011) ‘The navicular position test - a reliable measure of the navicular bone position during rest and loading.’, *International journal of sports physical therapy*, 6(3), pp. 199–205.

Sports Ireland (2021) ‘Irish Sports Monitor Report’, *Irish Sports Monitor Report* [Preprint].

Starbuck, C., Bramah, C., Herrington, L. and Jones, R. (2021) ‘The effect of speed on Achilles tendon forces and patellofemoral joint stresses in high-performing endurance runners’, *Scandinavian Journal of Medicine and Science in Sports*, 31(8), pp. 1657–1665. Available at:

https://doi.org/10.1111/sms.13972.

Stark, T., Walker, B., Phillips, J.K., Fejer, R. and Beck, R. (2011) ‘Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: A systematic review’, *PM and R*, pp. 472–479. Available at: https://doi.org/10.1016/j.pmrj.2010.10.025.

Stephen, J.M., Marsland, D., Masci, L., Calder, J.D.F. and Daou, H. El (2018) ‘Differential Motion and Compression Between the Plantaris and Achilles Tendons: A Contributing Factor to Midportion Achilles Tendinopathy?’, *American Journal of Sports Medicine*, 46(4), pp. 955–960. Available at: https://doi.org/10.1177/0363546517745291.

Stergiou, N.;, Bates and Kurz, M.J. (2003) *Subtalar and knee joint interaction during running at various stride lengths*, *Journal of Sports Medicine and Physical Fitness*.

Sugimoto, D., Kelly, B.D., Mandel, D.L., D’Hemecourt, D.A., Carpenito, S.C., D’Hemecourt, C.A. and D’Hemecourt, P.A. (2019) ‘Running Propensities of Athletes with Hamstring Injuries’, *Sports*, 7(9), p. 210. Available at: https://doi.org/10.3390/sports7090210.

Sun, X., Lam, W.K., Zhang, X., Wang, J. and Fu, W. (2020) ‘Systematic review of the role of footwear constructions in running biomechanics: Implications for running-related injury and performance’, *Journal of Sports Science and Medicine*, 19(1), pp. 20–37.

Sun, X., Yang, Y., Wang, L., Zhang, X. and Fu, W. (2018) ‘Do Strike Patterns or Shoe Conditions have a Predominant Influence on Foot Loading?’, *Journal of human kinetics*, 64, pp. 13–23. Available at: https://doi.org/10.1515/hukin-2017-0205.

Szymanek, E.B., Miller, E.M., Weart, A.N., Morris, J.B. and Goss, D.L. (2020) ‘Is step rate associated with running injury incidence?’, *International Journal of Sports Physical Therapy*, 15(2), pp. 221–228. Available at: https://doi.org/10.26603/ijspt20200221.

Tabachnick & Fidell (2013) *Tabachnick & Fidell, Using Multivariate Statistics, 6th Edition | Pearson*, *Pearson*.

Tamura, A., Akasaka, K., Otsudo, T., Sawada, Y., Okubo, Y., Shiozawa, J., Toda, Y. and Yamada, K. (2016) ‘Fatigue Alters Landing Shock Attenuation During a Single-Leg Vertical Drop Jump’, *Orthopaedic Journal of Sports Medicine*, 4(1). Available at: https://doi.org/10.1177/2325967115626412.

Tate, J.J. and Milner, C.E. (2010) ‘Real-time kinematic, temporospatial, and kinetic biofeedback during gait retraining in patients: A systematic review’, *Physical Therapy*, 90(8), pp. 1123–1134. Available at: https://doi.org/10.2522/ptj.20080281.

Taunton, J.E., Ryan, M.B., Clement, D.B., Mckenzie, C. and Lloyd-Smith, R. (2002) *A retrospective case-control analysis of 2002 running injuries*, *Br J Sports Med*.

Taunton, J.E., Ryan, M.B., Clement, D.B., McKenzie, D.C., Lloyd-Smith, D.R. and Zumbo, B.D. (2003) ‘A prospective study of running injuries: the Vancouver Sun Run " In Training " clinics', *Br J Sports Med*, 37, pp. 239–244.

Taylor-Haas, J.A., Hugentobler, J.A., DiCesare, C.A., Hickey Lucas, K.C., Bates, N.A., Myer, G.D. and Ford, K.R. (2014) 'Reduced hip strength is associated with increased hip motion during running in young adult and adolescent male long-distance runners.', *International journal of sports physical therapy*, 9(4), pp. 456–67.

Taylor, W.R., Ehrig, R.M., Duda, G.N., Schell, H., Seebeck, P. and Heller, M.O. (2005) 'On the influence of soft tissue coverage in the determination of bone kinematics using skin markers', *Journal of Orthopaedic Research*, 23(4), pp. 726–734. Available at: https://doi.org/10.1016/j.orthres.2005.02.006.

Taylor, W.R., Kornaropoulos, E.I., Duda, G.N., Kratzenstein, S., Ehrig, R.M., Arampatzis, A. and Heller, M.O. (2010) 'Repeatability and reproducibility of OSSCA, a functional approach for assessing the kinematics of the lower limb', *Gait and Posture*, 32(2), pp. 231–236. Available at: https://doi.org/10.1016/j.gaitpost.2010.05.005.

Tenforde, A.S., Sayres, L.C., McCurdy, M.L., Sainani, K.L. and Fredericson, M. (2013) 'Identifying sex-specific risk factors for stress fractures in adolescent runners', *Medicine and Science in Sports and Exercise*, 45(10), pp. 1843–1851. Available at: https://doi.org/10.1249/MSS.0b013e3182963d75.

Teng, H.L. and Powers, C.M. (2014) 'Sagittal plane trunk posture influences patellofemoral joint stress during running', *Journal of Orthopaedic and Sports Physical Therapy*, 44(10), pp. 785–792. Available at: https://doi.org/10.2519/jospt.2014.5249.

Teran-Yengle, P., Cole, K.J. and Yack, H.J. (2016) 'Short and long-term effects of gait retraining using real-time biofeedback to reduce knee hyperextension pattern in young women', *Gait and Posture*, 50, pp. 185–189. Available at: https://doi.org/10.1016/j.gaitpost.2016.08.019.

Teyhen, D.S., Stoltenberg, B.E., Collinsworth, K.M., Giesel, C.L., Williams, D.G., Kardouni, C.H., Molloy, J.M., Goffar, S.L., Christie, D.S. and McPoil, T. (2009) 'Dynamic plantar pressure parameters associated with static arch height index during gait', *Clinical Biomechanics*, 24(4), pp. 391–396. Available at: https://doi.org/10.1016/j.clinbiomech.2009.01.006.

Thabane, L., Mbuagbaw, L., Zhang, S., Samaan, Z., Marcucci, M., Ye, C., Thabane, M., Giangregorio, L., Dennis, B., Kosa, D., *et al.* (2013) 'A tutorial on sensitivity analyses in clinical trials: The what, why, when and how', *BMC Medical Research Methodology*, 13(1). Available at: https://doi.org/10.1186/1471-2288-13-92.

Thacker, S.B., Gilchrist, J., Stroup, D.F. and Kimsey, C.D. (2004) 'The Impact of Stretching on Sports Injury Risk: A Systematic Review of the Literature', *Medicine and Science in Sports and Exercise*, pp. 371–378. Available at: https://doi.org/10.1249/01.MSS.0000117134.83018.F7.

Theisen, D., Malisoux, L., Genin, J., Delattre, N., Seil, R. and Urhausen, A. (2014) 'Influence of midsole hardness of standard cushioned shoes on running-related injury risk', *British Journal of Sports Medicine*, 48(5), pp. 371–376. Available at: https://doi.org/10.1136/bjsports-2013-092613.

Thijs, Y., De Clercq, D., Roosen, P. and Witvrouw, E. (2008) ‘Gait-related intrinsic risk factors for patellofemoral pain in novice recreational runners’, *British Journal of Sports Medicine*, 42(6), pp. 466–471. Available at: https://doi.org/10.1136/bjsm.2008.046649.

Thijs, Y., Pattyn, E., Van Tiggelen, D., Rombaut, L. and Witvrouw, E. (2011) ‘Is hip muscle weakness a predisposing factor for patellofemoral pain in female novice runners? A prospective study’, *American Journal of Sports Medicine*, 39(9), pp. 1877–1882. Available at: https://doi.org/10.1177/0363546511407617.

Thompson, M.A., Lee, S.S., Seegmiller, J. and McGowan, C.P. (2015) ‘Kinematic and kinetic comparison of barefoot and shod running in mid/forefoot and rearfoot strike runners’, *Gait and Posture*, 41(4), pp. 957–959. Available at: https://doi.org/10.1016/j.gaitpost.2015.03.002.

Thorborg, K., Petersen, J., Magnusson, S.P. and Hölmich, P. (2010) ‘Clinical assessment of hip strength using a hand-held dynamometer is reliable’, *Scandinavian Journal of Medicine and Science in Sports*, 20(3), pp. 493–501. Available at: https://doi.org/10.1111/j.1600-0838.2009.00958.x.

Van Tiggelen, D., Wickes, S., Stevens, V., Roosen, P. and Witvrouw, E. (2008) ‘Effective prevention of sports injuries: A model integrating efficacy, efficiency, compliance and risk-taking behaviour’, *British Journal of Sports Medicine*, pp. 648–652. Available at: https://doi.org/10.1136/bjsm.2008.046441.

Timpka, T., Alonso, J.M., Jacobsson, J., Junge, A., Branco, P., Clarsen, B., Kowalski, J., Mountjoy, M., Nilsson, S., Pluim, B., *et al.* (2014) ‘Injury and illness definitions and data collection procedures for use in epidemiological studies in Athletics (track and field): Consensus statement’, *British Journal of Sports Medicine*, 48(7), pp. 483–490. Available at: https://doi.org/10.1136/bjsports-2013-093241.

Tomczak, M. and Tomczak, E. (2014) ‘The need to report effect size estimates revisited. An overview of some recommended measures of effect size’, *Trends in Sport Sciences*, 1(21), pp. 19–25.

Tonoli, D.C., Cumps, E., Aerts, I., Verhagen, E. and Meeusen, R. (2010) ‘Incidence, risk factors and prevention of running related injuries in long-...: Library resources’, *Sport & Geneeskunde*, (5), pp. 12–19.

Torp, D., Donovan, L., Gribble, P., Thomas, A.C., Bazett-Jones, D.M. and Beard, M.Q. (2018) ‘No baseline strength differences between female recreational runners who developed an injury and injury free runners during a 16-week formalized training program’, *Physical Therapy in Sport*, 34, pp. 1–7. Available at: https://doi.org/10.1016/j.ptsp.2018.08.001.

Torres-Costoso, A., López-Muñoz, P., Martínez-Vizcaíno, V., Álvarez-Bueno, C. and Cavero-Redondo, I. (2020) ‘Association Between Muscular Strength and Bone Health from Children to Young Adults: A Systematic Review and Meta-analysis’, *Sports Medicine*, 50(6), pp. 1163–1190. Available at: https://doi.org/10.1007/s40279-020-01267-y.

Vadeboncoeur, T.F., Silvers, S.M., Taylor, W.C., Shapiro, S.A., Roth, J.A., Diehl, N., Mahoney, S.M. and Mohseni, M.M. (2012) ‘Impact of a high body mass index on lower extremity injury in marathon/half-marathon participants', *Journal of Physical Activity and Health*, 9(1), pp. 96–103. Available at: https://doi.org/10.1123/jpah.9.1.96.

Vannatta, C. and Kernozek, T. (2015) 'Patellofemoral joint stress during running with alterations in foot strike pattern', *Medicine and Science in Sports and Exercise*, 47(5), pp. 1001–1008. Available at: https://doi.org/10.1249/MSS.0000000000000503.

Veras, P., Moreira, P., Lacerda Catharino, L., Elias Filho, J., Simões Fonseca, D. and Carvalho Felício, D. (2020) 'Incidence of injuries and associated factors in treadmill runners: a prospective cohort study', 26, p. 10200038. Available at: https://doi.org/10.1590/S1980-6574202000030038.

Vigotsky, A.D., Lehman, G.J., Beardsley, C., Contreras, B., Chung, B. and Feser, E.H. (2016) 'The modified Thomas test is not a valid measure of hip extension unless pelvic tilt is controlled', *PeerJ*, 2016(8), p. e2325. Available at: https://doi.org/10.7717/peerj.2325.

Vitez, L., Zupet, P., Zadnik, V. and Drobnič, M. (2017) 'Running injuries in the participants of Ljubljana Marathon', *Zdravstveno Varstvo*, 56(4), pp. 196–202. Available at: https://doi.org/10.1515/sjph-2017-0027.

Vlahek, P. and Matijević, V. (2018) 'Lower extremity injuries in novice runners: Incidence, types, time patterns, sociodemographic and motivational risk factors in a prospective cohort study', *Acta Clinica Croatica*, 57(1), pp. 31–38. Available at: https://doi.org/10.20471/acc.2018.57.01.04.

Walter, S., Hart, L., McIntosh, J. and Sutton, J. (1989) 'The Ontario cohort study of running-related injuries', *Archives of Internal Medicine*, 149(11), pp. 2561–2564. Available at: https://doi.org/10.1001/archinte.149.11.2561.

Ward, S.R., Winters, T.M. and Blemker, S.S. (2010) 'The architectural design of the gluteal muscle group: Implicati ons for movement and rehabilitation', *Journal of Orthopaedic and Sports Physical Therapy*, pp. 95–102. Available at: https://doi.org/10.2519/jospt.2010.3302.

Warne, J.P., Gruber, A.H., Cheung, R. and Bonacci, J. (2021) 'Training and technique choices predict self-reported running injuries: An international study', *Physical Therapy in Sport*, 48, pp. 83–90. Available at: https://doi.org/10.1016/j.ptsp.2020.12.017.

Warr, B., Fellin, R., Sauer, S. and Goss, D. (2015) 'Characterization of foot-strike patterns: lack of an association with injuries or performance in soldiers', *Military Medicine*, 180(7), pp. 830–834.

Warren, M.P. and Chua, A.T. (2008) 'Exercise-induced amenorrhea and bone health in the adolescent athlete', in *Annals of the New York Academy of Sciences*. Blackwell Publishing Inc., pp. 244–252. Available at: https://doi.org/10.1196/annals.1429.025.

Webster, K.E., McPherson, A.L., Hewett, T.E. and Feller, J.A. (2019) 'Factors Associated With a Return to Preinjury Level of Sport Performance After Anterior Cruciate Ligament Reconstruction Surgery', *American Journal of Sports Medicine*, 47(11), pp. 2557–2562. Available at: https://doi.org/10.1177/0363546519865537.

Weir, J.P. (2005) ‘Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM’, *Journal of Strength and Conditioning Research*, pp. 231–240. Available at: https://doi.org/10.1519/15184.1.

Whitting, J.W., Steele, J.R., McGhee, D.E. and Munro, B.J. (2011) ‘Dorsiflexion capacity affects Achilles tendon loading during drop landings’, *Medicine and Science in Sports and Exercise*, 43(4), pp. 706–713. Available at: https://doi.org/10.1249/MSS.0b013e3181f474dd.

Whyte, E., Doinn, T., Downey, M. and O’Connor, S. (2021) ‘Reliability of a smartphone goniometric application in the measurement of hip range of motion among experienced and novice clinicians’, *Journal of Sport Rehabilitation*, 30(6), pp. 969–972. Available at: https://doi.org/10.1123/JSR.2020-0165.

de Wijer, A., van Cingel, R., Staal, J.B., Nijhuis-van der Sanden, M.W.G., van der Worp, M.P. and ten Haaf, D.S.M. (2015) ‘Injuries in Runners; A Systematic Review on Risk Factors and Sex Differences’, *PLOS ONE*, 10(2), p. e0114937. Available at: https://doi.org/10.1371/journal.pone.0114937.

Wille, C.M., Lenhart, R.L., Wang, S., Thelen, D.G. and Heiderscheit, B.C. (2014) ‘Ability of sagittal kinematic variables to estimate ground reaction forces and joint kinetics in running’, *Journal of Orthopaedic and Sports Physical Therapy*, 44(10), pp. 825–830. Available at: https://doi.org/10.2519/jospt.2014.5367.

Williams, D.S., Davis, I.M.C., Scholz, J.P., Hamill, J. and Buchanan, T.S. (2004) ‘High-arched runners exhibit increased leg stiffness compared to low-arched runners’, *Gait and Posture*, 19(3), pp. 263–269. Available at: https://doi.org/10.1016/S0966-6362(03)00087-0.

Williams, D.S. and McClay, I.S. (2000) ‘Measurements Used to Characterize the Foot and the Medial Longitudinal Arch: Reliability and Validity’, *Physical Therapy*, 80(9), pp. 864–871. Available at: https://doi.org/10.1093/ptj/80.9.864.

Williams, D.S., McClay, I.S. and Hamill, J. (2001) ‘Arch structure and injury patterns in runners’, *Clinical Biomechanics*, 16(4), pp. 341–347. Available at: https://doi.org/10.1016/S0268-0033(01)00005-5.

Williams, D.S.B., Tierney, R.N. and Butler, R.J. (2014) ‘Increased medial longitudinal arch mobility, lower extremity kinematics, and ground reaction forces in high-arched runners’, *Journal of Athletic Training*, 49(3), pp. 290–296. Available at: https://doi.org/10.4085/1062-6050-49.3.05.

Williams, D.S.B., Zambardino, J.A. and Banning, V.A. (2008) ‘Transverse-plane mechanics at the knee and tibia in runners with and without a history of achilles tendonopathy’, *Journal of Orthopaedic and Sports Physical Therapy*, 38(12), pp. 761–767. Available at: https://doi.org/10.2519/jospt.2008.2911.

Williams, J.M. and Andersen, M.B. (1998) ‘Psychosocial antecedents of sport injury: Review and critique of the stress and injury model’’, *Journal of Applied Sport Psychology*, 10(1), pp. 5–25.

Available at: https://doi.org/10.1080/10413209808406375.

Willson, J.D., Ratcliff, O.M., Meardon, S.A. and Willy, R.W. (2015) ‘Influence of step length and landing pattern on patellofemoral joint kinetics during running’, *Scandinavian Journal of Medicine and Science in Sports*, 25(6), pp. 736–743. Available at: https://doi.org/10.1111/sms.12383.

Willwacher, S., Goetze, I., Fischer, K.M. and Brüggemann, G.P. (2016) ‘The free moment in running and its relation to joint loading and injury risk’, *Footwear Science*, 8(1), pp. 1–11. Available at: https://doi.org/10.1080/19424280.2015.1119890.

Willy, R.W. (2018) ‘Innovations and pitfalls in the use of wearable devices in the prevention and rehabilitation of running related injuries’, *Physical Therapy in Sport*, 29, pp. 26–33. Available at: https://doi.org/10.1016/j.ptsp.2017.10.003.

Willy, R.W. and Davis, I.S. (2011) ‘The effect of a hip-strengthening program on mechanics during running and during a single-leg squat’, *Journal of Orthopaedic and Sports Physical Therapy*, 41(9), pp. 625–632. Available at: https://doi.org/10.2519/jospt.2011.3470.

Willy, R.W., Manal, K.T., Witvrouw, E.E. and Davis, I.S. (2012) ‘Are mechanics different between male and female runners with patellofemoral pain?’, *Medicine and Science in Sports and Exercise*, 44(11), pp. 2165–2171. Available at: https://doi.org/10.1249/MSS.0b013e3182629215.

Winiarski, S. and Rutkowska-Kucharska, A. (2009) ‘Estimated ground reaction force in normal and pathological gait Estimated ground reaction force in normal and pathological gait’, *Acta of Bioengineering and Biomechanics*, 11(January 2009), pp. 53–60. Available at: https://doi.org/101194794 [pii].

Winkelmann, Z.K., Anderson, D., Games, K.E. and Eberman, L.E. (2016) ‘Risk factors for medial tibial stress syndrome in active individuals: An evidence-based review’, *Journal of Athletic Training*, 51(12), pp. 1049–1052. Available at: https://doi.org/10.4085/1062-6050-51.12.13.

Winter, D.A. (2009) *Biomechanics and Motor Control of Human Movement: Fourth Edition*, *Biomechanics and Motor Control of Human Movement: Fourth Edition*. John Wiley & Sons. Available at: https://doi.org/10.1002/9780470549148.

Winter, S.C., Gordon, S., Brice, S.M., Lindsay, D. and Barrs, S. (2020) ‘A Multifactorial Approach to Overuse Running Injuries: A 1-Year Prospective Study’, *Sports Health*, 12(3), pp. 296–303. Available at: https://doi.org/10.1177/1941738119888504.

Van Der Worp, H., Vrielink, J.W. and Bredeweg, S.W. (2016) ‘Do runners who suffer injuries have higher vertical ground reaction forces than those who remain injury-free? A systematic review and meta-analysis’, *British Journal of Sports Medicine*, 50(8), pp. 450–457. Available at: https://doi.org/10.1136/bjsports-2015-094924.

Van Der Worp, M.P., Ten Haaf, D.S.M., Van Cingel, R., De Wijer, A., Nijhuis-Van Der Sanden, M.W.G. and Bart Staal, J. (2015) ‘Injuries in runners; a systematic review on risk factors and sex differences', *PLoS ONE*. Available at: https://doi.org/10.1371/journal.pone.0114937.

Van Der Worp, M.P., De Wijer, A., Van Cingel, R., Verbeek, A.L.M., Nijhuis-Van Der Sanden, M.W.G. and Staal, J.B. (2016) 'The 5- or 10-km Marikenloop run: A prospective study of the etiology of running-related injuries in women', *Journal of Orthopaedic and Sports Physical Therapy*, 46(6), pp. 462–470. Available at: https://doi.org/10.2519/jospt.2016.6402.

Van Der Worp, M.P., De Wijer, A., Staal, J.B. and Van Der Sanden, M.W.G.N. (2014) 'Reproducibility of and sex differences in common orthopaedic ankle and foot tests in runners', *BMC Musculoskeletal Disorders*, 15(1). Available at: https://doi.org/10.1186/1471-2474-15-171.

Wyndow, N., De Jong, A., Rial, K., Tucker, K., Collins, N., Vicenzino, B., Russell, T. and Crossley, K. (2016) 'The relationship of foot and ankle mobility to the frontal plane projection angle in asymptomatic adults', *Journal of Foot and Ankle Research*, 9(1). Available at: https://doi.org/10.1186/s13047-016-0134-9.

Xu, D., Quan, W., Zhou, H., Sun, D., Baker, J.S. and Gu, Y. (2022) 'Explaining the differences of gait patterns between high and low-mileage runners with machine learning', *Scientific Reports*, 12(1), p. 2981. Available at: https://doi.org/10.1038/s41598-022-07054-1.

Yagi, S., Muneta, T. and Sekiya, I. (2013) 'Incidence and risk factors for medial tibial stress syndrome and tibial stress fracture in high school runners', *Knee Surgery, Sports Traumatology, Arthroscopy*, 21(3), pp. 556–563. Available at: https://doi.org/10.1007/s00167-012-2160-x.

Yamaguchi, T., Takizawa, K. and Shibata, K. (2015) 'Acute effect of dynamic stretching on endurance running performance in well-trained male runners', *Journal of Strength and Conditioning Research*, 29(11), pp. 3045–3052. Available at: https://doi.org/10.1519/JSC.0000000000000969.

Yamato, T.P., Saragiotto, B.T., Hespanhol Junior, L.C., Yeung, S.S. and Lopes, A.D. (2015) 'Descriptors used to define running-related musculoskeletal injury: A systematic review', *Journal of Orthopaedic and Sports Physical Therapy*, 45(5), pp. 366–374. Available at: https://doi.org/10.2519/jospt.2015.5750.

Yamato, T.P., Saragiotto, B.T. and Lopes, A.D. (2015) 'A consensus definition of running-related injury in recreational runners: A modified Delphi approach', *Journal of Orthopaedic and Sports Physical Therapy*, 45(5), pp. 375–380. Available at: https://doi.org/10.2519/jospt.2015.5741.

Zadpoor, A.A. and Nikooyan, A.A. (2011) 'The relationship between lower-extremity stress fractures and the ground reaction force: A systematic review', *JCLB*, 26, pp. 23–28. Available at: https://doi.org/10.1016/j.clinbiomech.2010.08.005.

Zifchock, R.A., Davis, I. and Hamill, J. (2006) 'Kinetic asymmetry in female runners with and without retrospective tibial stress fractures', *Journal of Biomechanics*, 39(15), pp. 2792–2797. Available at: https://doi.org/10.1016/j.jbiomech.2005.10.003.

Zifchock, R.A., Davis, I., Higginson, J., McCaw, S. and Royer, T. (2008) 'Side-to-side differences in overuse running injury susceptibility: A retrospective study', *Human Movement Science*, 27, pp. 888–902. Available at: https://doi.org/10.1016/j.humov.2008.03.007.

Zuil-Escobar, J.C., Martínez-Cepa, C.B., Martín-Urrialde, J.A. and Gómez-Conesa, A. (2018) 'Medial Longitudinal Arch: Accuracy, Reliability, and Correlation Between Navicular Drop Test and Footprint Parameters', *Journal of Manipulative and Physiological Therapeutics*, 41(8), pp. 672–679. Available at: https://doi.org/10.1016/j.jmpt.2018.04.001.

8. Appendices

8.1. Appendix A: DCU RISC Survey

Section A - Demographics

Q.1. What is your unique ID number?

Open-ended response.

Q.2. What age are you?

Open-ended response [Numerical].

Q.3. Please select your gender.

- *Male*
- *Female*
- *Prefer not to say*

Section B - Training

Q.4. Do you attend any exercise classes? Please tick all that apply.

- *Yoga*
- *Pilates*
- *Aerobics*
- *Dance/Zumba*
- *Spinning*
- *Altitude Chamber*
- *Boxercise*
- *HIIT (High Intensity Interval Training)*
- *S&C (Strength & Conditioning)*
- *TRX*
- *CrossFit*
- *Swimming*
- *MMA*
- *Other (Please specify)*
- *No I don't attend exercise classes*

Q.4. (a) How many times per week do you attend exercise classes?

- *1 time per week*
- *2 times per week*
- *3 times per week*
- *4 times per week*
- *5 times per week*
- *6 times per week*
- *7 times per week*
- *7+ times per week*

Q.5. Do you regularly go to the gym? Please tick no if you go to the gym for the purpose of group exercise classes.

- ☐ *Yes, 1-2 times per week*
- ☐ *Yes, 3-4 times per week*
- ☐ *Yes, 5-7 times per week*
- ☐ *No, I don't go to the gym*

Q.5. (a) What does a typical gym session consist of for you? Please tick all that apply.

- ☐ *Cardiovascular (e.g. Rowing, Cross Trainer, Swimming, Bike)*
- ☐ *Strength (e.g. Free Weights, Weight Machines)*
- ☐ *Flexibility (e.g. Stretching)*
- ☐ *Plyometrics (e.g. Hops, Jumps, Box Jumps)*
- ☐ *Other (Please specify)*

Q.6. Since you first started running training, what is the total amount of years that you have trained? (Please do not include years when you did not train regularly e.g. taking a year out).

- ☐ *6-12 months*
- ☐ *1-2 years*
- ☐ *3-5 years*
- ☐ *6-10 years*
- ☐ *11-15 years*
- ☐ *15+ years*

Q.7. Do you run throughout the year or on a seasonal basis?

- ☐ *Throughout the year*
- ☐ *Seasonal basis*

Q.7. (a) If you ticked "seasonal basis", how many months of the year do you run?

- ☐ *1 month*
- ☐ *2 months*
- ☐ *3 months*
- ☐ *4 months*
- ☐ *5 months*
- ☐ *6 months*
- ☐ *7 months*
- ☐ *8 months*
- ☐ *9 months*
- ☐ *10 months*
- ☐ *11 months*

Q.8. What is the purpose of running for you? Please tick all that apply.

- ☐ *Fitness*
- ☐ *Physique*
- ☐ *Enjoyment*
- ☐ *Mental health*
- ☐ *Train for competition*
- ☐ *To accomplish a personal goal*
- ☐ *Social interaction*
- ☐ *Convenience*
- ☐ *Other (Please specify)*

Q.8. (a) Please rank in order of importance the purpose of running for you. e.g. 1= primary purpose.

Select number from drop-down menu beside each respective motivation.

Q.9. Do you have any running related events that you are currently training for or that you plan to train for within the next year? Please tick all that apply.

- *5km*
- *10km*
- *Mini-marathon*
- *10 mile*
- *Half-marathon*
- *¾ marathon*
- *Marathon*
- *Ultra-marathon*
- *Ironman*
- *Duathlon*
- *Triathlon*
- *Cross-country*
- *Adventure race*
- *Trail/Mountain race*
- *Organised track and field event*
- *Other (Please specify)*
- *I am not training for a running related event*

Q.10. On average, how many times per week do you run?

- *1 time per week*
- *2 times per week*
- *3 times per week*
- *4 times per week*
- *5 times per week*
- *6 times per week*
- *7 times per week*
- *7+ times per week*

Q.11. At present, what distance (kilometres) per week do you run?

Open-ended response [Numerical].

Q.12. How many kilometres collectively have you ran over the course of the last three months?

Open-ended response [Numerical].

Q.13. What is your average running pace? (km/hr) If you are unsure, please refer to pace graph provided.

Open-ended response [Numerical].

Q.14. Do you regularly increase the intensity of running training week to week?

- *Yes*
- *No*

- ☐ *I am unsure*

Q.14. (a) How do you increase the intensity of running training from week to week? Please tick all that apply.

- ☐ *Increase distance*
- ☐ *Increase pace*
- ☐ *Increase the number of running sessions*
- ☐ *Change gradient*
- ☐ *Do tempo runs*
- ☐ *Other (Please specify)*

Q.15. Do you include any of the following sessions as part of your running training? Please tick all that apply.

- ☐ *Interval training*
- ☐ *Speed work*
- ☐ *Hill running*
- ☐ *Fartlek*
- ☐ *Other (Please specify)*

Q.16. What surface do you run on most often? If you run on multiple surfaces for an equal number of sessions, please tick those that apply.

- ☐ *Road*
- ☐ *Grass*
- ☐ *Footpath*
- ☐ *Track*
- ☐ *Sand*
- ☐ *Treadmill*
- ☐ *Astroturf*
- ☐ *Other (Please specify)*

Q.17. How often do you change running shoes?

- ☐ *Every 0-3 months*
- ☐ *Every 4-6 months*
- ☐ *Every 7-12 months*
- ☐ *Every 12+ months*

Q.18. Do you wear insoles or insole devices in your running shoes? (Arch support, heel lift, etc.)

- ☐ *Yes, they were prescribed to me*
- ☐ *Yes, I bought them in a shop*
- ☐ *Yes, my shoes are manufactured with a specific arch support/shock absorption feature*
- ☐ *No, I don't wear insoles or insole devices*
- ☐ *I am unsure*

Q.19. Do you apply any strapping/taping/braces/supports before going for a run? (Please do not include orthotic devices/insoles).

- ☐ *Yes, always*

- *Yes, sometimes*
- *No, I don't apply strapping/taping/braces/supports*
- *I am unsure*

Q.19. (a) What location of the body do you apply strapping/taping/support/brace to? Please tick all that apply.

- *Lower back*
- *Sacroiliac joint*
- *Hip*
- *Inner thigh*
- *Buttock*
- *Front of thigh*
- *Back of thigh*
- *Outer thigh*
- *Knee*
- *Shin*
- *Calf*
- *Ankle*
- *Foot*
- *Heel*
- *Toes*

Q.20. Do you currently have any persistent or nagging pain or complaint in your lower back/lower limbs that you experience while running but does not restrict your training?

- *Yes*
- *No*
- *I am unsure*

Q.20. (a) Please give details of this persistent pain (e.g. you may describe the location, type, severity, duration, etc.).

Open-ended response [Text].

Q.21. Delayed Onset of Muscle Soreness (DOMS) is a muscular pain/ache following a session of increased intensity or unfamiliar activity. The soreness typically lasts 24-72 hours. Do you experience DOMS?

- *Yes, typically once a week*
- *Yes, typically once a fortnight*
- *Yes, typically once a month*
- *Yes, typically multiple times per year*
- *No, I do not experience DOMS*
- *I am unsure*

Q.22. Do you usually warm up before a running session?

- *Yes, always*
- *Yes, sometimes*
- *No, I do not usually warm-up*
- *I am unsure*

Q.22. (a) What does your warm up consist of? Please tick all that apply.

- *Static stretch*
- *Dynamic stretch*
- *Cardiovascular*
- *Foam rolling*
- *Plyometrics*
- *Joint mobility*
- *Other (Please specify)*

Q.23. Do you usually warm down/cool down after a running session?

- *Yes, always*
- *Yes, sometimes*
- *No, I do not usually warm-up*
- *I am unsure*

Q.23. (a) What does your warm down/cool down normally consist of? Please tick all that apply.

- *Static stretch*
- *Dynamic stretch*
- *Cardiovascular*
- *Foam rolling*
- *Massage*
- *Swimming*
- *Other (Please specify)*

Q.24. Do you include any recovery sessions as part of your training? A recovery session is a planned session where the objective is to re-establish an optimal state for training (e.g. rest, massage, light cardio, baths).

- *Yes, always*
- *Yes, sometimes*
- *No, I do not usually warm-up*
- *I am unsure*

Q.24. (a) Which of the following are included in your recovery session? Please tick all that apply.

- *Rest*
- *Foam rolling*
- *Stretching*
- *Light run*
- *Cycle*
- *Swim*
- *Cryotherapy*
- *Hot baths*
- *Massage*
- *Light resistance training*
- *Other (Please specify)*

Section C – Running-related Injury

Q.25. Have you ever experienced a running- related injury? (A running related injury is any muscle, bone tendon or ligament pain that caused you to stop running/restricted your running (either your speed, distance or duration) and lasted 7 days or three consecutive training sessions/ required you to seek a physician or health care practitioner.)

- *Yes*
- *No*
- *I am unsure*

Q.26. Have you had any previous running related injuries in the past 2 years? A running-related injury is any muscle, bone, tendon or ligament pain in the lower back/legs/knee/foot/ankle that caused you to stop running/ restricted your running (either your distance, speed, duration or training)

AND

i. lasted at least 7 days or 3 consecutive scheduled training sessions

OR

ii. required you to consult a physician or other health care professional.

- *Yes, I had a lower back/lower limb running-related injury that lasted at least 7 days or 3 scheduled training sessions (i).*
- *Yes, I had a lower back/lower limb running-related injury that required me to consult a physician or other healthcare professional (ii).*
- *Yes, I had a lower back/lower limb running-related injury that lasted at least 7 days or 3 scheduled training sessions (i) AND that required me to consult a physician or other healthcare professional (ii).*
- *No, I have not has any lower back/lower limb running-related injury in the past 2 years.*
- *I am unsure.*

Q.26. (a) How many lower back/lower limb running-related injuries have you had in the past 2 years?

- *1 running-related injury*
- *2 running-related injuries*
- *3 running-related injuries*
- *4 running-related injuries*
- *5 running-related injuries*
- *5+ running-related injuries*

Q.26. (a)(i) Thinking of one of these back/lower limb running-related injuries in the past 2 years please select the location of the body that you had this injury.

- *Lower back*
- *Sacroiliac joint*
- *Hip*
- *Inner thigh*
- *Buttock*
- *Front of thigh*
- *Back of thigh*
- *Outer thigh*

- *Knee*
- *Shin*
- *Calf*
- *Ankle*
- *Foot*
- *Heel*
- *Toes*

Q.26. (a)(ii) What month did this injury occur?

Select month from drop-down menu.

Q.26. (a)(iii) What year did this injury occur?

Select year from drop-down menu.

Q.26. (a)(iv) Still thinking of this injury, what type of injury was it?

- *Cut/Graze*
- *Contusion/Bruise*
- *Ligament tear/Sprain (e.g. twisted ankle)*
- *Subluxation/Dislocation*
- *Broken bone/Fracture (*NOT a stress fracture)*
- *Cartilage/Meniscus/Labrum injury*
- *Stress fracture*
- *Muscle strain/tear/rupture*
- *Tendon injury*
- *Nerve injury*
- *Shin splints type pain (*NOT a stress fracture)*
- *Bursitis*
- *Fat pad aggravation*
- *Blisters*
- *Other (Please specify)*

Q.26. (a)(v) Still thinking of this injury, did you miss any training because of it?

- *No, I did not miss training*
- *Yes, I missed less than 7 days*
- *Yes, I missed between 7 and 28 days*
- *Yes, I missed between 1 and 6 months*
- *Yes, I missed more than 6 months*
- *I am unsure*
- *Other (Please specify)*

Q.26. (a)(vi) Still thinking of this injury, did you require any medical advice? Please tick all that apply.

- *No, I did not require any medical advice*
- *Yes, I got medical advice from an internet resource*
- *Yes, I received medical advice from my coach*
- *Yes, I received medical advice from my GP/doctor*

- *Yes, I received medical advice from a medical professional (Chartered Physiotherapist, Certified Athletic Therapist, Physical Therapist, Chiropractor, Osteopath)*
- *I had to go to A&E*
- *I received medical advice from a family member or fried who is not a medical professional*

Q.26. (a)(vii) Still thinking of this injury, did you complete a rehabilitation programme after the injury? A rehabilitation programme usually involves completing a set of exercises that have been specifically tailored to your injury.

- Yes, I was given once by a medical professional *(Doctor, Chartered Physiotherapist, Certified Athletic Therapist, Physical Therapist, Chiropractor, Osteopath)*
- *Yes, I rehabilitated the injury myself*
- *No, I did not need a rehabilitation programme*
- *I am unsure*
- *Other (Please specify)*

Q.26. (a)(viii) Still thinking of this injury, do you feel you have recovered fully from this injury?

- *Yes*
- *No*
- *I am unsure*

Q.26. (a)(ix) Still thinking of this injury, has there been any exacerbation or re-injury of this in the past 2 years? Exacerbation refers to the worsening of your initial injury before it was fully recovered. Re-injury refers to a recurring injury after your initial injury had recovered.

- *Yes, I had a re-injury at the same location and of the same type*
- *Yes, I have had an exacerbation at the same location and of the same type*
- *Yes, I had a re-injury at the same location and of a different type*
- *Yes, I have had an exacerbation at the same location and of a different type*
- *I am unsure*
- *No, I have not had any exacerbations or re-injuries*

Q.26. (a)(ix)(1) How soon after the initial injury did the exacerbation occur?

- *Within 2 months*
- *Between 2 and 12 months*
- *Between 12 and 24 months*
- *I am unsure*

Q.26. (a)(ix)(2) How soon after the initial injury did the re-injury occur?

- *Within 2 months*
- *Between 2 and 12 months*
- *Between 12 and 24 months*
- *I am unsure*

8.2. Appendix B: Reliability of musculoskeletal clinical measures

Introduction:

Reliability has been defined previously as "the extent to which measurements can be replicated" (Koo and Li, 2016, p. 155). Knowledge of the interrater (consistency between testers) and intrarater (consistency between same rater) reliability allows us to establish the level to which we are confident that there is consistency between and within testers. Furthermore, from the reliability, figures such as the minimal detectable change (MDC) may be calculated. The MDC determines how much of a difference in a measure is likely to be related to error in measurement or an actual change in the value. The aim of this experiment was to investigate the interrater and intrarater reliability of musculoskeletal clinical measures. A secondary aim was to determine the MDC of each measure.

Methods:

Seventeen injury-free recreational runners were recruited via campus-wide email. To assess intrarater reliability, each participant attended the laboratory on four occasions, during which the following measures were recorded bilaterally; muscle strength (hip abduction, hip extension, plantar flexion, knee flexion and knee extension), functional foot alignment (Foot Posture Index and navicular drop) and range of motion (knee to wall, hip internal rotation, hip external rotation and hip extension range) in line with the methodology outlined above (Chapter 3). For measures of range of motion and functional foot alignment, each test was repeated three times and the average was recorded. For the muscle strength measures, the maximum of three attempts was recorded. To assess interrater reliability, participants were assessed by Rater 2 one day after the first testing session using the same protocol outlined above. Rater 1 was a Chartered Physiotherapist with 1-year post-graduate experience, Rater 2 was an Certified Athletic therapist with 8 years post-graduate experience. To assess intrarater reliability, participants were assessed by each rater one week after the first testing session. Figure 13 displays the order of testing sessions.

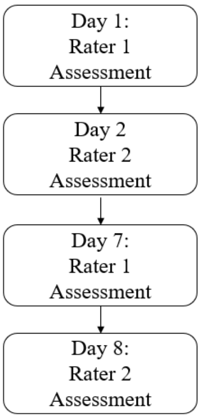


Figure 13 Flowchart of assessment protocol.

Statistical analysis:

The means and standard deviations of the demographic participants (age, mass, height) were calculated. Intrarater reliability was assessed using intraclass correlation coefficient (ICC) estimates and their 95% confident intervals, based on absolute-agreement, 2-way mixed-effects models. Interrater reliability was assessed using ICC estimates and their 95% confident intervals, based on a mean-rating (k = 3), consistency, 2-way mixed-effects model. In line with previous research, ICC values < 0.5, between 0.5 and 0.75, between 0.75 and 0.9, >0.90 indicate poor, moderate, good and excellent reliability respectively (Koo and Li, 2016). Data was analysed using IBM statistics (version 27).

Standard error of the mean was calculated as:

$SD\sqrt{(1-ICC)}$

Minimal detectable change was calculated as:

$1.96*\sqrt{2}*(SEM)$

As per Haley and Fragala-pinkham (2006)

Pooled standard deviation was calculated using the definition by (Cohen, 1998), whereby pooled standard deviation was calculated as:

$\sqrt{((SD_1^2 + SD_2^2)/2)}$

Where:

SD_1= standard deviation 1

SD_2= standard deviation 2

Results:

Seventeen participants (9 females, 8 males) were included in this study, with both sides of the body being assessed, producing 34 sets of data. The demographic details of the participants are reported in Table 98. Moderate to excellent interrater (Table 100) and good to excellent intrarater reliability (Table 99) was found for all clinical measures. Minimal detectable change and standard error of measurement values were reported.

Table 98 Demographic details of participants.

Demographic Factor	***Mean ± Standard deviation***
Age (years)	24.7 ± 3.8
Mass (kg)	72.2 ± 12.1
Height (m)	1.75 ± 0.72

Table 99 Intrarater reliability of clinical measures.

	Mean Time 1	*SD Time 1*	*Mean Time 2*	*SD Time 2*	*ICC*	*Lower Bound (95% CI)*	*Upper Bound (95% CI)*	*Interpretation*	*SEM*	*MDC*
Strength										
Hip Abduction (Nm/kg)	1.79	0.40	1.77	0.41	0.91	0.77	0.96	Excellent	0.12	0.34
Hip Extension (Nm/kg)	2.12	0.34	2.03	0.37	0.92	0.85	0.97	Excellent	0.10	0.38
Plantar Flexion (Nm/kg)	0.88	0.21	0.87	0.19	0.96	0.93	0.98	Excellent	0.04	0.15
Knee Extension (Nm/kg)	1.11	0.22	1.08	0.23	0.88	0.74	0.94	Good	0.08	0.28
Knee Flexion (Nm/kg)	0.94	0.24	0.97	0.30	0.87	0.68	0.94	Good	0.10	0.35
Range of Motion										
Hip Internal Rotation (◦)	36.2	5.1	35.2	7.1	0.91	0.82	0.95	Excellent	1.86	7.05
Hip External Rotation (◦)	36.5	4.7	36.2	5.2	0.78	0.61	0.89	Good	2.30	6.37
Hip Extension (◦)	33.2	3.2	33.1	4.1	0.88	0.75	0.94	Good	1.28	4.83
Knee to Wall (◦)	37.5	3.41	36.63	3.28	0.87	0.74	0.94	Good	1.21	4.39
Foot Functional Alignment										
Navicular Drop (mm)	6.70	2.60	7.10	2.90	0.94	0.87	0.97	Excellent	0.10	0.27
Foot Posture Index	4.68	4.44	4.74	4.69	0.98	0.97	0.99	Excellent	0.76	2.12

Abbreviations: SD= standard deviation, ICC= intraclass correlation coefficient, CI= confidence interval, SEM= standard error of the mean, MDC= minimal detectable change.

Table 100 Interrater reliability of clinical measures.

	Mean Rater 1	*SD Rater 1*	*Mean Rater 2*	*SD Rater 2*	*ICC*	*Lower Bound (95% CI)*	*Upper Bound (95% CI)*	*Interpretation*	*SEM*	*MDC*
Isometric muscle strength										
Hip Abduction (Nm/kg)	1.79	0.40	1.72	0.40	0.95	0.91	0.98	Excellent	0.10	0.29
Hip Extension (Nm/kg)	2.12	0.34	2.06	0.35	0.94	0.88	0.97	Excellent	0.09	0.25
Plantar Flexion (Nm/kg)	0.88	0.21	0.86	0.18	0.91	0.83	0.96	Excellent	0.06	0.18
Knee Extension (Nm/kg)	1.11	0.22	1.11	0.24	0.84	0.70	0.92	Good	0.10	0.27
Knee Flexion (Nm/kg)	0.94	0.24	0.95	0.27	0.88	0.77	0.94	Good	0.09	0.26
Range of Motion										
Hip Internal Rotation (◦)	35.6	6.1	36.2	5.1	0.83	0.68	0.91	Good	2.35	6.5
Hip External Rotation (◦)	37.1	4.3	36.2	5.1	0.76	0.57	0.87	Good	2.38	6.6
Hip Extension (◦)	34.4	3.9	33.1	4.1	0.87	0.76	0.94	Good	1.65	4.6
Knee to Wall (◦)	37.4	2.7	37.5	3.4	0.73	0.58	0.86	Moderate	1.58	4.4
Foot Functional Alignment										
Navicular Drop (mm)	6.65	2.67	7.35	2.81	0.92	0.84	0.96	Excellent	0.09	0.25
Foot Posture Index	5.06	4.85	4.68	4.44	0.96	0.91	0.98	Excellent	1.00	2.76

Abbreviations: SD= standard deviation, ICC= intraclass correlation coefficient, CI= confidence interval, SEM= standard error of the mean, MDC= minimal detectable change.

Discussion:

The interrater and intrarater reliability of musculoskeletal clinical tests were found to be moderate to excellent and minimal detectable change was established for each measure.

Strength

Strength measures demonstrated good to excellent interrater and intrarater reliability, in line with a previous study investigating similar methods of muscle strength testing (Mentiplay *et al.*, 2015).

Foot Position

Navicular drop demonstrated good interrater and intrarater reliability, as previously has been reported in similar studies (Spörndly-Nees *et al.*, 2011). In terms of Foot Posture Index, excellent interrater and intrarater reliability was found which is line with previous studies (Aquino *et al.*, 2018).

Range of Motion (ROM)

Good interrater and excellent intrarater reliability was found in relation to hip rotation and extension ROM measures, similar to what has previously been reported using the same methodology (Whyte *et al.*, 2021). Knee to wall measures demonstrated moderate interrater and good intrarater reliability, similar to as is reported in previous research (Powden, Hoch and Hoch, 2015). Average minimal detectable change values were also similar to what was previously reported (Powden, Hoch and Hoch, 2015).

Conclusion:

The interrater and intrarater reliability were found to be good to excellent across all clinical measures. This is with the exception of knee to wall, which was found to have moderate reliability between raters. This study indicates that the clinical measures of strength, range of motion and functional foot alignment should be consistent between the same rater across as well as between two raters. MDC values were established which may be useful for interpretation of differences between groups in injury aetiology data.

8.3. *Appendix C: Are peak and rate of accelerations during treadmill running representative of those produced over ground?*

This study is under review:

Dillon, S., Burke, A., O'Connor, S., Whyte, E., Gore, S., Moran, K., 2022. Are peak and rate of acceleration during treadmill running representative of those produced overground? Gait and Posture (Awaiting decision).

This is presented in full, with only minor formatting changes.

Abstract

Background: Although many runners train overground, measuring impact accelerations on a treadmill may be advantageous for researchers and clinicians. Previous investigations of peak and rate of acceleration ($peak_{accel}$, $rate_{accel}$) during treadmill running compared to overground running have not examined the relative consistency and absolute agreement of these measures, or the effect of treadmill stiffness.

Research Question: (1) Are $peak_{accel}$ and $rate_{accel}$ produced during running on a stiff and less stiff treadmill 'representative' of those produced during overground running? (2) Are $peak_{accel}$ and $rate_{accel}$ measured on treadmills of different stiffness 'representative' of each other?

Methods: Eighteen participants ran at a self-selected pace on three surfaces: Treadmill 1 (reduced stiffness), Treadmill 2 (increased stiffness) and overground on asphalt, whilst $peak_{accel}$ and $rate_{accel}$ were recorded at the shank and lower back. Relative consistency (ICC [3,1]), absolute agreement (Bland-Altman analysis) and systematic differences (ANOVA) were assessed.

Results: ICCs revealed moderate to excellent relative consistency in $peak_{accel}$ and $rate_{accel}$ between surfaces, with higher consistency for measures at the lower back. Absolute agreement was low, with the Bland Altman limits of agreement exceeding the clinical acceptable range for all comparisons. For systematic differences in means, $peak_{accel}$ and $rate_{accel}$ at the shank were significantly higher overground than on either treadmill; with no difference evident at the lower back. No differences were found for surface with respect to shank or lower back $peak_{accel}$ and $rate_{accel}$ between treadmills.

Significance: Moderate to excellent relative consistency of $peak_{accel}$ and $rate_{accel}$ between the surfaces suggests that using different surfaces in research involving rank ordering of participants by acceleration magnitude may be acceptable (e.g. prospective studies examining if impact accelerations are related to injury). However, low absolute agreement indicates that data collected on treadmills of different stiffness and overground should not be used interchangeably (e.g. running-retraining studies).

Keywords: biomechanics, locomotion, movement, kinetics, running

Introduction

With over 85% of runners predominantly training overground (Running USA, 2017) it can be argued that the majority of running related injuries (RRIs) are associated specifically with overground running. However, laboratory-based treadmill testing of RRI risk factors remains common, most likely because it facilitates biomechanical analysis (i.e. concurrent loading, kinematics), enables easier provision of feedback/biofeedback (Chan *et al.*, 2018) and allows for control of environmental conditions and running speed. It is unclear however, if treadmill-based assessment of loading is representative of loading during overground running.

Assessing loading during running is common both for research (Milner *et al.*, 2006b; Zifchock, Davis and Hamill, 2006; Schütte *et al.*, 2018) and clinical (Willy, 2018) purposes. Whilst measurement of ground reactions forces (GRFs) via a force-plate is most common, the use of accelerometer-based assessment (Milner, Davis and Hamill, 2006; Zifchock, Davis and Hamill, 2006; Zifchock *et al.*, 2008; Willy, 2018) is growing because they are cheaper and allow data collection in multiple environments. Additionally, force-plates measure loading on the body's centre-of-mass; it does not actually represent the loading on any one body segment. In contrast, accelerometers measure loading on individual segments (Zifchock, Davis and Hamill, 2006; Schütte *et al.*, 2018), which is important as injuries are site-specific. Increased $peak_{accel}$ may be related to increased risk of RRIs, as found for tibial stress fractures (Milner *et al.*, 2006b; Zifchock, Davis and Hamill, 2006). Furthermore, since reducing loading during running-retraining can be effective in injury prevention (Chan *et al.*, 2018), accelerometers provide a new avenue for running-retraining during both overground and treadmill running, since they are easily integrated into phone applications for real-time biofeedback. Assessing rate of acceleration ($rate_{accel}$) is also useful because rate of loading is highly related to tissue damage in animal-based studies (Ewers *et al.*, 2001) and more closely related to stress fracture injury (Zadpoor and Nikooyan, 2011) than peak loading. Therefore, in light of the potential role of impact accelerations ($peak_{accel}$ and $rate_{accel}$) in RRI research and clinical practice, it is important to determine if segmental accelerations collected on a treadmill are representative of those collected during overground running, and *vice-versa*.

Only six studies have directly compared impact accelerations across treadmill and over ground surfaces, primarily examining shank $peak_{accel}$ (Bigelow *et al.*, 2013; García-Pérez *et al.*, 2014; Fu *et al.*, 2015; Montgomery *et al.*, 2016; Oliveira *et al.*, 2016; Milner, Hawkins and Aubol, 2020). However, to gain a more complete understanding, three additional aspects need further investigation. Firstly, only one study (Bigelow *et al.*, 2013) has examined impact accelerations at the lower back, despite it being a site of RRIs (Van Gent *et al.*, 2007). Secondly, only one study (García-Pérez *et al.*, 2014) has examined $rate_{accel}$. Finally, only one study (Fu *et al.*,

2015) has examined if segmental accelerations are similar when measured on different treadmill models, despite treadmills potentially having different stiffness characteristics. Therefore, it is unclear as to whether impact acceleration values can be interchanged between different treadmill models, for example in the case of running-retraining.

In addressing this study's aims, in line with recommendations by Atkinson and Neville (Atkinson and Nevill, 1998), we propose examining three levels of 'representation' and relating each interpretation to specific research and clinical implications. Firstly, an examination of mean systematic differences across surfaces will allow comparison to previous research. Five of the six previous studies exclusively employed this analysis approach, yielding mixed findings of both non-significant (Bigelow *et al.*, 2013; Fu *et al.*, 2015; Montgomery *et al.*, 2016; Oliveira *et al.*, 2016) and significant differences (García-Pérez *et al.*, 2014; Milner, Hawkins and Aubol, 2020). Where non-significant findings are evident, some studies implicitly or explicitly state that the surfaces are therefore comparable. However, mean differences should not be employed alone as an assessment of reliability, as it neither takes into account nor provides an indication of the magnitude of random variation (Atkinson and Nevill, 1998). To address this, the intraclass correlation (ICC) is useful as a measure of relative consistency (Weir, 2005). The ICC measures the consistency of the rank order of runners across surfaces; for example, in the context of RRIs, the greater the ICC, the greater the likelihood that an association with accelerations measured on one surface will be evident on the other surface. The ICC however, does not measure absolute reliability or agreement between surfaces (Weir, 2005), which can be assessed using a Bland-Altman analysis. A high level of agreement between surfaces indicates that measures collected on one surface are sufficiently similar to those collected on the other surface and the results can be used interchangeably (Bland M. and Altman G, 1999). To date, no studies have examined either relative consistency or absolute agreement in comparing impact accelerations between running surfaces.

Using the above three levels of analysis, this study aims to investigate whether $peak_{accek}$ and $rate_{accel}$ (at the shank and lower back) produced during running on treadmills of differing stiffness are 'representative' of those produced during overground running. A secondary aim is to investigate if the impact accelerations measured on treadmills of different stiffness are 'representative' of each other.

It was hypothesised that $peak_{accel}$ and $rate_{accel}$ would be significantly larger for overground than treadmill running, but that acceptable levels of relative consistency and absolute agreement would be evident. The secondary hypothesis was that no significant difference in $peak_{accel}$ and

$rate_{accel}$ would be evident between treadmills, with acceptable levels of relative consistency and absolute agreement.

Methodology

Participants

Uninjured participants, running a minimum of 10 km per week for the previous six months, were recruited via email. An *a priori* calculation of sample size was conducted based on the ICC analysis (Bujang and Baharum, 2017). A minimum sample of 16 participants was required to achieve a minimum correlation of 0.4 (alpha = 0.05, power = 80%). This was amended to 18 for potential dropout. Ethical Approval was granted from DCU Research Ethics Committee.

Procedures

Participants attended the laboratory on one occasion. Following informed consent, mean body height (m) and body mass (kg) were recorded. Two inertial measurement units (Shimmer, Ireland) (dimensions: 65 mm x 32 mm x 12 mm, mass: 31 gm, acceleration range: ±16 g) were attached tightly bilaterally 5 cm proximal to the medial malleolus using double-sided sticky tape, overlayed with tightly applied Hypafix tape, aligned superiorly along the shank's long-axis. A single IMU (dimensions: 51 mm x 34 mm x 14 mm, mass: 23.6 gm, acceleration range: ±8 g) was similarly secured, aligned superiorly along the vertical midline of the S2 spinous process. This was secured further by tape and an elastic waistband on top (Johnson, Outerleys, *et al.*, 2020). Triaxial accelerometer data were captured at 512 Hz (Hennig, Milani and Lafortune, 1993) and calibrated using the Shimmer 9DOF Calibration Application.

Participants ran on three different surfaces wearing their own training shoes: Treadmill 1 (Runner-DTM2500i, Netherlands), Treadmill 2 (Tunturi-J9F, Netherlands) and overground on a flat asphalt path. To quantify the stiffness of the two treadmills, the displacement of the surfaces was assessed under static loading conditions with masss ranging from 60 to 200 kg (Smith, McKerrow and Kohn, 2017). Stiffness was calculated as the applied weight (Newtons) divided by the associated displacement (metres). Mean and maximum vertical stiffness were calculated (Treadmill 1: 165.87 kNm^{-1} and 178.26 kNm^{-1}, respectively; Treadmill 2: 187.51 kNm^{-1} and 217.26 kNm^{-1}, respectively).

Participants performed a dynamic warm-up (Yamaguchi, Takizawa and Shibata, 2015). The surface order was randomised using predetermined block-randomisation. For the treadmill trials, participants ran on each treadmill for three minutes for familiarisation, followed by two minutes at a constant self-selected pace that represented their typical running speed (Heiderscheit *et al.*, 2011), which was read from the treadmill display. For the overground condition, participants ran outside on a straight 800 m flat asphalt path at a self-selected speed that represented their typical running pace, determined using timing gates (MuscleLab, Norway) 60 m apart, located 600 and 660 m along the path. To minimise the effects of exertion, participants were given five minutes rest between each testing condition; if their Borg Rate of Perceived Exertion (RPE) (Borg, 1954) had not returned to baseline, additional time was provided.

Data analysis

Data from the accelerometers were processed using custom-written software (MATLAB R2018a). Following a residual analysis (Winter, 2009) the data were filtered using a 4^{th}-order zero-lag Butterworth filter (60 Hz) (Sinclair, 2016). Dropped packets were filled using a cubic spline, and the time series data were time-aligned via the Shimmer software (Shimmer Consensys, Ireland). For treadmill running, data were collected during the second minute of the two-minute treadmill trials. For the 800 m overground run, this was collected between the 600 to 620 m points. Foot strike was identified using the shank mounted accelerometer as the local maxima preceding the peak negative acceleration. The peak accelerations associated with impact are represented as negative values. $Rate_{accel}$ was calculated as the slope of the $peak_{accel}$ (Figure 14). No drift was detected in the accelerometer signal and therefore was not compensated for.

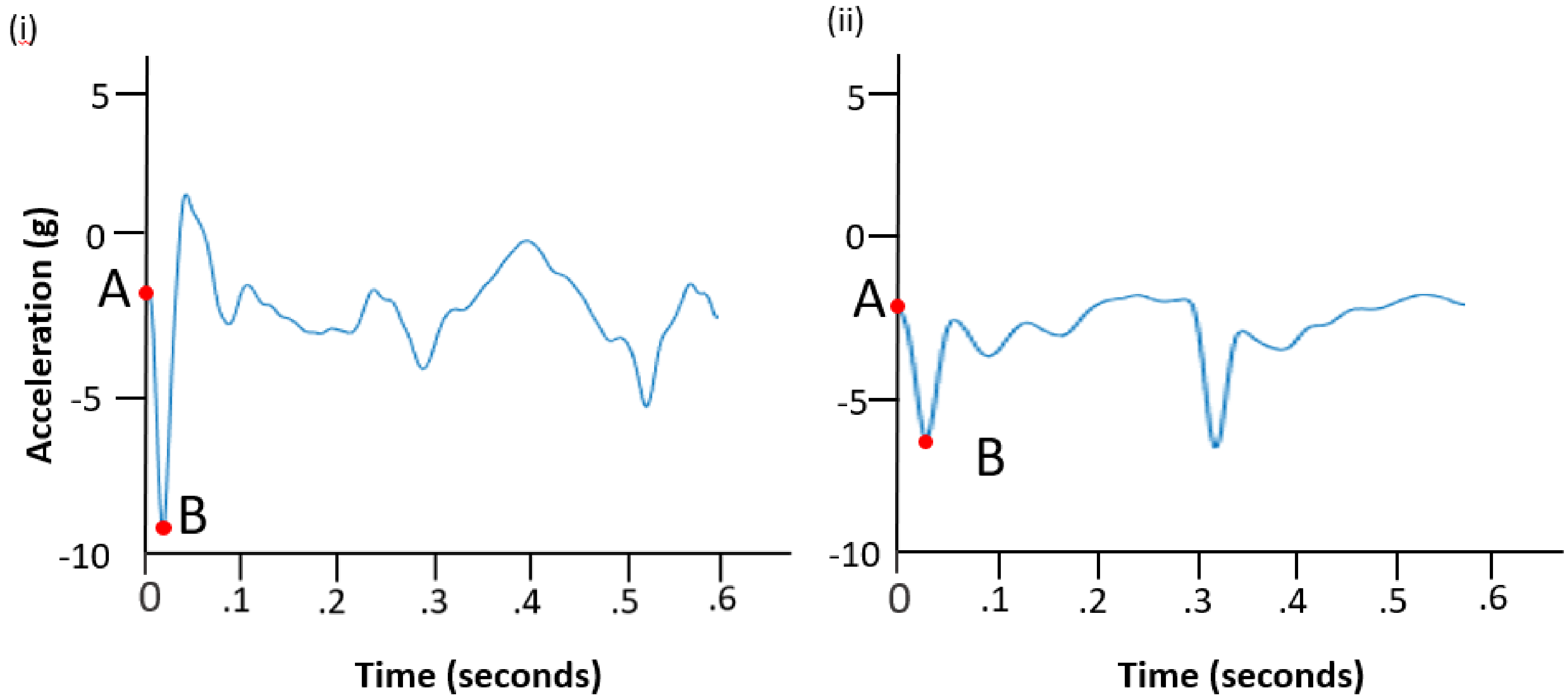


Figure 14 Example acceleration traces for treadmill running for the (i) shank and (ii) lower back. Peakacc (B) and the lower point (A) used for determining the rateaccel are indicated.

Statistical Analysis:

Means and standard deviations of the accelerometery data were calculated, and differences in treadmill and overground self-selected speeds were assessed using paired t-tests. Relative consistency was assessed using a two-way mixed-effects, consistency, single-measure intraclass correlation coefficient model [ICC (3,1)]. ICC was interpreted with <0.5, 0.5 - 0.75, 0.75 - 0.9 and >0.9 indicative of poor, moderate, good and excellent relative consistency, respectively (Koo and Li, 2016). Bland-Altman plots examined the absolute agreement of impact accelerations between running surfaces. If a significant correlation was found between the difference in surface comparisons and their average, a regression approach was implemented (Bland M. and Altman G, 1999).

The 95% limits of agreement between surfaces (mean difference ± 1.96 SD) were calculated for fixed bias (systematic difference between surfaces) and proportional bias (relationship of the differences between surfaces and their average) (Bland M. and Altman G, 1999). The *a priori* clinically acceptable range (CAR) was set at 15%, based on previous findings by Milner et al (Milner *et al.*, 2006b). Agreement between surfaces was considered acceptable when the difference in the Outer Limits of Agreement (OLOA) [upper $CI_{95\%}$ for the upper Limit of Agreement – lower $CI_{95\%}$ for the lower Limit of Agreement] did not exceed the CAR (Bland M. and Altman G, 1999; Preiss and Fisher, 2008).

Eighteen participants were included in the study, with both sides of the body assessed, providing 36 sets of data for both the shank and the lower back. Repeated measures ANOVAs were used to evaluate mean systematic differences at each segment for the three running surfaces. Data were tested for normality using Shapiro-Wilk Test. Post-hoc evaluation used pairwise comparisons. Non-parametric data were assessed using the Friedman's Test, with Wilcoxon signed-rank post-hoc testing. Bonferroni corrections were used for all post-hoc tests, resulting in a $p < 0.017$ alpha level. Effect sizes were calculated using Cohen's *d*, with 0.2, 0.5 and 0.8 interpreted as small, medium and large, respectively (Cohen, 2013). The ICC and ANOVA were completed using IBM SPSS statistics (version 27). The Bland-Altman analysis was completed using in-house developed templates with Microsoft Excel (version 2106).

Results

Ten males and eight females (age: 24.6 ± 4.4 years, body mass: 68.7 ± 10.1 kg, body height 1.71 ± 0.09 m, weekly running distance: 30.3 ± 12.7 km) participated in this study. Means and standard deviations of $peak_{accel}$ and $rate_{accel}$ across the three surfaces are presented in Table 101. The self-selected speed during treadmill (2.97 ± 0.33 m/s) and overground (3.50 ± 0.36 m/s) conditions were statistically different ($p < .001$).

Table 101 The mean ± standard deviation of peak acceleration and rate of acceleration at the shank and lower back across the surfaces.

Shank		***OG***	***T1***	***T2***
	Peak Acceleration (g)	-19.2 ± 4.4	-7.9 ± 2.6	-8.4 ± 2.8
	Rate of Acceleration (g/s)	2433.9 ± 977.0	694.4 ± 375.1	782.5 ± 465.1
Lower back				
	Peak Acceleration (g)	-4.0 ± 0.9	-4.1 ± 1.0	-4.1 ± 0.9
	Rate of Acceleration (g/s)	194.3 ± 71.7	181.8 ± 63.2	198.0 ± 63.9

Abbreviations: OG- overground, T1- Treadmill 1, T2- Treadmill 2.

ICC and Bland-Altman results are provided in Table 102 and Table 103, respectively as well as the post-hoc interactions. The ICCs indicate moderate to good consistency for the shank (Table 102) and moderate to excellent consistency for the lower back (Table 103) between all surfaces. The Bland-Altman analyses indicate that the outer limits of agreement were greater than the CAR for all comparisons across all surfaces, indicating a large and unacceptable level of absolute agreement (see Figure 15, Figure 16). There was a statistically significant systematic mean difference in $peak_{accel}$ ($\chi^2(2) = 54.914$, $p < 0.001$) at the shank across surfaces. $Peak_{accel}$ at the shank was significantly greater on the overground surface compared to on both Treadmills 1 ($Z =-5.159$, $p < 0.001$) and 2 ($Z = -5.159$, $p < 0.001$), but no significant difference existed between Treadmills 1 and 2 ($Z = -2.129$, $p = 0.033$). Similarly, there was a main simple effect for surface in relation to shank $rate_{accel}$ ($\chi^2(2) = 52.629$, $p < 0.001$). Shank $rate_{accel}$ was significantly greater on the overground surface compared to both Treadmill 1 ($Z = 5.159$, $p < 0.001$) and Treadmill 2 ($Z = -5.159$, $p < 0.001$). There was no significant difference in shank $rate_{accel}$ between Treadmills 1 and 2 ($Z= -1.425$, $p = 0.152$). There were no statistically significant mean systematic differences in $peak_{accel}$ ($F (2,70)$, $p = 0.132$) or $rate_{accel}$ ($\chi^2(2) = 1.167$, $p = 0.558$) at the lower back between surfaces.

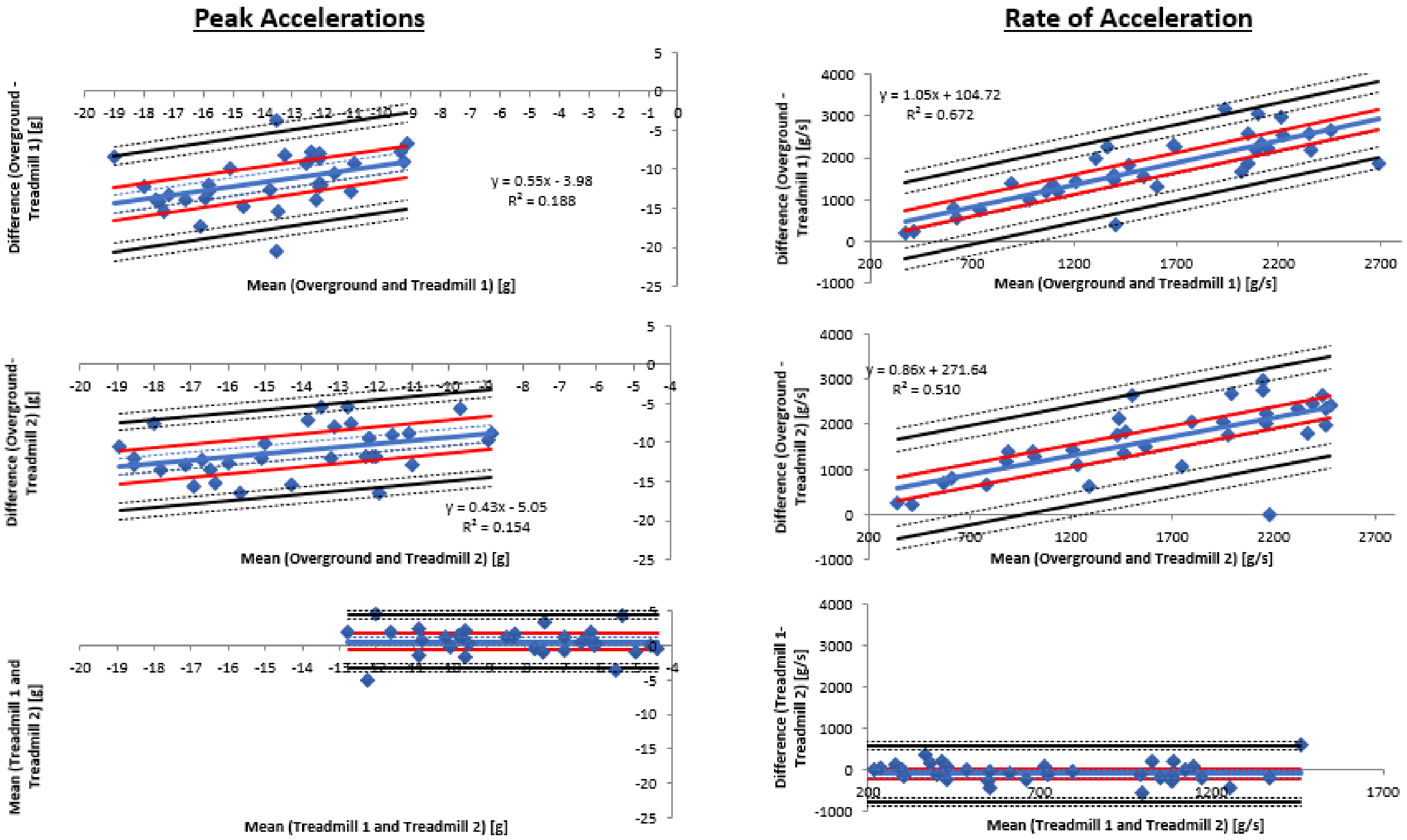


Figure 15 Bland-Altman Plots demonstrating the absolute agreement between accelerations across surfaces at the shank. The red lines represent the upper and lower limits of the clinically acceptable range. The black lines represent the upper and lower limits of agreement. All dotted lines show the 95% confidence intervals

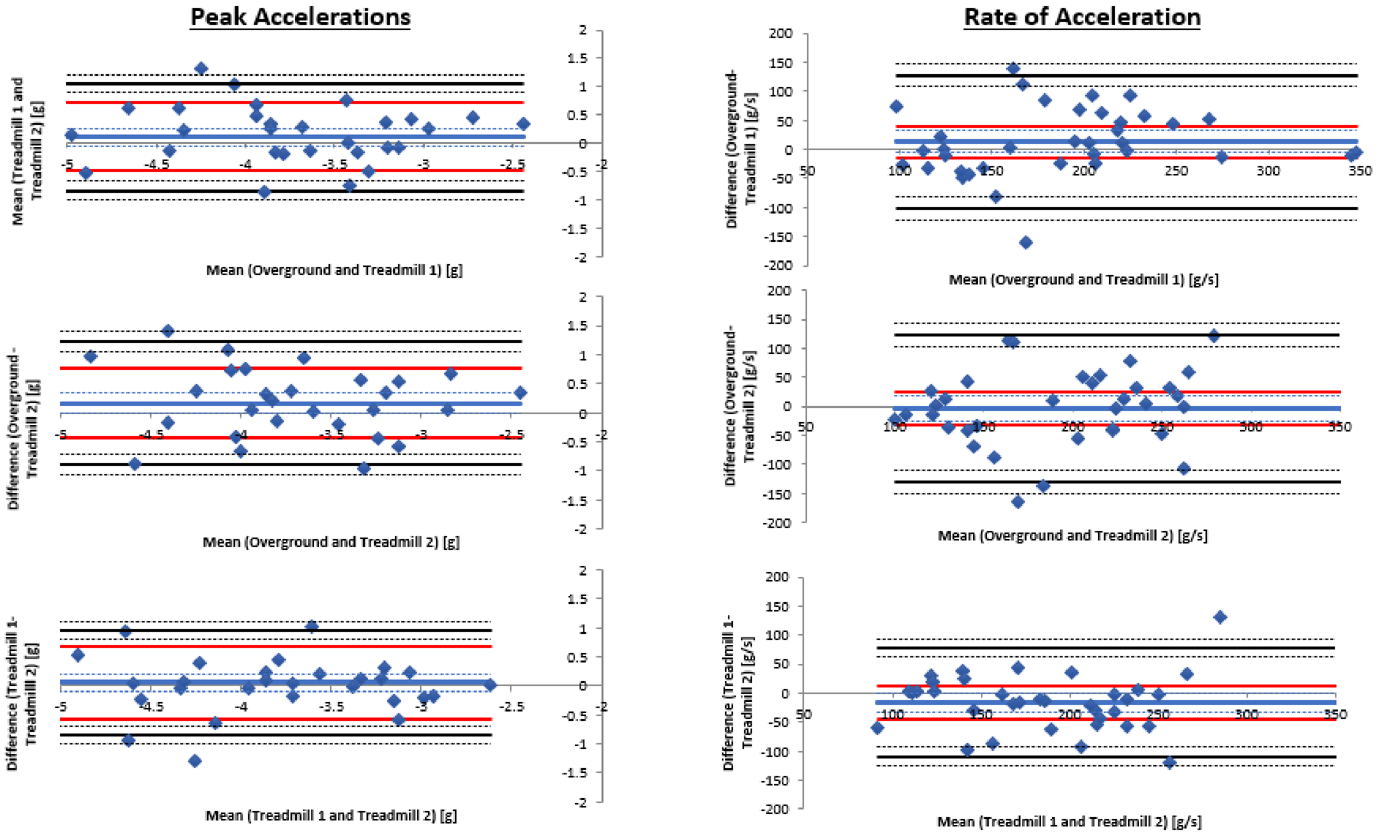


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Figure 16 Bland-Altman Plots demonstrating the absolute agreement between accelerations across surfaces at the lower back. The red lines represent the upper and lower limits of the clinically acceptable range. The black lines represent the upper and lower limits of agreement. All dotted lines show the 95% confidence intervals.

Table 102 Relative consistency, absolute agreement and systematic mean differences in peakacc and rateacc at the shank between surfaces.

	Peak Acceleration (g)			***Rate of Acceleration (g/s)***		
Relative Consistency	OG vs T1	OG vs T2	T1 vs T2	OG vs T1	OG vs T2	T1 vs T2
ICC (3-1) (95%CI)	0.65 (0.31- 0.82)	0.73 (0.46- 0.86)	0.86 (0.72- 0.93)	0.59 (0.19- 0.80)	0.64 (0.29- 0.82)	0.80 (0.60- 0.90)
ICC interpretation	Moderate	Moderate	Good	Moderate	Moderate	Good
Absolute Agreement						
Bias Mean Difference (95% CI) [a]	y = 0.55x – 3.98 $R^2 = 0.188$	y = 0.43x - 5.05 $R^2 = 0.154$	0.5 (1.2, -0.1)	y = 1.05x + 104.7 $R^2 = 0.672$	y = 0.86x + 271.6 $R^2 = 0.510$	-88 (26, 202)
ULOA (95% CI)	y = 0.55x + 2.15	y = 0.43x + 0.64	4.4 (5.0, 3.7)	y = 1.05x + 1011.8	y = 0.86x + 1369.0	588 (702, 473)
LLOA (95% CI)	y = 0.55x – 10.12	y = 0.43x - 10.74	-3.3 (-2.6, -4.0)	y = 1.05x- 802.4	y = 0.86x – 825.8	-764 (-650, -878)
95% ULOA (upper 95% CI) - 95% LOA (lower 95% CI)	14.6	13.5	9.0	2341	2716	1580
Required CAR [%]	-53	48	55	75	69	109
LOA interpretation	Unacceptable	Unacceptable	Unacceptable	Unacceptable	Unacceptable	Unacceptable
Systematic Mean Differences						
p value	<0.001*	<0.001*	0.033	<0.001*	<0.001*	0.154
Effect Size (Cohen's d)	-3.1 (Large)	-2.9 (Large)	0.2 (Small)	2.4 (Large)	2.2 (Large)	-0.2 (Small)
Interpretation	OG > T1	OG > T2	(T1, T2)	OG > T1	OG > T2	(T1, T2)

Abbreviations: OG: overground, T1: Treadmill 1, T2: Treadmill 2, ICC: intraclass coefficient, CI: confidence interval, ULOA- upper limit of agreement, LLOA- lower limit of agreement. N/A: The upper and lower limits of agreement were not applicable as a regression equation was used. CAR: clinically acceptable range. *Significant difference in means. [a] The difference between the surfaces correlated with the average of the surfaces and therefore the regression equation is provided but not the 95% CI.

Table 103 Relative consistency, absolute agreement and systematic mean differences of peakaccel and rateaccel at the lower back between surfaces.

		Peak Acceleration (g)			***Rate of Acceleration (g/s)***	
Relative Consistency	OG vs T1	OG vs T2	T1 vs T2	OG vs T1	OG vs T2	T1 vs T2
ICC (3,1) (95%CI)	0.92 (0.85-.96)	0.90 (0.81-0.95)	0.93 (0.86-0.96)	0.77 (0.55-0.88)	0.71 (0.43-0.85)	0.84 (0.68-0.92)
ICC interpretation	Excellent	Good	Excellent	Good	Moderate	Good
Absolute Agreement						
Bias Mean Difference (95% CI)	0.1 (-0.3, 0.0)	0.2 (0.3, 0.0)	0.1 (0.2, -0.1)	-16.2 (-0.6, -31.8)	12.5 (31.6, -6.5)	-3.7 (-17.4, -24.7)
ULOA (95% CI)	1.1 (1.2, 0.9)	1.4 (1.1, -0.9)	0.9 (1.1, 0.8)	77.2 (92.7, 61.6)	127.0 (146.0, 107.9)	123 (144, 101)
LLOA (95% CI)	-0.8 (-0.7, -1.0)	-0.9 (-0.7, -1.1)	-0.8 (-0.7, -1.0)	-109.6 (-94.0, -125.1)	-101.9 (-82.8, -121.0)	-130 (-109, -151)
ULOA (95% CI) - LLOA (95% CI)	2.2	2.5	2.1	267.0	294.4	217.9
CAR Required (%)	28	31	26	57	71	76
LOA interpretation	Unacceptable	Unacceptable	Unacceptable	Unacceptable	Unacceptable	Unacceptable
Systematic Mean Differences						
p value	0.18	0.08	0.18	0.226	0.814	0.038
Effect Size (Cohen's d)	0.1 (Small)	0.2 (Small)	0.1 (Small)	0.2 (Small)	-0.1 (Small)	-0.3 (Small)
Interpretation	(OG, T1)	(OG, T2)	(T1, T2)	(OG, T1)	(OG, T2)	(T1, T2)

Abbreviations: OG: overground, T1: Treadmill 1, T2: Treadmill 2, ICC: intraclass coefficient, CI: confidence interval, ULOA- upper limit of agreement, LLOA- lower limit of agreement. CAR: clinically acceptable range.

Discussion

The study's primary aim was to investigate if $peak_{accel}$ and $rate_{accel}$ at the shank and lower back measured during treadmill running were representative of those produced during overground running. In terms of relative consistency, the ICCs suggest $peak_{accel}$ and $rate_{accel}$ were moderately consistent for the shank across all surfaces, but had greater consistency at the lower back, with ICCs classified as good or excellent (Table 102, Table 103). Since the ICC is a measure of relative consistency, the results indicate that individuals with high/low impact accelerations relative to the group during treadmill-based testing, will have high/low impact accelerations relative to the group when tested overground outdoors. That is, individuals will maintain a similar group rank ordering, irrespective of running surface. Therefore, any research or clinical applications that uses rank ordering of individuals for $peak_{accel}$ and $rate_{accel}$ can use either surface to achieve the same finding. For example, a prospective study using logistic regression to examine the relationship between $peak_{accel}$ and subsequent injury occurrence, will arrive at similar finding irrespective of whether all participants are assessed on a treadmill or all participants are assessed overground running. This is, in part, because a logistic regression is 'scale invariant'. However, the moderate relative consistency at the shank has wide 95% confidence intervals meaning that results must be interpreted with caution.

In contrast, Bland-Altman plots demonstrated low levels of absolute agreement for impact acceleration values across the surfaces. It is not possible to compare our findings to previous research because no other studies have compared $peak_{accel}$ or $rate_{accel}$ across surfaces using a Bland-Altman analysis for absolute agreement. However, previous research (Milner, Hawkins and Aubol, 2020) has found that only half of the variance in the magnitude of treadmill shank $peak_{accel}$ can be predicted from overground accelerations. Our study suggests that $peak_{accel}$ and $rate_{accel}$ collected on overground and treadmill surfaces are not interchangeable. This finding has important implications where absolute measurements are relevant. For example, when employing running-retraining using bio-feedback (Chan *et al.*, 2018), recommendations to maintain $peak_{accel}$ or $rate_{accel}$ below a certain threshold will only be relevant to the surface from which the original recommendations were determined. Similarly, if studies are aiming to determine the absolute $peak_{accel}$ and/or $rate_{accel}$ that causes an injury, the findings would be surface specific. This is an important consideration for clinicians and researchers in that even using different treadmill types or surfaces may influence values.

Investigation of the mean systematic differences across overground and treadmill surfaces showed significantly greater $peak_{accel}$ and $rate_{accel}$ at the shank during overground running compared to both treadmills. This agrees with some previous research which compared overground to treadmill running (García-Pérez *et al.*, 2014; Milner, Hawkins and Aubol, 2020), although others report no significant differences (Fu *et al.*, 2015; Montgomery *et al.*, 2016; Oliveira *et al.*, 2016). The greater $peak_{accel}$ and $rate_{accel}$ may reflect differences in the mechanical properties between the asphalt and treadmill surfaces. Our treadmills had mean vertical displacements of 7.5 mm (Treadmill 1) and 6.4 mm (Treadmill 2), whereas displacement of asphalt approaches zero (Colino *et al.*, 2020). Furthermore, asphalt absorbs little shock at impact relative to a treadmill, in addition to having a much larger energy restitution capacity (Colino *et al.*, 2020). Therefore, the treadmills act to attenuate the $peak_{accel}$ and $rate_{accel}$ at initial impact.

There were no significant differences in $peak_{accel}$ or $rate_{accel}$ at the lower back in overground compared to treadmill running; in agreement with previous literature (Bigelow *et al.*, 2013), which has been sparse. Lowering superior (proximal to the head) impact forces appears important in maintaining head stability during running (Hamill, Lim and van Emmerik, 2020), which may explain why differences are evident at the shank, but not the lower back. This protection of superior structures has been previously documented in comparing different foot strike patterns (Gruber *et al.*, 2014) and levels of fatigue (García-Pérez *et al.*, 2014).

A secondary aim was to examine if $peak_{accel}$ and $rate_{accel}$ measured on one treadmill were representative of those measured on a second treadmill, when treadmills differed in stiffness. Good to excellent relative consistency was found between Treadmills 1 and 2 for measures of both $peak_{accel}$ and $rate_{accel}$. This indicates that the rank ordering of runners is consistent across treadmills. For example, if a study that uses a stiff treadmill finds runners with low/high accelerations relative to the group have a greater incidence of injury, the same pattern in findings would likely be found if measured on a less stiff treadmill. Therefore, any research or clinical applications that uses rank ordering of individuals for $peak_{accel}$ or $rate_{accel}$ can use either treadmill to achieve the same overall finding.

In contrast, Bland-Altman plots revealed low absolute agreement between Treadmill 1 and 2 for both $peak_{accel}$ and $rate_{accel}$ at both the shank and lower back. This suggests that absolute values of impact acceleration collected on different treadmills cannot be used interchangeably. This finding also signals a need for researchers to report the stiffness characteristics of treadmills they use.

Another potential explanation for the significantly greater $peak_{accel}$ at the shank during overground compared to treadmill running was the greater running speed of participants during overground running (+0.47 m/s). However, although increased running speed can contribute to greater $peak_{accel}$ (Mercer *et al.*, 2002), the magnitude of difference in shank $peak_{accel}$ in the present study exceeds the amount that could be explained *solely* by differences in running speed. Mercer et al (Mercer *et al.*, 2002) found that for every 1 m/s increase in speed, shank $peak_{accel}$ increases by approximately 42%. Therefore, our increased speed overground would likely only contribute to a maximum of a 20% increase in $peak_{accel}$. In addition, previous research has found that preferred running speed is slower on treadmills compared to overground surfaces (Kong *et al.*, 2012), indicating that the present study's findings are ecologically valid. This is very important as treadmill-based assessments in both clinical practice and research are generally based on self-selected running speeds directly determined on a treadmill (Napier *et al.*, 2018; Johnson, Tenforde, *et al.*, 2020), rather than based on measured overground running speeds.

Limitations

The main limitation of this study is that findings are only applicable to overground asphalt running and the specific treadmill models tested.

Conclusion

$Peak_{accel}$ and $rate_{accel}$ at the shank and lower back had moderate to excellent relative consistency across surfaces, with higher consistency at the lower back. This indicates that treadmills could be used to assess runners instead of assessing them whilst overground running when only the relative or rank ordering of individuals for $peak_{accel}$ and $rate_{accel}$ is required. However, poor absolute agreement, indicates that accelerometery data from treadmill and overground running cannot be interchanged when the absolute magnitude is important.

8.4. *Appendix D: Images of marker and IMU placement.*

Figure 17 Posterior view of experimental set up for motion analysis demonstrating attachment sites of the Vicon reflective markers and inertial measurement units.

Figure 18 Anterior view of experimental set up for motion analysis demonstrating attachment sites of the Vicon reflective markers and inertial measurement units.

8.5. Appendix E: Results of the correlation analysis for Chapter 5.

Table 104 Results of correlation analysis for Chapter 5.

Variable 1	**Variable 2**	**Spearman's Rho**
Peak hip adduction	Hip adduction at initial contact	0.73
Hip flexion at initial contact	Peak hip flexion	1.00
Hip flexion at initial contact	Pelvis anterior tilt at initial contact	0.82
Hip flexion at initial contact	Pelvis anterior tilt at toe-off	0.74
Hip flexion at initial contact	Peak pelvis anterior tilt	0.75
Hip flexion at initial contact	Minimum anterior pelvis tilt	0.74
Hip flexion at toe-off	Minimum hip flexion	0.99
Hip flexion at toe-off	Pelvis anterior tilt at initial contact	0.71
Hip flexion at toe-off	Pelvis anterior tilt at toe-off	0.78
Hip flexion at toe-off	Peak pelvis anterior tilt	0.76
Hip flexion at toe-off	Minimum anterior pelvis tilt	0.70
Peak hip flexion	Pelvis anterior tilt at initial contact	0.82
Peak hip flexion	Pelvis anterior tilt at toe-off	0.76
Peak hip flexion	Peak pelvis anterior tilt	0.77
Peak hip flexion	Minimum anterior pelvis tilt	0.75
Minimum hip flexion	Pelvis anterior tilt at initial contact	0.72
Minimum hip flexion	Pelvis anterior tilt at toe-off	0.79
Minimum hip flexion	Peak pelvis anterior tilt	0.77
Minimum hip flexion	Minimum anterior pelvis tilt	0.72
Hip internal rotation at initial contact	Peak hip internal rotation	0.90
Peak hip internal rotation	Minimum hip internal rotation	0.78
Knee varus at initial contact	Knee varus at toe-off	0.89
Knee varus at initial contact	Peak knee varus	0.95
Knee varus at initial contact	Minimum knee varus	0.85
Knee varus at toe-off	Peak knee varus	0.91
Peak knee varus	Minimum knee varus	0.86
Minimum knee varus	Knee varus at toe-off	0.82
Peak pelvis contralateral rotation	Pelvis contralateral rotation at toe-off	0.97
Peak thorax rotation to the contralateral side	Thorax rotation to contralateral side at toe-off	1.00
Thorax rotation to contralateral side at initial contact	Minimum thorax rotation to the contralateral side	1.00

All variables were significantly correlated at the $p < .01$ level.

8.6. *Appendix F: Results of the univariable analysis for Chapter 5.*

Table 105 Results of the univariable analysis for Chapter 5.

Variable	Uninjured	Injured	Unadjusted				Adjusted*			
	Mean ± SD	Mean ± SD	Sig.	OR	95% C.I.for OR		Sig.	OR	95% C.I.for OR	
Demographics					Lower	Upper			Lower	Upper
Age (years)	43.6 ± 9.3	43.4 ± 8.4	0.888	1.00	0.97	1.03				
BMI (kg/m2)	24.2 ± 2.9	23.7 ± 2.9	0.188	0.94	0.86	1.03	0.094	0.92	0.83	1.02
Female sex (reference is male)	41 females (38%)	43 females (37%)	0.851	0.95	0.55	1.63				
Training and injury history										
History of RRI < 1 year ago	38 (35%)	57 (49%)	0.041	1.75	1.02	2.99	0.05	1.72	1.00	2.95
Average weekly mileage (km)	36.4 ± 21.2	34.5 ± 19.4	0.481	1.00	0.98	1.01				
Self-reported average running pace (km/hr)	11.3 ± 1.9	11.5 ± 1.6	0.289	1.09	0.93	1.27	0.222	1.11	0.94	1.32
Running experience > 10 years (Reference is <10 years' experience)	27 (25%)	24 (21%)	0.422	0.77	0.41	1.45	0.383	0.76	0.40	1.42
Clinical Tests										
Navicular drop (mm)	9.0 ± 3.3	7.9 ± 2.9	0.005	0.88	0.81	0.96	0.004	0.26	0.11	0.65
Navicular Drop > 10 mm (reference is navicular drop <10 mm)	40 (37%)	30 (26%)	0.066	0.59	0.33	1.04	0.05	0.56	0.31	1.00
Foot Posture Index: Pronated foot (reference is neutral foot)	60 (56%)	64 (55%)	0.894	1.04	0.59	1.84	0.921	0.97	0.55	1.72
Foot Posture Index: Supinated foot (reference is neutral foot)	10 (9%)	14 (12%)	0.511	1.36	0.54	3.45	0.522	1.36	0.53	3.46
Hip abduction strength (Nm/kg)	1.70 ± 0.32	1.64 ± 0.30	0.17	0.55	0.24	1.29	0.149	0.52	0.21	1.27
Hip extension strength (Nm/kg)	1.91 ± 0.45	1.90 ± 0.45	0.904	0.97	0.54	1.73	0.923	0.97	0.53	1.78
Plantar flexion strength (Nm/kg)	0.58 ± 0.21	0.56 ± 0.21	0.36	0.56	0.16	1.96	0.353	0.54	0.15	1.97
Knee extension strength (Nm/kg)	1.33 ± 0.41	1.27 ± 0.37	0.289	0.69	0.35	1.37	0.253	0.65	0.30	1.37
Knee flexion strength (Nm/kg)	0.99 ± 0.28	0.93 ± 0.25	0.104	0.44	0.16	1.18	0.076	0.37	0.12	1.11
Hip internal rotation ROM (°)	39.4 ± 6.6	40.3 ± 6.6	0.305	1.02	0.98	1.06	0.278	1.02	0.98	1.07
Hip external rotation ROM (°)	37.1 ± 6.6	36.8 ± 5.7	0.749	0.99	0.95	1.04	0.721	0.99	0.95	1.04
Hip extension ROM (°)	12.1 ± 7.0	11.8 ± 7.2	0.766	0.99	0.96	1.03	0.824	1.00	0.96	1.03
Ankle dorsiflexion ROM (°)	40.2 ± 4.0	39.8 ± 4.2	0.423	0.97	0.91	1.04	0.415	0.97	0.91	1.04
Running kinetics										
Peak sacrum accelerations (g)	-5.87 ± 1.66	-5.80 ± 1.86	0.972	1.00	0.86	1.16	0.919	0.99	0.85	1.16
Peak shank accelerations (g)	-7.26 ± 2.35	-7.21 ± 2.09	0.389	1.05	0.94	1.18	0.472	1.05	0.93	1.18
Sacrum rate of accelerations (g/s)	305 ± 144	311 ± 172	0.808	1.00	1.00	1.00	0.706	1.00	1.00	1.00

Shank rate of accelerations (g/s)	600 ± 371	572 ± 317	0.544	1.00	1.00	1.00	0.68	1.00	1.00	1.00
Running kinematics										
Ankle eversion at initial contact (°)	2.0 ± 2.2	1.7 ± 2.1	0.411	0.95	0.84	1.07	0.405	0.95	0.84	1.08
Ankle eversion at toe-off (°)	0.1 ± 2.1	-0.1 ± 2.0	0.445	0.95	0.83	1.08	0.408	0.95	0.83	1.08
Ankle eversion inversion excursion (°)	6.8 ± 2.1	6.5 ± 1.9	0.358	0.94	0.82	1.07	0.351	0.94	0.82	1.07
Peak ankle eversion (°)	6.7 ± 2.8	6.3 ± 2.5	0.198	0.94	0.85	1.04	0.184	0.93	0.84	1.03
Minimum ankle eversion (°)	-0.1 ± 2.7	-0.3 ± 1.9	0.421	0.95	0.83	1.08	0.39	0.94	0.82	1.08
Ankle dorsiflexion at initial contact (°)	10.4 ± 6.3	10.2 ± 6.0	0.806	1.00	0.95	1.04	0.727	0.99	0.95	1.04
Ankle dorsiflexion at toe-off (°)	-14.5 ± 6.1	-15. 2 ± 5.9	0.42	0.98	0.94	1.03	0.354	0.98	0.93	1.03
Ankle dorsiflexion-plantarflexion excursion (°)	41.9 ± 5.8	42.5 ± 5.6	0.426	1.02	0.97	1.07	0.374	1.02	0.97	1.07
Peak ankle dorsiflexion (°)	27.4 ± 4.0	27.3 ± 4.0	0.919	1.00	0.93	1.07	0.876	1.00	0.93	1.06
Minimum ankle dorsiflexion (°)	-14.5 ± 6.1	-15.2 ± 5.9	0.409	0.98	0.94	1.03	0.342	0.98	0.93	1.02
Ankle internal rotation at initial contact (°)	-7.4 ± 8.4	-6.6 ± 8.5	0.487	1.01	0.98	1.04	0.488	1.01	0.98	1.04
Ankle internal rotation at toe-off (°)	-0.3 ± 8.2	0.6 ± 8.2	0.445	1.01	0.98	1.05	0.403	1.01	0.98	1.05
Ankle internal rotation external rotation excursion (°)	25.1 ± 5.5	25.0 ± 5.3	0.358	0.94	0.82	1.07	0.984	1.00	0.95	1.05
Peak ankle internal rotation (°)	0.5 ± 8.0	1.3 ± 7.8	0.429	1.01	0.98	1.05	0.392	1.02	0.98	1.05
Minimum ankle internal rotation (°)	-24.6 ± 7.9	-23.7 ± 7.8	0.401	1.02	0.98	1.05	0.39	1.02	0.98	1.05
Foot strike pattern: MFS (reference is RFS)	10 (9%)	14 (12%)	0.535	1.31	0.56	3.11	0.484	1.37	0.57	3.26
Foot strike pattern: FFS (reference is RFS)	7 (6%)	6 (5%)	0.705	0.80	0.26	2.48	0.726	0.81	0.26	2.58
Foot dorsiflexion at initial contact (°)	14.9 ± 7.6	14.7 ± 7.4	0.8	1.00	0.96	1.03	0.713	0.99	0.96	1.03
Foot dorsiflexion at toe-off (°)	-54.1 ± 6.9	-54.4 ± 6.6	0.736	0.99	0.96	1.03	0.698	0.99	0.95	1.03
Foot dorsiflexion plantarflexion excursion (°)	69.1 ± 9.8	69.1 ± 9.6	0.958	1.00	0.97	1.03	0.998	1.00	0.97	1.03
Peak foot dorsiflexion (°)	15.0 ± 7.5	14.7 ± 7.3	0.79	1.00	0.96	1.03	0.704	0.99	0.96	1.03
Minimum foot dorsiflexion (°)	-54.1 ± 6.9	-54.4 ± 6.6	0.732	0.99	0.96	1.03	0.694	0.99	0.95	1.03
Hip adduction at initial contact (°)	10.1 ± 4.0	9.1 ± 3.8	0.054	0.93	0.87	1.00	0.062	0.93	0.86	1.00
Hip adduction at toe-off (°)	1.1 ± 3.4	-0.0 ± 3.7	0.022	0.92	0.85	0.99	0.024	0.92	0.85	0.99
Hip adduction abduction excursion (°)	13.8 ± 4.3	13.8 ± 3.9	0.977	1.00	0.94	1.07	0.934	1.00	0.94	1.07
Peak hip adduction (°)	14.7 ± 4.6	13.6 ± 4.0	0.057	0.94	0.88	1.00	0.067	0.94	0.88	1.00
Minimum hip adduction (°)	0.9 ± 3.4	-0.18 ± 3.7	0.057	0.94	0.88	1.00	0.023	0.91	0.85	0.99
Hip flexion at initial contact (°)	38.9 ± 6.5	37.8 ± 6.6	0.189	0.97	0.94	1.01	0.166	0.97	0.93	1.01
Hip flexion at toe-off (°)	-5.0 ± 6.1	-6.2 ± 6.0	0.113	0.97	0.92	1.01	0.071	0.96	0.91	1.00
Hip flexion extension excursion (°)	44.2 ± 5.5	44.5 ± 5.6	0.821	1.01	0.96	1.05	0.764	1.01	0.96	1.06
Peak hip flexion (°)	39.1 ± 6.5	38.0 ± 6.6	0.239	0.98	0.94	1.02	0.207	0.97	0.93	1.02
Minimum hip flexion (°)	-5.2 ± 6.0	-6.4 ± 5.9	0.133	0.97	0.92	1.01	0.085	0.96	0.91	1.01
Hip internal rotation at initial contact (°)	-1.5 ± 6.3	-0.1 ± 6.4	0.107	1.04	0.99	1.08	0.054	1.05	1.00	1.10
Hip internal rotation at toe-off (°)	-8.6 ± 6.4	-8.2 ± 6.7	0.573	1.01	0.97	1.05	0.475	1.02	0.97	1.06
Hip internal rotation external rotation excursion (°)	10.8 ± 3.8	11.7 ± 3.8	0.066	1.07	1.00	1.15	0.052	1.08	1.00	1.16

Peak hip internal rotation (°)	0.9 ± 6.2	2.0 ± 6.1	0.172	1.03	0.99	1.08	0.105	1.04	0.99	1.09
Minimum hip internal rotation (°)	-9.8 ± 5.9	-9.7 ± 6.1	0.817	1.01	0.96	1.05	0.693	1.01	0.97	1.06
Knee varus at initial contact (°)	-2.9 ± 2.6	-1.2 ± 3.11	0.001	1.19	1.08	1.32	0.001	1.20	1.08	1.33
Knee varus at toe-off (°)	-3.9 ± 3.0	-2.7 ± 3.1	0.004	1.15	1.05	1.26	0.004	1.15	1.04	1.26
Knee varus valgus excursion (°)	3.9 ± 1.6	4.3 ± 1.7	0.06	1.17	0.99	1.38	0.051	1.18	1.00	1.40
Peak knee varus (°)	-2.1 ± 2.7	-0.8 ± 3.1	0.003	1.16	1.05	1.28	0.003	1.16	1.05	1.28
Minimum knee varus (°)	-5.9 ± 2.9	-5.00 ± 3.5	0.032	1.10	1.01	1.19	0.038	1.10	1.01	1.19
Knee flexion at initial contact (°)	17.8 ± 5.1	17.6 ± 4.7	0.757	0.99	0.94	1.05	0.886	1.00	0.94	1.05
Knee flexion at toe-off (°)	16.0 ± 6.0	15.5 ± 6.5	0.553	0.99	0.95	1.03	0.534	0.99	0.94	1.03
Knee flexion extension excursion (°)	30.9 ± 5.4	31.0 ± 5.5	0.627	1.01	0.97	1.06	0.635	1.01	0.96	1.06
Peak knee flexion (°)	44.2 ± 4.4	44.3 ± 4.7	0.868	1.01	0.95	1.07	0.845	1.01	0.95	1.07
Minimum knee flexion (°)	13.5 ± 4.4	13.2 ± 5.1	0.698	0.99	0.94	1.04	0.733	0.99	0.94	1.05
Knee internal rotation at initial contact (°)	4.3 ± 6.4	4.4 ± 6.4	0.853	1.00	0.96	1.05	0.897	1.00	0.96	1.05
Knee internal rotation at toe-off (°)	3.8 ± 6.6	3.7 ± 6.3	0.86	1.00	0.96	1.04	0.752	0.99	0.95	1.04
Knee internal rotation external rotation excursion (°)	20.9 ± 4.5	22.4 ± 5.4	0.024	1.07	1.01	1.13	0.024	1.07	1.01	1.13
Peak knee internal rotation (°)	22.9 ± 6.7	24.1 ± 7.7	0.228	1.02	0.99	1.06	0.269	1.02	0.98	1.06
Minimum knee internal rotation (°)	2.0 ± 6.3	1.7 ± 5.8	0.678	0.99	0.95	1.04	0.602	0.99	0.95	1.03
Pelvis contralateral drop at initial contact (°)	2.2 ± 2.7	1.9 ± 2.3	0.371	0.95	0.86	1.06	0.393	0.96	0.86	1.06
Pelvis contralateral drop at toe-off (°)	-4.8 ± 2.7	-4.9 ± 2.7	0.733	0.98	0.89	1.09	0.725	0.98	0.89	1.09
Pelvis contralateral-ipsilateral drop excursion (°)	9.8 ± 3.4	9.4 ± 2.77	0.307	0.96	0.88	1.04	0.276	0.95	0.87	1.04
Peak pelvis contralateral drop (°)	4.9 ± 2.7	4.4 ± 2.5	0.203	0.94	0.85	1.04	0.2	0.94	0.85	1.04
Minimum pelvis contralateral drop (°)	-5.0 ± 2.6	-5.0 ± 2.6	0.932	1.00	0.90	1.10	0.942	1.00	0.90	1.11
Pelvis anterior tilt at initial contact (°)	15.6 ± 5.7	14.6 ± 5.2	0.168	0.97	0.92	1.02	0.133	0.96	0.92	1.01
Pelvis anterior tilt at toe-off (°)	18.1 ± 5.7	17.0 ± 4.9	0.14	0.96	0.92	1.01	0.103	0.96	0.91	1.01
Pelvis anterior-posterior tilt excursion (°)	7.6 ± 2.1	7.5 ± 2.0	0.626	0.97	0.85	1.10	0.586	0.96	0.85	1.10
Peak pelvis anterior tilt (°)	18.4 ± 5.7	17.4 ± 5.0	0.159	0.97	0.92	1.01	0.12	0.96	0.91	1.01
Minimum pelvis anterior tilt (°)	10.8 ± 5.9	9.9 ± 5.1	0.056	0.94	0.87	1.00	0.187	0.97	0.92	1.02
Pelvis contralateral rotation at initial contact (°)	-2.8 ± 3.6	-3.5 ± 4.6	0.169	0.96	0.90	1.02	0.117	0.95	0.89	1.01
Pelvis contralateral rotation at toe-off (°)	3.6 ± 4.1	2.3 ± 3.9	0.018	0.92	0.86	0.99	0.014	0.92	0.85	0.98
Pelvis contralateral rotation external rotation excursion (°)	9.2 ± 3.4	9.1 ± 3.7	0.85	0.99	0.92	1.07	0.88	0.99	0.91	1.08
Peak pelvis contralateral rotation (°)	3.8 ± 3.7	2.8 ± 3.7	0.029	0.92	0.86	0.99	0.024	0.92	0.85	0.99
Minimum pelvis contralateral rotation (°)	-5.3 ± 3.6	-6.4 ± 4.2	0.056	0.94	0.87	1.00	0.042	0.93	0.87	1.00
Thorax contralateral side flexion at initial contact (°)	-2.8 ± 2.4	-3.2 ± 2.4	0.314	0.95	0.85	1.06	0.332	0.95	0.85	1.06
Thorax contralateral side flexion at toe-off (°)	0.6 ± 2.3	0.8 ± 2.4	0.612	1.03	0.92	1.15	0.619	1.03	0.92	1.15
Thorax contralateral-ipsilateral side flexion excursion (°)	5.1 ± 1.7	5.6 ± 2.2	0.077	1.13	0.99	1.29	0.084	1.13	0.98	1.29
Peak thorax contralateral side flexion (°)	0.7 ± 2.3	0.9 ± 2.3	0.566	1.03	0.92	1.16	0.572	1.03	0.92	1.16
Minimum thorax contralateral side flexion (°)	-4.4 ± 2.4	-4.7 ± 2.2	0.311	0.94	0.84	1.06	0.325	0.94	0.84	1.06

Thorax forward flexion at initial contact (°)	7.4 ± 4.7	8.1 ± 4.6	0.288	1.03	0.97	1.09	0.292	1.03	0.97	1.09
Thorax forward flexion at toe-off (°)	7.1 ± 4.8	7.5 ± 4.8	0.615	1.01	0.96	1.07	0.292	1.03	0.97	1.09
Thorax flexion-extension excursion (°)	3.7 ± 1.3	3.9 ± 1.4	0.268	1.12	0.92	1.36	0.204	1.15	0.93	1.42
Peak thorax forward flexion (°)	10.2 ± 4.6	10.8 ± 4.7	0.346	1.03	0.97	1.09	0.344	1.03	0.97	1.09
Minimum thorax forward flexion (°)	6.5 ± 4.7	6.9 ± 4.6	0.449	1.02	0.97	1.08	0.458	1.02	0.97	1.08
Thorax rotation towards contralateral side at initial contact (°)	-13.0 ± 4.4	-13.8 ± 4.1	0.222	0.96	0.91	1.02	0.165	0.96	0.90	1.02
Thorax rotation towards contralateral side at toe-off (°)	14.6 ± 4.7	13.7 ± 4.1	0.147	0.96	0.90	1.02	0.14	0.95	0.89	1.02
Thorax rotation contralateral-ipsilateral rotation excursion (°)	27.7 ± 6.3	27.5 ± 6.3	0.868	1.00	0.96	1.04	0.937	1.00	0.95	1.05
Peak thorax rotation towards contralateral side (°)	14.6 ± 4.7	13.7 ± 4.1	0.141	0.96	0.90	1.02	0.134	0.95	0.89	1.02
Minimum thorax rotation towards contralateral side (°)	-13.1 ± 4.4	-13.8 ± 4.6	0.22	0.96	0.91	1.02	0.163	0.96	0.90	1.02
Spatiotemporal parameters										
Stride length (metres)	2.18 ± 0.32	2.15 ± 0.28	0.402	0.69	0.29	1.65	0.39	0.68	0.28	1.64
Flight time (milliseconds)	441 ± 38	434 ± 39	0.209	1.00	0.99	1.00	0.209	1.00	0.99	1.00
Stance time (milliseconds)	269 ± 38	265 ± 28	0.405	1.00	0.99	1.01	0.314	1.00	0.99	1.00
Stride rate (strides/min)	84.86 ± 4.80	85.63 ± 4.17	0.207	1.04	0.98	1.10	0.215	1.04	0.98	1.10
Step time (milliseconds)	708 ± 43	707 ± 39	0.773	1.00	0.99	1.01	0.609	1.00	0.99	1.01

Abbreviations: SD = standard deviation, Sig = significant, CI = confidence interval, OR = odds ratio, ROM = range of motion. * Adjusted for age, sex and weekly mileage. The following denote the direction of the moment: Ankle dorsiflexion (positive), plantar flexion (negative), ankle inversion (positive), ankle eversion (negative), ankle internal rotation (positive), ankle external rotation (negative), knee flexion(positive), knee extension (negative), knee varus (positive), knee valgus (negative), knee internal rotation (positive), knee external rotation (negative), hip flexion (positive), hip extension (negative), hip adduction (positive), hip abduction (negative), hip internal rotation (positive), hip external rotation (negative), thorax anterior tilt (positive), thorax posterior tilt (negative), thorax drop to contralateral side (positive), thorax drop to ipsilateral; side (negative), thorax rotation to contralateral side (positive), thorax rotation to ipsilateral side (negative), pelvis anterior tilt (positive), pelvis posterior tilt (negative), pelvis drop to contralateral side (positive), pelvis drop to ipsilateral; side (negative), pelvis rotation to contralateral side (positive), pelvis rotation to ipsilateral side (negative

8.7. Appendix G: Results of the correlation analysis for Chapter 6.

Table 106 Results of the correlation analysis for Chapter 6.

Variable 1	Variable 2	Spearman's Rho
Ankle internal external rotation excursion	Ankle eversion inversion excursion	0.81
Ankle dorsiflexion at toe-off	Ankle dorsiflexion plantar flexion excursion	-0.78
Ankle dorsiflexion at toe-off	Minimum ankle dorsiflexion	1.00
Minimum ankle dorsiflexion	Ankle dorsiflexion plantar flexion excursion	-0.78
Ankle eversion inversion excursion	Ankle internal external rotation excursion	0.81
Minimum hip adduction	Hip adduction at toe-off	0.98
Peak hip flexion	Hip flexion at initial contact	0.98
Minimum hip flexion	Hip flexion at toe-off	0.99
Hip internal rotation at initial contact	Peak hip internal rotation	0.90
Hip internal rotation at toe-off	Peak hip internal rotation	0.76
Hip internal rotation at toe-off	Minimum hip internal rotation	0.93
Peak hip internal rotation	Hip internal rotation at initial contact	0.90
Peak hip internal rotation	Hip internal rotation at toe-off	0.76
Peak hip internal rotation	Minimum hip internal rotation	0.79
Minimum hip internal rotation	Hip internal rotation at initial contact	0.69
Minimum hip internal rotation	Hip internal rotation at toe-off	0.93
Minimum hip internal rotation	Peak hip internal rotation	0.79
Knee varus at initial contact	Knee varus at toe-off	0.88
Knee varus at initial contact	Peak knee varus	0.95
Knee varus at initial contact	Minimum knee varus	0.84
Knee varus at toe-off	Knee varus at initial contact	0.88
Knee varus at toe-off	Peak knee varus	0.91
Knee varus at toe-off	Minimum knee varus	0.81
Minimum knee varus	Knee varus at initial contact	0.95
Minimum knee varus	Knee varus at toe-off	0.91
Peak knee varus	Minimum knee varus	0.86
Knee flexion at toe-off	Knee flexion/extension excursion	-0.70
Knee flexion at toe-off	Minimum knee flexion	0.80
Minimum pelvic contralateral rotation	Pelvis contralateral rotation at initial contact	0.79
Peak thorax rotation towards contralateral side	Thorax rotation towards contralateral side at toe-off	1.00
Thorax rotation excursion	Minimum thorax rotation towards contralateral side	-0.7-

8.8. *Appendix H: Results of the univariable analysis for Chapter 6.*

Table 107 Results of the univariable analysis for Chapter 6.

Variable	***Uninjured***	***Injured***	***Unadjusted***				***Adjusted****			
	Mean ± SD	***Mean ± SD***	***Sig.***	***OR***	***95% C.I. for OR***		***Sig.***	***OR***	***95% C.I. for OR***	
Demographics					Lower	Upper			Lower	Upper
Age (years)	43.6 ± 9.3	44.1 ± 6.3	0.794	1.01	0.96	1.05				
BMI (kg/m^2)	24.2 ± 3.0	23.4 ± 2.7	0.167	0.90	0.78	1.04	0.074	0.86	0.72	1.02
Female sex (reference is male)	41 (38%)	13 (42%)	0.689	1.18	0.52	2.66				
Training and injury history										
History of RRI < 1 year ago (reference is never injured)	38 (35%)	14 (45%)	0.313	1.52	0.68	3.41	0.142	2.61	0.72	9.38
Self-reported weekly mileage (km/week)	36.42 ± 21.2	30.71 ± 18.1	0.191	1.00	1.00	1.00				
Self-reported average running pace (km/hr)	11.2 ± 1.9	11.9 ± 2.01	0.124	1.18	0.96	1.45	0.035	1.29	1.02	1.63
Clinical Tests										
Navicular drop (mm)	9.04 ± 3.30	7.43 ± 3.11	0.018	0.84	0.732	0.972	0.013	0.83	0.71	0.96
Navicular Drop > 10 mm (reference is navicular drop <10 mm)	40 (37%)	7 (23%)	0.138	0.50	0.20	1.25	0.102	0.45	0.17	1.17
Foot Posture Index: Pronated foot (reference is neutral foot)	60 (56%)	12 (40%)	0.122	0.51	0.21	1.20	0.099	0.48	0.20	1.15
Foot Posture Index: Supinated foot (reference is neutral foot)	10 (9%)	4 (13%)	0.984	1.01	0.28	3.74	0.955	1.04	0.28	3.93
Hip abduction strength (Nm/kg)	1.7 ±0.32	1.73 ± 0.32	0.682	1.30	0.72	4.47	0.427	1.72	0.45	6.60
Hip extension strength (Nm/kg)	0.58 ±0.21	0.59 ± 0.22	0.131	1.95	0.82	4.62	0.069	2.33	0.94	5.78
Plantar flexion strength (Nm/kg)	1.91 ±0.45	2.06 ± 0.49	0.773	1.32	0.20	8.83	0.644	1.57	0.23	10.55
Knee extension strength (Nm/kg)	1.33 ±0.41	1.32 ± 0.36	0.915	0.95	0.35	2.58	0.659	1.29	0.41	4.06
Knee flexion strength (Nm/kg)	0.99 ±0.28	1 ± 0.23	0.811	1.20	0.27	5.23	0.428	2.01	0.36	11.35
Hip internal rotation ROM (°)	39.4 ± 6.6	40.3 ± 6.9	0.533	1.02	0.96	1.08	0.494	1.02	0.96	1.09
Hip external rotation ROM (°)	37.1 ± 5.9	35.9 ± 7.5	0.356	0.97	0.91	1.04	0.27	0.96	0.90	1.03
Hip extension ROM (°)	12.1 ± 7.0	11.1 ± 6.4	0.688	0.99	0.93	1.05	0.595	0.98	0.93	1.05

Ankle dorsiflexion ROM (°)	40.2 ± 4.0	39.1 ± 4.9	0.199	0.94	0.85	1.03	0.178	0.94	0.85	1.03
Running kinetics										
Peak sacrum accelerations (g)	-5.81 ± 1.65	-5.66 ± 1.72	0.651	1.06	0.83	1.35	0.622	1.07	0.83	1.37
Peak shank accelerations (g)	-7.47 ± 2.4	-7.61 ± 2.16	0.767	0.98	0.82	1.15	0.633	0.96	0.80	1.14
Sacrum rate of accelerations (g/s)	305 ± 143	302 ± 155	0.908	1.00	1.00	1.00	0.835	1.00	1.00	1.00
Shank rate of accelerations (g/s)	600 ± 371	647 ± 350	0.524	1.00	1.00	1.00	0.398	1.00	1.00	1.00
Running kinematics (degrees)										
Ankle eversion at initial contact (°)	2.0 ± 2.2	2.3 ± 2.6	0.491	1.06	0.89	1.27	0.632	1.05	0.87	1.26
Ankle eversion at toe-off (°)	0.1 ± 2.1	-0.2 ± 2.1	0.544	0.94	0.77	1.15	0.372	0.91	0.75	1.12
Ankle eversion inversion excursion (°)	6.8 ± 2.1	7.4 ± 2.0	0.163	1.14	0.95	1.38	0.144	1.16	0.95	1.41
Peak ankle eversion (°)	6.7 ± 2.8	7.1 ± 2.7	0.511	1.05	0.91	1.21	0.617	1.04	0.90	1.21
Minimum ankle eversion (°)	-0.1 ± 2.06	-0.3 ± 2.2	0.588	0.95	0.78	1.15	0.418	0.92	0.75	1.12
Ankle dorsiflexion at initial contact (°)	10.4 ± 6.3	9.7 ± 5.1	0.571	0.98	0.92	1.05	0.613	0.98	0.92	1.05
Ankle dorsiflexion at toe-off (°)	-14.5 ± 6.1	-16.7 ± 5.8	0.085	0.94	0.88	1.01	0.044	0.92	0.85	1.00
Ankle dorsiflexion-plantarflexion excursion (°)	41.9 ± 5.8	43.6 ± 5.4	0.137	1.06	0.98	1.14	0.072	1.08	0.99	1.18
Peak ankle dorsiflexion (°)	27.4 ± 4.0	27.0 ± 3.1	0.63	0.97	0.88	1.08	0.583	0.97	0.87	1.08
Minimum ankle dorsiflexion (°)	-14.5 ± 6.1	-16.7 ± 5.8	0.087	0.94	0.88	1.01	0.045	0.92	0.85	1.00
Ankle internal rotation at initial contact (°)	-7.4 ± 8.5	-8.5 ± 10.0	0.547	0.99	0.94	1.03	0.721	0.99	0.94	1.04
Ankle internal rotation at toe-off (°)	-0.3 ± 8.0	0.6 ± 8.3	0.604	1.01	0.96	1.07	0.377	1.02	0.97	1.08
Ankle internal rotation external rotation excursion (°)	25.1 ± 5.5	26.6 ± 6.4	0.184	1.05	0.98	1.13	0.099	1.07	0.99	1.15
Peak ankle internal rotation (°)	0.5 ± 8.0	1.3 ± 8.5	0.641	1.01	0.96	1.06	0.417	1.02	0.97	1.08
Minimum ankle internal rotation (°)	-24.6 ± 7.9	-25.4 ± 8.4	0.622	0.99	0.94	1.04	0.733	0.99	0.94	1.05
Foot dorsiflexion at initial contact (°)	14.9 ± 7.6	14.3 ± 6.6	0.683	0.99	0.94	1.04	0.718	0.99	0.94	1.05
Foot dorsiflexion at toe-off (°)	-54.1 ± 6.9	-54.5 ± 5.1	0.793	0.99	0.93	1.06	0.647	0.99	0.92	1.05
Foot dorsiflexion plantarflexion excursion (°)	69.1 ± 9.8	68.8 ± 7.7	0.882	1.00	0.96	1.04	0.97	1.00	0.96	1.05
Peak foot dorsiflexion (°)	15.0 ± 7.5	14.3 ± 6.6	0.657	0.99	0.94	1.04	0.703	0.99	0.93	1.05
Minimum foot dorsiflexion (°)	-54.1 ± 6.9	-54.0 ± 5.1	0.791	0.99	0.93	1.06	0.645	0.99	0.92	1.05

Hip adduction at initial contact (°)	10.1 ± 3.4	8.5 ± 3.5	0.058	0.90	0.81	1.00	0.079	0.90	0.80	1.01
Hip adduction at toe-off (°)	1.1 ± 3.4	-1.4 ± 3.6	0.001	0.81	0.71	0.92	0.001	0.80	0.70	0.91
Hip adduction abduction excursion (°)	13.8 ± 4.3	15. ± 4.3	0.123	1.08	0.98	1.18	0.067	1.10	0.99	1.22
Peak hip adduction (°)	14.7 ± 4.6	13.6 ± 4.4	0.238	0.95	0.87	1.04	0.295	0.95	0.86	1.05
Minimum hip adduction (°)	0.9 ± 3.4	-1.5 ± 3.7	0.001	0.81	0.72	0.92	0.001	0.80	0.70	0.92
Hip flexion at initial contact (°)	38.9 ± 6.6	36.8 ± 7.4	0.117	0.952	0.90	1.01	0.136	0.95	0.90	1.02
Hip flexion at toe-off (°)	-5.0 ± 6.1	-7.1 ± 5.6	0.088	0.94	0.88	1.01	0.056	0.93	0.86	1.00
Hip flexion extension excursion (°)	44.3 ± 5.5	44.5 ± 5.0	0.828	1.01	0.94	1.09	0.652	1.02	0.94	1.10
Peak hip flexion (°)	39.1 ± 6.5	37.4 ± 7.1	0.218	0.96	0.91	1.02	0.246	0.96	0.90	1.03
Minimum hip flexion (°)	-5.2 ± 6.0	-7.1 ± 5.6	0.117	0.95	0.88	1.01	0.079	0.93	0.87	1.01
Hip internal rotation at initial contact (°)	-1.5 ± 6.3	0.6 ± 6.8	0.131	1.05	0.99	1.12	0.088	1.06	0.99	1.14
Hip internal rotation at toe-off (°)	-8.6 ± 6.4	-7.0 ± 7.0	0.219	1.04	0.98	1.11	0.161	1.05	0.98	1.12
Hip internal rotation external rotation excursion (°)	10.8 ± 3.8	11.6 ± 3.3	0.248	1.07	0.957	1.187	0.24	1.07	0.96	1.20
Peak hip internal rotation (°)	0.9 ± 6.2	3.2 ± 6.6	0.085	1.06	0.99	1.13	0.043	1.08	1.00	1.16
Minimum hip internal rotation (°)	-9.8 ± 5.9	-8.5 ± 6.6	0.26	1.04	0.97	1.11	0.178	1.05	0.98	1.13
Knee varus at initial contact (°)	-2.9 ± 2.6	-0.8 ± 3.1	0.001	1.34	1.13	1.60	0.001	1.35	1.13	1.61
Knee varus at toe-off (°)	-3.9 ± 3.0	-1.7 ±2.7	0.001	1.32	1.12	1.55	0.001	1.32	1.12	1.56
Knee varus valgus excursion (°)	3.9 ± 1.6	4.1 ± 1.4	0.429	1.11	0.86	1.42	0.413	1.11	0.86	1.44
Peak knee varus (°)	-2.1 ± 2.7	0.0 ± 3.0	0.001	1.31	1.11	1.54	0.001	1.32	1.12	1.56
Minimum knee valgus (°)	-5.9 ± 2.9	-4.1 ± 3.3	0.006	1.22	1.06	1.40	0.006	1.23	1.06	1.42
Knee flexion at initial contact (°)	17.8 ± 5.1	16.2 ± 5.4	0.128	0.94	0.87	1.02	0.194	0.95	0.88	1.03
Knee flexion at toe-off (°)	16.0 ± 6.0	13.0 ± 5.4	0.017	0.91	0.85	0.98	0.011	0.90	0.83	0.98
Knee flexion extension excursion (°)	30.7 ± 5.4	32.4 ± 4.3	0.12	1.06	0.98	1.15	0.117	1.07	0.98	1.16
Peak knee flexion (°)	44.2 ± 4.4	43.6 ± 3.9	0.526	0.97	0.88	1.07	0.571	0.97	0.89	1.07
Minimum knee flexion (°)	13.5 ± 4.7	11.3 ± 4.7	0.026	0.91	0.83	0.99	0.029	0.90	0.82	0.99
Knee internal rotation at initial contact (°)	4.3 ± 6.4	5.1 ± 8.0	0.562	1.02	0.96	1.08	0.822	1.01	0.95	1.07
Knee internal rotation at toe-off (°)	3.8 ± 6.6	3.18 ± 7.8	0.646	0.99	0.93	1.05	0.348	0.97	0.91	1.03

Knee internal rotation external rotation excursion (°)	20.9 ± 4.5	23.8 ± 5.1	0.004	1.14	1.04	1.25	0.003	1.15	1.05	1.26
Peak knee internal rotation (°)	22.9 ± 6.7	25.3 ± 8.1	0.107	1.05	0.99	1.11	0.191	1.04	0.98	1.10
Minimum knee internal rotation (°)	2.0 ± 6.3	1. ± 7.35	0.692	0.99	0.93	1.05	0.411	0.97	0.91	1.04
Pelvis contralateral drop at initial contact (°)	2.2 ± 2.7	2.1 ± 2.4	0.893	0.99	0.85	1.15	0.991	1.00	0.86	1.17
Pelvis contralateral drop at toe-off (°)	-4.8 ± 2.7	-5.4 ± 2.9	0.26	0.92	0.79	1.07	0.25	0.91	0.78	1.07
Pelvis contralateral-ipsilateral drop excursion (°)	9.8 ± 3.4	10.0 ± 3.1	0.826	1.01	0.90	1.14	0.842	1.01	0.89	1.15
Peak pelvis contralateral drop (°)	4.9 ± 2.7	4.5 ± 2.9	0.547	0.96	0.82	1.11	0.551	0.96	0.82	1.11
Minimum pelvis contralateral drop (°)	-5.0 ± 2.6	-5.5 ± 2.8	0.362	0.93	0.80	1.09	0.37	0.93	0.79	1.09
Pelvis anterior tilt at initial contact (°)	15.6 ± 5.7	14.5 ± 5.1	0.333	0.96	0.90	1.04	0.29	0.96	0.89	1.04
Pelvis anterior tilt at toe-off (°)	18.1 ± 5.7	17.2 ± 5.0	0.443	0.97	0.90	1.05	0.428	0.97	0.90	1.05
Pelvis anterior-posterior tilt excursion (°)	7.6 ± 2.1	7.7 ± 2.3	0.789	1.03	0.85	1.24	0.959	1.01	0.83	1.22
Peak pelvis anterior tilt (°)	18.4 ± 5.7	17.6 ± 5.0	0.474	0.97	0.91	1.05	0.449	0.97	0.90	1.05
Minimum pelvis anterior tilt (°)	10.8 ± 5.9	9.9 ± 5.29	0.432	0.97	0.91	1.04	0.46	0.97	0.91	1.05
Pelvis transverse plane contralateral rotation at initial contact (°)	-2.8 ± 3.6	-3.0 ± 4.7	0.805	0.99	0.89	1.10	0.577	0.97	0.87	1.08
Pelvis transverse plane contralateral rotation at toe-off (°)	3.6 ± 4.1	1.2 ± 4.5	0.008	0.88	0.79	0.97	0.004	0.86	0.77	0.95
Pelvis transverse plane contralateral rotation external rotation excursion (°)	9.2 ± 3.4	8.7 ± 3.1	0.464	0.96	0.84	1.08	0.433	0.94	0.82	1.09
Peak transverse plane pelvis contralateral rotation (°)	3.8 ± 3.7	1.9 ± 4.1	0.015	0.87	0.78	0.98	0.008	0.85	0.76	0.96
Minimum transverse plane pelvis contralateral rotation (°)	-5.3 ± 3.6	-6.8 ± 4.6	0.063	0.90	0.81	1.01	0.04	0.89	0.80	1.00
Thorax contralateral side flexion at initial contact (°)	-2.8 ± 2.4	-3.1 ± 2.4	0.632	0.96	0.81	1.14	0.632	0.96	0.81	1.14
Thorax contralateral side flexion at toe-off (°)	0.6 ± 2.3	0.5 ± 2.3	0.768	0.97	0.82	1.16	0.734	0.97	0.81	1.16
Thorax contralateral-ipsilateral side flexion excursion (°)	5.1 ± 1.7	5.3 ± 1.9	0.722	1.04	0.83	1.31	0.734	0.97	0.81	1.16
Peak thorax contralateral side flexion (°)	0.7 ± 2.3	0.6 ± 2.2	0.785	0.98	0.82	1.17	0.796	1.03	0.82	1.30
Minimum thorax contralateral side flexion (°)	-4.4 ± 2.36	-4.7 ± 2.1	0.592	0.95	0.80	1.13	0.727	0.97	0.81	1.16
Thorax forward flexion at initial contact (°)	7.4 ± 4.7	7.8 ± 3.8	0.68	1.02	0.93	1.11	0.72	1.02	0.93	1.12
Thorax forward flexion at toe-off (°)	7.2 ± 4.8	7.3 ± 3.9	0.854	1.01	0.92	1.10	0.971	1.00	0.92	1.10
Thorax flexion-extension excursion (°)	3.7 ± 1.3	4.2 ± 1.3	0.071	1.32	0.98	1.77	0.041	1.42	1.02	2.00
Peak thorax forward flexion (°)	10.2 ± 4.6	11.0 ± 4.1	0.425	1.04	0.95	1.14	0.463	1.04	0.94	1.13

Minimum thorax forward flexion (°)	6.5 ± 4.7	6.8 ± 3.8	0.733	1.02	0.93	1.11	0.797	1.01	0.92	1.11
Thorax rotation towards contralateral side at initial contact (°)	-13.1 ± 4.4	-12.9 ± 4.9	0.901	1.01	0.92	1.10	0.877	1.01	0.92	1.11
Thorax rotation towards contralateral side at toe-off (°)	14.6 ± 4.7	13.2 ± 4.0	0.148	0.94	0.85	1.02	0.109	0.93	0.84	1.02
Thorax rotation contralateral-ipsilateral rotation excursion (°)	27.7 ± 6.3	26.2 ± 5.8	0.275	0.95	0.87	1.04	0.157	0.95	0.88	1.02
Peak thorax rotation towards contralateral side	14.6 ± 4.7	13.2 ± 4.0	0.238	0.96	0.90	1.03	0.101	0.92	0.84	1.02
Minimum thorax rotation towards contralateral side (°)	-13.1 ± 4.4	-12.9 ± 4.9	0.139	0.93	0.85	1.02	0.882	1.01	0.92	1.11
Spatiotemporal parameters										
Stride length (metres)	2.2 ± 0.3	2.2 ± 0.3	0.733	1.25	0.35	4.51	0.642	1.37	0.36	5.21
Flight time (milliseconds)	4401 ± 38	439 ± 38	0.823	1.00	0.99	1.01	0.865	1.00	0.99	1.01
Contact time (milliseconds)	269 ± 38	260 ± 28	0.239	0.99	0.98	1.01	0.112	0.99	0.98	1.00
Stride frequency (stride/minute)	84.9 ± 4.8	86.0 ± 3.9	0.295	1.05	0.96	1.14	0.302	1.05	0.96	1.15
Step time (milliseconds)	708 ± 43	704 ± 33	0.865	1.00	0.99	1.01	0.497	1.00	0.99	1.01

Abbreviated terms: SD = standard deviation, OR = odds ratio, C.I.= confidence interval, ROM = range of motion. *Adjusted for sex, age and mileage. The following denote the direction of the moment: Ankle dorsiflexion (positive), plantar flexion (negative), ankle inversion (positive), ankle eversion (negative), ankle internal rotation (positive), ankle external rotation (negative), knee flexion (positive), knee extension (negative), knee varus (positive), knee valgus (negative), knee internal rotation (positive), knee external rotation (negative), hip flexion (positive), hip extension (negative), hip adduction (positive), hip abduction (negative), hip internal rotation (positive), hip external rotation (negative), thorax anterior tilt (positive), thorax posterior tilt (negative), thorax drop to contralateral side (positive), thorax drop to ipsilateral; side (negative), thorax rotation to contralateral side (positive), thorax rotation to ipsilateral side (negative), pelvis anterior tilt (positive), pelvis posterior tilt (negative), pelvis drop to contralateral side (positive), pelvis drop to ipsilateral; side (negative), pelvis rotation to contralateral side (positive), pelvis rotation to ipsilateral side (negative).

8.9. STROBE Checklist for Chapter 5

STROBE Statement—checklist of items that should be included in reports of observational studies (Von Elm *et al.*, 2008).

	Item No.	Recommendation	Page No.	Relevant text from manuscript
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract		Lines 24-25: Running towards injury? A prospective investigation of running related injuries in recreational runners.
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found		Lines 35-48: Methods and results of manuscript.
Introduction				
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported		Lines 87-117 (Introduction)
Objectives	3	State specific objectives, including any prespecified hypotheses		Lines 118-121 "This study aims to prospectively examine the association between RRIs and demographics, injury history and training history, clinical measures, impact accelerations and running technique in a large cohort. A further aim was to evaluate

			the potential of these factors in screening for RRI. It was hypothesised that factors associated with running injuries would be identified.”
Methods			
Study design	4	Present key elements of study design early in the paper	Lines 122-180 (Methodology)
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	Lines 122-136 Lines 169-180 (Methodology)
Participants	6	(*a*) *Cohort study*—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case-control study*—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study*—Give the eligibility criteria, and the sources and methods of selection of participants	Lines 126-131 “Inclusion eligibility was; recreational runner, between 18-65 years old, with no history of injury within the last three months. Participants were excluded if they participated in contact, team, or high impact sports, to limit the effects of injuries related to non-running activities. A recreational runner was defined as a person who ran a minimum of 10km per week, for at least six months prior to inclusion in the study. Participants were excluded if

			they previously or currently participated at an international level.”
		(*b*) *Cohort study*—For matched studies, give matching criteria and number of exposed and unexposed *Case-control study*—For matched studies, give matching criteria and the number of controls per case	Lines 174-177 “After this testing session, participants were encouraged to train as normal and RRIs were tracked prospectively for one year”
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	Lines 180-182 “All injuries were diagnosed by the researchers (SD (Chartered Physiotherapist) and AB (Certified Athletic Therapist). Where this was not possible, the diagnosis was confirmed via phone call.”
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	Table 1 Lines 144-166
Bias	9	Describe any efforts to address potential sources of bias	The trial methodology was registered before data collection.

			Reporting bias: Positive and negative findings were clearly reported. Recall bias: Participants were contacted about injuries every 2 weeks to minimise recall bias.
Study size	10	Explain how the study size was arrived at	Lines 131-135

Continued on next page

Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	Lines 187-195
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	Lines 195-234
		(*b*) Describe any methods used to examine subgroups and interactions	Lines 207-209 "Since sex, age and mileage may be associated with injury, these were included as covariates and both the adjusted and unadjusted results reported."
		(*c*) Explain how missing data were addressed	Lines 220-223 "Imputing missing variables was achieved by utilising the: clinical, kinematic, anthropometric and demographic variables, along with the training history. Numeric data were first scaled to unit variance and zero mean, while the categorical data were dummy encoded. Data were then imputed using multivariable imputation by chained equations and a Bayesian ridge regression approach"
		(*d*) *Cohort study*—If applicable, explain how loss to follow-up was addressed *Case-control study*—If applicable, explain how matching of cases and controls was addressed *Cross-sectional study*—If applicable, describe analytical methods taking account of sampling strategy	Detailed in Figure 1 Participants who dropped out were not included in the final analysis as it was not possible to classify them as injured or uninjured (the dependent variable categories).
		(*e*) Describe any sensitivity analyses	This study examined analysed data with and without adjustment for age, sex and mileage (Thabane *et al.*, 2013)
Results			

Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	Figure 1
		(b) Give reasons for non-participation at each stage	Figure 1
		(c) Consider use of a flow diagram	Figure 1
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	Table 2
		(b) Indicate number of participants with missing data for each variable of interest	N/A
		(c) *Cohort study*—Summarise follow-up time (eg, average and total amount)	Lines 174-175 "After this testing session, participants were encouraged to train as normal and RRIs were tracked prospectively for one year"
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time	
		Case-control study—Report numbers in each exposure category, or summary measures of exposure	Lines 236-237 "Of the 274 runners entering the study, 225 runners (82%) remained in the study to follow up. Reasons for exclusion are detailed in Figure 1. Over the 1-year period, 52% (n=117) reported at least one RRI"
		Cross-sectional study—Report numbers of outcome events or summary measures	
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which	Tables 3-6

	confounders were adjusted for and why they were included	
	(*b*) Report category boundaries when continuous variables were categorized	Tables 4-6
	(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	N/A

Continued on next page

Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	Tables 4-6
Discussion			
Key results	18	Summarise key results with reference to study objectives	Lines 537-549 (conclusions)
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	Lines 524-535 (limitations section)
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	Lines 537-549 (conclusions)
Generalisability	21	Discuss the generalisability (external validity) of the study results	Lines 511-522 (clinical relevance section)
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	Lines 555-557 (funding section)

*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.