Plantar loading and shoe-surface interaction: from early rehabilitation to return to football.

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Contributions by others to the thesis

I would like to acknowledge the contributions of Dr Chris Bleakley and Dr Rod Whiteley to this thesis through assistance on statistical analysis and data visualisation, as well as final editing of the document. I hereby state this thesis is my own work. Contribution of my colleagues through data collection, statistical analysis and feedback has been acknowledged throughout the thesis via the use of collective pronouns. No parts of this thesis have been submitted elsewhere to qualify for any other award or degree.

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Abstract

Lower extremity injuries are common in soccer football. Return to sport (RTS) is a continuum consisting a series of rehabilitation phases. Minimising risk of reinjury during this process, or after RTS, is of paramount importance. However, there is a lack of empirical evidence to help guide practicing clinicians through these rehabilitation phases or advise players on minimisation of reinjury risk.

The aims of this thesis are to examine the magnitude and location of plantar loading and traction forces at the player-shoe-surface interface during different phases of rehabilitation; to assess modifiable risk factors associated with shoe-surface interaction in football; to ensure findings are practical to allow translation for use in elite sport rehabilitation facilities. Study designs consist of three case-control studies, one systematic review with meta-analysis, and one longitudinal controlled laboratory (on-field) study.

Notable results of the first three case-controls studies are; Running speed and body weight alterations affect the amount of in-shoe force on an AlterG (reduced bodyweight) treadmill. Football players have significant limb asymmetries until nine months after surgical reconstruction of the anterior cruciate ligament. Regional plantar loading is altered in elite football players after fifth metatarsal stress fracture during certain movement tasks.

Systematic review highlights the lack of research about the shoe-surface interface and injury in soccer football. Meta-analysis of three prospective studies in American football showed players are more than 2.5 times more likely to sustain a lower limb injury when shoe-surface traction is high.

Peak rotational traction measured at the shoe-surface interface varied substantially across different months of the year, different grass species and with different shoe outsole types during a longitudinal study.

This thesis provides objective data to assist decision-making processes around specific rehabilitation phases or footwear choices to suit playing surface conditions to minimise risk of reinjury.

Introduction

Background

Lower extremity injuries are highly prevalent across the football codes causing the majority of time-loss injuries (Ekstrand et al., 2011b, Ekstrand et al., 2019, Gissane et al., 2002, Mack et al., 2018, Orchard and Seward, 2002, Schwellnus et al., 2014). Elite male soccer (football) players are injured on average twice per season in European football with the majority of injuries (75-85%) affecting the lower extremities. Furthermore, players returning from injury are at a greater risk of re-injury which forms 12%-30% of all injuries in European football (Ekstrand et al., 2011b, Hägglund at al., 2006, Walden et al., 2001). Consequently, initiatives to improve rehabilitation of injured players or minimise primary and/or subsequent re-injury risk are paramount.

Following injury, rehabilitation for a timely and safe return to sport is a continuum in which objective data can help inform decisions on the path back to participation (Ardern et al., 2016b, Grindem et al., 2016, Kyritsis 2016). Coaches, players, management and other stakeholders are chiefly interested in how long an injured player will be missing from training or matches (Ardern at al., 2016a). Establishing some fundamentals with questions such as: which injuries are most serious (in terms of time loss)? can give a realistic account of the issues medical and rehabilitation teams may have to manage (Ardern et al., 2016a, Bahr et al., 2017). Two injuries that cause significant burden (time away from the game) are anterior cruciate ligament (ACL) tear and fifth metatarsal stress fracture (Ekstrand and Van Dijk 2013, Waldén et al., 2011). Figure 1 illustrates the impact these injuries have in terms of time loss compared to a more common and generally less severe injury (hamstring muscle injury).

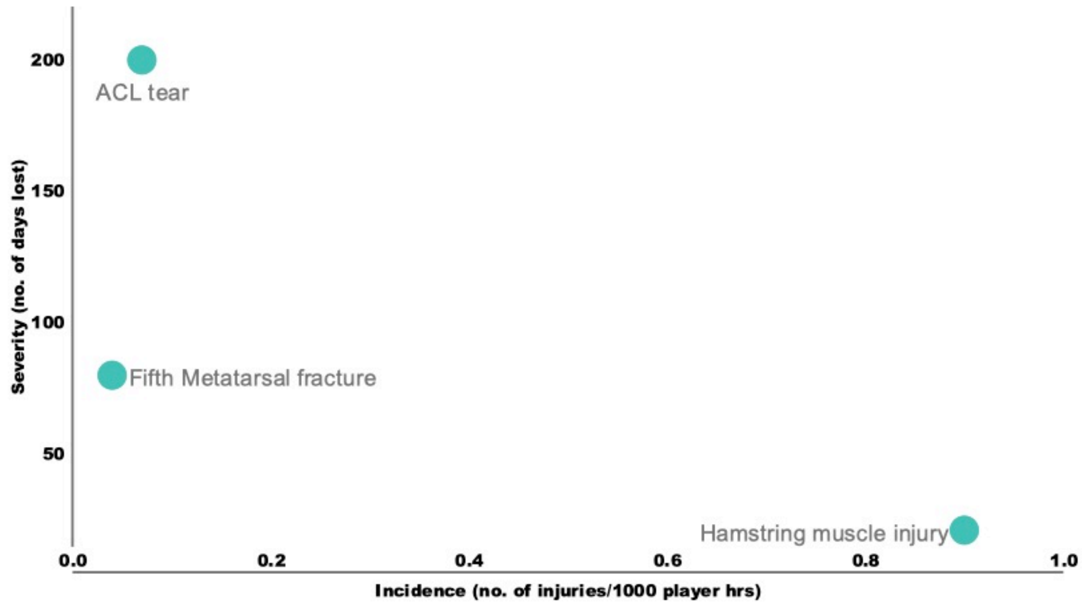


Figure 1 Relationship between severity and incidence in UEFA Champions league football. Severity = average number of days lost. Incidence = number of injuries per 1000hrs. Adapted from Bahr et al., (2017) and Ekstrand & Van Dijk, (2013).

Whilst it makes sense to focus attention and resources on the injuries that happen more often (higher incidence), severe injuries have perhaps greater implications on factors such as long-term health of the athlete (Gelber et al., 2000, Roos 1998) and club financial stability. On average, an injured UEFA champions league level player will cost the club > €600,000 per month (Ekstrand 2016). Moreover, injuries negatively affect the overall performance of the team in terms of league standings (Eirale et al., 2013, Hägglund at al., 2013). A 16-year study examining injuries in UEFA football clubs found ACL ruptures cause a median absence of 205 days (95%CI: 198 to 218 days) which is approximately 6-7 months away from football.

Research that informs clinical practice for managing such injuries is important. Objective data to help guide initial progression of loading or assist decisions making in later phases of rehabilitation are scarce. Little objective information exists on the magnitude, location or timing of plantar loads (pressure distribution, vertical ground reaction force, contact time etc) in early phases of rehabilitation after these injuries. Likewise, there is a dearth of published evidence regarding traction (grip) between the players' shoe and the playing surface especially in soccer football where no previous studies have examined a relationship between high shoe-surface traction and lower extremity injury. Three prospective studies have been conducted in American football that link high traction at the shoe-surface interface to increased risk of non-contact lower extremity injury with a focus on ACL injuries (Torg et al., 1971, Lambson et al., 1996, Wannop et al., 2013). (This is examined by systematic review in chapter 4).

Anterior cruciate ligament injury in male football players

85% of ACL injuries in professionals football occur in non-contact or indirect contact mechanisms (Walden et al., 2015). Three different playing situations have been identified in the lead-up to ACL injury.

1. Pressing or defending.
2. Regaining balance after kicking
3. Landing after heading the ball.

Video analysis of the mechanism of injury suggests most ACL injuries occur at, or immediately following, foot contact after landing or decelerating before a change in direction. The knee tends to be near full extension (< 30º of flexion) at time of injury with a valgus collapse of the knee during/after injury. (Dowling et al. 2010). Greater distance from the centre of mass to the support limb (e.g., planting the foot very wide during a cutting manoeuvre) has also been implicated during the mechanism of injury for ACL (Dowling et al., 2010, Krosshaug et al., 2007).

A 15-year prospective study of 78 men's professional football clubs found ACL injury occurs at a rate of 0.4 per team per season. This equates to one ACL injury at each team every second season (Walden et al., 2016). ACL injury rate is 20-fold higher during matches (0.340 injuries per 1000h) compared to training (0.017 injuries per 1000h). Only two-thirds of players who sustained an ACL injury competed at the highest level 3 years later (Walden et al., 2016).

Grassi et al (2019) reported similar findings during 7 consecutive seasons of Serie A championship male professional football (2011-2012 to 2017-2018) with a 14-fold higher injury incidence in matches compared to training. 25% of the 84 total ACL injuries were second injuries. There was a 2-fold higher incidence in teams ranked in the top 4 positions of the championship league.

Despite the many advance in physical preparation coaching, sports science and sports medicine no declining trend of ACL injury rate is apparent. This could be attributed to multiple factors of which previous injury, match congestion (Grassi et al., 2019), climate and subsequent shoe-surface conditions (Orchard et al., 2013) have been implicated, among other factors. To date there are no validated return to sport rehabilitation programs with a global consensus. Much debates remains regarding the criterion used during ACL rehabilitation and the duration a rehabilitation course should take before return to sport (Van Melick et al., 2016).

Timeframes for duration of rehabilitation of an ACL injury in football have seen many changes over the years. Negelli & Hewett (2017) report a marked increase in early second ACL injuries that corresponds with a shift from conservative postoperative rehabilitation to so-called 'accelerated rehabilitation' plans in which there was an expectation that a player would return to full sports participation at six months after surgery. Growing evidence suggests that players may require more than the previously advocated 6 months of postoperative rehabilitation to allow complete biological healing of the ACL graft and knee joint (Beischer et al., 2020, Negelli & Hewett., 2017, Grindem et al., 2016, Van Melick et al., 2016). Grindem et. al (2016) reported a 51% reduction in risk of reinjury in athletes for each month return to sport is delayed until 9 months after ACLR. Analogous findings by Beischer et al. (2020) suggests young athletes have a 7-fold increased rate of sustaining a second ACL injury if they return to sport before 9 months after ACLR. Negelli & Hewett (2017) suggest that young athletes should perhaps take up to 2 years to return to full participation in cutting or pivoting sports after ACLR to minimise risk of reinjury.

Given running forms a large component of football related movements, both during rehabilitation and after return to sport, it is surprising that limited research exists that has objectively measured running kinetics at time of return to sport clearance.

Stress fracture of the fifth metatarsal

Ekstrand & Van Dijk (2013) found the incidence of fifth metatarsal stress fractures to be 0.04 injuries/1000h of exposure in a study examining 13 754 injuries across 64 male professional football teams in Europe. This equates to approximately one MT-5 fracture every 5 seasons in an average squad of 25 players. Higher incidence of injury was found in Japanese elite football players estimated at 0.12injuries/1000h of exposures (Fujitaka et al., 2015). Further retrospective research from Japan (n=1854 competitive football players) suggests increased playing time on artificial turf is a risk factor for developing MT-5 fracture in football players (Miyamori et al., 2018). Players who played on artificial turf > 80% of the total time were up to 3 times more likely to sustain a MT-5 fracture compared to players who played 0-20% of total time on artificial grass.

Return to sport following fifth metatarsal (MT-5) stress fracture in football (soccer) players can be problematic and protracted. Average absence from football is 3–5 months when healing and rehabilitation go to plan (Ekstrand and Torstveit, 2012). Complications, however, are common with non-union and refracture being among the chief concerns, which makes this injury potentially 'career-ending' (Ekstrand and van Dijk, 2013).

Young players, during the preseason period of training, are most affected with the non-dominant (stance leg when kicking) limb more frequently involved in the midfielder playing position (Ekstrand and van Dijk, 2013, Fujitaka et al., 2015, Matsuda et al., 2017). Early surgical intervention with insertion of a large-diameter compression screw is thought to lead to better outcomes for athletes compared to conservative management (Kerkhoffs et al., 2012, Porter et al., 2005).

Stress fractures are the end stage of a continuum known as bone stress injury which fall under the "overuse injury" aetiology. Warden et al. (2014) describe bone stress injuries (BSI) as the "inability of bone to withstand repetitive loading, which results in structural fatigue and localized bone pain and tenderness".

Understanding the magnitude, timing and distribution of forces acting at players' feet when performing common football movements is therefore important to minimise the risk of primary injury or refracture after surgical fixation. Greater ground reaction forces and impact loading rates occur when running in football boots compared with training shoes (Smith et al., 2004).

Football footwear is known to increase plantar loading at specific anatomical areas of the foot during movements like running, cutting and kicking. The 5^{th} metatarsal sustains higher plantar loads especially during cross-over cutting and at the stance leg when kicking (Eils et al., 2004, Queen et al., 2008). Males have been shown to load the lateral margin of the foot more than female football players during side-cut, cross-over cut, and acceleration tasks when using firm ground football boots (Sims et.al., 2008).

Young soccer players have plantar pressure asymmetries with the non-preferred (stance leg when kicking) showing higher pressure at the hallux, 5^{th} metatarsal and medial rearfoot (Azevedo et al., 2016). However, static plantar pressure distribution did not differ between collegiate male soccer players with a history of MT-5 fracture and healthy control players (n = 335 with n= 30 in fracture group) when measured standing on tip-toes on a pressure mat (Matsuda et al., 2017). Dynamic plantar loading parameters have not been investigated during game relevant movements in players after MT-5 stress fracture especially when running. Hestroni et al. (2010) investigated dynamic plantar loading patterns in ten professional soccer players after MT-5 fracture and ten control healthy players while they walked across a pressure plate in a biomechanics laboratory setting. Pressure reduction at the 5^{th} metatarsal of the previously injured group was the main finding when walking. There were no differences in static foot and arch measurements between the groups. The authors suggest a focus on dynamic rather than static measurements for assessment after MT-5 fractures. No studies to date have examined plantar loading parameters during game-relevant movements in players after MT-5 stress fracture.

Return to sport after lower extremity injuries

Return to sport after injury is a complex and multifactorial continuum that has been described as an exercise in risk management (Ardern et al., 2016). Ideally a collaborative shared decision-making approach with the athlete at the centre of this process makes intuitive sense to ensure a safe and timely return to sport (Dijkstra et al., 2017). Rehabilitation and return to sport after lower extremity injury can be viewed as a continuum in which graded, criterion-based progressions are used to guide the athlete through three phases defined in a consensus statement by Ardern et al (2016).

1. Return to participation – Rehabilitation, modified training or even sport at a lower level.
2. Return to sport – Playing sport but may not be performing at desired performance level.
3. Return to performance – Athlete is performing at or above pre-injury level.

During all phases load is progressively increased to promote tissue healing via mechano-transduction (Glasgow et al., 2015, Khan and Scott, 2009, Warden et al., 2013). Load modification may be required to avoid tissue damage or overload and is often monitored via subjective and objective markers following rehabilitation or training (Taberner et al., 2019).

Taberner et al. (2019) proposed a framework for progression of rehabilitation in lower limb injuries in football that consists of five phases of progression as follow;

1. High control – Aims : Return to running with high control over running speed and loads. Linear running with low acceleration/deceleration demands.

2. Moderate control – Aims : Introduce change of direction and increase speed/ volume of running.

3. Control to chaos – Aims: Introduce football specific weekly structure. Transition from control to chaos of match type scenarios with a limitation on volume of unanticipated or reactive movements. Acceleration/deceleration and change of direction in restricted areas.

4. Moderate Chaos – Aims: Increase high speed running under moderate chaos consisting of unpredicted movements and minimal limitations.

5. <u>High Chaos</u> – Aims: Return player to relative weekly training demands including drills to test worse case scenarios.

Modifiable risk factors

The mechanisms underlying lower extremity injuries in sport are multifaceted and complex (Bahr et al.2003, Hägglund at al., 2006, Mack et al., 2018).

A welcome moment for any player after a long-term injury is the return to sports specific ‘field-based’ rehabilitation or training. However, as a player returns to sport specific training on the field of play it is important to consider modifiable risk factors that may mediate or moderate risk of re-injury. One factor that has been implicated as influencing lower extremity injury risk is the interaction between a players’ footwear and the playing surface (Mack et al., 2018, Olsen et al 2003., Orchard et al., 2005, Wannop et al., 2013). Players adjust their leg stiffness, movement strategies and style of play according to the surface they interact with through the shoes on their feet. Extremes in traction (too low/ high) or surface compliance (too soft/hard) incur biomechanical adjustments by the player that may directly increase the risk of lower extremity injury – via high traction at the shoe-surface interface for example, or indirectly through fatigue, which may be affected by surface compliance or energy absorption (Mack et al., 2018, Rennie et al., 2016).

It is therefore important to understand the subtle variations in playing surface properties and footwear conditions (eg effect of different types of studs/cleats on the outsole) and how these properties may influence resultant traction and ground reaction forces and hence injury risk for the player.

Player physical demands in football

Association football (soccer) is an invasion game involving multiple bouts of intermittent sprinting and directional changes. Elite footballers undertake 1500–3100 metres of high intensity running per match (Bradley et al., 2010, Bradley et al., 2009), with accelerations contributing 7–10% of the total player load, and decelerations contributing 5–7% (Dalen et al., 2016). A recent systematic review examining activity demands of team sports found that the highest volume of cutting movements occur in football, with players performing up to 800 cuts per game (Taylor et al., 2017). A study examining the evolution of physical and technical soccer performance parameters across a 7-season period in the English premier league (n =14700 match performance observations) found sprinting distances increased by 35% with an average of 232m in 2006-07 season compared to an average of 350M in the 2012-13 season ($p < 0.001$;ES 0.93). Number of sprints increased by 85% with an average of 31 per match in 2006-07 and 57 per match in 2012-13 season ($p < 0.001$; ES 1.46). Clearly the game is changing with the vast improvements to playing surface technology, football boot design, physical preparation, and tactical methods and other advances.

An investigation into high ($> 2.5 m \cdot s^{-2}$) and very high ($> 3.5 m \cdot s^{-2}$) intensity accelerations and deceleration demands of 469 male participants from elite team sports (Australian football, American football, rugby league, rugby sevens, rugby union, and soccer) revealed that all sports (except American football) had a greater frequency of high and very high decelerations compared to accelerations. Australian football had the highest full match distance spent accelerating (202m), followed by soccer (178m) and rugby union (54m). Soccer had the highest full match distance spent decelerating at high intensity (162m), followed by Australian rules football (149m and rugby union (54m) (Harper et al., 2019).

Shoe-surface interaction

A player's ability to accelerate, decelerate, and change direction is largely influenced by the available traction between the football shoe and playing surface (Sterzing et al., 2009, Pedroza et al., 2010). Two important components of traction exist: translational traction which is the horizontal force required to overcome the resistance between the shoe outsole (studs) and playing surface; and rotational traction which is the rotational force required to release the studs through the playing surface in a rotational manner. Although increases in translational traction (straight line or side-to- side) are linked to improved performance (e.g., time to complete an agility course or acceleration task)) (Sterzing et al., 2009, Pedroza et al., 2010), higher levels of rotational traction are linked to greater risk of lower limb injury (Wannop and Stefanyshyn, 2016, Lambson et al., 1996, Olsen et al., 2003, Wannop et al., 2013, Orchard et al., 2013).

Optimal shoe-surface conditions should therefore attenuate rotational resistance whilst maintaining translational traction or playing performance (no slipping for players) (Wannop and Stefanyshyn, 2016, Wannop et al., 2013). This is sometimes difficult to achieve as traction varies according to shoe outsole, stud/ cleat configuration (Müller et al., 2010), and the characteristics of the playing surface (Stiles et al., 2011, Villwock et al., 2009), among other factors (Sterzing et al., 2009). Further challenges arise based on the wide array of outsole designs currently on the market and intermittent changes in playing surface throughout a playing season (Orchard et al., 2013, James, 2011).

By what mechanism may high shoe-surface traction relate to injury?

Drakos et al. (2010) used a cadaveric model to demonstrate that certain soccer shoe-surface combinations cause significantly more strain in the ACL when performing a cutting manoeuvre. Likewise, Dowling et al. (2010) determined that high friction conditions at the shoe-surface interface incur changes to movement strategies during a cutting task that may increase that risk of ACL injury, providing a biomechanically plausible rationale for the increased incidence of ACL injuries on high traction surfaces (Orchard et al., 2013). Importantly, higher rotational traction, as opposed to translational traction, has been found to be a significant predictor of peak ACL force during a maximal change of direction task (Sinclair and Stainton, 2017).

Orchard et al. (2005) examined the field surface conditions as they related to injury and concluded that athletes were at greatest risk of the shoe becoming ‘trapped’ on the playing surface when RT is high. This group suggested that certain grass species that display more lateral root growth or ‘thatch’ are causative of the player’s foot becoming ‘trapped’ (Orchard et al., 2005) and preliminary evidence supports this. A 12-year audit of field sport injury data (soccer and Australian rules football), across two continents (Orchard and Powell, 2003) and involving 229 827 player-weeks of exposure, reported a higher incidence of ankle sprains and ACL injuries in warmer climate zones. Although the direct effect of ambient temperature on injury risk cannot be overlooked, it is also likely that heat influences the playing surface (hence injury risk) through a range of moderating factors such as grass species, soil type and ground hardness, which in turn alter the nature of the shoe surface interaction and subsequently injury risk (Torg et al., 1996).

Aims of the thesis

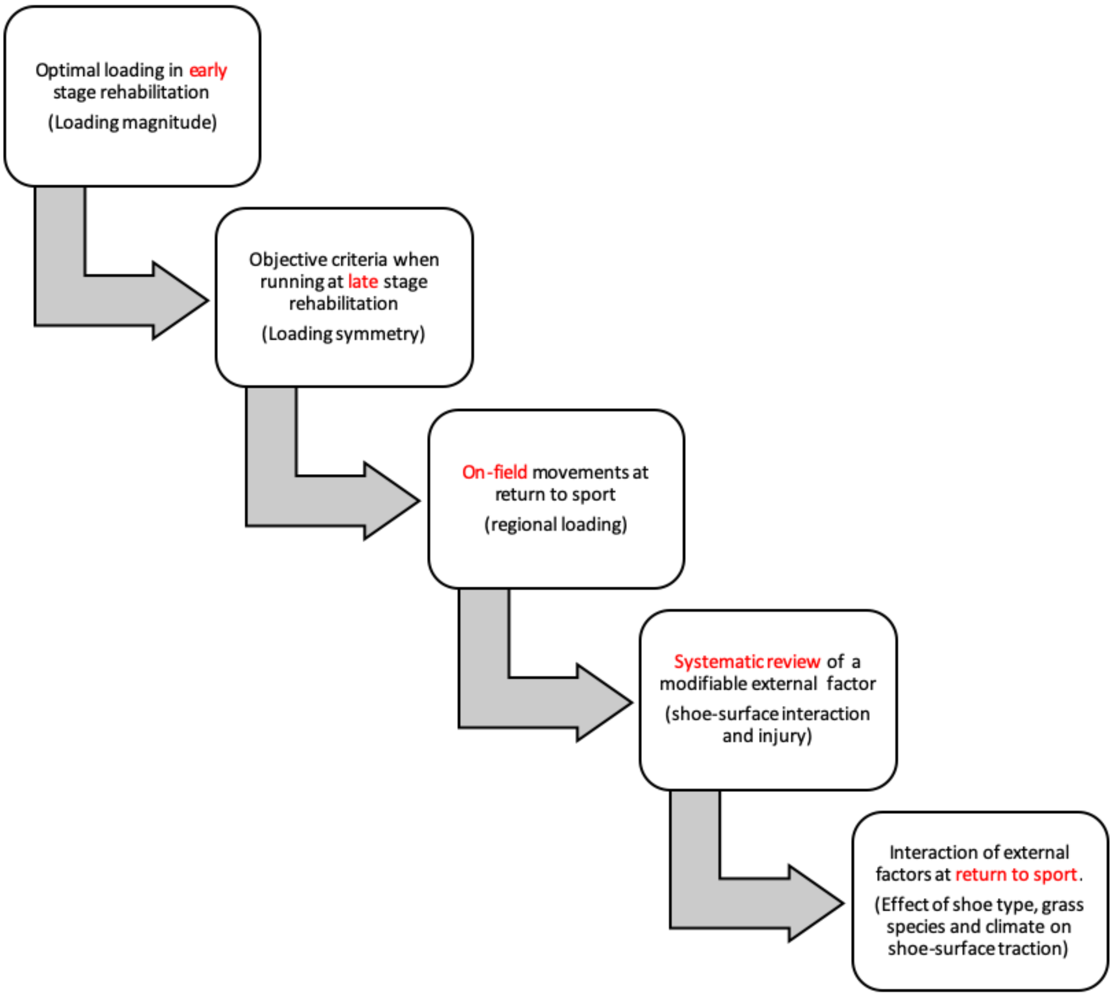
General

To examine the magnitude and location of plantar loading and traction forces at the player-shoe-surface interface during different phases of rehabilitation and return to sport. Ensure findings are directly applicable to use in the clinic or on the field.

Specific

1. To quantify plantar loads borne by the athlete during rehabilitation using a reduced gravity (AlterG) treadmill. **(Chapter 1)**
2. Compare maximum plantar force and limb symmetry during running in soccer players after anterior cruciate ligament reconstruction as they pass return to sport criteria. **(Chapter 2)**
3. Evaluate regional plantar loading during 'on-field' football movements in players after fifth metatarsal stress fracture. **(Chapter 3)**
4. To systematically review the nature and magnitude of traction forces occurring at the shoe-surface interface in the football codes and investigate the relationship with lower limb injury. **(Chapter 4**)
5. To assess temporal changes in shoe-surface traction associated with six different football shoes throughout a full playing season encompassing climatic and grass species variations. **(Chapter 5)**

Outline of thesis



Logic framework (above) provides an overview of the thesis.

This thesis encompasses four original research projects and one systematic review aimed at adding clinically useful objective data to aid clinicians guiding players' return from injury. Optimal loading of injured tissues forms a central tenet of rehabilitation. Reduced gravity (AlterG) treadmills are often used in early stages of rehabilitation to manipulate loading. Firstly, we examine the magnitude of plantar loading across a range of gait speeds and percentage of supported bodyweight while using a reduced gravity treadmill **(Chapter 1)** to help inform early progression of loading.

Running at full bodyweight, and increasing speeds, often follows on from initial reduced bodyweight work along the return to sport continuum. In **Chapter 2** we compare gait characteristics during moderate to fast running in male football players after anterior cruciate ligament reconstruction who had met functional criteria to return to sport. However, both these studies were conducted in the clinic setting at early to late stage rehabilitation phases. Thus, further research is required to examine loading characteristics during on-pitch tasks that are ecologically valid. Consequently, **Chapter 3** evaluates regional plantar loads of the foot during 'on-field' football movements in elite male football players following fifth metatarsal stress fracture.

Minimization of external risk factors, such as the effects of shoe-surface interaction and their implications for loading, is important after return to sport. In **Chapter 4** We systematically review the nature and magnitude of traction forces occurring at the shoe-surface interface in the various football codes and investigate the relationship with lower limb injury.

Subsequently in **Chapter 5,** we assess temporal changes in shoe-surface traction associated with six different football shoes throughout a full elite football playing season and examine the moderating effects of temperature, humidity, soil moisture, and surface hardness to inform footwear choices for players.

Finally, in **Chapter 6** the chief findings, their limitations and 'real world' practical uses are discussed.

Methods

Chapters one to five have a dedicated methods section within each individual chapter. However, the following two tools were used for the original research chapters therefore a summary of each is provided here.

In-Shoe measurement system

Athletes interact with the surface they run or play on through the shoes on their feet. Quantification of plantar forces or pressure distribution acting between the shoe and foot can provide objective kinetic data to help assess limb asymmetry (overall plantar force) or regional pressure issues (local pressure distribution) after injury (Hennig., 2014).

Three studies in this thesis (chapters 1-3) use the Novel Pedar-X in-shoe system (Novel, Munich, Germany). The system consists of thin (1.9mm) flexible insoles that have an array of capacitive sensors (99 sensors in a us size 9 insole) connected via cables to a data logger box that is carried in a small backpack. The sensor number is relative to shoe size/ area. Data is sampled at 100Hz and transmitted to a laptop in real-time via Bluetooth. Insoles are inserted into sports-specific shoes (eg football boots) to provide information on vertical ground reaction force and pressure acting at the shoe-foot interface. The system has been used extensively in sports medicine and biomechanics research (Bentley et al., 2011, Eils et al., 2004, Ford et al., 2006, Hennig., 2014, Girard at al., 2007, Girard et al., 2011, Queen et al., 2008, Ribeiro et al., 2015, Smoglia et al., 2015, Wong et al., 2007).

Advantages for using in-shoe measurement systems include the ability to collect steps continuously (multiple steps), using sports specific footwear, on the actual field of play (Kernozek et al., 1996, Stoggle & Martiner., 2017). Disadvantages include lower sampling rates (100Hz in this case) and vertical or ‘normal’ force measurement only. In contrast, force plates are considered the gold standard for acquisition of force data with higher sampling rates (>1000Hz) and acquisition of ground reaction force in three-dimensions (not just vertical force). However, force plates are usually fixed in the floor thereby usually limiting them to indoor laboratory settings. Other issues include collection of a single step when running, and the possibility that athletes may ‘target’ the force plate landing area during running trials which may alter running biomechanics (Barnett et al., 2001, Stoggle & Martiner., 2017).

Validity and reliability of the PedarX system has previously been reported as excellent (Barnett et al., 2001, Kernozek et al., 1996, McPoil et., 1995, Stoggle & Martiner., 2017, Van Alsenoy et al., 2019). Overall peak vertical ground reaction force is slightly under-estimated on the system when compared to a force plate. However, the underestimation is repeated in a reliable manner (Barnett et al., 2001, Stoggle & Martiner., 2017, Van Alsenoy et al., 2019). During this thesis the author was involved in a study examining the validity and reliability of the Pedar-X system. The full study can be viewed at appendices of this thesis. Briefly, during walking and running speeds within-session intra-participant step-to-step variability was found to be excellent with intraclass correlation coefficient (ICC) values between 0.96 and 0.98 for maximum plantar force at the various gait speeds.

Shoe-surface traction

In chapter five we examine traction forces at the shoe-surface interface. Traction between the shoe and surface was measured using a commercially available portable traction testing device (S2T2, Exeter Research USA). The device consists of a prosthetic foot-form (size 10.5 US), on which shoes are fitted and positioned at 20° of plantar flexion to ensure only the forefoot studs are in contact with the surface (Serensits and McNitt, 2014, Wannop and Stefanyshyn, 2012). The foot can be rotated to measure peak rotational traction or locked into a linear position along the long axis of the shoe and then dragged forward across the surface to measure translational traction (Wannop and Stefanyshyn, 2012, Wannop et al., 2013). The floating foot-mass ensures the vertical normal load (added barbell weight plates) is applied through the shoe to the playing surface and not the supporting frame. Wheels allow for movement across multiple testing locations on the playing surface. (See supplementary figure 14)

Measurements were taken manually by a single operator (AT) for all pilot validation tests and within study tests. Each shoe model was tested at twelve separate locations on the playing surface during the five individual time points (November 2017, January, March, April and May 2018) for rotational traction and six separate locations for translational traction. See supplementary figure 15

For rotational traction a vertical load of of 580N (59.1kg) was applied and the test foot rotated through 90° at a speed of approximately 90°/s via a torque wrench (ETW-PR-100, Checkline, NY, USA) located at the top of the machine that was manually driven by a single operator (AT). Two operators who had a combined mass of 163kg stood on each end of the frame to stabilise during test. Peak rotational traction was recorded in newton meters (N.m) for both internal rotation and external rotation directions by a digital torque wrench sampling at 500Hz (ETW-PR-100, Checkline, NY, USA) with an accuracy of ± 1% of indicated measurement in a range of 10-100N.m.

Rotational traction and vertical load displayed a linear relationship during our pilot work with the S2T2 tester on this natural grass playing surface as previously reported (Wannop and Stefanyshyn, 2012). Thus, 580N was deemed to cause an acceptable amount of damage for grounds-staff to manage on a high use football surface and is a vertical load used for previous studies in American football (Wannop and Stefanyshyn, 2012, Wannop et al., 2013).

For translational traction a normal load (vertical) of 300N was applied to the test foot while a digital force gauge (Chatillon DFE2-500, Ametek, USA) sampling at 7000Hz with an accuracy of ±0.25% of indicated measurement, measured peak horizontal force (Newtons) resisting linear motion between the shoe and surface. The translational traction coefficient was calculated as a ratio of peak horizontal force divided by vertical force. This gives an indication of the horizontal force required to overcome the resistance between the shoe and surface as the shoe is dragged across the surface in a linear movement. During pilot work several speeds and vertical loads were used for translation traction testing with ground-staff present to assess damage to the playing surface. 300N of normal load and approximately 200mm/s allowed surface damage acceptable to ground staff.

Reliability and validity of shoe-surface traction tester

The reliability and validity of the S2T2 traction tested was conducted prior to commencing the full study in Chapter five using a test-retest protocol comprising 528 measurements of a single football pitch playing surface for internal rotation, external rotation and translational traction between a single shoe and the surface. Intra-class correlation coefficients are excellent for both internal and external rotational traction (ICC = 0.94) and acceptable for translational traction (ICC = 0.76). Table 12 shows the full results including minimal detectable change and standard error of measurement for the S2T2.

List of publications

Thesis related.

THOMSON, A., EINARSSON, E., WITVROUW, E. AND WHITELEY, R., 2017. Running speed increases plantar load more than per cent body weight on an AlterG® treadmill. *Journal of sports sciences*, *35*(3), pp.277-282.

THOMSON, A., EINARSSON, E., HANSEN, C., BLEAKLEY, C. AND WHITELEY, R., 2018. Marked asymmetry in vertical force (but not contact times) during running in ACL reconstructed athletes< 9 months post-surgery despite meeting functional criteria for return to sport. *Journal of science and medicine in sport*.

THOMSON, A., AKENHEAD, R., WHITELEY, R., D'HOOGHE, P., VAN ALSENOY, K. AND BLEAKLEY, C., 2018. Fifth metatarsal stress fracture in elite male football players: an on-field analysis of plantar loading. *BMJ Open Sport & Exercise Medicine*, *4*(1), p.e000377.

THOMSON, A., WHITELEY, R. AND BLEAKLEY, C., 2015. Higher shoe-surface interaction is associated with doubling of lower extremity injury risk in football codes: a systematic review and meta-analysis. *Br J Sports Med*, *49*(19), pp.1245-1252.

THOMSON, A., WHITELEY, R., WILSON, M. and BLEAKLEY, C., 2019. Six different football shoes, one playing surface and the weather; Assessing variation in shoe-surface traction over one season of elite football. *PloS one*, 14(4), p.e0216364.

Chapter 1: Optimising plantar loading in the early stages of rehabilitation using a reduced gravity treadmill.

1. Abstract

AlterG® treadmills allow for running at different speeds as well as at reduced bodyweight (BW) and are used during rehabilitation to reduce the impact load. The aim of this study was to quantify plantar loads borne by the athlete during rehabilitation. Twenty trained male participants ran on the AlterG® treadmill in 36 conditions: all combinations of indicated BW (50–100%) paired with different walking and running speeds (range 6–16km/hr) in a random order. In-shoe maximum plantar force (Fmax) was recorded using the Pedar-X system. Fmax was lowest at the 6 km/hr at 50% indicated BW condition at 1.02 ± 0.21BW and peaked at 2.31 ± 0.22BW for the 16 km/hr at 100% BW condition. Greater increases in Fmax were seen when increasing running speed while holding per cent BW constant than the reverse (0.74BW–0.91BW increase compared to 0.19–0.31BW). A table is presented with each of the 36 combinations of BW and running speed to allow a more objective progression of plantar loading during rehabilitation. Increasing running speed rather than increasing indicated per cent BW was shown to have the strongest effect on the magnitude of Fmax across the ranges of speeds and indicated per cent BWs examined.

2. Introduction

The concept of optimal loading to maximise healing and remodelling of injured tissues is considered a central tenet of modern sports physiotherapy (Bleakley et al., 2012). Manipulation of loading variables can have profound effects on the morphology and mechanical properties of the musculoskeletal system (Glasgow et al., 2015, Järvinen et al., 2013, Khan and Scott, 2009, Warden et al., 2013). Progressive or graduated return to weight-bearing activity is important in the management of many lower limb injuries including stress fractures (Bennell et al., 1999, Korpelainen et al., 2001, Pegrum et al., 2012), cartilage injury (Mithoefer et al., 2009, Mithoefer et al., 2012), ligament injury (Beynnon et al., 2011), muscle injury, (Ahmad, et al., 2013) and others.

Identification and progression of the optimal level of load is paramount to maximise physiological adaptation while preventing excessive overload (Bleakley et al., 2012, Glasgow et al., 2015, Khan and Scott, 2009). Maximum plantar forces (Fmax), the peak load applied to the plantar surface of the foot during weight-bearing, are a proxy of ground reaction forces (GRFs) borne by the lower limbs (Barnett et al., 2001). Thus, estimations of these forces during clinically relevant activities can be of use in designing and implementing rehabilitation programmes where graded loading is important (Hreljac, 2004, Willems et al., 2007).

Recently, reduced gravity treadmills have become a clinical tool (Gojanovic et al., 2012, Saxena and Granot, 2011, Tenforde et al., 2012). When using reduced gravity treadmills such as the AlterG®, users wear shorts that are zipped into a chamber surrounding the treadmill. By recording both the positive air pressure as well as the weight applied through the deck of the treadmill during a calibration phase, the amount of air pressure required to reduce bodyweight (BW) to varying amounts can be calculated. The amount of reduction in BW commonly used can range from no reduction (100% BW) all the way down to 20% of BW (i.e., extra air pressure added to lift 80% BW off the deck).

Despite more widespread use of AlterG® treadmills in elite sport and rehabilitation, there is little objective information available for the treating clinician to guide the stages of rehabilitation using this equipment. Smoliga at al. (2015) examined running speeds ranging from 12.6 km/hr to 17.6 km/hr and AlterG® indicated BW ranging from 25 to 100% BW (Smoliga et al., 2015). At these combinations, a 1.4% increase in Fmax for every unit increase in BW % was reported. However, those speeds could not examine the transition from walking to running and what effect this may have on Fmax and regional plantar loading.

During over-ground (Kaplan et al., 2014) and treadmill (Kemozek and Zimmer, 2000) walking and running, it is known that increasing velocity increases plantar loads; however, it is not known what the relationship is when performing the same progressions in reduced gravity environments. Variation in plantar forces, thus loading for the lower limbs, is considered important for prescription of loading during rehabilitation. The purpose of this study was to quantify the Fmax across a range of clinically relevant speeds and indicated percentage BWs while on a reduced gravity treadmill.

1.3 Methods

Participants

Twenty male recreational football players participated who reported they ran a minimum of 20km/week (age 35.4 ± 7.8 years, weight 77.6 ± 8.4 kg, height 179.1 ± 5.6 cm). Runners had to be injury-free for 6 months prior to the study. Informed consent was obtained for each participant, and the experiment was conducted with the approval of the local ethics committee (Anti-doping laboratory Qatar - F2013000001).

Equipment

Plantar loading parameters were measured using a Novel Pedar-X in-shoe system (Novel, Munich, Germany). Each pressure insole is 1.9 mm thick and contains 99 capacitive sensors which were calibrated using a calibration device prior to testing (Trublu Calibration, Novel, Munich, Germany). The insoles relayed data to a Pedar-X data logger that was fixed to the AlterG® treadmill (G-trainer pro 2.0, AlterG®, California USA). Force sensor insoles were placed inside the participants' own preferred running shoes and data were sampled at 100 Hz via Bluetooth. The insole was placed between the sock and shoe with no other manufacturer's insoles or foot orthotics in place so that the Pedar-X insoles were (Spooner et al., 2010). No participants used orthotic supports.

The validity (McPoil, Cornwall et al., 1995) and reproducibility (Kemozek and Zimmer, 2000) of the capacitive sensors in the Pedar-X have previously been reported to be excellent. Furthermore, the vertical component of force data obtained by the Pedar in-shoe system correlated well with that obtained by a Kistler force platform with the benefit of being able to capture several footfalls in one trial (Barnett et al., 2001). Only the vertical component (perpendicular to the insole sensors) of GRF is captured using the Pedar system which may be a limitation when using in-shoe measurement systems compared to force platforms.

Testing Protocol

Each participant underwent a single assessment. All participants ran for 6 min at 12 km/hr (3.3 m · s^{-1}) on an AlterG® treadmill to warm up with no BW assistance (100% BW) (Hardin et al., 2004). Thirty-six running trials were each a combination of running speeds from 6 km/hr to 16 km/hr increasing in 2 km/hr increments and indicated BW from 50% BW to 100% indicated BW increasing in 10% increments. Trial conditions were presented in a random order for each participant at each condition. Participants were instructed to run or walk until they felt comfortable, and then indicate the point where their gait felt "normal". Six km/hr was chosen as the minimum speed after a pilot investigation showed this to be considered a fast walking speed for all participants, whereas 16 km/hr was chosen as a maximum as this was the maximum speed that would be above the aerobic threshold for great majority of recreationally active individuals representing a theoretical 2:40 marathon time. Accordingly, this range of speeds were thought to encompass all speeds typically encountered during rehabilitation: from walking up to relatively fast running.

Statistical Analysis

Plantar loading data from the stance phase of six consecutive footfalls were extracted for both the left and right feet and were averaged for subsequent analysis using Novel Pedar-X evaluation software (Groupmask Evaluation, Novel Munich, Germany). The maximum force was normalised to each participant's BW in order to facilitate comparison and was examined for the whole foot for each of the 36 running trials (Girard et al., 2007). The maximum force data collected by the Pedar-X insoles are reported in units of BW. The indicated BW on the AlterG® treadmill is reported as percentage of BW.

Descriptive and inferential statistics were employed to describe the data using both Microsoft Excel for Windows (Office 2013, Washington, USA) and SPSS (version 21.0, Chicago Illinois USA). Regression analysis was used to describe the relation between peak force and the independent variables of running speed and indicated per cent BW with $p < 0.05$ set as indicating statistical significance.

Initial comparison (independent samples paired t-test) was made between left and right foot peak force at each of the 36 trial conditions. After Bonferonni correction for multiple comparison, no statistically significant differences in maximum force were seen between left and right legs. Examination of effect size differences showed a maximum side-to-side difference of 0.22 SD (16 km/hr at 70% indicated BW condition; 2.01 ± 0.195BW compared to 1.96 ± 0.191BW for the right and left legs, respectively). No other side-to-side difference exceeded 0.2 SD. Accordingly, data from the left and right legs were pooled for all subsequent analysis.

1.4 Results

Maximum Plantar Force

To examine the effect on maximum plantar force (Fmax) of altering running speed compared to altering indicated per cent BW, regression analyses and descriptive data are presented. Fmax (times BW) for each of the 36 individual trial conditions are presented in Table 1, Figure 2 and Figure 3.

The relationship between indicated per cent BW and maximum force was found to be linear at all running speeds (Figure 2), whereas the relation between running speed and Fmax (at all percentages of BW) was best described with a logarithmic curve (Figure 3, Equation 1, adjusted R2: 0.928). The relative differences in Fmax were seen to be greatest when increasing speed from 6 to 16 km/hr while holding indicated per cent BW constant (range: 0.74BW– 0.91BW increase) whereas increasing indicated per cent BW from 50% to 100% showed a smaller increase in peak force (range 0.19BW– 0.31BW) (Table 2)

Speed \ Bodyweight	50%	60%	70%	80%	90%	100%
6 km/hr	1.0170 [.2095]	1.0260 [.2080]	1.0670 [.1865]	1.1440 [.1830]	1.1775 [.1780]	1.2095 [.1900]
8 km/hr	1.3675 [.2350]	1.4230 [.2580]	1.4945 [.2290]	1.5380 [.2245]	1.6570 [.2685]	1.7160 [.2415]
10 km/hr	1.5585 [.2255]	1.6940 [.2160]	1.7695 [.2045]	1.8880 [.2165]	1.9785 [.2290]	2.0115 [.2230]
12 km/hr	1.6415 [.2070]	1.8010 [.2150]	1.8775 [.2075]	1.9845 [.2205]	2.1095 [.2130]	2.1475 [.2240]
14 km/hr	1.6925 [.2405]	1.8195 [.1855]	1.9560 [.1995]	2.0770 [.2180]	2.1875 [.2365]	2.2495 [.2240]
16 km/hr	1.7665 [.2085]	1.8715 [.1950]	1.9860 [.1930]	2.1140 [.2085]	2.2230 [.2240]	2.3090 [.2195]

1.0170	Minimum
1.6630	
1.8783	
1.9860	
2.0506	
2.0937	
2.3090	Maximum

Table 1. *Maximum plantar force (BW multiples (SD)) at the different combinations of indicated percentage BW (50–100%), and speed of running/walking (km/hr).*

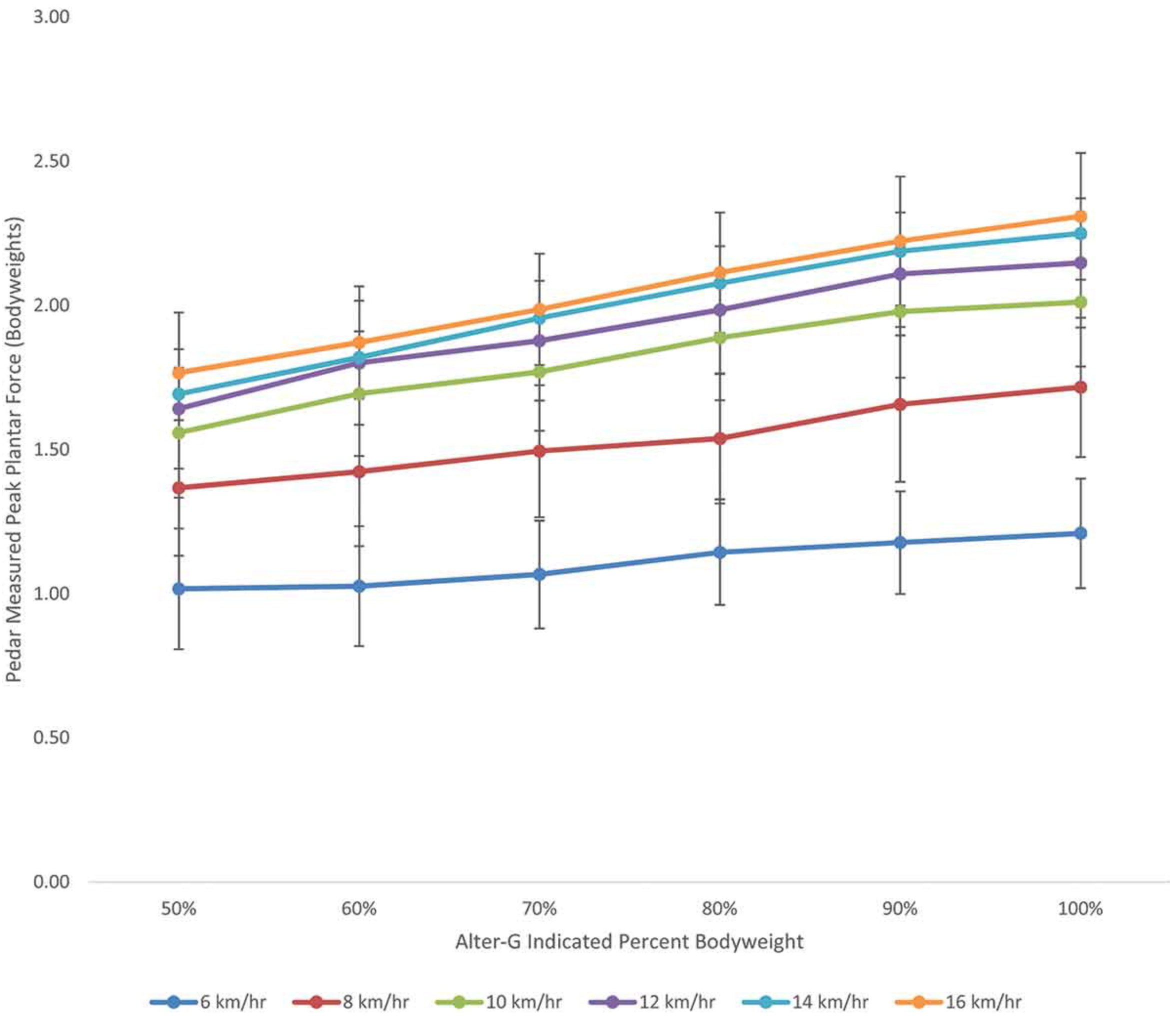


Figure 2. *Maximum plantar force at each of the different indicated per cent BW and running speed combinations.*

$$\text{Maximum Plantar Force} = 0{:}42 \cdot \text{Indicated bodyweight} + 0.7766 \cdot \text{Ln (Speed)} - .4307 \qquad (1)$$

Equation 1. *Regression equation describing the relation between Maximum Plantar Force (in multiples of BW), Indicated BW (percentage) and running speed (in km/hr), $P < 0.01$, $R^2 = 0.95$, Adjusted $R^2 = 0.93$, Standard error estimate = 0.72.*

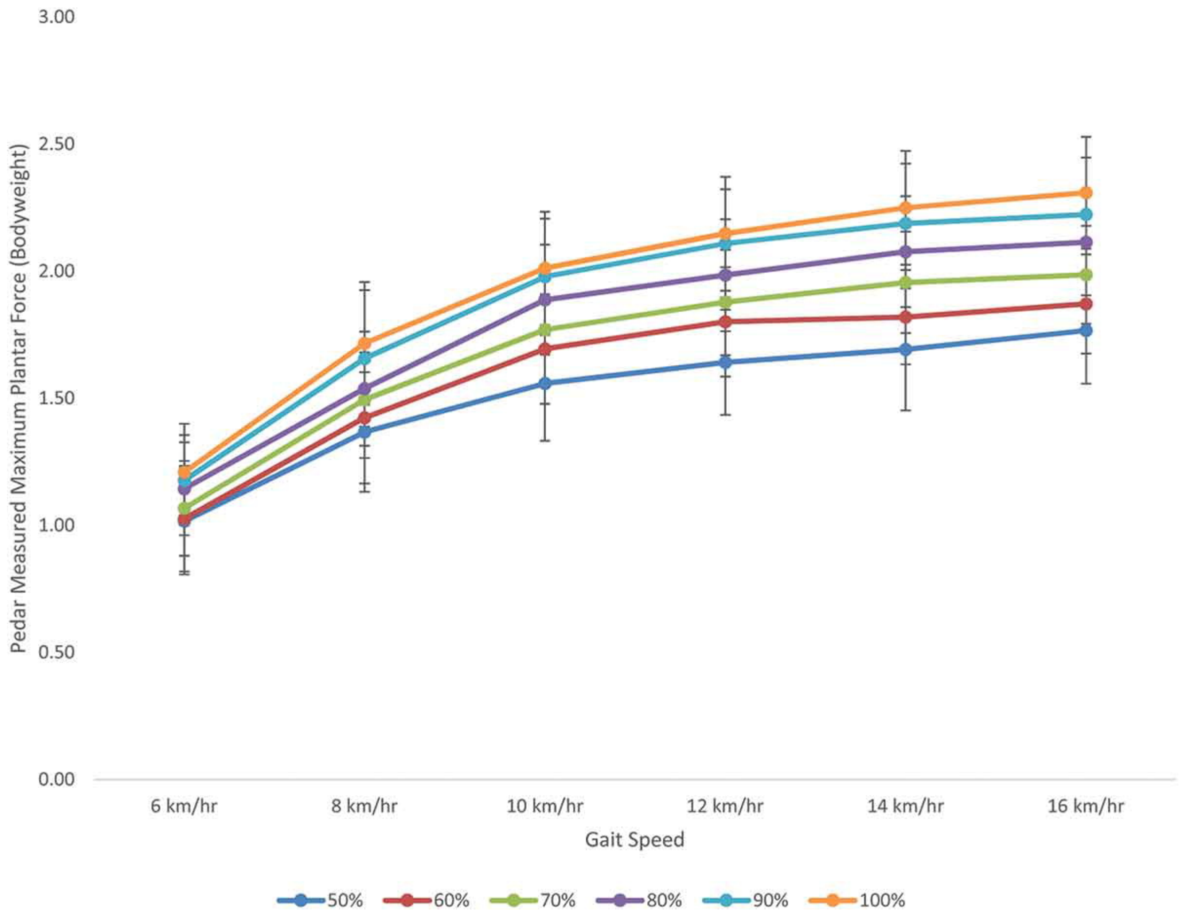


Figure 3. *Maximum plantar force at each of the different combinations of running speed and indicated AlterG® % BW support.*

Contact Time

Walking and running speed had the largest effect on contact time rather than altering BW on the AlterG® treadmill. Contact time for the whole foot decreased as running speed increased. Longest contact time was 572.85 ± 75.55ms for the 100% indicated BW at 6 km/hr trial. Shortest contact time was 186.65 ± 23.70ms for the 50% indicated BW and 16 km/hr trial. Altering indicated BW had a much smaller effect on contact time. A table documenting contact times for all 36 combinations of indicated BW and running speed is provided as a **Supplemental Table 1**.

Relative change between 50% and 100% indicated Alter-G bodyweight		Relative change between 6km/hr and 16km/hr	
At 6 km/hr	0.189	At 50%	0.737
At 8 km/hr	0.255	At 60%	0.824
At 10 km/hr	0.291	At 70%	0.861
At 12 km/hr	0.308	At 80%	0.848
At 14 km/hr	0.329	At 90%	0.888
At 16 km/hr	0.307	At 100%	0.909

Table 2. *Relative change in Maximum force (compared to the maximum observed) for both running speed and percent bodyweight. For example, when considering the 6km/h condition, there was a change of 0.189BW when moving from 50% indicated bodyweight to 100% indicated bodyweight. Conversely, at the 50% indicated bodyweight condition, there was an increase of 0.737BW when moving from 6km/hr to 16km/hr. In all cases, increasing running speed across a range of indicated bodyweight resulted in a much larger increase in force compared to increasing indicated percentage bodyweight.*

1.5 Discussion

Increasing gait speed resulted in larger increments of Fmax for the total foot than increases of indicated per cent BW in the ranges examined here. Clinicians can use Table 1 to estimate increases in Fmax for their injured athletes as they progress their rehabilitation on an AlterG® treadmill. It can be seen that the initial increases when walking from 1.02BW up to 1.21BW occur by stepping the indicated per cent BW from 50% to 100%, and then the next smallest step to 1.37BW occurs back at 50% of indicated BW, at 8 km/hr. Table 1 can then be used to progressively increase either running speed or per cent BW while considering the Fmax. It is suggested that such steps in loading, married up with clinical findings can result in a more systematic approach to return to sport and other running activities.

We had initially suspected that moving from 50% indicated BW to 100% indicated BW would result in an approximate doubling of the peak plantar forces across all running speeds. The data, however, showed the Fmax to increase by as little as 0.19BW to a maximum of 0.31BW. Moreover, in the 50% indicated BW condition, participants were experiencing a minimum of 1BW in peak plantar force at all speeds examined. If it were important to reduce Fmax to less than 1BW, even lower indicated BW or slower gait speeds would be required most likely.

These findings are in accordance with the work of Grabowski (Grabowski and Kram, 2008) who documented active peak loads between 0.98BW and 2.38BW with participants running between 10.8 km/hr and 18.0km/hr. However, this data contrasts with the work of Raper et al. (2014) who examined tibial loads using a surface-mounted accelerometer, and considered running speeds from 10 km/hr to 20 km/hr. We make several suggestions for this apparent discrepancy. First, the impact force measured with a surface-placed accelerometer on the tibia will likely provide a different reading than a plantar reading from the Pedar-X in-shoe measurement equipment used here. Further, there is the likelihood that some dampening of the force occurs at the foot and ankle, resulting in different forces experienced at the tibia. Finally, we note that, moving from 6 km/hr to 8 km/hr saw the largest relative and absolute increases in Fmax, with the second largest peaks occurring when stepping from 8 km/hr to 10 km · hr^{-1}. These slower speeds were not examined in the study conducted by Raper et al. (2014).

Speeds between 6 km/hr and 10 km/hr represent a transition from walking to running in which several kinetic, kinematic and physiological changes occur. During walking, there are two periods within the stance phase of gait in which double-support occurs whereby both feet are in contact with the surface. As gait speed progresses to running there are no periods when both feet are in contact with the ground, meaning a single foot will deal with the GRF and impulse associated with foot-strike (Novacheck, 1998). Contact time gradually decreased as speed increased. All participants walked at the 6 km/hr speed in which contact time was 579.15 ± 75.55 ms for the 100% indicated BW condition. All participants ran at the 10 km/hr speed in which contact time was 264.55 ± 33.50ms for the 100% indicated BW condition. The 8 km/hr trials at various indicated BW represented a transition from walking to running for participants (Table 1, supplemental data). AlterG® indicated BW had little effect on contact time. For example, at 16 km/hr contact time was 186.65 ± 23.70ms for the 50% indicated BW and 193.6 ± 17.80 ms for the 100% indicated BW conditions (supplemental data).

These findings are in accordance with contact times from a recent study by Ribeiro et al. (2015) in which a control group of 30 participants ran over-ground at 12 km/hr and 100% BW and recorded contact time of 234 ± 21.30ms. Our findings concur with contact time of

235.40 ± 30.45ms for the 12 km/hr at 100% indicated BW condition on the AlterG® treadmill (Ribeiro et al., 2015).

Fmax is a measure of in-shoe force experienced at the plantar surface of the foot. The relationship with forces experienced in other joints of the lower limb is complex. Recent work calculating joint torques while over-ground running at 8, 12 and 16 km/hr suggests that the peak torques increased both at the ankle and knee at the higher speeds, with greater increases at the ankle (compared to the knee) (Petersen et al., 2014). Similar to the work done here, a larger relative and absolute increase was seen in the step from 8 to 12 km/hr compared to the step from 12 to 16 km/hr.

Patil et al. (2013) measured in vivo forces at the knee using a custom tibial prosthesis in four elderly participants while they walked on an AlterG® treadmill at speeds ranging from 2.41 to 7.24 km/hr and indicated BWs ranging from 25 to 100% BW (Patil et al., 2013). Tibiofemoral force peaked at 5.1 times BW for the 7.24 km/hr at 100% indicated BW trial. Lowest force recorded was 0.8 times BW for the 2.41 km/hr at 25% indicated BW trial. It is important to note that these forces at the knee are a measure of not only the external GRF during stance phase of the gait cycle but also the muscle force production that occurs in anticipation for or response to interaction with the surface.

The data presented here for Fmax can be used in conjunction with the contact times table (supplemental data) and knowledge of the relations between the load sharing through the lower limb during gait to plan a staged rehabilitation process. However, an individual's response to loading will of course be subject specific and it is suggested that clinical reasoning be used by the clinician in an attempt to find optimal load to expedite rehabilitation from injury.

There are a number of limitations to this study. A potential limitation is the collection frequency of 100 Hz which could result in the loss of true peak value for Fmax. In-shoe force measurement gives the vertical component of GRF only and therefore does not capture medial-lateral of "shear" force that may be important components when considering lower extremity injury (Tessutti et al., 2012). Caution should be exercised when comparing these Fmax plantar loads from AlterG® treadmill running to over-ground running as it is known that loads increase with over-ground running and this may result in an under-estimation of Fmax at the given running speeds (Hong et al., 2012). Finally, this study was conducted in healthy adult male participants wearing their preferred footwear; it is unknown if the findings would be replicated in injured participants, women or children where gait parameters will likely vary.

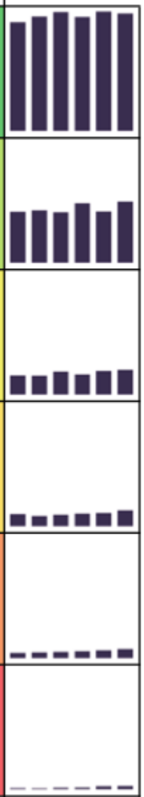
1.6 Conclusions

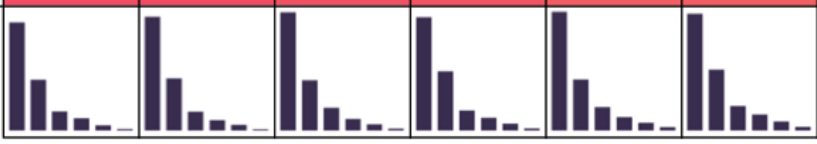
Data are presented allowing an evidence-informed graduated return to loading on a reduced gravity treadmill – clinicians can use the tables or regression formula to estimate peak plantar forces for different combinations of running speed (from 6 to 16 km · hr^{-1}) and per cent indicated BW (from 50% to 100%). Increasing running speed, rather than increasing indicated per cent BW, was shown to have the strongest effect on the magnitude of peak plantar forces across the ranges of speeds and indicated per cent BWs examined.

Practical Implications

Faster running speeds (up to 16km/hr) caused greater maximum plantar force than increases in per cent BW (up to 100%) on the AlterG® treadmill in healthy male runners for the speeds and BWs tested. Table 1 can be used as a guide to allow clinicians to more objectively progress plantar loading during rehabilitation on the AlterG® treadmill for different BW and running speed combinations. To reduce plantar loading to below 1 BW in the early stages of rehabilitation it may be necessary to walk at below 6 km · h^{-1} and 50% indicated BW, which was the slowest speed and BW combination used here.

Speed \ Bodyweight	50%	60%	70%	80%	90%	100%
6 km/hr	544.00 (119.30)	563.05 (103.75)	577.80 (97.00)	561.25 (88.30)	579.15 (92.30)	572.85 (75.55)
8 km/hr	351.25 (93.10)	356.60 (93.45)	349.85 (96.90)	379.50 (93.05)	352.65 (91.30)	385.35 (100.10)
10 km/hr	245.60 (27.65)	244.70 (26.90)	257.90 (42.25)	249.05 (25.80)	260.35 (36.90)	264.55 (33.50)
12 km/hr	223.10 (40.15)	216.75 (20.60)	220.75 (18.45)	224.75 (20.35)	227.10 (21.20)	235.40 (30.45)
14 km/hr	199.25 (17.80)	200.90 (22.95)	202.70 (19.30)	204.65 (17.40)	207.85 (19.25)	211.60 (19.55)
16 km/hr	186.65 (23.70)	186.10 (18.50)	188.65 (21.35)	189.45 (15.95)	193.00 (15.65)	193.60 (17.80)





Supplemental Table 1 Average contact times (ms) for all subjects for each of the 36 conditions. Bar graphs adjacent to the cells represent the values in the corresponding row (on the right, percentage bodyweight change for the same gait speed) or column (at the bottom, gait speed change for the same relative bodyweight). Vertical axes are the same scale for each bar graph.

Chapter 2: Marked asymmetry in vertical force (but not contact times) during running in ACL reconstructed football players <9 months post-surgery despite meeting functional criteria for return to sport.

2.1 Abstract

Objectives. Compare maximum plantar force (Fmax) during running in soccer players following anterior cruciate ligament reconstruction (ACLR) as they pass return to sport (RTS) criteria.

Design. Case control study.

Methods. Soccer players after ACLR (n = 16) and matched healthy controls (n = 16) ran on a treadmill at 12, 14 and 16 km/h while plantar loading data was measured using an in-shoe pressure system (Pedar-X, Novel). Fmax and contact time of the injured and uninjured limbs in athletes <9 months post-ACLR and those ≥9 months ACLR were compared to healthy players (no ACLR).

Results. Significant differences with large effect sizes in Fmax asymmetry were seen at all running speeds for the athletes <9 months ACLR compared to those ≥9 months, and the healthy subjects. Fmax difference peaked at 16 km/h; 32 ± 11%BW in <9 months ACLR group compared to 6 ± 5%BW in ≥9 months group; ES = 1.67, $p < 0.01$. There was a non-significant trend for increasing asymmetry with increasing speed for subjects who were <9 months after ACLR while the reverse was true for those ≥9 months and the healthy subjects.

Conclusions. Relatively large unloading of the ACLR limb (but not differences in contact times) are seen during running for athletes <9 months post-ACLR despite having completed functional criteria required to permit RTS training. These asymmetries appear to slightly increase with increasing speed, and the reverse is true for healthy controls and those ≥9 months after ACLR surgery.

2.2 Introduction

Following anterior cruciate ligament reconstruction (ACLR) a decision must be made on when an athlete should return to sport (RTS). To increase the likelihood of successful and safe RTS, specific criteria have been developed with the aim of returning to the same level of participation, protected from re-injury, as quickly as possible (Ardern et al., 2016a, Ardern et al., 2016b) Decision rules that govern when an athlete returns to sport can reduce re-injury rate by up to 84% if adhered to (Grindem et al., 2016). Grindem et al. (2016) showed that for every month return to sport was delayed, until 9 months after ACLR, the rate of knee re-injury was reduced by 51%. Kyritsis et al. (Kyritsis et al., 2016) showed that failing to achieve certain functional clinical discharge criteria before RTS was associated with a 4-times greater risk of ACL graft rupture. Clinically it's unclear if discharge rules should be time-based, criteria-based, or some combination of both.

Gait parameters are an objective measurement that have been widely analysed with adaptations seen to occur in individuals that have undergone ACLR (Devita et al., 1998, Di Stasi et al., 2013, Gokeler et al., 2013). Various kinematic (e.g. joint angles), spatiotemporal (e.g. step length or contact time) and kinetic (e.g. Ground Reaction Force) parameters have been measured during gait analysis following ACLR (Di Stasi et al., 2013, Minning et al., 2009). However, this work has mainly been done during the early stages of rehabilitation (Hadizadeh et al., 2016) at walking speeds (Minning et al., 2009).

ACLR does not restore normal knee joint gait biomechanics during walking according to a systematic review and meta-analysis of 34 studies (Hart et al., 2016). Altered sagittal plane kinematics and force moments during walking is the most consistent finding after ACLR for which there was moderate evidence. Further sensitivity analysis showed the type of graft may influence gait parameters after ACLR with hamstring grafts being associated with increased knee adduction angle when walking, while patella grafts are not (Hart et al., 2016).

No studies have examined running kinetics when athletes pass their other more common return to sport criteria tests. Therefore very little is known about the magnitude (or when) limb asymmetries reduce for gait parameters such as maximum vertical ground reaction force (Fmax) or ground contact time (CT), especially at faster running speeds more akin to those required by athletes at RTS.

Physiotherapists, strength & conditioning staff and others involved in rehabilitation of athletes after ACLR often utilise a limb symmetry index when comparing the ACLR limb to the healthy uninvolved limb during a functional criteria test, especially at discharge for RTS. Often an athlete must achieve a certain proficiency for limb function (e.g. <10% difference between limbs) during these functional tests (Kyritsis et al., 2016). However, limb asymmetry data during moderate to high speed running tasks in athletes after ACLR has not been published to date. Therefore, the aim of this study was to compare gait characteristics during moderate to fast speed running of ACLR patients who had met functional criteria for RTS while controlling for time after ACLR surgery.

3. Methods

32 male soccer players participated in the study. Informed consent was obtained for each participant, and the experiment was conducted with the approval of the local ethics committee (IRB number F2013000001). Sixteen athletes who had undergone a primary ACL reconstruction (age 26 ± 4 years, weight 74 ± 6 kg, height 178 ± 6 cm) and 16 matched healthy (no injury) athletes (28 ± 4 years, 77 ± 9 kg, 179 ± 6 cm) were recruited (Table 3).

All participants were either professional or high-level recreational football players matched for activity level, age, height and weight. All players who underwent ACL reconstruction (hamstring graft n = 9, bone-patella tendon-bone graft n = 7) were included only after passing a criteria-based rehabilitation program (Kyritsis et al., 2016) at Aspetar Sports Medicine and Orthopaedic Hospital (Doha, Qatar). The six major discharge criteria were as follows;

1. Isokinetic strength testing at 60……..Pass when Quadriceps deficit <10% at 60 °/s.
2. Single leg hop………………………Pass when limb symmetry index > 90%
3. Triple hop (single leg)………………Pass when limb symmetry index > 90%
4. Triple hop (single leg)………………Pass when limb symmetry index > 90%
5. On-field sports rehabilitation……….Pass when fully completed
6. Running T test………………………Pass when running time < 11seconds

See Kyritsis et al. (2016) for full details on discharge criteria.

ACLR participants were tested between 5-10 months after surgery as they successfully passed the criteria-based rehabilitation program in preparation for RTS. ACLR participants were arbitrarily divided into two groups; those <9 months post ACLR at the time of testing and those over ≥9 months post ACLR (Grindem et al., 2016) (Table 3). ACLR players all intended to return to play at either professional or high-level recreational soccer. Healthy participants had no previous anterior cruciate ligament injury and had to be injury-free for 6 months prior to the study.

All participants ran for 6 min at 12 km/h (3.3 m s^{-1}) on a treadmill to warm-up (HP Cosmos Quasor, Germany) in their own preferred running shoes. Three running trials at 12, 14, and 16 km/h were performed in a random order for each participant on a treadmill while kinetic and spatiotemporal data were collected. After the warm-up participants were instructed to run until their gait felt "consistent and regular". Plantar loading data collection started after this point with a minimum of 6 consecutive stance phase steps recorded for subsequent analysis. These speeds were selected as moderate running speeds that would be commonly used in rehabilitation settings prior to RTS (Thomson et al., 2017). Each participant underwent a single assessment. Plantar loading parameters were measured using the Pedar-X in-shoe system (Novel, Munich, Germany). Each insole is 1.9 mm thick and contains 99 capacitive sensors which were calibrated prior to testing (Trublu Calibration, Novel, Munich, Germany). The insoles relay data to a Pedar-X data logger that was fixed to the treadmill frame (Thomson et al., 2017). Force sensor insoles were placed inside the participants' own preferred running shoes and data sampled at 100 Hz via Bluetooth. Each Pedar-X insole was placed between the sock and shoe with no other manufacturer's insoles or foot orthotics in place so that the Pedar-X insoles were flat. No participants used orthotic supports. The validity (McPoil et al., 1995) and reproducibility (Kemozek and Zimmer, 2000) of the capacitive sensors in the Pedar-X have previously been reported to be excellent.

Plantar loading data from the stance phase of a minimum of six consecutive footfalls were extracted for both the left and right feet and were averaged for subsequent analysis using Novel Pedar- X evaluation software (Groupmask Evaluation, Novel Munich, Germany).

The maximum force (Fmax) was normalised to each participant's bodyweight (BW) to facilitate comparison and was examined for the whole foot for each of the running trials (Girard et al., 2007). Fmax recorded by Pedar-X is a proxy measure of vertical ground reaction force (vGRF) and has been shown to correlate well with a Kistler force platform (Barnett et al., 2001). Contact time for the whole foot was reported in milliseconds (ms) in absolute values. The between limb difference for both Fmax and CT was calculated by (uninjured limb − ACLR limb) for each ACLR participant and also healthy participant (Left − right limb).

ACLR participants were arbitrarily divided into two groups; those <9 months post ACLR and those over ≥9 months post ACLR (Grindem et al., 2016). Difference in maximum vertical ground reaction force (Fmax) and contact time (CT) were compared across the different running speeds for each participant group. Gait characteristics for the whole ACLR group (regardless of time post ACLR) were also compared with the matched healthy controls (no history of ACLR) to show the "normal" variability during running trials in this population of athletes.

Between group differences were estimated with an analysis of variance and post-hoc testing with $p < 0.05$ set as indicating statistical significance. Between group differences (<9 months post ACLR, ≥9 months post ACLR, and healthy) were reported using Cohen's d. The differences were reported as small, medium, large, very large, and huge when they reached 0.2, 0.5, 0.8, 1.2, and 2.0 respectively (Cohen, 1992, Sawilowsky, 2009)

__Table 3.__ Demographics for participants (n=32)

	<9 months ACLR (n = 11)	**≥ 9 months ACLR (n = 5)**	**Healthy (n = 16)**
ACLR graft type (BTB, Ham)	BTB 5, Ham 6	BTB 2, Ham 3	
Age (y)	26 ± 2	26 ± 6	28 ± 4
Body Mass (kg)	74 ± 8	74 ± 6	77 ± 9
Height (cm)	178 ± 4	178 ± 8	179 ± 6

BTB = Bone patella tendon bone graft.
Ham = Hamstring graft.
No significant differences for any demographic data between groups.

2.4 Results

Descriptive data for inter-limb differences in Fmax and CT during running trials are presented in Table 4. There was no significant difference in Fmax or CT for within group comparison of graft type. Therefore, graft types were combined to get group averages before conducting between group comparisons.

Significant differences with large to huge effect sizes in Fmax symmetry were seen at all running speeds for the athletes <9 months after ACLR surgery compared to those ≥9 months, or the healthy subjects. Fmax difference peaked at 16 km/h running speed; 32 ± 11%BW in <9 months ACLR group compared to 6 ± 5%BW in ≥9 months group; ES = 1.67, $p < 0.01$. (Figure 4). There was a non-significant trend for increasing asymmetry in Fmax with increasing speed for subjects who were <9 months after ACLR while the reverse was true for those ≥9 months and the healthy subjects (Table 4).

The only difference in contact times seen for any of the conditions was when comparing the ACLR subjects <9 months and the healthy subjects when running at 16 km/h; ES: 1.19, $p = 0.04$.

Table 4. *Fmax (percent of bodyweight) Inter-limb difference (un-injured limb–ACLR limb) for each group of athletes at each running speed. Positive values indicate relative unloading of the injured limb. Contact time in milliseconds (ms). Magnitude of inter-limb difference for each group expressed as effect size (Cohens d) between groups.*

*Asterisk * = significant difference between groups (p < 0.05).*

	Speed km/h	**<9 months ACLR (1)**	**≥9 months ACLR (2)**	**Healthy (3)**	**Effect size**		
					(1-2)	(1-3)	(2-3)
Difference in maximum force (%BW) (healthy–ACLR)	12	28 ± 15	11 ± 11	11 ± 8	1.06*	2.04*	0.04
	14	30 ± 17	10 ± 7	10 ± 7	1.15*	1.25*	0
	16	32 ± 11	6 ± 5	9 ± 7	1.67*	1.58*	0.43
Difference in contact time (ms) (healthy–ACLR)	12	25 ± 37	8 ± 10	11 ± 10	0.45	0.59	0.26
	14	8 ± 5	6 ± 8	7 ± 7	0.44	0.33	0.04
	16	20 ± 19	14 ± 13	6 ± 4	0.33	1.19*	0.84

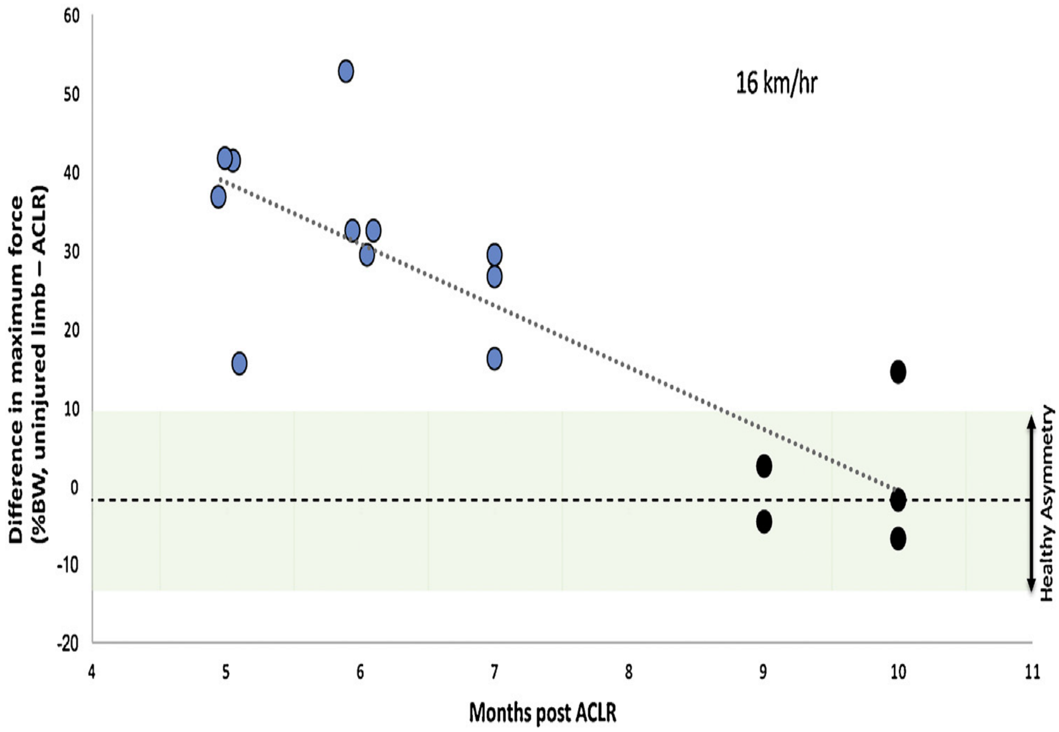


Figure 4. *Inter-limb difference (un-injured limb – ACLR limb) in Fmax reported in % bodyweight for each group of athletes at 16 km/h (4.4 m s−1) running speed. Positive values indicate relative unloading of the injured limb. Blue dots = <9 months after ACLR group. Black dots = ≥9months after ACLR group. Green shaded area = asymmetry seen in healthy control group. Note the general reduction in asymmetry with increasing time post ACLR, specifically no subjects <9 months after ACLR had less than 10% asymmetry while only 1 out of the 5 ≥ 9 months after ACLR group were outside the 'healthy' range.*

2.5 Discussion

Clear significant between-limb differences in maximum vertical force are evident in this study for athletes who clear RTS criteria early (<9 months after ACLR) compared to athletes who pass RTS criteria later (≥9 months post ACLR) or healthy control athletes during moderate to fast running on a treadmill (Figure 4). To our knowledge this is the first study to investigate kinetic asymmetry in athletic ACLR participants at moderately fast running speeds (14 & 16 km/h) as they are cleared to return to sports specific training. Whilst the case-control study design provides a "snapshot" with no further longitudinal or follow-up data, there are interesting findings that warrant further consideration.

Grindem et al. (2016) reported a significant reduction in re-injury risk after ACLR if RTS can be delayed by 9 months or more following ACLR surgery. Here we arbitrarily allocated our groups according to the suggested temporal criteria of Grindem et al. (2016) and have shown a striking difference for Fmax (but not contact time) symmetry. Reasons for this may include the time required for biological, neuromuscular and functional recovery of the knee joint along with remodelling and maturation of the ACLR graft. Moreover, Nagelli & Hewitt, (2017) advocate young athletes (<20 years) should consider delaying RTS for 2 years to lessen the risk of second ACL injury (Nagelli and Hewett, 2017). Our findings add another perspective to that of Grindem et al. (2016), at least from a global lower limb function viewpoint, with kinetic asymmetries being much greater in the accelerated rehabilitation athletes (<9 months) in our study (Table 4). Further research with a longitudinal study design may help shed light on our preliminary findings, including re-injury follow-up data.

Using a typical limb symmetry measure (side-to-side percentage differences) a trend emerged suggesting increasing symmetry as speed increased for both normal subjects and those ≥9 months after ACLR surgery, and the opposite for those less than 9 months (Table 4). This is an interesting finding that warrants further investigation with a larger sample size.

Recent work by Milandri et al. (2017) showed residual differences in kinematic and kinetic parameters long after ACLR (5.2 ± 3.2 years). Specifically, peak GRF was lower in the ACLR limb of male participants when compared to the unaffected limb and healthy control participants running at around 12 km/h (3.3 m s−). This suggests that GRF (vertical) limb asymmetry may remain long after ACLR for some. It remains to be seen if rehabilitation methods, ACLR graft type, gender or other factors alter these findings, as well as whether these findings are of clinical importance in, for example, re-injury rates or functional status.

Jumping and hopping movement tasks have been used to assess the effect time from surgery has on kinematic limb asymmetry in a youth athletic population of males and females. Analogous to our current findings, Myer et al. (2012) found significantly different asymmetry values for vGRF in ACLR athletes compared to healthy control athletes up to 11 months after ACLR. The ACLR limb having lower Fmax values on landing and also lower jump height when compared to the un-injured limb or the healthy (control) athletes during the single leg hopping task. In contrast to our data, the between-limb vertical Fmax differences when hopping showed no association with time from surgery in the young athletes until 11 months after ACLR. Potential reasons for this contrast in findings may be different the population (10 males, 23 females), younger age of the athletes, rehabilitation protocols, ACLR graft type, or other factors. Further running related research for athletes after ACLR, especially at faster running speeds akin to RTS speeds, is required in different populations (both genders, different sport type, various age groups) to follow-up on these preliminary findings here.

There were almost no meaningful differences in contact times between the groups (Table 4). Clinically, ground contact time asymmetry may be detected visually through high-speed video analysis or other wearable technology (Gilgen-Ammann et al., 2017) however the data presented here showed this to be less strongly associated with surgical status (only for the <9 months ACLR group compared to the healthy athletes at 16 km/h) than Fmax differences (Table 4). We suggest that this may underscore the importance of force measurements in comparison to more easily captured temporal aspects in these patients.

Limitations such as the small sample size, and case-control design should be considered when interpreting the clinical implications for these results which can only apply to adult male athletes following ACLR who have completed a specific criteria-based rehab program. It is unknown if athletes displayed similar or other limb asymmetries prior to ACL injury or at any other time points than the single testing session here. Longitudinal data is required to confirm these and to ascertain their clinical significance. In this study Fmax or vertical ground reaction force is a global measure of force at the foot-shoe-treadmill interface so there is no information given on joint moments at specific proximal structures such as the ankle, knee or hip. Further, we were unable to investigate within-group comparisons due to the small sample size.

2.6 Conclusion

Relatively large unloading of the ACLR limb (but not differences in contact times) are seen during running for athletes <9 months post-ACLR despite having completed functional criteria required to permit RTS training. These asymmetries appear to slightly increase with increasing speed, and the reverse is true for healthy controls and those ≥9 months after ACLR surgery.

Practical Implications

- Relative unloading of the ACLR limb is apparent in male soccer players who complete a criteria-based rehabilitation programme until 9 months after surgery.
- Healthy control players display less asymmetry in vertical force as running speed increases. The reverse is apparent in ACLR players <9 months after surgery.
- These preliminary findings suggest that vertical force (but not contact times) are worthy of further consideration as objective criteria to be used in successful RTS considerations.

Chapter 3: Fifth metatarsal stress fracture in elite male football players: an on-field analysis of plantar loading

3.1 Abstract

Objective. Evaluate plantar loading during 'on-field' common football movements in players after fifth metatarsal (MT-5) stress fracture and compare with matched healthy players.

Methods. Fourteen elite male soccer players participated in the study conducted on a natural grass playing surface using firm ground football boots. Seven players who had suffered a primary stress fracture (MT-5 group) and seven matched healthy players (controls, CON) performed three common football movements while in-shoe plantar loading data were collected.

Results. Large between-group differences exist for maximal vertical force (Fmax) measured in Newtons and normalised to bodyweight (BW) at the lateral toes (2-5) of the stance leg during a set-piece kick (MT-5: 0.2±0.06 bodyweight (BW), CON: 0.1±0.05 BW, effect size (ES) 1.4, $p < 0.05$) and the curved run where the MT-5 group showed higher Fmax with very large effect size at the lateral forefoot of the injured (closest to curve) limb when running a curve to receive a pass (MT- 5 injured−CON=0.01 BW, ES 1.5, $p < 0.05$). Small between-group differences were evident during straight-line running. However, between-limb analysis of MT-5 group showed significant unloading of the lateral forefoot region of the involved foot.

Conclusions. Elite male football players who have returned to play after MT-5 stress fracture display significantly higher maximum plantar force at the lateral forefoot and lateral toes (2-5) compared with healthy matched control players during two football movements (kick and curved run) with the magnitude of these differences being very large. These findings may have important implications for manipulating regional load during rehabilitation or should a player report lateral forefoot prodromal symptoms.

3.2 Introduction

Return to sport following fifth metatarsal (MT-5) stress fracture in football (soccer) players can be problematic and protracted. Average absence from football is 3–5 months when healing and rehabilitation go to plan (Ekstrand and Torstveit, 2012). Complications, however, are common with non-union and refracture being among the chief concerns, which makes this injury potentially 'career-ending' (Ekstrand and van Dijk, 2013).

Young players, during the preseason period of training, are most affected with the non-dominant (stance leg when kicking) limb more frequently involved in the midfielder playing position (Ekstrand and van Dijk, 2013, Fujitaka et al., 2015, Matsuda et al., 2017). Early surgical intervention with insertion of a large-diameter compression screw is thought to lead to better outcomes for athletes compared to conservative management (Kerkhoffs et al., 2012, Porter et al., 2005).

Understanding the magnitude, timing and distribution of forces acting at players' feet when performing common football movements is therefore important to minimise the risk of primary injury or refracture after surgical fixation. Greater ground reaction forces and impact loading rates occur when running in football boots compared with training shoes (Smith et al., 2004). In-shoe plantar loading is a proxy of vertical ground reaction force (vGRF) experienced by the player, and while in-shoe systems are known to slightly underestimate peak vGRF compared with force plate measurements, they allow valid and reliable collection of multiple steps during 'on-field' testing (Barnett et al., 2001, Stöggl and Martiner, 2017). Additionally, analysis of regional loading at specific anatomical sites of the foot is possible rather than one global measure of vGRF (Bentley et al., 2011, Ford et al., 2006, Eils et al., 2004).

Football footwear is known to increase plantar loading at specific anatomical areas of the foot during movements like running, cutting and kicking (Bentley et al., 2011, Ford et al., 2006, Eils et al., 2004). How these plantar loading parameters are altered following MT-5 stress fracture when compared with healthy matched players during common football movements is unknown.

Therefore, the primary aim of this study is to evaluate plantar loading during 'on-field' common football movements in players after return to sport following MT-5 stress fracture and compare with matched healthy players. A secondary aim was to identify football movements that increase load at the lateral forefoot to guide activity modification should prodromal symptoms be reported to medical personnel.

3. Methods

This study was approved by the ethics committee of the Anti-Doping Lab Qatar institutional review board (IRB no. F2016000194).

Participants

Fourteen elite male soccer players participated in the study. Seven players (professional and/or international players) who had suffered a primary stress fracture of the fifth MT (MT-5 group—age 25±5 years, weight 74±6 kg, height 178±6 cm) and seven matched healthy (no injury) players (control group—26±4 years, 76±4 kg, 179±5 cm) were recruited. All MT-5 injured players underwent surgery at Aspetar Sports Medicine and Orthopaedic Hospital (Doha, Qatar) by the same orthopaedic surgeon (PD) for intramedullary screw fixation±bone graft from the pelvis. Postoperative care comprised 3 weeks in a non-weight-bearing cast and 3 weeks in a partial weightbearing boot. Physiotherapy was started after cast removal with combined hydrotherapy and reduced gravity treadmill (Alter-G) in the initial phase. After 6 weeks, all players progressed to full-weight-bearing. For all MT-5 injured players, the affected foot was at their stance or non-dominant limb when kicking with 86% (6/7) of the players reporting prodromal symptoms prior to stress fracture. All stress fractures occurred with insidious onset and were not frank or acute traumatic fractures (Ekstrand and van Dijk, 2013) (Figure 5). Playing positions comprised four midfield players, one wing, one striker and one defender.

Inclusion in the current study occurred only after MT-5 players had returned to play following complete radiographic union of the stress fracture and completion of rehabilitation programme with end-stage field-based return-to-play tests at the rehabilitation department in Aspetar Sports Medicine and Orthopaedic Hospital. MT-5 group players were on average 240±60 days after surgery during on-field biomechanical testing.

***Figure 5**. X-ray of one players' fifth metatarsal stress fracture (insidious onset) after surgical fixation with an intramedullary screw. Note location distal to the tuberosity where traumatic avulsion fractures occur.*

Healthy matched control participants were injury-free for 6 months prior to the study with no previous history of injury to MT-5 or anterior cruciate ligaments. Healthy participants were matched for playing position, body mass, height and level of competition.

Testing Protocol

Participants were fitted with appropriate-sized firm ground soccer boots (Nike Tiempo Genio leather II; Nike, Beaverton, Oregon, USA) for field-based biomechanical testing (Figure 6) to decrease the effect different cleat types can have on plantar loading (Bentley et al., 2011). Natural Bermuda grass (Cynodon dactylon) surface over-seeded with rye grass (Lolium perenne) with a predominantly sand rootzone at the Aspire zone (Doha, Qatar) was used for testing. Ground staff maintained the surface to have consistent mechanical properties for the duration of the study.13 Surface hardness (69±6 g using FIFA-approved 2.25 kg Clegg hammer), rotational resistance (43±7 N.m using FIFA-approved studded disc apparatus) and temperature (26±6 °C using Kestrel 4400 heat stress tracker, USA) were recorded.

Figure 6. Firm ground football shoe used by all participants (Nike Tiempo Genio II).

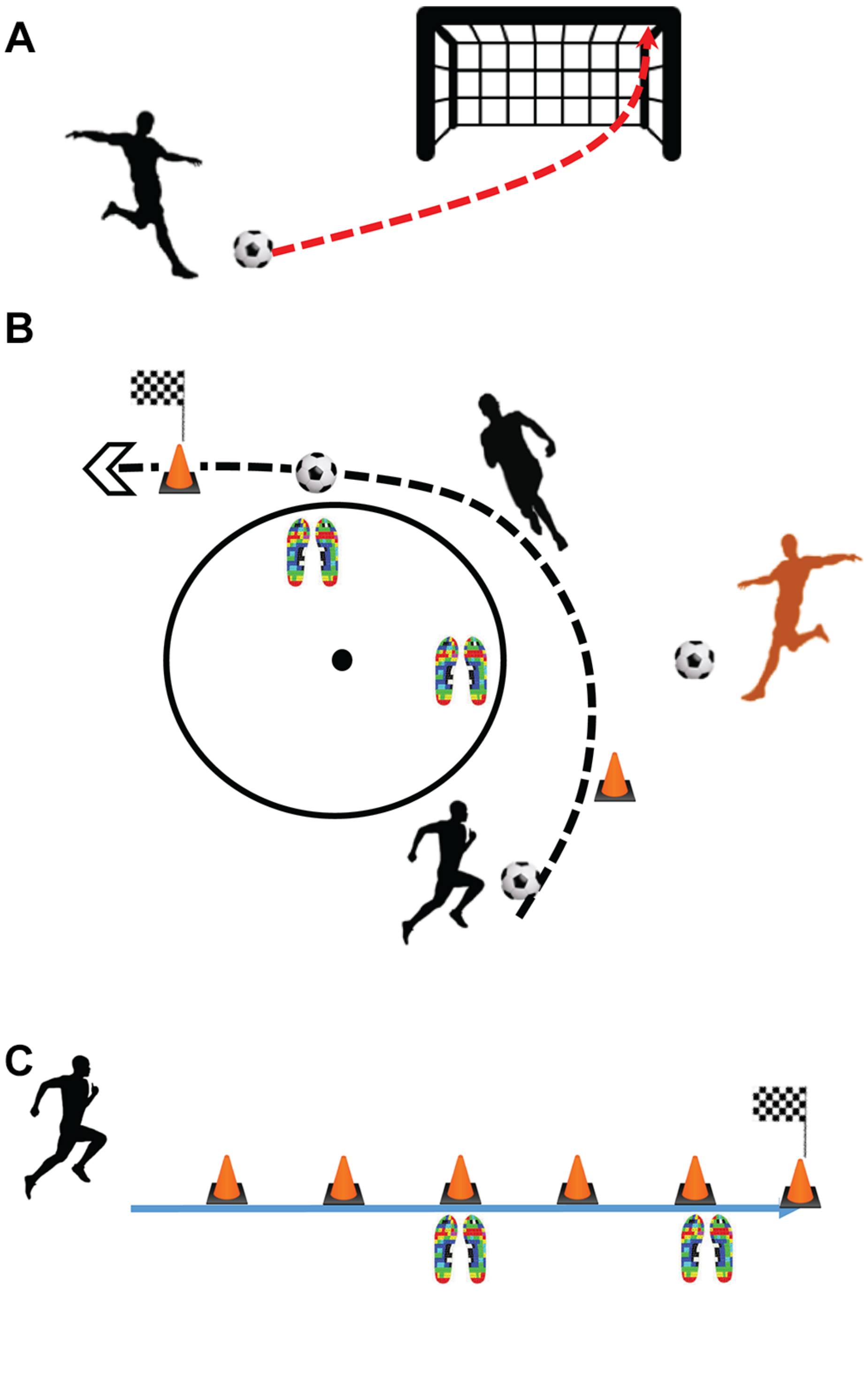


Figure 7. Football-specific movements. (A) Set-piece kick (B) Curved run with ball interplay. (C) Forward straight-line run at 5.5 m s−1. The pressure insole icons denote areas where data collection started and finished during the running trials.

Plantar loading parameters were collected using the Pedar-X in-shoe system (Novel, Munich, Germany). Each insole is 1.9 mm thick and contains 99 capacitive sensors, which were calibrated prior to testing (Trublu Calibration; Novel). The validity and reproducibility of Pedar-X is excellent for running (Stöggl and Martiner, 2017, Kemozek and Zimmer, 2000).
Briefly, the Pedar-X insoles relay data sampled at 100 Hz to a data logger (carried in a custom-made back-pack) and then to a laptop via Bluetooth technology. Insoles are placed bilaterally with no foot orthotics in place so that the Pedar-X insoles were flat.

A global positioning system (GPS) sampling at 10Hz (Catapult OptimEye, Catapult Innovations, Team Sport 5.0, Melbourne, Australia) was used to as a further verification of approximate running speed of the trials (Roe et al., 2017). Each participant wore the GPS unit in vest supplied by company in the appropriate size (Catapult OptimEye, Catapult Innovations, Team Sport 5.0, Melbourne, Australia). The unit was positioned between the shoulder blades in the upper-back or trunk area. GPS velocity was downloaded using catapult Openfield software (version1.12.0, GPS open, Catapult innovations, Melbourne, Austrlia). Velocity doppler shift was taken from Catapult Sprint Software (version5.4.1, GPS sprint) (Catapult innovations, Melbourne, Australia). Average number of satellites for the unit was 14.1± 0.16).

Standardised 'warm-up' protocol consisting of progressing running speeds, lower body resistance exercises (bodyweight) and dynamic stretching was conducted by the same physical performance coach (RA).

Following this, participants completed three soccer football-specific movement tests (Figure 7). For each test, three familiarisation trials were first performed, followed by three trials of each test while kinetic and spatiotemporal data were collected via the Pedar-X and GPS unit as follows:

1. *Set-piece kick:* Participants were instructed to hit the furthermost top corner of the goal posts from a spot 10 m adjacent to the corner of the 18 yd box during three trials of curved set-piece kicks at 75% of maximum effort while data were collected from the stance leg.

2. *Curved run with ball interplay:* Participants performed three curved runs to mimic running into space onto a pass. Participants dribbled the football to a cone where they passed to a stationary team-mate (RA) who sent out a subsequent pass for the participant to run onto while following the arc of the centre circle (Figure 7B). Participants were instructed to accelerate into the curved run, after passing the ball, at 75% of maximum effort (Eils et al., 2004).

3. *Forward straight-line run:* Participants ran 60 m at a speed of 5.5 m s−1 (19.8 km/h). Running speed was controlled using audio cues in which the participant should pass each 10 m distance marker cone as the audio cue (beep) sounds. Speed was checked with the GPS system and any trials outside ±10% were discarded.

After pilot tests at various running speeds players confirmed that 5.5 m s−1 (19.8 km/h) was the speed they felt most comfortable to perform repeat trials in a reliable manner using the audio cues and corresponding distance cones. This represents moderate to high speed running which is a common element in football and rehabilitation of elite players (Taberner et al., 2019, Taylor et al., 2017).

For the straight run, plantar loading data from the stance phase of a minimum of six consecutive footfalls were extracted for both the left and right feet and were averaged for subsequent analysis using Novel evaluation software (Groupmask Evaluation; Novel). For the curved run with ball interplay, the maximum force (F_{max}) of the inside foot (closest to the curve) was averaged over the three trials. For the set-piece kick, the F_{max} at the non-dominant stance leg was averaged over the three trials. The F_{max} was normalised to each participant's bodyweight to facilitate between-participant comparison and was examined for the whole foot as well as anatomical regional areas (‘masks’) for each task (Figure 8) (Girard et al., 2011). F_{max} recorded by Pedar-X is a proxy measure of vertical ground reaction force (vGRF) and has been shown to correlate well with a Kistler force platform (Barnett et al., 2001). The between limb difference for F_{max} was calculated subtracting the value of the MT-5 injured limb from the uninjured limb for each MT-5 participant, and arbitrarily for the healthy participants as right leg subtracted from the left leg. Data for the whole foot and also anatomical masks were analysed with a focus on the lateral foot. The masks examined were ‘lateral midfoot’, ‘lateral forefoot’ and ‘lateral toes (2-5)’.

Statistical Analysis

Between-limb and between-group differences were examined with a repeated-measures analysis of variance. Bonferroni adjustment for multiple comparison was applied to subsequent post hoc testing with $p < 0.05$ set as indicating statistical significance. Between-group differences were reported using Cohen’s d (Cohen, 1992) The differences were reported as small, medium, large and very large when they reached 0.2, 0.5, 0.8 and 1.2, respectively (Sawilowsky, 2009).

3.4 Results

Between-group differences at the lateral foot for each movement task are presented in Table 5. Differences for each anatomical region of interest are expressed as effect sizes (Cohen’s d) in Figure 8A–C. Between-limb differences within the MT-5 group for the forward run task are presented in Table 6 and Figure 8D.

Table 5. Maximum force (normalised to BW) for each anatomical region during three movement tasks

Maximum force (normalised to BW)	Anatomical region	Control group	MT-5 group	Effect size (Cohen's d)
Set-piece kick	Lateral toes 2–5	0.11±0.05BW	0.20±0.06 BW	1.4*
	Lateral forefoot	0.60±0.09 BW	0.62±0.08 BW	0.1
	Lateral midfoot	0.79±0.02 BW	0.95±0.01 BW	0.7
	Total foot	2.93±0.31 BW	3.29±0.50 BW	0.8
Curved run with ball	Lateral toes 2–5	0.17±0.09 BW	0.25±0.08 BW	0.9
	Lateral forefoot	0.75±0.10 BW	0.89±0.05 BW	1.5*
	Lateral midfoot	0.88±0.02 BW	0.82±0.02 BW	−0.3
	Total foot	3.04±0.32 BW	3.30±0.19 BW	0.9
Forward straight-line run	Lateral toes 2–5	0.20±0.01 BW	0.24±0.09 BW	0.4
	Lateral forefoot	0.78±0.01 BW	0.76±0.02 BW	−0.2
	Lateral midfoot	0.67±0.01 BW	0.68±0.02 BW	0.1
	Total foot	2.96±0.20 BW	2.96±0.30 BW	0

Between-group differences (MT-5 group injured limb−control group equivalent limb or average of R and L limbs) expressed as effect size. Force was measured in Newtons and normalised to bodyweight (BW).
*Significant difference between groups ($p<0.05$).

Set-Piece kick

Between group differences of > moderate effect size (stance leg of MT-5 group−stance leg of control (CON) group) are reported for each lateral anatomical region.

Lateral midfoot: Increase in Fmax compared with the control group with moderate ES (MT-5 1.0±0.01 BW, CON 0.8±0.02 BW, ES 0.7, $p>0.05$).

Total foot: Overall, for the total foot, the MT-5 group produced higher Fmax than the control group during a set-piece kick (MT-5 3.3±0.6 BW, CON 2.9±0.3 BW, ES 0.8, $p>0.05$).

Lateral toes 2–5: Substantial increase in Fmax (MT-5 0.2±0.06 BW, CON 0.1±0.05 BW, effect size (ES) 1.4, $p=0.03$) with very large effect size when kicking.

Curved run with ball interplay

Significant differences (MT-5 injured limb−control group inside limb when running towards curve) are reported for each lateral anatomical area.

Lateral forefoot: MT-5 group showed higher Fmax with very large effect size at the lateral forefoot of the inside (closest to curve) limb when running a curve to receive a ball (MT-5 injured−CON=0.01 BW, ES 1.5, p=0.004).

Lateral toes 2–5: Higher Fmax with large effect size compared with the control group (MT-5 injured−CON=0.005 BW, ES 0.9, p>0.05).

Total foot: Overall for the total foot, the MT-5 group had higher Fmax with large effect size than the control group (MT-5 injured−CON=0.02 BW, ES 0.9, p>0.05).

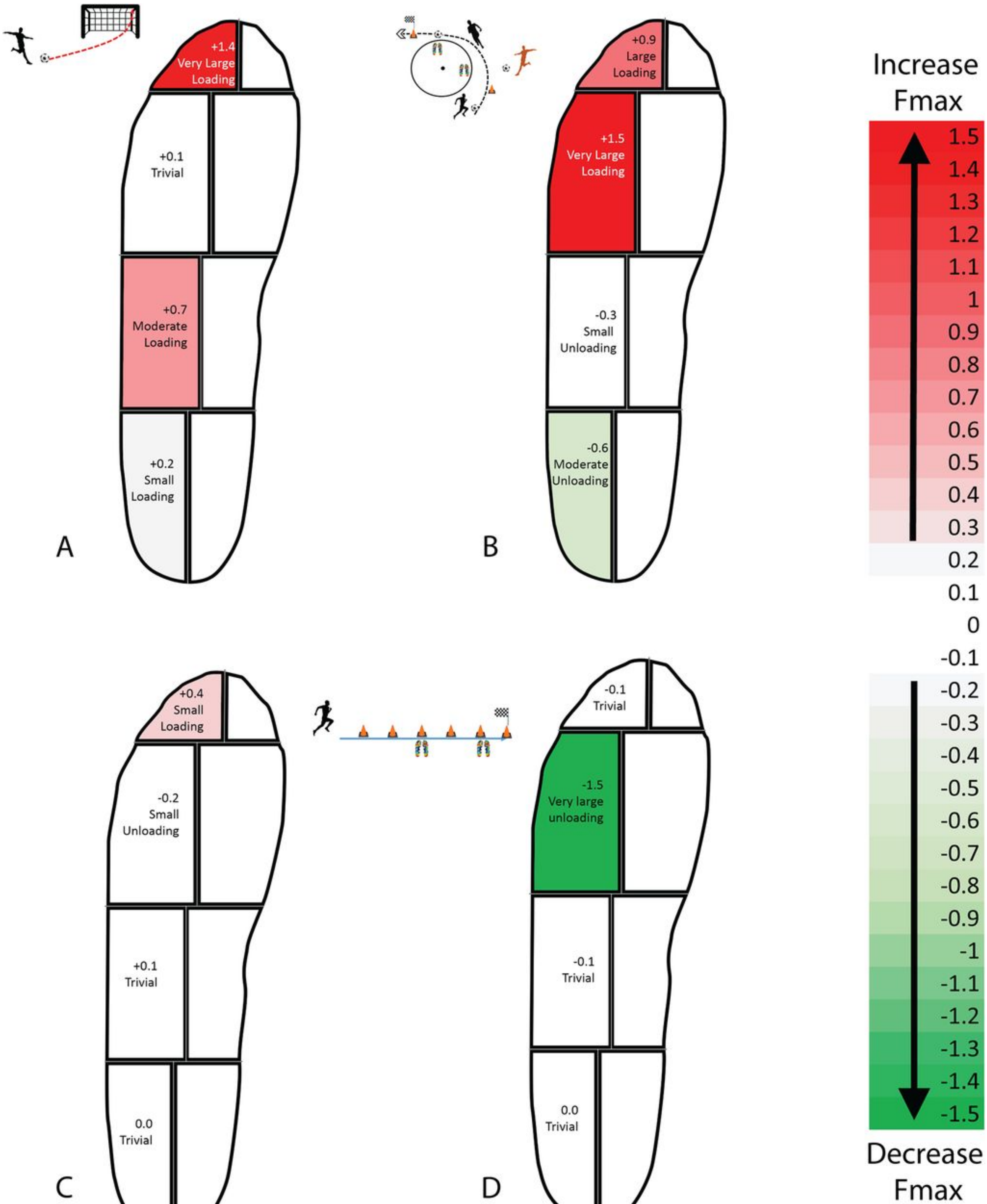


Figure 8 Between-group differences (MT-5 injured group vs control group) for specific anatomical regions of the foot expressed as effect sizes (Cohen's d). (A) Set-piece kick. (B) Curved run with ball interplay. (C) Forward straight-line run at 5.5 m s⁻¹. (D) Between-limb difference (within the MT-5 injured group) during a forward straight-line run at 5.5 m s⁻¹.

Forward straight-line run at 5.5 m s^{-1}

Between-group analysis (MT-5 injured limb−average of both control players' limbs)

Lateral toes 2–5: Fmax (0.04 BW, ES 0.4, p>0.05) increased with small effect sizes compared with the control group.

MT-5 group between-limb analysis (injured limb−uninjured limb)

Lateral forefoot: An unloading strategy was apparent for the previously injured MT-5 limb in comparison with the healthy limb of the MT-5 group players with a substantial decrease in Fmax (MT-5 injured−healthy limb=0.13 BW) at the lateral forefoot with the magnitude of effect being very large (ES=−1.5, p=0.03) (Figure 8D and Table 6).

Total foot: Overall, for the total foot, a decrease in Fmax with small effect size was noted when comparing the MT-5 injured limb with the healthy limb for a forward run at 5.5 m s−1 (MT-5 injured−healthy limb=0.06 BW, ES−0.2, p>0.05).

Table 6. Maximum force (normalised to BW) for each anatomical region during a forward straight-line run at 5.5m s^{-1} (19.8 km/h)

Maximum force (normalised BW)	**Anatomical region**	**MT-5 group uninvolved limb**	**Effect size (Cohen's d)**	**MT-5 group injured limb**
Forward straight-line run	Lateral toes 2–5	0.24±0.09BW	−0.1	0.23±0.07BW
	Lateral forefoot	0.89±0.01BW	−1.5*	0.76±0.01BW
	Lateral midfoot	0.70±0.17BW	−0.1	0.69±0.19BW
	Total foot	2.96±0.30BW	−0.2	2.94±0.19BW

Inter-limb difference within the MT-5 group (injured-uninvolved limb)
*Significant difference between groups (p<0.05)
Force was measured in Newtons and normalised to BW, Bodyweight

3.5 Discussion

To the authors' knowledge, this is the first study to examine 'on-field' game relevant movements of elite football players (using football boots) who have returned to play after surgical fixation of a fifth metatarsal stress fracture and compared the kinetic data with healthy matched control players.

Football-specific movements (set-piece kick and curved run with ball interplay) showed much larger between group differences at the lateral aspect of the foot than a straight-line running task in this cohort of male football players. Recent prospective research (n=335) by Matsuda *et al. (2017)* implied static plantar pressure measurements are not effective for identifying those players who will go on to develop a MT-5 stress fracture. Alongside current data presented here, we further advocate the need for assessment during on-field game relevant movements rather than static posture or even straight-line running alone.

Lateral maximum force was highest for the MT-5 group players at the stance leg during the set-piece kick or the inside foot when accelerating into a curved run (Figure 8A and B). However, straight-line running at 5.5 m s−1 (19.8 km/h) showed very little plantar load at the lateral foot other than the lateral toes (2-5) (Figure 8C). Previous research in healthy football players indicated increased plantar loading at the medial (not lateral) forefoot when cutting, running at moderate speeds and sprinting (Eils et al., 2004, Wong et al., 2007). This information may allow players to stay involved at training with certain movement strategy modifications should they report lateral foot pain.
Between-limb comparison within the MT-5 injured group showed an 'unloading' strategy at the lateral forefoot (Figure 8D) when running straight. The contrast in lateral loading when compared with the other movement tasks may represent an inability of previously injured MT-5 players to 'stress-shield' or unload the area once the task becomes more challenging. This finding is similar to pressure plate laboratory barefoot walking research conducted on 10 professional football players after they had returned to sport following MT-5 stress fracture (Hetsroni et al., 2010).

High index of suspicion with prodromal signs

Prodromal symptoms (such as vague lateral foot pain) might provide an important window of opportunity to intervene and manipulate an individual's loading variables following intense blocks of training (Ekstrand and van Dijk, 2013, Eirale, 2018). Eighty-six per cent (6/7) of participants in the MT-5 group reported prodromal symptoms prior to full stress fracture. It appears that these symptoms are frequently encountered: Ekstrand and Van Dijk, (2013) reported 45% of players who sustain a MT-5 fracture reported prodromal symptoms at the lateral foot and Popovic *et al.,* (2005) noted all 17 players had prodromal symptoms prior to stress fracture in a surgically managed cohort. Provided medical teams have a 'player wellness' monitoring system in place, early intervention may be possible.

From the current findings, it is suggested that accelerating into curved runs towards the injured foot or performing set-piece kicks that curl towards a target such as high ball velocity crosses, corner kicks and set-piece penalty kicks may substantially increase lateral loading and should be monitored until symptoms have resolved (Table 5). Previous research suggests crossover cutting may also be viewed with caution due to increases in lateral foot pressure (Queen et al., 2008).

Maximum plantar force alone is likely not a sufficient metric to be used as an indicator for when stress fracture will ensue due to the multifactorial nature of lower limb injuries, and it is suggested that the volume of kick type (Whiteley et al., 2017) as well as running and direction change demands (Mohr et al., 2003) should be individualised to player position when considering return to sport programming. These data may provide further insight into pathogenesis of MT-5 stress fracture when combined with the current data and other factors (eg, sleep quality, training load, vitamin D status, match congestion, anatomical variation including local vascularity, and player age) (Ekstrand and Torstveit, 2012, Ekstrand and van Dijk, 2013, Fujitaka et al., 2015, Warden et al., 2014).

Toe-flexor strength and management of ground reaction force

Decreased toe-grip strength measured with a digital dynamometer in a large prospective cohort of male football players (n=273) was found to be a prospective risk factor in players who went on to develop MT-5 stress fracture (Fujitaka et al., 2015). The lateral toes 2–5 anatomical region showed much larger magnitudes of Fmax in the MT-5 group for all three movements tested here, peaking with the set-piece kick (Figure 8A). This suggests the external vGRF is greater at the lateral toes in injured players, which might be a result of kicking technique (more foot inversion and staying lateral through roll-over progression to toe-off) at the stance leg during kicking.

External GRFs must be absorbed and managed by internal forces via the lateral plantar fascia, peroneus brevis/tertius muscle–tendon unit attachments and bending moments at the MT-5 bone itself. Decreased toe-flexor strength may incur higher bending moment forces on the MT-5 bone due to inability to manage the external GRF that generate large torsion, tension and axial loads especially when the foot is inverted prior to contact such as during full effort set-piece kicking (Gu et al., 2010, Vertullo et al., 2004).

Football boots

All players wore identical soccer boots (Figure 6). While this helped control for the effect different footwear might have on plantar loading, it also means that footwear was not tailored to the individual's foot anatomy or preference. Given the large magnitude of lateral loading with the football-specific tasks, it is suggested that stud plate outsole width at the midfoot and forefoot must be wide enough to prevent lateral 'overhang' of the MT-5 bone in an attempt to offer some form of protection from the playing surface.

Queen et al. (2008) suggested the addition of midsole cushioning, increased number of studs and decreased stud length reduced forefoot pressure during two football-specific tasks (side cut and cross cut) when using turf shoes instead of football boots. Additionally, clinical experience of the authors suggest footwear companies should perhaps work to incorporate forefoot cushioning into the outsole of football boots as many international and professional players remove the football shoe insole (sock liner) completely in attempt to improve 'feel' for the ball by wearing very tight shoes.

Further studies are required, with larger sample size, to assess if early intervention and manipulation of loading variables following prodromal symptoms does indeed reduce progression to stress fracture or if these findings extend to other populations (women, adolescents, older players and different playing levels).

An obvious limitation of this study in that 'in-shoe' systems measure vertical force and hence we miss the medial–lateral and anterior–posterior components of GRF. Cross-sectional design of this study should also be considered when interpreting the results as we cannot discern whether the higher lateral loads seen in the MT-5 group were the cause of stress fracture or a consequence of the injury.

However, even after completing a graduated rehabilitation programme and having returned to previous level of competitive football, the MT-5 injured players examined here displayed large differences in plantar loading at the lateral foot. These data should implore practitioners to exercise a high index of suspicion should prodromal symptoms occur in a player with history of previous MT-5 stress fracture and manipulate football movements accordingly.

3.6 Conclusions

Elite male football players who have returned to play after MT-5 stress fracture display significantly higher maximum plantar force at the lateral forefoot and lateral toes (2-5) compared with healthy matched control players during two football movements (kick and curved run) with the magnitude of these differences being very large. These findings may have important implications for manipulating regional load during rehabilitation or should a player report lateral forefoot prodromal symptoms.

Chapter 4: Higher shoe-surface interaction is associated with doubling of lower extremity injury risk in American football: a systematic review and meta-analysis of the football codes.

4.1 Abstract

Background. Turning or cutting on a planted foot maybe an important inciting event for lower limb injury, particularly when shoe-surface traction is high. We systematically reviewed the relationship between shoe-surface interaction and lower-extremity injury in football sports.

Methods. A systematic literature search of four databases was conducted up to November 2014. Prospective studies investigating the relationship between rotational traction and injury rate were included. Two researchers independently extracted outcome data and assessed the quality of included studies using a modified Downs and Black index. Effect sizes (OR+95% CIs) were calculated using RevMan software. Where possible, data were pooled using the fixed effect model.

Results Three prospective studies were included (4972 male athletes). The methodological quality was generally good with studies meeting 68–89% of the assessment criteria. All studies categorised athletes into low (lowest mean value 15 N.m) or high traction groups (highest mean value 74N.m) based on standardised preseason testing. In all cases, injury reporting was undertaken prospectively over approximately three seasons, with verification from a medical practitioner. Injury data focused on: all lower limb injuries, ankle/knee injuries or ACL injury only. There was a clear relationship between rotational traction and injury and the direction and magnitude of effect sizes were consistent across studies. The pooled data from the three studies (OR=2.73, 95% CI 2.13 to 3.15; $\chi^2=3.19$, df=2, p=0.21; $I^2=36.5\%$) suggest that the odds of injury are approximately 2.5 times higher when higher levels of rotational traction are present at the shoe-surface interface.

Summary and conclusions. Higher levels of rotational traction influence lower limb injury risk in American Football athletes. We conclude that this warrants considerable attention from clinicians and others interested in injury prevention across all football codes.

4.2 Introduction

Lower extremity injuries are prevalent across the football codes including soccer (Ekstrand et al., 2011b), Australian rules football (Orchard and Seward, 2002), gaelic football (Murphy et al., 2012), rugby league (Gissane et al., 2002), rugby union (Schwellnus et al., 2014) and American football (Dick et al., 2007). Elite soccer players sustain an average of two injuries per season (Ekstrand et al., 2011b) and collegiate American football players have approximately five injuries per 1000 h of playing/practice exposure to their lower limbs (Dick et al., 2007). There are immediate and long-term ramifications for the team (Eirale et al., 2013, Hägglund et al., 2013) and player (Gelber et al., 2000, Roos, 1998).

The mechanisms underlying lower limb injuries in sport are multifaceted (Ekstrand et al., 2011a, Hägglund et al., 2006, Hrysomallis, 2013, Waldén et al., 2011). Among the modifiable risk factors, interaction between player's footwear and the surface has been implicated as influencing non-contact lower extremity injury risk (Orchard et al., 2005, Lambson et al., 1996, Torg and Quedenfeld, 1971, Olsen et al., 2003, Pasanen et al., 2008b). One common mechanism associated with injury in the football codes is rotation on a planted foot coupled with high levels of traction at the shoe-surface interface (Dowling et al., 2010, Faunø and Jakobsen, 2006). In this case, studs on the football shoe can become 'trapped' in the grass of the playing surface, with the resulting rotational forces or torque shifted proximally to the ankle, knee or other joints (Drakos et al., 2010, Kaila, 2007, Stefanyshyn et al., 2010).

Football shoe design and playing surface properties are constantly evolving to reflect changes in the football codes (Barnes et al., 2014, Gray and Jenkins, 2010, Robbins et al., 2013). Shoe outsoles can differ significantly in terms of stud shape, length and position on the shoe outsole to augment player traction and performance for a given playing surface or climatic conditions (Hilgers and Walther, 2011, Hennig, 2014). Pioneering studies from the1970s showed a significant reduction in the incidence and severity of knee and ankle injuries when players switched to shoes that decreased rotational traction (RT) at the shoe-surface interface (Torg and Quedenfeld, 1971, Cameron and Davis, 1973).

Playing surfaces are broadly categorised into natural or artificial. However, there are many different varieties of each, based on new generations of artificial turf, engineered grasses and soils. Subtle variations in natural turf are also important as altering the grass variety, soil type, lateral root growth (thatch) and moisture may influence the resultant traction forces and hence injury risk (Stiles et al., 2009, Torg et al., 1996, Orchard et al., 2005) . It is therefore important to examine shoe-surface interactions and the associated traction and their relation to injury risk.

Our primary objective was to systematically review the nature and magnitude of traction forces occurring at the shoe-surface interface in the football codes, and investigate the relationship with lower limb injury. To further aid the practising clinician, our secondary objective was to document factors that may affect RT of different shoe-surface combinations.

4.3 Methods

Inclusion Criteria

Inclusion and exclusion criteria were determined by three authors (AT, CB and RW) prior to the database search and are documented in Table 7. Studies must have used a prospective design involving human subjects, of any age, participating in the football codes. Studies must have reported lower limb injury data (eg, yes/no, injury rates, prevalence figures) and shoe-surface RT derived from standardised mechanical measurements (Table 7). To keep the mechanical testing methods as close as possible to game relevant loading scenarios(Kent et al., 2012), included studies must have measured RT using a portable testing device (artificial foot fitted with commercially available soccer shoes) on the actual playing surface, at the start of a relevant playing season. There were no restrictions made on the magnitude of axial loading during testing. Studies using other means to assess shoe-surface interaction, such as the studded disc apparatus, were excluded due to the reliability issues previously established for such devices (Twomey et al., 2012, Webb et al., 2014). The same criteria were used for the secondary objective. However, these studies had only objective traction measurements at the shoe-surface interface and no injury data.

Table 7. Study selection criteria

Search strategy	Inclusion	Exclusion
Database: Ovid MEDLINE (R) <1946 to November week 1 2014>Search Strategy: 1. Soccer/ 2. Football/	Prospective and case-control studies evaluating shoe-surface interaction and injury	Cohorts with neurological, systemic or degenerative conditions
3. australian rules football.mp. 4. AFL.mp. 5. rugby union.mp. 6. rugby league.mp.	English language, human subjects, football code players with no age limit	Opinion articles or single case-studies and non-systematic reviews
7. (gaelic football or GAA).mp. 8. grass.mp. 9. turf.mp. 10. Climate/ 11. stud length.mp.	Must have data for lower limb injury and shoe-surface rotational traction measurements	Shoe-surface traction testing on non-portable devices with a sample of grass and not at the actual playing surface location
12. shoe property.mp. 13. Temperature/ 14. Shoes/or cleat.mp. 15. stud.mp. 16. outsole.mp. 17. playing surface.mp.	Must use portable traction testing device with an artificial foot on which the football footwear can be loaded	Traction measurements on device without players soccer shoe loaded. Such as the studded disc apparatus
18. Traction/ 19. Torque/ 20. Wounds and Injuries	Provide injury diagnosis protocol	Artificial turf
21. OR 1–7 22. OR 8–20 23. 20 and 21	Natural grass surfaces tested at the actual playing surface location	

Search strategy

A systematic search of MEDLINE, SPORTDiscus, CINAHL and Google Scholar databases was conducted from inception to November 2014 using a standardised search strategy previously agreed on by three authors (AT, CB and RW). The following Medline subject headings and key words were combined using Boolean logic (soccer, football, Australian rules football, AFL, rugby union, rugby league, gaelic football; grass, turf, climate, stud, shoe property, temperature, shoes, cleat, outsole, playing surface, traction, torque, wounds and injuries). In addition, reference lists of included papers were manually searched for additional papers. Titles and abstracts were screened for relevant studies by two authors independently (AT and CB). A third independent mediator (RW) resolved any disparities regarding study inclusion. Full text versions meeting inclusion criteria were retrieved for further review.

Methodological quality

A modified version of the Downs and Black quality index was used to evaluate the methodological quality of included studies with 8 of the 27 items deemed not applicable removed. This checklist has been validated for the assessment of randomised controlled trials and non-controlled studies (Downs and Black, 1998). Included studies were rated by two authors independently (AT and CB). A third independent mediator (RW) was engaged when consensus was not reached. While stringent inclusion criteria were applied to the secondary objective, no quality index was used due to lack of injury data. Secondary objective studies were included to display possible factors that may affect traction at the shoe-surface interface on natural grass playing surface as a guide only.

Data extraction and analysis

Two researchers (AT and CB) independently extracted study characteristics and outcome data. Data were extracted for RT (N.m) and injury rates. Separate injury data were extracted for high and low friction groups. In each study, participants were sub-grouped into either two or three subgroups according to their frictional scores obtained at the start of the playing season. ORs (±95% CIs) were used to compare injury incidence in each subgroup (high traction vs low traction) using RevMan software (V.5.2). Meta-analysis was undertaken after assessing studies for clinical homogeneity based on age, gender and sporting population. Statistical heterogeneity was assessed by visual inspection of the forest plot, in conjunction with the χ^2 test for heterogeneity and the I^2 statistic.

4.4 Results

Included studies

Details of the search results and study inclusion process are shown in Figure 9

The initial search yielded 343 studies, of which 320 were excluded based on the title/ abstract screening. Twenty-three full text studies were then read; 20 were excluded (not prospective or failed to report injury data) leaving 3 prospective studies eligible for inclusion.

Study characteristics

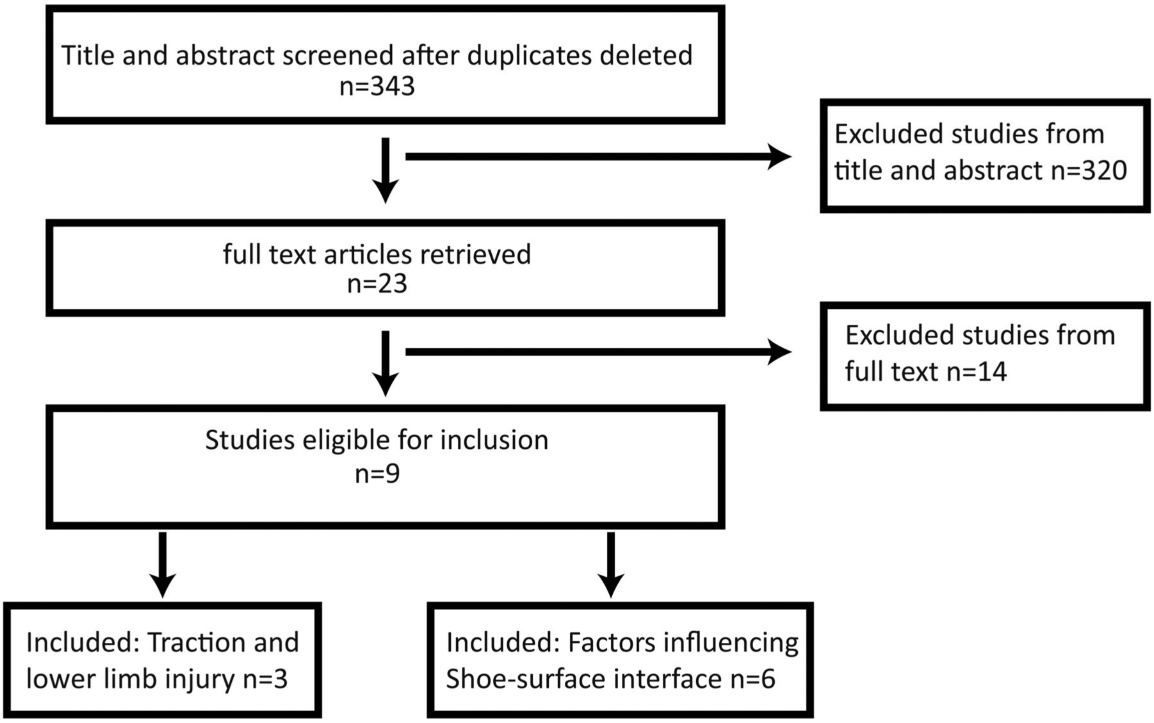


Figure 9. Flow chart of search results

Primary objective - RT at the shoe-surface interface and lower extremity injury

Three prospective studies investigated the relationship between shoe-surface interaction and non-contact lower limb injury in high school athletes playing American football, using a combined total of 4972 male athletes. Each of the three studies was conducted over a 3-year period. Details of participants, surface characteristics, RT data and injury data are collated in Table 8. In one case, data were extracted from two separate reports: injury data evaluating stud type and lower-limb injury was extracted from Torg and Quedenfeld (Torg and Quedenfeld, 1971) and combined with the RT data measurements, performed on the same shoes, in a follow-up study by Torg et al.(Torg, Quedenfeld et al., 1974)

In the study of Wannop et al (2013), games were played on both artificial and natural grass surfaces. The other studies were conducted on natural grass surfaces. The method used to record RT was generally consistent across studies. In two studies (Lambson et al., 1996, Wannop et al., 2013), forefoot contact was used during RT testing, whereas Torg et al. (1974) used a foot-flat position. The axial loading during testing was similar and ranged from 445 and 580N with rotation test speed standardised to 90° per second. In two of the studies(Lambson et al., 1996, Torg and Quedenfeld, 1971), there were no details on the grass species or soil type.

Table 8. Details of participants, surface characteristics, RT data and injury data

Study	Participants	Grass type and characteristics	Methods for RT testing	Injury effect size	Injury incidence notes
Lambson et al. (Prospective 3 years)	High school American football n=3119	NG—no description of species or soil-type Four games played on AG in 3 years excluded from data	Footwear with 4 different cleat designs rotated 90°/ second on a Vermont release torque wrench. Forefoot position with 446N load	Players using an edge cleat design (highest peak RT) had a 3.4 times higher ACL injury rate than all other cleat designs combined	38 injuries of 2231 players using edge design cleats (0.017%). 4 ACL injuries of 888 players using non-edge design cleats (0.005%) Edge cleat design highest peak RT 31 N.m, mean of 3 lowest shoes: 23.6 N.m
Wannop et al (Prospective 3 years)	High school American football n=555	NG—Kentucky Bluegrass. Soil —40% clay, 30% sand and 30% silt. AG—Duraspine by Fieldturf 3G	Players' own footwear rotated at 90°/second on a portable robotic machine. Forefoot position with 580N load	High RT associated with a 4.6 times higher rate of non-contact lower limb injuries	Steady increase from 4.2 injuries/1000 game exposures at low RT (15.0–30.9 N.m) to 19.2 injuries/1000 game exposures at high RT (39.0 N.m—54.9 N.m)
Torg and Quedenfeld (1971) (3 year Prospective) Torg et al (1974)	High school American football n=1298	NG—2 inch blade. No species info	Players' footwear rotated to 90° on a portable device with a torque wrench. Foot flat position with 445N load	A 2.4-fold reduction in the knee injury rate with a switch to lower RT shoes	Significant decrease in incidence and severity of knee and ankle injuries when players switched to shoes with lower RT. Switched from shoes with 7 cleats 19 mm in length (RT 74 N.m) to shoes with 14 cleats 9.5 mm in length (RT 38 N.m) Average number of knee injuries decreased from 0.33 inj/team/game down to 0.14 inj/team/game when using shoes with lower RT

AG, artificial grass; NG, natural grass; RT, rotational traction.

Table 9. Modified downs and black quality score for the included studies

	1. Clear aim/ hypothesis	2. Outcome measures	3. Patient characteristics described	5. Confounding variables described	6. Main findings	9. Lost to follow-up characteristic described	10. Actual probability values reported	11. Participants asked to participate representative of entire population	12. Participants prepared to participate representative of entire population	15. Blinding of outcome measures
Lambson et al	1	1	1	1	1	0	1	1	0	0
Torg and Quedenfeld	1	1	1	2	1	0	1	1	1	0
Wannop et al	1	1	1	2	1	1	1	1	0	1

Note that for items 1–3, 6–27: 0=no, 1=yes, U=unable to determine. For item 5: 0=no, 1=partially, 2=yes.

Table 9. Continued

	16. Analysis completed was planned	**17. Follow-up time adjusted for**	**18. Appropriate statistics**	**20. Valid and reliable outcome measures**	**21. Appropriate case control matching**	**22. Participants recruited over same time period**	**25. Adjustment made for confounding variables**	**26. Participants' loss to follow-up accounted for**	**Score (out of 19)**	**Percent**
Lambson et al	0	1	1	1	0	1	0	U	11	58
Torg and Quedenfeld	0	1	1	1	0	0	0	U	13	68
Wannop et al	1	1	1	1	1	1	0	1	17	89

Note that for items 1–3, 6–27: 0=no, 1=yes, U=unable to determine. For item 5: 0=no, 1=partially, 2=yes.

Methodological quality

Results from the Downs and Black quality index scale are shown in Table 9. Scores for the included studies ranged from 11 (58%) to 17 (89%) of a possible 19. Only the study of Wannop et al. (2013) used a double-blind design whereby the researchers responsible for recording injury were blinded to the traction measurements. There was also some risk of attrition bias as only one study (Wannop et al., 2013) provided adequate information on participants' retention over time and loss to follow-up. Although all studies acknowledged important confounding variables, such as previous injury, these were not adjusted for within the data analysis.

RT and Injury

In two studies, (Wannop et al., 2013, Lambson et al., 1996) injuries were verified by a medical practitioner. Although the injury verification methods used in Torg and Quedenfeld's (1971) study were not explicit, injuries were classified by clinical grade by an orthopaedic surgeon. Wannop et al. (2013) reported on any lower limb injury that required either medical attention or a missed game. The remaining two studies (Lambson et al., 1996, Torg and Quedenfeld, 1971) reported knee injuries, with Lambson et al. (1996) focusing on arthroscopically confirmed ACL ruptures. All studies reported injury rates, which was calculated as either the number of injuries/playing exposure (Wannop et al., 2013, Torg, Quedenfeld et al., 1974) or number of injuries/number of players (Lambson et al., 1996).

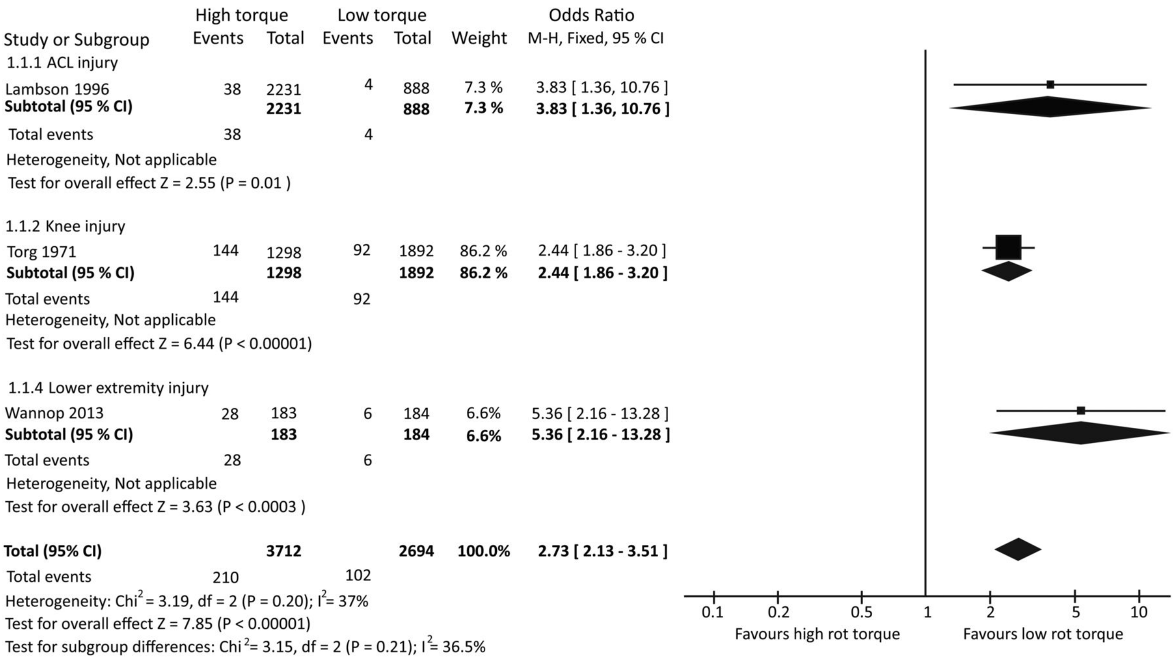
In all cases, separate injury rates were calculated for high and low traction groups. Wannop et al. (2013) divided participants into three equal groups, defined as low RT (15–30.9 N.m), medium RT (31–38.9 N.m) and high RT (39–54.9 N.m). A steady increase of lower extremity non-contact injury from 4.2 injuries/1000 game exposures at low RT (15.0–30.9 N.m) to 19.2 injuries/ 1000 game exposures at high RT (39.0 N.m—54.9 N.m) was found. High RT was associated with a 4.6 times higher rate of non-contact lower extremity injuries. To facilitate comparison with other studies, we extracted data from the low RT and high RT groups only.

Lambson et al. (1996) measured RT associated with four different types of cleat at the start of the season. Edge style cleats were defined as the higher RT group (mean 31.0±2.6 N.m), whereas the remaining three cleat types (flats, screw in, pivot disc) recorded similar tractions and were defined as the lower RT group based on mean rotational torques between 21.5 (±1.9) and 25.5 (±1.9). There were 38 ACL injuries of 2231 players using edge design cleats (0.017%) and just 4 ACL injuries of 888 players using non-edge design cleats (0.005%). Players using edge cleat design shoes (highest peak RT) had a 3.4 times higher ACL injury rate than all other cleat designs combined.

The Torg et al. (1971) study involved two cohorts wearing either conventional shoes with 7 studs (19 mm in length) or moulded soccer style shoes with 14 studs (9.5 mm in length). The average number of knee injuries decreased from 0.33 inj/team/game down to 0.14 inj/team/game when teams changed to using soccer style (14 stud 9.5 mm) shoes with lower RT. A 2.4-fold reduction in knee injury rate was noted with the switch to lower RT shoes. RT data measurements were performed on these shoes in a follow-up study by Torg et al., (1974) allowing classification of the conventional shoes as high RT (74 N.m) and moulded soccer shoe as low RT (38 N.m).

Figure 10 summarises the association between the magnitude of RT and injury. There is clear evidence that higher levels of RT are associated with higher injury rates. This was consistent for ACL injury (OR=3.83, 95% CI 1.36 to 10.76), (Lambson et al., 1996) knee injury (OR=2.44, 95% CI 1.86 to 3.20)(Torg and Quedenfeld, 1971) and lower extremity injury (OR=5.36, 95% CI 2.16 to 13.28) (Wannop et al., 2013). Pooled data from the three studies (OR=2.73, 95% CI 2.13 to 3.15; $\chi2$=3.19, df=2, p=0.21; I2=36.5%) suggest that the odds of injury are approximately 2.5 times higher when high RTs are present at the shoe-surface interface.

Figure 10. Forest plot of pooled results examining rotational torque and injury odds.



Our secondary objective was to document comparable traction data for different shoe types on different surfaces. These data show that rotational measurements are greatly influenced by the testing methodology including whether the foot was loaded through the forefoot position or a foot-flat position during testing for peak torque or RT. As such, we extracted additional data from n=6 laboratory-based studies to try to determine specific shoe-surface combinations that may affect the way in which the player's shoe interacts with the playing surface (Table 11).

Turf shoes with several very short studs or cleats consistently displayed lower RT at the shoe-surface interface than other stud configurations (Serensits and McNitt, 2014, Villwock et al., 2009). A linear relationship may exist for axial load and RT measures (Smeets et al., 2012). As the load increased, the RT measurements also increased (Wannop et al., 2012). This means testing at loads that do not cause excessive damage to the playing surface grass coverage may be adequate. Sand-based natural grass displayed higher RT measures than soil-based natural grass surfaces(Villwock et al., 2009).

Table 11. Rotational traction data for different shoe-surface combinations

Paper/grass and soil type	Outsole	Cleats (n)	Max stud length (mm)	Peak torque (N.m)	Vertical load	Testing methods	Shoe position on test	Outcomes
Serensits and McNitt	SG stud—screw-in	7		58.7	787, 1054, and 1321N	Pennfoot traction tester used to rotate the shoe 45°	Forefoot	Shoe outsole type had a large influence on RT under 3 normal loads. Shoe with seven screw-in studs had the highest RT (58.7 N.m) Shoe with multiple short studs produced the lowest peak torque (49 N.m)
Kentucky bluegrass (40% 105, 30% award, 30% midnight) sand-based rootzone (94% sand, 3% silt, 3% clay)	FG stud—mould	9		53.1				
	Turf shoe	‘Multiple’		52.7				
	Turf shoe	‘Multiple’		52.4				
	FG blade mould edge	12		52.1				
	FG stud—mould edge	12		51.1				
	FG stud—mould edge	12		49.1				
	Turf shoe	‘Multiple’		49				
Smeets et al	FG Stud Mould	12	16	33.76	200, 300, and 400N	Rotated to 30°	Flat	Linear relationship for RT and normal load. Blades showed significantly higher peak torque (external rotation) than studs on natural grass
75% Perennial 25% Kentucky bluegrass	FG Blade Mould	13	14	35.2				

Torg et al	SG stud – screw-in	7	19	74.2	445N	Shoe rotated to 90°	Flat	Shoe with seven longer (19 mm) cleats had a significantly higher rotational traction on NG and were deemed to be unsafe for use in high school American football
Natural grass no species or soil details	FG stud mould	15	9.5	38.4				
Villwock et al	FG stud – mould edge	14	16.3	115.6 (NG +sand)/87.6 (NG+soil)	1000N	Shoe rotated through 90°	Flat	Turf shoe with multiple short studs produced a significantly lower RT than all other shoes (59.6 N.m) on sand based NG. Shoes with longest studs (16.3 mm) had the highest RT (115.6 N.m) on sand based NG. Sand based NG surface higher RT than soil based NG. Mean 95.9 N.m for all shoes on sand based. Mean 83.1 N.m all shoes on soil based

Continued

Paper/grass and soil type	Outsole	Cleats (n)	Max stud length (mm)	Peak torque (N.m)	Vertical load	Testing methods	Shoe position on test	Outcomes
2 natural grass surfaces: Kentucky bluegrass+small % rye grass in soil; Kentucky blue grass+small % Rye grass in 90% sand 10% silt/clay	FG stud – mould edge	13	12.5	107.4/95				
	FG blade mould edge	12	12	100.4/98.6				
	FG blade mould edge	15	13	98.6/79.8				
	FG blade mould edge	15	11	74.2/77.8				
	AG stud mould	21	11	101.4/73.6				
	AG stud Mould	20	12	84.8/81.4				
	SG stud — screw-in	7	12.5	112.4/83				
	SG stud — screw-in	7	12.5	104.6/94.4				
	Turf shoe	88	6.5	59.6/60.0				

Wannop and Stefanyshyn	Mould stud — turf	'Multiple'	Data extraction not possible	Tests at increments from 335N-776 N	RT tested at speeds of 30–90°/s. Measured by force transducer @ 2000 Hz. Normal load, moisture content and speed of testing altered to investigate affect on traction	Forefoot	Stud shoe had a reduction in TT and an Increase in RT when water was added to NG surface. Normal load had a linear effect on traction. Movement speed had a linear effect on TT but was constant for RT
NG—Kentucky bluegrass, AG —Field Turf 3G	SG studs — screw-in Edge Mould blade— turf	'Multiple'					

Wannop	Mould stud-turf	'Multiple'	Data extraction not possible	580N	Tests conducted at 20 yard and 40 yard line at the end of the season	Forefoot	Traction values on NG change considerably over the course of one season. More uniform RT measures at start of season. Large differences in RT at end of season. Cleat-type affected RT over the season and at different pitch locations due to heavy wear. Reduction in traction as the season progresses as a result of wear and alterations in surface hardness
Kentucky Bluegrass 40% clay, 30% sand, 30% silt	SG stud — screw-in edge Mould blade-turf	7					

AG, artificial grass; FG, firm ground; NG, natural grass; RT, rotational traction; SG, soft ground.

4.5 Discussion

Data from three prospective studies on 4972 participants suggest that an important relationship exists between RT and lower limb injury. High RT at the shoe-surface interface was associated with a 2.5 times higher risk of injury to the lower extremities. These results extend findings from other sports such as Australian rules football (Orchard et al., 2005), handball (Olsen et al., 2003) and Finnish floorball (Pasanen et al., 2008a). These three studies did not measure RT, but showed higher friction surfaces to be associated with greater injury rates. This supports the hypothesis that high RT at the shoe-surface interface may increase the risk of lower extremity injury. We note that the highest quality study (Wannop et al., 2013) demonstrated the largest effect size on injury rate, and the magnitude of this effect size— a 5.4-fold difference—may alarm the practising clinicians.

By what mechanism may high shoe-surface traction relate to injury?

Drakos et al. (2010) used a cadaveric model to demonstrate that certain soccer shoe-surface combinations cause significantly more strain in the ACL when performing a cutting manoeuvre. Likewise, Dowling et al. (2010) determined that high friction conditions at the shoe-surface interface incur changes to movement strategies during a cutting task that may increase that risk of ACL injury, providing a biomechanically plausible rationale for the increased incidence of ACL injuries on high traction surfaces (Orchard et al., 2013).

Orchard et al. (2005) examined the field surface conditions as they related to injury and concluded that athletes were at greatest risk of the shoe becoming ‘trapped’ on the playing surface when RT is high. This group suggested that certain grass species that display more lateral root growth or ‘thatch’ are causative of the player’s foot becoming ‘trapped’ (Orchard et al., 2005) and preliminary evidence supports this. A 12-year audit of field sport injury data (soccer and Australian rules football), across two continents (Orchard and Powell, 2003) and involving 229 827 player-weeks of exposure, reported a higher incidence of ankle sprains and ACL injuries in warmer climate zones. Although the direct effect of ambient temperature on injury risk cannot be overlooked, it is also likely that heat influences the playing surface (hence injury risk) through a range of moderating factors such as grass species, soil type and ground hardness, which in turn alter the nature of the shoe surface interaction and subsequently injury risk (Torg et al., 1996).

The magnitude of RT is dependent on a range of factors including: grass variety, playing surface maintenance practices, soil type, soil moisture, player movement strategies, as well as footwear. Within these, footwear is the factor most under the athlete's control and amenable to modification (Wannop et al., 2013). However, objective information on the playing surface characteristics and climatic conditions should be made available to players and medical staff to allow adequate footwear selection. This systematic review suggests that the odds of sustaining a lower extremity injury are approximately 2.5 times higher for certain shoe and surface combinations that cause high RT.

Footwear variables which affect shoe-surface interaction

Shoe outsole stud design, length and orientation vary widely. Outsoles with longer and fewer studs, or edge style cleats, increase peak RT, rotational stiffness (rate of torque development) and plantar foot pressures (Lambson et al., 1996, Torg et al., 1974, Villwock et al., 2009, Queen, et al., 2008, Ford, 2013).

Different loading characteristics have been observed when soft ground outsole configurations (fewer, long, detachable or screw-in studs) have been compared to outsole designs with smaller or no studs (Stefanyshyn et al., 2010). Shoes that increase RT for a given surface have also been shown to increase ankle and knee joint external rotation moments when players performed a 180° turn (Stefanyshyn et al., 2010). Moreover, greater loading rates and ground reaction forces have been reported in soft ground shoes compared to turf-style shoes (multiple short rubber studs) (Smith et al., 2004).

Much debate remains over the effect blade-style cleats have on RT and plantar loading. Medical staff and football managers have expressed fears over blade style cleats with risk of lacerations and a higher incidence of fifth metatarsal stress fractures being among the chief concerns (Bentley et al., 2011, Hall and Riou, 2004, Murray et al., 2011). However, the findings are conflicting and unclear when comparing RT in blades versus other cleat designs as definitive experiments including injury data are yet to be conducted (Kaila, 2007, Serensits and McNitt, 2014, Villwock et al., 2009, Smeets et al., 2012). We suggest that prospective studies investigating both the shoe as well as the surface are required to shed light on these questions, especially in soccer in which no prospective studies were identified that measured footwear traction and lower extremity injury.

Playing surface variables which affect shoe-surface interaction

While excessive RT is problematic, the multidirectional and dynamic nature of field sport necessitates some level of friction. It is suggested that for a given sport, an optimal zone of traction may exist that minimises the lower limb injury risk but allows for optimal performance (Smeets et al., 2012, Luo and Stefanyshyn, 2011, Nigg and Segesser, 1988). Indeed, it is proposed that higher levels of translational traction (ie, resistance forward/ back, side/side) are associated with reduced injury frequency (Wannop et al., 2013) and higher performance (Ekstrand and Nigg, 1989).

Although many shoe manufacturers produce a range of different outsoles, the ideal outsole configuration (number, length and geometry of cleats) may differ depending on the playing surface properties and the movement strategies used by the athlete (Müller et al., 2010). Unfortunately, playing surfaces are not always uniform either: within the playing area itself, or during the season. Peak torque on bare areas of the playing surface can be below 4 N.m (with a rotational stiffness of <1 N.m/°) while the grassed areas of the same pitch may have a peak torque as high as 75 N.m (with a rotational stiffness of 7 N.m/°) (Ford, 2013).

Ground staff often use different grass species at specific times of the season to ensure 100% grass coverage on the playing surfaces. The playing surfaces used for professional football in Doha Qatar, for example, use a warm-season grass (Cynodon dactylon, 'Bermuda' or Paspalum vaginatum 'Paspalum') over the summer months as this species can cope with the hot summers. In autumn, the playing surface is over-sown with a cool-season grass (Lolium perenne 'Perennial Rye') in preparation for winter. Research documenting grass types at matches played in the Australian football league between 1992 and 2004 found rye grass to be associated with fewer ACL injuries than bermuda grass (Orchard et al., 2005). The lateral root growth or 'thatch' seen with bermuda grass is thought to increase the 'trapping' of the football shoe studs on the playing surface, which in turn increases the magnitude of force required to rotate the shoe through the grass.

Villwock et al. (2009) found that a sand-based natural grass playing surface displayed higher RT and rotational stiffness measurements than a soil-based natural grass surface across a number of football shoe outsole configurations. Likewise, playing surface moisture can have a large effect on footwear traction that is shoe specific and surface specific (Wannop and Stefanyshyn, 2012, Heidt et al., 1996).

In the practical setting of football, clinicians and researchers should communicate with ground staff in charge of preparations of playing surfaces to understand the various properties that may influence player footwear selection. For example, in the Qatar stars league (soccer) in Doha, planning is a place to provide soil temperature, moisture, ground hardness and grass species and RT data to medical staff before and after each game. These data may allow the player to make a more objective and informed decision regarding footwear selection for the playing surface and conditions on that day.

Clinical implications

Individual players generally choose their footwear on a given day for a given playing surface. In soccer, players are reported to select footwear based on: comfort, traction and stability while protection from injury is given low priority (Hennig, 2014). Players should have multiple shoes with varied outsole configurations available to allow optimisation of traction at the shoe-surface interface. For example, a high traction shoe (fewer, long studs located on the edge of a shoe) which may be appropriate on a low traction, wet, rye grass surface would be inappropriate on a high traction, dry, bermuda grass surface. Objective measurements detailing how specific combinations of shoes and surfaces, and climatic conditions may influence traction forces at the shoe-surface interface, may decrease the chance of lower extremity non-contact injury in football players.

Kinchington et al. (2011) used a lower-limb comfort index to guide a tailored footwear programme consisting of player education, prescription of footwear, monitoring of footwear and footwear modification. This randomised intervention reduced lower-limb injury by approximately 20% in an investigation into two elite Australian rugby league teams. Turf shoes were used for the majority of training hours which generally have lower RT regardless of the playing surface (Serensits and McNitt, 2014, Villwock et al., 2009). Moreover, greater ground reaction force and impact loading rates occur when running in traditional six-stud football shoes compared to turf shoes with multiple short rubber studs (Smith et al., 2004). We suggest that turf shoes (multiple short rubber studs) be used for training that involves increased running distance with fewer skill-based elements.

Limitations and future research.

This systematic review was only able to pool data for high school males playing American Football, and these findings may not be applicable to other populations (adults, females) or sports.

The pooled analysis includes data from studies which only included anterior cruciate injury only (Lambson et al., 1996), knee and ankle injury (Torg and Quedenfeld, 1971), all non-contact lower limb injury(Wannop et al., 2013). In each, the magnitude of the risk elevation was a similar order of magnitude;

however, future research should work to identify individual risk factors for each area of interest.

This review only examined data regarding rotational torque. One study (Wannop et al., 2013) presented both rotational and translational (linear) traction data with respect to injury rates. The interaction between rotational and translational traction remains un-investigated and could be a significant confounder in terms of injury risk.

It is suggested that further development of portable, subject specific testing devices that can quantify the rate of torque development (rotational stiffness) at the shoe-surface interface may provide a more sensitive mechanical measurement in terms of the timing injuries occurring in game-relevant loading scenarios (Grund and Senner, 2010).

Mechanical traction measurements may not provide an accurate representation of forces experienced by players in vivo (Kent et al., 2012). Intuitively, research that attempts to quantify shoe-surface interaction with the actual player wearing the soccer shoes would allow for greater external validity (Dowling et al., 2010, Kirk, Noble et al., 2007). It is thought that players adjust their leg stiffness and movement strategies according to the surface they encounter, which is not simulated by mechanical testing devices (Hennig, 2014, Kent et al., 2012, Girard et al., 2011, Sterzing et al., 2009).

Summary and Conclusion

Our systematic review indicates that high RT influences lower limb injury risk in American football 2.5 times, and this warrants attention from clinicians and others interested in injury prevention (Engebretsen, Bahr et al., 2014). Data are presented regarding shoe-surface combinations and their respective mechanical properties that can be used by clinicians; however, these data are incomplete and warrant further systematic investigation, especially in other football codes (Ekstrand et al., 2013).

Chapter 5: Six different football shoes, one elite playing surface and the weather; Assessing variation in shoe-surface traction over one season of elite football.

5.1 Abstract

Aim/Hypothesis: An optimal range of shoe-surface traction (grip) may exist to improve performance and minimise injury risk. Little information exists regarding the magnitude of traction forces at shoe-surface interface across a full season of elite soccer football using common football shoes.

Objective: To assess variation in shoe-surface traction of six different football shoes models throughout a full playing season in Qatar encompassing climatic and grass species variations.

Methods: Football shoes were loaded onto a portable shoe-surface traction testing machine at five individual testing time points, to collect traction data (rotational and translational) on a soccer playing surface across one season. Surface mechanical properties (surface hardness, soil moisture) and climate data (temperature and humidity) were collected at each testing time point.

Results: Peak rotational traction was significantly different across shoe models ($F = 218$, $df = 5$, $p < 0.0001$), shoe outsole groups ($F = 316.2$, $df = 2$, $p < 0.0001$), and grass species ($F = 202.8$, $df = 4$, $p < 0.0001$). No main effect for shoe model was found for translational traction.

Conclusions: The rotational (but not translational) traction varied substantially across different shoe types, outsole groups, and grass species. Highest rotational traction values were seen with soft ground outsole (screw-in metal studs) shoes tested on warm season grass. This objective data allows more informed footwear choices for football played in warm/hot climates on sand-based elite football playing surfaces. Further research is required to confirm if these findings extend across other football shoe brands.

5.2 Introduction

Association football (soccer) is an invasion game involving multiple bouts of intermittent sprinting and directional changes. Elite footballers undertake 1500–3100 metres of high intensity running per match (Bradley et al., 2010, Bradley et al., 2009), with accelerations contributing 7–10% of the total player load, and decelerations contributing 5–7% (Dalen et al., 2016). A recent systematic review examining activity demands of team sports found that the highest volume of cutting movements occur in football, with players performing up to 800 cuts per game (Taylor et al., 2017).

A player's ability to accelerate, decelerate, and change direction is largely influenced by the available traction between the football shoe and playing surface (Sterzing et al., 2009, Pedroza et al., 2010). Two important components of traction exist: translational traction which is the horizontal force required to over- come the resistance between the shoe outsole (studs) and playing surface; and rotational traction which is the rotational force required to release the studs through the playing surface in a rotational manner. Although increases in translational traction (straight line or side-to-side) are linked to improved performance (e.g., time to complete an agility course or acceleration task)) (Sterzing et al., 2009, Pedroza et al., 2010), higher levels of rotational traction are linked to greater risk of lower limb injury (Wannop and Stefanyshyn, 2016, Lambson et al., 1996, Olsen et al., 2003, Wannop et al., 2013, Orchard et al., 2013).

Optimal shoe-surface conditions should therefore attenuate rotational resistance whilst maintaining translational traction or playing performance (no slipping for players) (Wannop and Stefanyshyn, 2016, Wannop et al., 2013). This is sometimes difficult to achieve as traction varies according to shoe outsole, stud/ cleat configuration (Müller et al., 2010), and the characteristics of the playing surface (Stiles et al., 2011, Villwock et al., 2009), among other factors (Sterzing et al., 2009). Further challenges arise based on the wide array of outsole designs currently on the market and intermittent changes in playing surface throughout a playing season (Orchard et al., 2013, James, 2011).

Mechanical properties of natural grass playing surfaces are moderated by climatic factors such as. temperature and soil moisture. Surface hardness and subsequent penetration of the studs on the surface (Clarke and Carré, 2010, Orchard, 2001) ultimately alters traction (Orchard et al., 2013, James, 2011, Caple et al., 2012, Rennie et al., 2016, Thomson et al., 2015). Varied shoe-surface interface conditions change a players muscle recruitment patterns (Hales and Johnson, 2019) , movement strategies (Dowling et al., 2010), and injury risk (Orchard et al., 2013, Straw et al., 2018).

Importantly, varied climatic conditions means certain geographical regions support certain species of grass. Moreover, different grass species have different mechanical properties (Orchard et al., 2013, James, 2011). For example, drought resistant warm season grass species are associated with increased risk of anterior cruciate ligament injury compared to other cool season grass species in Australian rules football (Orchard et al., 2005). This is attributed to higher shoe-surface traction with warm season grass species.

Portable testing devices can now be used to objectively measure mechanical properties of playing surfaces and quantify their interaction with shoe outsoles. These data could help to streamline decision making concerning the suitability of football shoe outsoles, allowing players to tailor their selection for given climatic or surface conditions. Our primary aim is to assess variation in shoe surface traction of different football shoes on one football playing surface throughout a season in Qatar. As a secondary objective, any moderating effects of temperature, humidity, soil moisture, and surface hardness are examined.

5.3 Methods

Testing protocol

Playing surface

One natural grass football pitch (Qatar national team outdoor training pitch) with a sand rootzone and no hybrid reinforcement was tested at five time points over a single football season in Doha, Qatar (November 2017, January, March, April and May 2018).

The climatic conditions in Qatar mean that grass type consistently changes during a playing season: ranging from natural warm-season C_4 grass (*Paspalum vaginatum* 'Paspalum') in summer months; to warm-season grass over-seeded with cool-season C_3 grass (*Lolium perenne* 'Perennial Rye') in transition cooler months; to predominantly cool season (Perennial Rye) grass in the coldest month (January 2018). Warm season grasses are more heat and drought tolerant but become dormant at lower temperatures, thus the need to over-sow with cool-season grass (James, 2011).

Ground staff maintained 100% grass coverage with grass length at 25mm on the day of each test. Surface hardness was assessed using a 2.25kg Clegg hammer dropped from 450mm (SD instrumentation, England). Soil moisture (Delta-t ML2X/ML3 thetaprobe, England) and temperature/humidity (Kestrel 4400 heat stress tracker, USA) were also recorded. These surface tests were carried out in five different pitch locations and repeated five times in each location (moving to untested/unaffected grass for each test).

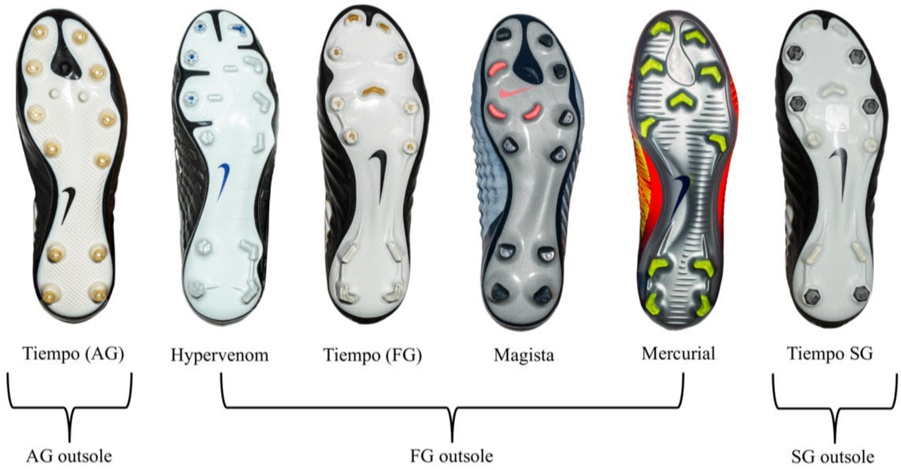


Figure 11. Shoe models and outsole type. AG = Artificial grass. FG = Firm ground. SG = Soft Ground.

Football shoe models

Six different football shoes manufactured by Nike (Beverton, Oregon USA) were tested. These consisted of one artificial grass (AG) outsole (Nike Tiempo legend VII Pro AG), four firm ground (FG) outsoles (Mercurial vapor XI FG, Magista obra II Elite FG, Tiempo legend VII FG and Hypervenom Phantom III FG), and one soft ground (SG) outsole (Tiempo legend VII Pro SG). According to a worldwide professional football boot database (Footballbootsdb.com), our sample boots consisted four of the six most used football shoes in the world.

Outsole types

Shoes were grouped according to their outsole type for further analysis. Shoes are marketed and sold in these “silos” with players expected to select an outsole type that best suits the surface and climate conditions they will play on. Soft ground (SG) shoes have fewer, longer, conical or tapered metal “screw-in” studs for wet, muddy, or low surface traction conditions. Firm ground (FG) shoes have moulded cleats, blades, or round studs (not screw-in) that are generally used on firm, dry surfaces. Artificial grass (AG) shoes have several small, short, round moulded studs that are generally used on artificial turf. (Figure 11)

Shoe-surface traction testing

Traction between the shoe and surface was measured using a commercially available portable traction testing device (S2T2, Exeter Research USA). The device consists of a prosthetic foot-form (size 10.5 US), on which shoes are fitted and positioned at 20° of plantar flexion to ensure only the forefoot studs are in contact with the surface (Serensits and McNitt, 2014, Wannop and Stefanyshyn, 2012). The foot can be rotated to measure peak rotational traction or locked into a linear position along the long axis of the shoe and then dragged forward across the surface to measure translational traction (Wannop and Stefanyshyn, 2012, Wannop et al., 2013). The floating foot-mass ensures the vertical normal load (added barbell weight plates) is applied through the shoe to the playing surface and not the supporting frame. Wheels allow for movement across multiple testing locations on the playing surface. (See supplementary figure 14)

Measurements were taken manually by a single operator (AT) for all pilot validation tests and within study tests. Each shoe model was tested at twelve separate locations on the playing surface during the five individual time points (November 2017, January, March, April and May 2018) for rotational traction and six separate locations for translational traction. See supplementary figure 15

For rotational traction a vertical load of of 580N (59.1kg) was applied and the test foot rotated through 90° at a speed of approximately 90°/s. Two operators who had a combined mass of 163kg stood on each end of the frame to stabilise during test. Peak rotational traction was recorded in newton meters (N.m) for both internal rotation and external rotation directions by a digital torque wrench sampling at 500Hz (ETW-PR-100, Checkline, NY, USA) with an accuracy of ± 1% of indicated measurement in a range of 10-100N.m.

Rotational traction and vertical load displayed a linear relationship during our pilot work with the S2T2 tester on this natural grass playing surface as previously reported (Wannop and Stefanyshyn, 2012). Thus, 580N was deemed to cause an acceptable amount of damage for grounds-staff to manage on a high use football surface and is a vertical load used for previous studies in American football (Wannop and Stefanyshyn, 2012, Wannop et al., 2013).

For translational traction a normal load (vertical) of 300N was applied to the test foot while a digital force gauge (Chatillon DFE2-500, Ametek, USA) sampling at 7000Hz with an accuracy of ±0.25% of indicated measurement, measured peak horizontal force (Newtons) resisting linear motion between the shoe and surface. The translational traction coefficient was calculated as a ratio of peak horizontal force divided by vertical force. This gives an indication of the horizontal force required to overcome the resistance between the shoe and surface as the shoe is dragged across the surface in a linear movement. During pilot work several speeds and vertical loads were used for translation traction testing with ground-staff present to assess damage to the playing surface. 300N of normal load and approximately 200mm/s allowed surface damage acceptable to ground staff.

Reliability and validity of shoe-surface traction tester

A test-retest protocol comprising 528 measurements of a single elite football pitch was conducted for internal rotation, external rotation, and translational traction, prior to commencing data collection for the current study. Intra-class correlation coefficients with 95% confidence intervals, standard error of measurement (SEM) and minimal detectable change (MDC) are presented in Table 12.

Table 12 - Intra-class correlation coefficients (ICC) with 95% confidence intervals, standard error of measurement (SEM) and minimal detectable change (MDC) for internal rotation, external rotational traction (in Newton meters) and translational traction (in Newtons). ICC values were classified as follows; ≥0.9 as excellent, ≥0.8 as good, ≥0.7 as acceptable, ≥0.6 as questionable, ≥0.5 as poor and <0.5 as unacceptable [27].

	ICC(95%CI)	**SEM**	**MDC (%)**
Internal Rot	0.94 (0.91-0.96) Excellent	1.8	5(12%)
External Rot	0.94 (0.91-0.96) Excellent	1.8	5 (12%)
Translation	0.76 (0.67-0.86) Acceptable	35	98 (17%)

Statistical analysis

The dependent variable was rotational traction. A 2-way analysis of variance was conducted using two factors: month/surface (5 levels) and shoe model (6 levels). Bonferroni post hoc tests were performed when indicated. This analysis was repeated to further examine the effect of month / surface (5 levels) and outsole pattern (3 levels). We also undertook a series of ANCOVAs. This was to compare main and interaction effects after controlling each of the following covariates which were dichotomised using median of temperature, humidity and ground hardness. All statistical tests were undertaken using SPSS (Version 25, IBM, Chicago, Illinois) with significance set at $P < .05$ in all analyses.

5.4 Results

Rotational traction

Table 13 summarises the mean rotational traction in newton meters (N.m) for individual shoe models at each testing time point with grass type in **bold**. Peak rotational traction was significantly different across shoe models ($F = 218$, $df = 5$, $p < 0.0001$). Consistently lower rotational traction was recorded with the Tiempo AG shoe across all months. Post hoc testing found significant differences between the Tiempo SG and all other models, with the largest difference occurring between the Tiempo SG (metal screw-in studs) and Tiempo AG (small round moulded studs) shoes (MD 17.5 N.m, $t=13.3$, $p<0.0001$). Consistently higher rotational traction was recorded for the Tiempo SG shoe across all months.

Peak rotational traction was also significantly affected by grass type ($F = 202.8$, $df=4$, $p < 0.0001$). Colder season grass (January) was associated with the lowest rotational traction. Conversely, highest values were reported when testing on warm season grass (during either November or May testing). The largest mean differences occurred when comparing May warm season grass (WS) vs. January Cool season grass (CS) (MD 13.2 N.m, $t=10.9$, $p<0.001$). (Table 13 and Supplementary Figure 12).

Large differences in rotational data were also reported when comparing January CS with November WS (MD 11.7 N.m, $t=9.7$, $p<0.001$). We also found a significant interaction between the two factors (month*shoe type) ($F = 5.4$, $DF = 20$, $p < 0.0001$).

Table 13. Mean rotational traction in newton meters (N.m) for individual shoe models at each testing time point with grass type in bold. WS = warm season grass. CS = Cool season grass. WS/CS = warm season grass over-sown with cool season grass. Outsole type groups AG = artificial grass, FG = firm ground and SG = Soft ground. Conditional formatting shows the minimum (green) and maximum (red) rotational traction shoe-surface combinations with the highest (dark red) being Tiempo SG shoe tested in May on warm season grass. Winter is December-February in Qatar hence the cool season grass and Tiempo AG shoe combination in January showed the lowest mean rotational traction (dark green).

		Month/Grass type						
Shoe	**Outsole**	Nov **WS**	Jan **CS**	March **CS/ WS**	April **WS**	May **WS**	Mean across grass	SD
Tiempo	AG	36.1	28.1[c]	34.8	37.2	42.3	35.7 [a]	5.1
Hyperveno m	FG	45.6	32.3	40.8	39.3	46.3	40.9 [a]	5.7
Tiempo	FG	50.4	34	44	43.6	45.7	43.8 [a]	6.0
Magista	FG	49.8	38.5	43	47.2	49.7	45.7 [a]	4.9
Mercurial	FG	49.6	40.4	40.8	48.3	54	46.2 [a]	5.8
Tiempo	SG	56.6	44.6	53.5	52.2	59.1[c]	52.2	6.2
	Mean across shoes	48.0	36.3[b]	42.8 [b]	44.6	49.5		
	SD	6.8	6.0	6.1	5.7	6.1		

Findings were similar when analyses were repeated using outsole classification (rather than shoe model). Again, we found significant main effects for outsole (F=316.2, df=2, p<.0001), grass type (F=87.1, df=4, p<.0001) and significant interaction effects (outsole*grass type) (F=2.7, df=8, p<.007). The largest mean difference for rotational traction was reported in November (warm season grass) between the SG and AG outsoles – 20.6N.m (*17.3-23.8* 95%CI) with very large effect size (ES = 5.4). See Table 14 and Figure 12.

*Table 14. Mean difference (95% CI) for rotational traction (N.m) and effect size (95%CI) for different shoe outsole types at each testing time point and grass type (bold). WS = warm season grass. CS = Cool season grass. WS/CS = warm season grass over-sown with cool season grass. Note the consistently large mean differences with very large effect size between the SG and AG outsoles across the entire season. * denotes very large effect sizes > 5.*

	Month/Grass type					
Outsole type	November **WS**	January **CS**	March **WS/ CS**	April **WS**	May **WS**	
FG vs AG	12.8 (10.5-15.0)	8.2 (5.3-10.9)	7.3 (4.9-9.1)	7.5 (4.7-10.2)	6.7 (4.3-9.1)	Mean Difference (95% CI)
	3.7 (2.8-4.6)	*1.9 (1.1-2.5)*	*1.9 (1.2-2.6)*	*1.8 (1.1-2.5)*	*1.8 (1.1-2.5)*	*Effect Size (95% CI)*
SG vs FG	7.8 (5.5-10.1)	8.4 (5.5-11.2)	11.3 (8.6-14.1)	7.6 (4.9-10.3)	10.2 (7.8-12.5)	
	2.2 (1.4-2.8)	*1.9 (1.2-2.6)*	*2.7 (1.9-3.5)*	*1.8 (1.1-2.5)*	*2.8 (1.9-3.6)*	
SG vs AG	20.6 (17.3-23.8)	16.5 (14.2-18.8)	18.6 (16.1-21.2)	15.1 (13.2-16.9)	16.8 (14.2-19.5)	
	*5.4 (3.5-6.8)**	*6.2 (4.1-7.8)**	*6.1 (4.1-7.8)**	*7.0 (4.7-8.9)**	*5.4 (3.6-7.0)**	

*Figure 12. Rotational traction (N.m) for outsole type at each testing time point. WS = warm season grass. CS = Cool season grass. WS/CS = warm season grass over-sown with cool season grass. The box represents 50% of the dataset, ends of the box show the 1st and 3rd quartiles, whiskers extend to the furthest data point within 1.5*IQR from the 1st and 3rd quartiles. 'X'within box = mean. Horizontal line within box = median. Whiskers of AG (blue) outsole never cross that of the SG (grey) outsole type for the entire season. Note the relative drop in rotational traction for all outsole groups in January with the cool season grass playing surface. AG = Artificial grass, FG = Firm Ground, SG = Soft ground outsole.*

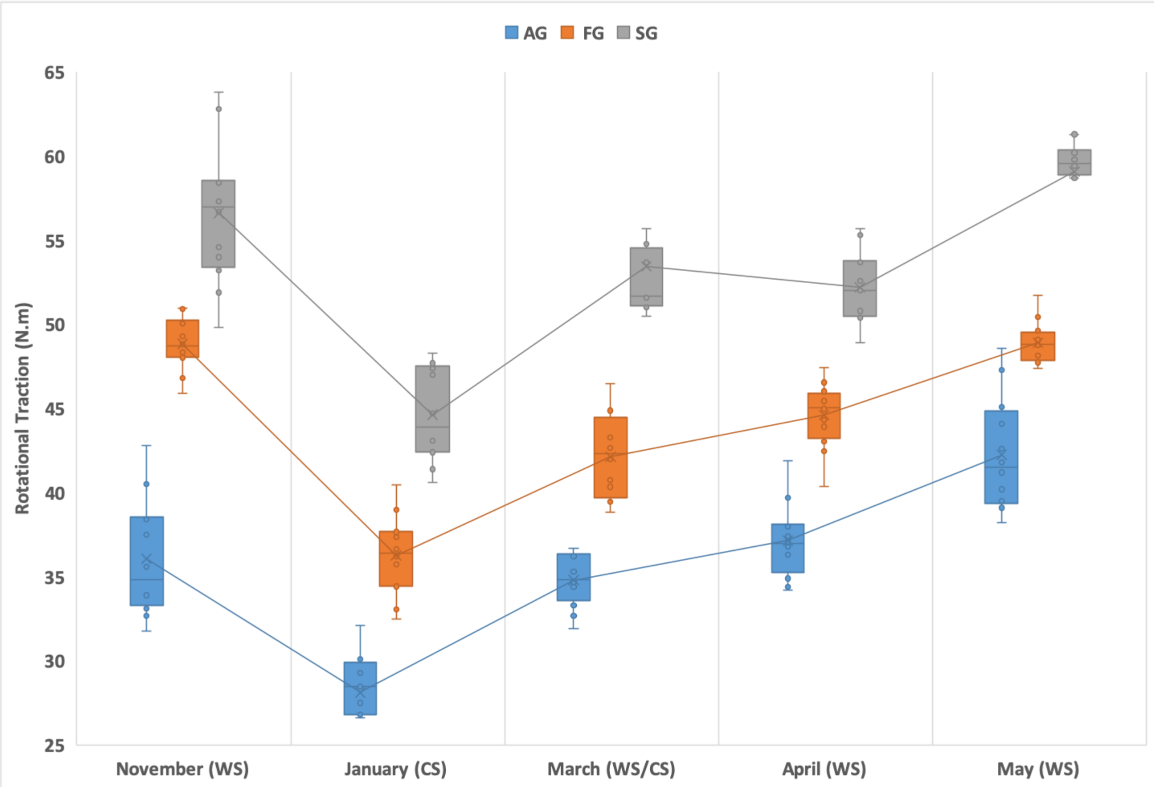


Table 15 shows the average values for climate and surface tests. Exploratory analyses (ANCOVA) found trends that lower humidity (B= -2.4, t=-1.9, p=.06) and greater ground hardness (B= 2.5, t=1.9, p=.052) were associated with higher rotational traction. Higher temperatures were also associated with higher levels of rotational traction (B= 3.18, t=2.5, p=.012). There was still a significant effect of shoe type and shoe*grass interaction, on levels of rotational traction after controlling for each of these covariates. Temperature was not included as a covariate when assessing the main effects of grass type due to the high level of correlation between these two variables. (r=.88, p<.0001).

Table 15. Average values for climate and surface tests conducted at five pitch locations and repeated five times at each location (move to unaffected grass for each test).

	Month/Grass type						
	November WS	January CS	March WS/CS	April WS	May WS	Mean	SD
Temperature (°C)	29	22	27	32	35	29	5
Humidity (%)	59	35	60	34	28	43	15
Soil Moisture (%)	25	24	21	19	21	22	2
Surface Hardness (g)	72	64	78	71	80	73	6

Translation traction

No main effect by shoe model for translational traction (F = 2.392 p = 0.07). However, there was a main effect for grass type (F = 3.861 p= 0.01) with the largest difference being warm season grass and Tiempo SG combination (Translational traction coefficient mean μ = 2.5±0.2) vs the rye grass and Tiempo AG combination (translational traction coefficient mean μ = 1.9 ±0.1). The translational traction coefficient was calculated as a ratio of peak horizontal force divided by vertical force (normal load).

5.5 Discussion

Large variations in the magnitude of shoe-surface traction are evident throughout one season of elite football played in a warm/hot climate. Shoe type, outsole group and grass species significantly affected rotational traction which has been linked to increased lower extremity injury (Mack et al., 2018, Olsen et al., 2003, Wannop et al., 2013). Implications for footwear selection will interest players, medical and sports science staff working in football played in warm climate zones. Particularly when it is vital to minimise rotational traction for given playing surface and climate conditions (eg return to on-field rehabilitation in football shoes after ACL injury).

The major strengths of this study include data collection of different shoe outsole designs, grass species, surface mechanical properties, and climate data at multiple time points on a playing surface maintained for elite soccer football (not a turf farm or laboratory setting).

Why is shoe-surface traction important?

While performance may be augmented with higher available traction at the shoe-surface interface, some concerning alterations to player movement can occur. Lower knee flexion angle, higher external knee valgus moments, increased knee joint loading and increased distance from the plant foot to the centre of mass during cutting manoeuvres are some of the changes under higher traction conditions at the shoe-surface interface (Wannop and Stefanyshyn, 2016, Orchard et al., 2013, Dowling et al., 2010).

These movement strategies, along with increased loading, have been implicated in anterior cruciate ligament (ACL) injury and other lower extremity injuries. This is corroborated with evidence from prospective studies showing a significant increase in lower limb injury risk associated with high levels of rotational traction (Lambson, Barnhill et al., 1996, Olsen, Myklebust et al., 2003, Wannop, Luo et al., 2013, Orchard, Walden et al., 2013). Importantly, higher rotational traction, as opposed to translational traction, has been found to be a significant predictor of peak ACL force during a maximal change of direction task (Sinclair and Stainton, 2017).

What can players do to modulate Rotational traction?

Parameters that are somewhat set once the player arrives to train or play a match include the climate, surface hardness, surface traction, and grass type etc. Pitch preparation and climate are also out of the athlete's control. Shoe outsole selection is one of the few immediately modifiable factors that can allow a player to modulate the traction experienced at the shoe-surface interface (Sterzing, Müller et al., 2009). Objective data on the surface should be made available to the athlete and medical or sports science teams so that footwear selection can be made with these parameters in mind.

Significant differences for rotational traction were found at the shoe-surface interface for different grass species (Table 13), shoe types (Table 13, Supplementary Figure 13), shoe outsoles (Figure 12). Overall, choosing a shoe with lower rotational traction that results in no consequent detriment to performance (high translational traction) is recommended, assuming the injury risk from other sports extends to soccer football (Wannop and Stefanyshyn, 2016, Lambson et al., 1996, Olsen et al., 2003, Wannop et al., 2013, Mack et al., 2018). Table 13, Supplementary Figure 13 and Figure 12 can be used to help inform footwear selection for players in warm climate zones.

Stud/cleat shape and surface conditions

Players deem optimal performance and/or risk of lower extremity injury to be intrinsically related to certain playing surface characteristics. Ninety-one percent of players from a worldwide cohort of elite footballers (n= 1129) think the type or condition of a playing surface increases the likelihood of injury with excessive hardness and traction ranked high on the list of concerns (Mears et al., 2018).

Optimum penetration of the stud/cleat into the surface is paramount in achieving the maximum traction (Clarke and Carré, 2010) (which is beneficial to performance) as all studs 'sink' into the surface to the outsole plate. Surface hardness therefore affects traction and comfort for the player depending on the type of shoe outsoles used. Ground staff kept the soil moisture and surface hardness within a small range of variation across each individual testing point in this study (Table 15). The SG outsole had the highest values for both rotational and translational traction over the season. Conical, tapered metal screw-in studs 11mm in length at the forefoot of the SG outsole allow for full penetration in the playing surface significantly increasing traction. This is evident in May with high surface hardness, high temperature, warm season grass and the SG outsole combined to give the highest mean peak rotational traction for the season (59N.m). Some of the FG shoes with bladed cleats had a larger cross-sectional area than the tapered conical studs of the SG shoe (Figure 11) and may not have penetrated completely to the outsole plate of the shoe and therefore demonstrated lower rotational traction values. However, the penetration depth of studs was not measured in this study.

Effect of grass type on rotational traction.

Warm season (Paspalum) grass showed higher rotational and translational traction particularly when coupled with the SG outsole. Cool season (Rye) grass showed lower rotational traction across all shoes highlighted by the relative "dip" in rotational traction values for all outsole types in January (Figure 12) compared to other months where there is either warm season grass or warm season grass over-sown with cool season grass. Our findings add a mechanically plausible explanation to those of Orchard *et al*., (2005) in which male Australian rules football players suffered less ACL injuries on cool season Rye grass than warm season (Bermuda) grass.

Considerations for return to field specific rehabilitation following injury.

Rotational traction for the AG outsole was consistently lower regardless of grass type, climate, and mechanical properties (e.g. hardness) of the pitch (Figure 12). We suggest this should be the outsole of choice for those players returning to on-field sports specific rehabilitation following ACL, syndesmosis or other lower extremity injuries where it is vital to minimise rotational traction forces.

Conversely, SG metal screw-in studs consistently showed high rotational traction and should ideally be avoided during early stage field specific rehabilitation.

Lambson *et al*. (1996) investigated the effect of cleat design on ACL injury risk in American football. Large cleats located along the edge of the forefoot in American football shoes were shown to have higher rotational traction (average 31N.m). Subsequently, 3.4 times more ACL injuries occurred with this cleat design than other stud or cleat designs that had lower rotational traction values (average 24N.m).

Comparisons are difficult as we tested with higher vertical load, on surfaces with different characteristics, and used a commercially available traction testing machine. Wannop *et al.,* (2013) used the same normal load as our study (580N or 60kg) on a more sophisticated traction testing machine to investigate the effect footwear traction has on lower extremity injury in American football. Non-contact lower extremity injuries peaked at 19.2/1000 game exposures in the high rotational traction group (range 39-54.9N.m) of male American football players compared to 4.2 injuries per 1000 games exposures in the low rotational traction group (range 15-30.9N.m). Again, it is difficult to compare values due to different methodology. Prospective studies are of course required in soccer football to see if these findings extend to elite soccer.

Translational traction testing on natural grass playing surfaces

Remarkably, only grass type affected translational traction. There was no main effect relating to translational traction seen for shoe type or outsole type. This was a surprising finding as there was considerable damage to the playing surface with each test. Previous research on the coefficient of translational traction tested on artificial playing surfaces suggests normal (vertical) loads of over 888N (approx. 90kg) are required to see meaningful differences between shoe outsole designs when a horizontal force is applied (Kuhlman et al., 2009).

Our findings suggest the normal load of 300N used here was not sensitive enough to see differences between the shoes tested on two species of natural grass. It was not feasible to test at higher loads due to the amount of damage incurred to the playing surface with each test. The elite playing surface examined was the Qatar national team's main training pitch which saw high traffic over the duration of the study. Speed of the horizontal translation (which was manually driven) may also have influenced the results (Wannop and Stefanyshyn, 2012). It is suggested that improved and more sensitive methods for testing translational traction need to be developed if it is to be implemented into regular monitoring at elite football clubs and federations.

Does mechanical traction testing equal traction utilised by a player?

In January cool season grass average peak rotational traction for the AG outsole slipped down to 28N.m compared to 36N.m and 45N.m for the FG and SG groups respectively (Table 14). Further biomechanical and perception testing of players performing football specific tasks are required to ascertain if performance decreases with this lower magnitude of rotational traction (Sterzing et al., 2009).

Our results suggest mechanical testing for traction at the shoe-surface interface is more sensitive to changes in the rotational component of traction compared to the translational component for the methods used here.

Limitations

Although portable testing devices facilitate tracking of surface properties over time and between different surfaces or different football shoes, they do not provide an accurate representation of forces experienced by players when they are actually playing sport. It is suggested that a functional traction course and traction perception rating be used alongside mechanical testing to allow players' intuition and perception of optimal traction to aid footwear selection (Sterzing et al., 2009). All shoes tested here are from one manufacturer. Future research should test across all football shoe manufacturers.

Impact of our findings

After ground staff have prepared a playing surface and the prevailing climatic conditions are known close to kick-off, thereafter players can only control the type of shoe outsole (e.g. soft ground outsole, firm ground outsole etc) by choosing the shoe that best suits these primary factors to modulate the amount of traction experienced by the player. The current data show that the variability within a single season are large enough to warrant tailoring across different months.

Further research

It is likely that the optimal level of traction may change based on sport or even playing position. It is also pragmatic to suggest even lower levels of rotational traction when players are returning to field specific rehabilitation or training following a significant injury (eg ACL). Further research should examine several playing surfaces, soil types and grass species to get a more complete understanding of shoe-surface traction.

5.6 Conclusions

The rotational (but not translational) traction varied substantially across different months of the year, different grass species, and with different shoe outsole types. Warm season grass tested with the soft ground shoe (screw-in metal studs) showed the highest magnitude of rotational traction while Cool season grass tested with an artificial grass shoe (small round moulded studs) showed the lowest. This objective information should allow for more informed footwear choices for football played in warm/hot climates. Further research is required to confirm if these findings extend across other football shoe brands.

Practical implications

Objective data presented here can help tailor footwear selection (from one manufacturer) across a season of elite football in warm/hot climate zones. The authors suggest a universally accepted (commercially available) portable shoe-surface traction device should be agreed upon to allow new footwear outsole designs to be tested on various playing surfaces and climate zones.

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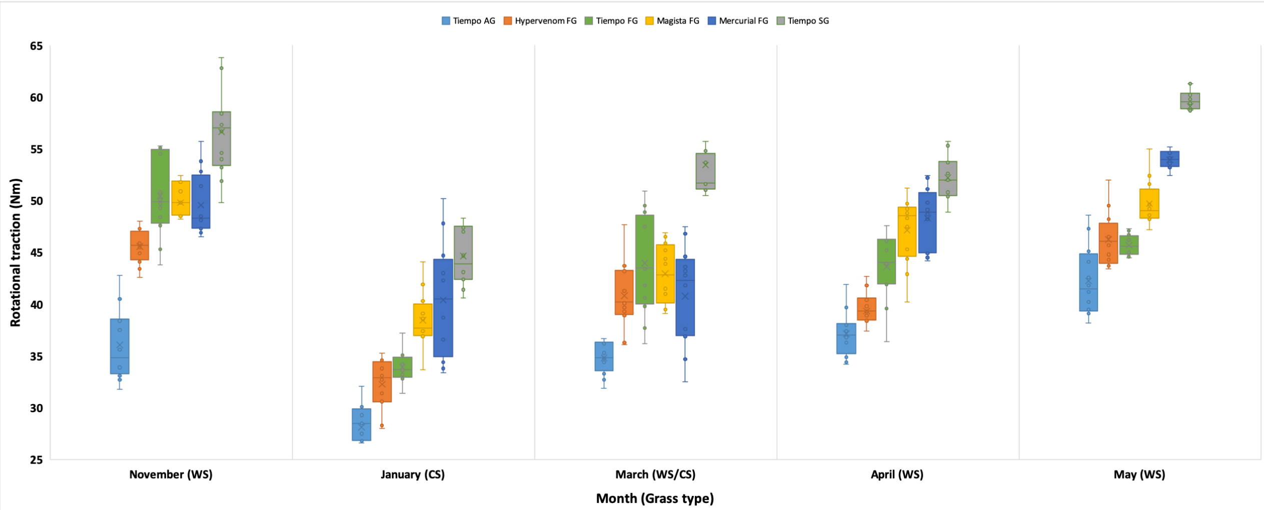
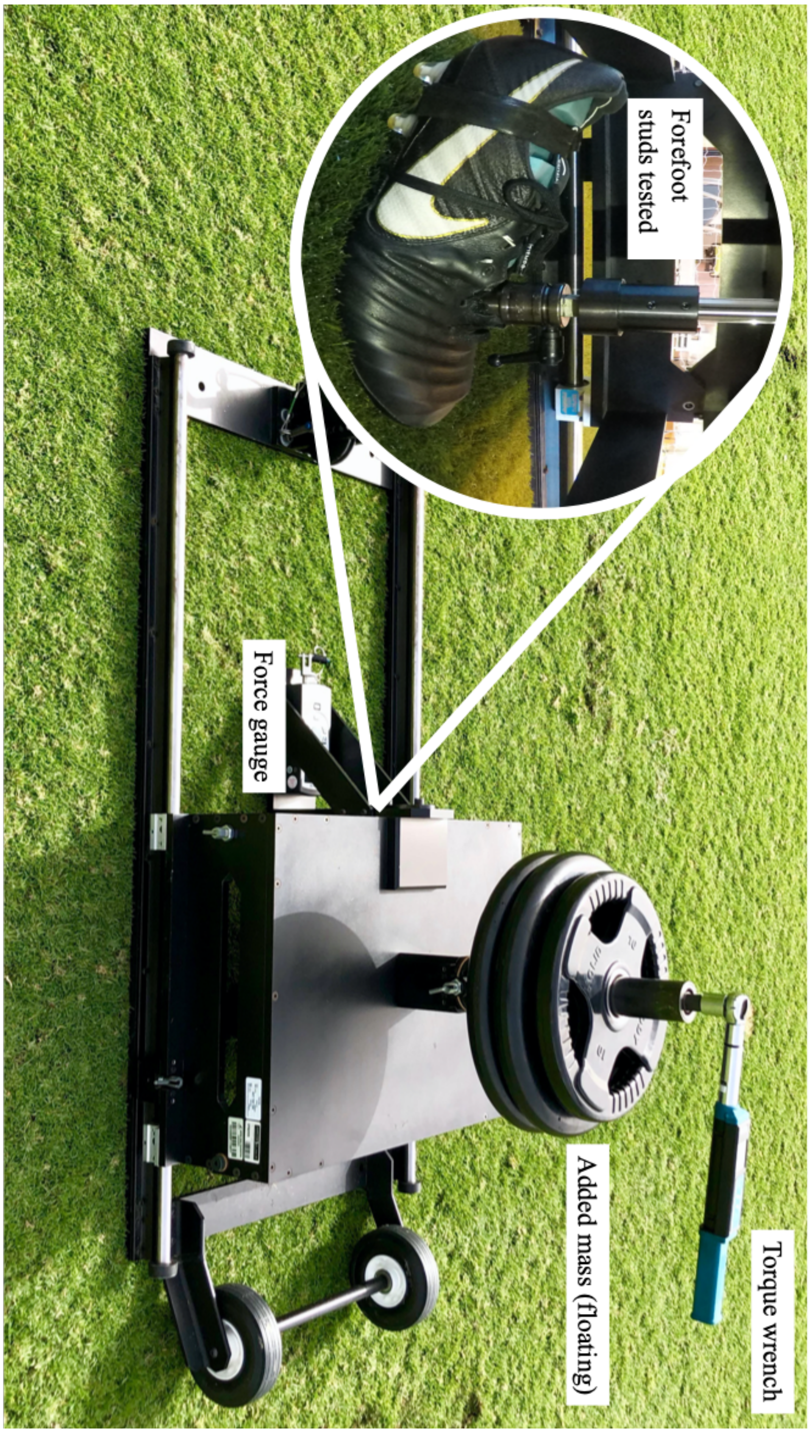
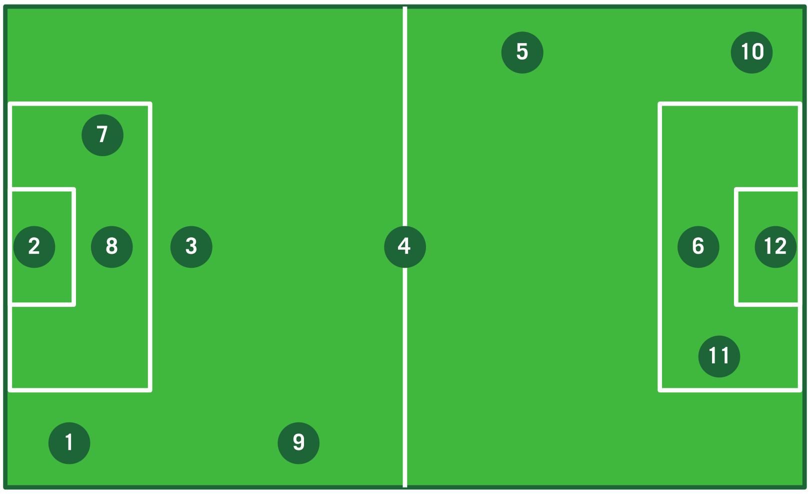
*Supplementary Figure 13. Rotational traction for each shoe at each testing time point and grass type. WS = warm season grass. CS = Cool season grass. WS/CS = warm season grass over-sown with cool season grass. The box represents 50% of the dataset, ends of the box show the 1st and 3rd quartiles, whiskers extend to the furthest data point within 1.5*IQR from the 1st and 3rd quartiles. 'X'within box = mean. Horizontal line within box = median.*



Supplementary Figure 14 Shoe-Surface traction tester (S2T2 Exeter Research, USA).



Supplementary Figure 14 Playing surface testing locations.



Chapter 6: Thesis summary.

6.1 Summary of key findings and practical applications

The overall aim of this thesis is to contribute practical objective data that can aid in the management of lower extremity injuries starting with early phases of rehabilitation, progressing to on-field movements and ultimately return to sport situations. Four original research studies and one systematic review present novel findings related to the biomechanical function of the lower limbs during rehabilitation and aspects of player-shoe and surface interaction at return to field-based training.

Real-world applicability is a mainstay of the thesis (in an elite sport setting where you are privileged to have access to the equipment/technology). Thus, several tables and figures provide objective data that can be used as a direct reference in a clinical setting (i.e. using an AlterG treadmill to progress loading in Table 1) or on-field setting (selecting football shoes to suit the ensuing playing surface conditions in football in Table 13).

Optimal load in rehabilitation

Manipulation of loading variables can have profound effects on the morphology and mechanical properties of the musculoskeletal system (Glasgow et al., 2015). Identification and progression of the optimal level of load is paramount to maximise physiological adaptation while preventing excessive overload (Bleakley et al., 2012, Khan and Scott, 2009). In **Chapter 1** we characterise the magnitude and timing of maximum plantar forces (vertical ground reaction force) that occur when walking or running on an AlterG treadmill. Faster running speeds caused greater maximum plantar force than increases in percent bodyweight on the AlterG® treadmill in healthy male runners for the speeds and bodyweight support percentages tested. Importantly, an increase in bodyweight support by 50% did not correspond to a comparable reduction in plantar loading (ie 50% less maximum plantar force). This finding is counter-intuitive and therefore important to report in the literature.

Manipulation of ‘regional’ load at the feet is examined in **Chapter 3.** Objective data presented aims to add to rehabilitation or training practices for elite football players who have suffered a fifth metatarsal fracture and provides a rationale for including (or avoiding) certain “on-field” movements at specific stages. Understanding the loading profile of common football movements will allow for load manipulation at regional anatomical structures, especially at the lateral aspect of the foot, in the event that prodromal (warning sign) symptoms are reported by the player.

Advice for clinical practice: Clinicians can refer to the data provided in **Chapter 1** to objectively progress plantar loading during rehabilitation for different bodyweight support and running speed combinations allowing manipulation of loading variables. This will be particularly useful after bone stress injury such as metatarsal stress fracture.

More specifically data from ‘on-field’ movements in **Chapter 3** may have important implications for manipulating regional load during rehabilitation or should a player report lateral forefoot prodromal symptoms. Young midfield players who perform numerous high-velocity passes or set-piece kicks and report lateral foot pain should warrant further investigation.

These data may help guide earlier ‘sports-specific’ on-field training after MT-5 surgery by allowing movements that do not impart large loading demands on the lateral aspect of the foot such as straight line running or curved running away from the injured limb.

Advice for future research: Investigating the effect faster running speeds, inclines, and declines have on maximum plantar force using different levels of bodyweight support will add further important data for clinicians to utilise. Further studies to characterise lateral foot loads in other populations (females, youth athletes etc). Future work should focus on altering load in players who report prodromal symptoms with adequate follow up to see if stress fracture can be avoided with activity modification using the data reported here in **Chapter 3**.

Return to sport criteria

Decision rules that govern when an athlete returns to sport can reduce re-injury rate by up to 84% if adhered to (Grindem et al., 2016). Temporal criteria may also be important to allow biological healing of injured tissues. Grindem et al. (2016) showed that for every month return to sport was delayed, until 9 months after ACLR, the rate of knee re-injury was reduced by 51%.

Applying these concepts, we arbitrarily split male soccer players into those < 9months after anterior cruciate ligament reconstruction (ACLR) and those > 9 months after ACLR in **Chapter 2** and examine inter-limb asymmetry as they pass functional criteria to return to sport. Clear significant between-limb differences in maximum vertical force are evident in this study for athletes who clear return-to-sport (RTS) criteria early (<9 months after ACLR) compared to athletes who pass RTS criteria later (≥9 months post ACLR) or healthy control athletes during moderate to fast running on a treadmill. Relatively large unloading of the ACLR limb (but not differences in contact times) are seen during running for athletes <9 months post-ACLR despite having completed functional criteria required to permit RTS training.

These preliminary findings suggest that vertical force (but not contact times) are worthy of further consideration as objective criteria to be used in successful RTS considerations and add to the suggestion that temporal (time-based) criteria may also be important.

Advice for clinical practice: Time after anterior cruciate ligament reconstruction should conceivably be considered along with functional criteria if limb symmetry during moderate to fast running is to be incorporated as a functional-criteria test to pass before return to sport.

Advice for future research: Longitudinal data on a larger sample size with return to sport and re-injury data are required to confirm these preliminary findings.

Shoe-surface interface

The mechanisms underlying lower extremity injuries in sport are multifaceted and complex (Bahr et al.2003, Hägglund at al., 2006, Mack et al., 2018). One factor implicated as influencing injury risk is the interaction between a players' shoe and the playing surface (Mack et al., 2018, Olsen et al 2003., Orchard et al., 2005, Wannop., 2013). Our systematic review of the football codes revealed that an athlete is over 2.5 times more likely to sustain a lower extremity injury if rotational traction forces are high at the shoe-surface interface **(Chapter 4)**.

However, these findings are from 3 large prospective studies examining non-contact injuries in American football only. Similar findings have been reported in European handball (Olsen et al., 2003) and Finnish floorball (Pasanen et al., 2008a, Pasanen et al., 2008b) although individual traction measurements were not taken between the shoe and surface.

Remarkably, no studies have been conducted in soccer football that measure shoe-surface traction forces and also investigate any relationship to lower extremity injury. Hence, to begin unwrapping any potential relationship we first set out to examine the temporal variation in shoe-surface traction across a full season at an elite (national team training pitch). This allowed to firstly analyse the validity of the traction testing machine (intra-class correlation, standard error of measurement and minimal detectable change etc) and secondly gain an understanding into the variability of shoe-surface traction across a season. Therefore, we also looked at parameters that may moderate shoe-surface traction such as temperature, soil moisture and surface hardness to present a more complete snapshot of this important interaction.

Advice for clinical practice: Peak rotational traction measured at the shoe-surface interface varied substantially across different months of the year, different grass species and with different shoe outsole types. This objective information should allow for more informed footwear choices for football played in warm/hot climates. It is pragmatic to suggest selecting low levels of rotational traction when players return to field specific rehabilitation or training following a significant lower extremity injury in which torque is involved as the primary mechanism of injury (such as anterior cruciate ligament tear or syndesmosis ankle injury).

Advice for future research: The authors suggest a universally accepted (commercially available) portable shoe-surface traction device should be agreed upon to allow new footwear outsole designs to be tested on various playing surfaces and climate zones. A prospective study investigating mechanical shoe-surface traction testing and lower extremity injury in soccer football is needed. The author is one year into a project that will continue after completion of this PhD. This prospective cohort study examines the injury data from 12 professional male football teams and any relationship to the magnitude of shoe-surface traction forces across three seasons of soccer football. Future research should investigate other populations (female players, youth and veteran players) and other playing surfaces (artificial v natural or hybrid reinforced grass etc).

6.2 Limitations

A major limitation of this thesis is that it investigates only male athletes who were generally elite professional or international football players (except chapter 1) and the corresponding elite (expensive) models of soccer footwear they may use. The injuries examined have a major burden in elite and recreational football yet can be considered relatively rare compared to more common locations like hamstring injuries. Further this means the sample sizes were relatively small. Future research should examine other populations (youth) and female players with larger sample sizes.

Whilst we were privileged to have access to technology such as in-shoe pressure systems, AlterG treadmill and shoe-surface traction testing devices they all come with their own set of limitations which are explained in detail in each specific chapter. The PedarX system for example, has a sample rate of 100 Hz and captures the vertical component of force only. New wireless sensors with higher sampling frequency will improve the validity of field-based research and are already available on the market. In this thesis maximum plantar force (Fmax) or vertical ground reaction force is a global measure of force at the foot-shoe-treadmill or playing surface interface so there is no information given on joint moments at specific proximal structures such as the ankle, knee or hip. Further research is required to calculate these variables which can generally only be measured in laboratory-based settings using 3D motion capture.

Mechanical traction measurements taken on a machine with an artificial foot do not allow for insights into how players will adjust their movement strategies for the given magnitudes of shoe-surface traction forces. Further biomechanical and player perception research is required to elucidate these interactions. This will form one stream of future research work that the author has already started using wearable technologies and various shoe and surface combinations. To date there is no universally accepted (commercially available) portable shoe-surface traction device. This is a major limitation in the area of shoe-surface traction testing. The many "one-off" machines constructed by university engineering departments or global footwear manufacturers and the subsequent research publications prove difficult to compare due to varied methodology, vertical load applied, and machinery used. Ideally a consensus for global soccer football would agree on a set list of commercially available machines to be used globally.

List of publications

<u>Thesis related.</u>

THOMSON, A., EINARSSON, E., WITVROUW, E. AND WHITELEY, R., 2017. Running speed increases plantar load more than per cent body weight on an AlterG® treadmill. *Journal of sports sciences*, *35*(3), pp.277-282.

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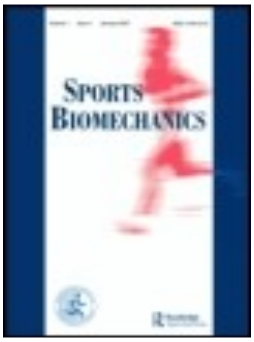
Appendix



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Reliability and validity of the Zebris FDM-THQ instrumented treadmill during running trials

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ABSTRACT

Little is known about the reliability, validity and smallest detectable differences of selected kinetic and temporal variables recorded by the Zebris FDM-THQ instrumented treadmill especially during running. Twenty male participants (age = 31.9 years (±5.6), height = 1.81 m (±0.08), mass = 80.2 kg (±9.5), body mass index = 24.53 kg/m² (±2.53)) walked (5 km/h) and ran (10 and 15 km/h) on an instrumented treadmill, wearing running shoes fitted with Pedar-X insoles. A testdouble retest protocol was conducted over two consecutive days.

day reliability, smallest detectable differences (SDD) and validity (95% limits of agreement (LOA)) were calculated. ICC values for the Zebris for Fmax were acceptable (ICC ≥ 0.7) while CT and FT reliability indices were predominantly good (ICC ≥ 0.8) to excellent (ICC ≥ 0.9). The Zebris significantly underestimated Fmax when compared with the Pedar-X. The 95% LOA increased with speed. SDD ranged between 96 N and 169 N for Fmax, 0.017s and 0.055s for CT and 0.021s and 0.026s for FT. In conclusion, Zebris reliability was acceptable to excellent for the variables examined, but inferior in comparison with Pedar-X. With increased running speeds, a bias effect (underestimation) existed for the Zebris compared with Pedar-X.

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running; gait; equipment

Introduction

Measurement of dynamic loading variables has emerged as an important approach in the management of athlete and patient well-being (Glasgow, Phillips, & Bleakley, 2015). Plantar pressure measurement systems are commonly used to evaluate dynamic foot and lower limb function. Historically, two basic types of systems have been used; (1) in-shoe pressure measurement insoles and (2) pressure plates that are fixed to the surface (Razak, Zayegh, Begg, & Wahab, 2012).

Recently, instrumented treadmills were introduced in an attempt to bridge the gap between these two systems by allowing for the capture of multiple steps combined with the calculation of temporal-spatial parameters at controlled speeds. The Zebris FDM-THQ instrumented treadmill (Zebris Medical GmbH, Germany), with a pressure plate embedded beneath the running belt, has been used in both clinical and research settings to examine gait parameters in children (Hollander, Riebe, Campe, Braumann, & Zech, 2014), healthy adults (Bates, Collins, et al., 2013; Bates, Savage, et al., 2013; Crawford, 2013), seniors (Faude, Donath, Roth, Fricker, & Zahner, 2012) and participants with neurological conditions (Kalron & Achiron, 2014; Kalron, Dvir, Frid, & Achiron, 2013; Kalron, Dvir, Givon, Baransi, & Achiron, 2014). However, data concerning the reliability and validity of the Zebris FDM-THQ is limited especially at running speeds (Faude et al., 2012; Lee, Song, Lee, Shin, & Shin, 2014; Reed, Urry, & Wearing, 2013).

Increase in running speed causes changes to kinetic parameters such as maximum vertical force (F_{max}) and temporal parameters such as flight time (FT) and contact time (CT) (Thomson, Einarsson, Witvrouw, & Whiteley, 2016). Running-related research has used these main parameters to calculate leg and vertical stiffness which have been implicated in both performance and injury (Brazier et al., 2014; Morin, Dalleau, Kyrolainen, Jeannin, & Belli, 2005). While these parameters are all produced by the Zebris FDM-THQ,the measurement error or smallest detectable difference (SDD) while running is unknown (De Mits et al., 2010; Gardinier, Manal, Buchanan, & Snyder-Mackler, 2013).

Therefore, the first aim of this study was to assess the within- and between-day reliability and validity of selected temporal and kinetic gait parameters obtained from the Zebris FDM-THQ treadmill with a focus on running speeds. By way of comparison, the Pedar-X in-shoe pressure system (Novel, Munich Germany) was used, which has been shown to have excellent reliability and validity (Hurkmans, Bussmann, Benda, Verhaar, & Stam, 2006; Hurkmans, Bussmann, Selles, et al., 2006; Putti, Arnold, Cochrane, & Abboud, 2007; Ramanathan, Kiran, Arnold, Wang, & Abboud, 2010). The related hypothesis of this study was defined as H1: there would be an acceptable (ICC ≥ 0.7) to excellent (ICC ≥ 0.9) reliability for the within- and between-day measurements (contact time, flight time and maximal vertical force) recorded by the Zebris FDM-THQ during running trials at 10 and 15 km/h. The second hypothesis was defined as H2: there would be no meaningful differences between the measurements (contact time, flight time and maximal vertical force) taken by the Zebris FDM-THQ and the Pedar-X during running trials at 10 and 15 km/h.

Methods

Twenty healthy male adult participants (age = 31.9 years(±5.6), height = 1.81 m(±0.08), mass = 80.2 kg (±9.5), body mass index = 24.53 kg/m^2 (±2.53)) were recruited for this study. Participants had no known history of cardiovascular, neurological or orthopaedic problems and gave written informed consent prior to participation in the study. Ethical approval for the study was provided by the Anti-Doping Laboratory Ethics Committee in Qatar and was undertaken according to the principles outlined in the Declaration of Helsinki.

An instrumented treadmill (HP Cosmos, Germany) with a capacitance-based pressure platform (FDM-THQ, Zebris Medical GmbH, Germany) was used in this study. The treadmill surface was set at 0° grade for all testing. The capture surface of the Zebris FDM-THQ system is 1.70 × 0.65 m and contains a sensing area of 1.36 × 0.64 m which consists of 10,240 sensors of 0.85 × 0.85 cm each. The sensor threshold was set to be 1 N/cm^2 and the measuring range is 1–120 N/cm^2. Plantar pressure data were concurrently collected using the Pedar-X in-shoe system (Novel GmbH, Munich, Germany). The latter system has been previously shown to exhibit a high level of accuracy, repeatability and validity (Kalron & Achiron, 2014; Kalron et al., 2014; Lee et al., 2014; Squadrone & Gallozzi, 2009). Each Pedar-X insole consists of 99 capacitive sensors embedded within a 1.9 mm thick insole. The insole has a sensor threshold of 2 N/cm^2 and a measurement range of 2–120 N/cm^2.

Data from both systems were sampled at 100 Hz. The Pedar-X insoles were calibrated once at the start of the study. Before each data collection trial, each participant stood still for 10 s on each left and right Pedar-X insole. Acceptable accuracy was where the weight measured by each insole was within 5% of the participants body weight, allowing an error of 5%, as per the manufacturer's guidelines (Trublu Calibration, Novel, Munich, Germany). Body weight was measured using a digital scale with a accuracy of 0.1 kg (0.98 N) (Detecto, Missouri, US).

During testing, all participants wore 'neutral' running shoes (Adidas™ Response, Germany) which were fitted with the Pedar-X insoles. The cables connecting to the data logger were held in place with Kinesio™ tape. The Pedar-X system's data logger was kept secure in a bespoke backpack. To familiarise themselves with the treadmill and other equipment, participants walked and ran on the treadmill for a maximum total of 10 min prior to the commencement of the testing protocol (Van de Putte, Hagemeister, St-Onge, Parent, & de Guise, 2006). All participants indicated feeling comfortable and ready for analysis before the end of the familiarisation period.

To commence the testing protocol, participants straddled the treadmill's belt while the speed of the treadmill's belt was increased to the first required testing speed. The speeds examined in this study were; 5 km/h (1.39 m/s) for walking and 10 km/h (2.78 m/s) and 15 km/h (4.17 m/s) for an 'easy' and more 'higher intensity' running speed. This order of testing was always used. At each speed, data were captured for 20 s immediately on the initial impact when stepping on the moving belt. This protocol was undertaken once on the first day of testing then it was performed twice when participants returned the following day. The testing sessions on the second day were consecutively performed without a rest period. Retesting was conducted at the same time of day, matched to the participant's initial session (Gribble, Tucker, & White, 2007).
Raw data from the Zebris FDM-THQ system were exported from the associated software in XML format. A customised software program written in R v3.2.1 (RCoreteam, 2015) using the xml2 package was used to extract the required data. For all steps registered during the data collection periods, the first series of 10 steps were removed and the next set of 10 steps (5 steps per side) were analysed. Raw data from the Pedar-X system were imported into the Novel Pedar evaluation software (Groupmask Evaluation, Novel Munich, Germany). The same 10 steps for analysis were defined, as described for the Zebris FDM-THQ system, using the Pedar Step analysis application.

Maximum plantar vertical force (F_{max}) in both systems was estimated by multiplying the pressure values measured by each of the individual sensors by the cross-sectional (constant in Zebris, variable in Pedar-X) area for each sensor. The resulting matrix of force data were then summed to then provide a final maximum vertical force value. Flight time (FT) and contact time (CT) were calculated from the temporal data. Flight time was defined and calculated as the time between the end of a step and the initial contact of the next step of the contralateral foot (Padulo, Chamari, & Ardigo, 2014). FT was not able to be measured for the walking condition because of the associated double support phase.

Prior to the commencement of the study, we estimated the sample to be 20 participants. This was based on an expected ICC from the test to be 0.85 as compared to the acceptable value of 0.70, with type-1 error as low as 0.05 and power 0.80. (Walter, Eliasziw, & Donner, 1998). Descriptive statistics (means and standard deviations) were calculated for each system (Zebris FDM-THQ, Pedar-X) for F_{max}, CT, FT and for each condition (5, 10 and 15 km/h) and for both sides of the body (left, right).

Within-day reliability (Day 2 Trial 1 and Day 2 Trial 2), and between-day reliability (Day 1 and Day 2 Trial 1 only) were calculated using intra-class correlation coefficients with their respective 95% confidence intervals (ICC's and 95%CI). The ICC(2,1) model was used to calculate bilateral reliability estimates for each system, for each condition, across all variables. ICC values were classified as follows; ≥0.9 as excellent, ≥0.8 as good, ≥0.7 as acceptable, ≥0.6 as questionable, ≥0.5 as poor and <0.5 as unacceptable (Brace, Kemp, & Snelgar, 2007). Relative standard error of measurement (SEM%) values were determined from the ICC values. Smallest detectable differences (SDD) values were also calculated as an indication of measurement error. SDD values were calculated as 1.96 × √2 x absolute SEM (Van Alsenoy, D'Aout, Vereecke, De Schepper, & Santos, 2014). A coefficient of variance (CV%) was also determined for the within- and between-day measures for both running conditions.

To assess the validity of variables collected from the Zebris FDM-THQ system, mean differences (Zebris FDM-THQ minus Pedar-X) and 95% limits of agreement for all conditions (5, 10 and 15 km/h), for each variable were calculated for all testing sessions. This was also done for each side of the body. To determine whether the mean differences were significant, linear mixed models were undertaken using pooled data with the observations (steps 1–5 for both left and right foot) set as a random factor and the system (Pedar-X and Zebris FDM-THQ) as a fixed factor. Limits of agreement were calculated using multiple observations (steps 1–5) per trial(Bland & Altman, 2007). All statistical analyses were performed in R v3.2.2 using customised scripts (RCoreteam, 2015).

Results

The Zebris registered a mean F_{max} of 802 N (±68) and 799 N (±77) and mean CT of 0.685s (±0.033) and 0.686s (±0.029) for left and right foot, respectively, during walking. For the same walking trials, the Pedar-X registered a mean F_{max} of 864 N (±103) and 892 N (±116) and mean CT of 0.656s (±0.039) and 0.646s (±0.053) for left and right foot, respectively. The Zebris registered F_{max} values between 1097 N (±95) and 1136 N (±97) for the left foot and 1090 N (±107) and 1126 N (±105) for the right foot at 10 km/hr. This increased to values between 1270 N (±112) and 1306 N (±128) for the left foot and 1285 N (±107) and 1234 N (±126) for the right foot at 15 km/hr. The Pedar-X registered consistently higher F_{max} values between 1694 N (±171) and 1722 N (±185) for the left foot and 1712 N (±209) and 1732 N (±221) for the right foot at 10 km/h. At 15 km/h, values were between 1903 N (±196) and 1932 N (±205) for the left foot and 1915 N (±248) and 1929 N (±219) for the right foot. Contact and flight times recorded by both systems were very similar with values between 0.264s (±0.022) and 0.287s (±0.025) and 0.088s (±0.017) and 0.116s (±0.019), respectively, at 10 km/h. Values between 0.211s (±0.022) and 0.227s (±0.020) and 0.123s (±0.018) and 0.139s (±0.020) for CT and FT at 15 km/h (Table 1).

Table 1. Descriptive data mean (± *SD*) for selected kinetic and temporal variables for the Zebris and Pedar-X system.

	10 km/hr						15 km/hr					
	D1		D2T1		D2T2		D1		D2T1		D2T2	
	Zebris	Pedar	Zebris	Pedar	Zebris	Pedar	Zebris	Pedar	Zebris	Pedar	Zebris	Pedar
Left foot												
F_{max} [N]	1136 *(97)*	1722 *(185)*	1128 *(100)*	1694 *(171)*	1097 *(95)*	1703 *(173)*	1306 *(128)*	1932 *(205)*	1305 *(102)*	1903 *(196)*	1270 *(112)*	1908 *(208)*
CT [s]	0.285 *(0.022)*	0.265 *(0.023)*	0.285 *(0.023)*	0.266 *(0.024)*	0.287 *(0.025)*	0.267 *(0.025)*	0.226 *(0.017)*	0.212 *(0.018)*	0.227 *(0.019)*	0.213 *(0.020)*	0.225 *(0.020)*	0.211 *(0.022)*
FT [s]	0.095 *(0.019)*	0.114 *(0.019)*	0.088 *(0.017)*	0.110 *(0.015)*	0.091 *(0.020)*	0.114 *(0.019)*	0.126 *(0.019)*	0.139 *(0.020)*	0.123 *(0.016)*	0.139 *(0.017)*	0.123 *(0.016)*	0.137 *(0.016)*
Right foot												
F_{max} [N]	1126 *(105)*	1727 *(183)*	1105 *(109)*	1712 *(209)*	1090 *(107)*	1732 *(221)*	1285 *(107)*	1929 *(219)*	1281 *(126)*	1915 *(237)*	1234 *(126)*	1915 *(248)*
CT [s]	0.283 *(0.023)*	0.264 *(0.023)*	0.286 *(0.022)*	0.264 *(0.022)*	0.285 *(0.024)*	0.263 *(0.024)*	0.225 *(0.018)*	0.214 *(0.022)*	0.227 *(0.020)*	0.212 *(0.020)*	0.225 *(0.021)*	0.212 *(0.021)*
FT [s]	0.097 *(0.019)*	0.116 *(0.019)*	0.093 *(0.018)*	0.111 *(0.018)*	0.094 *(0.021)*	0.114 *(0.018)*	0.126 *(0.018)*	0.137 *(0.022)*	0.125 *(0.016)*	0.137 *(0.016)*	0.123 *(0.018)*	0.137 *(0.018)*

Day 1[D1]; Day 2, test 1[D2T1]; Day 2, immediate retest [D2T2]; Standard Deviation [SD]; maximal vertical plantar pressure [F_{max}]; contact time [CT]; flight time [FT]; Left foot [L]; Right foot [R]; Newton[N]; Seconds[s]. The italic values represents ± *SD*.

Reliability

When considering all variables during walking and running, within-session intra-participant step-to-step variability was found to be acceptable to excellent with ICC values between 0.71 and 0.83 for F_{max} and between 0.86 and 0.95 for temporal parameters (CT and FT) measured by the Zebris FDM-THQ system.

The ICC values determined by the Pedar-X were considered good to excellent with values between 0.96 and 0.98 for F_{max} and 0.86 and 0.96 for CT and FT.

Table 2 shows within- and between-day ICC's (with 95%CI), SEM%, SDD and CV% values for; each system; F_{max}, CT and FT, each running speed and both sides of the body. The within-day and between-day ICC values for the Zebris FDM-THQ system for F_{max} were acceptable (ICC ≥ 0.7) registering between 0.70 and 0.78. The CT and FT reliability indices were predominantly good (ICC ≥ 0.8) to excellent (ICC ≥ 0.9), registering between 0.88 – 0.92 and 0.73 – 0.87 respectively.

The minimum change the Zebris FDM-THQ instrumented treadmill can detect with 95% confidence for repeated measurements made on the same day varied between 4.3 and 4.8% for F_{max}, 1.4 and 2.9% for CT and 6.3 and 11.3% for FT. These percentages varied slightly when repeating measurements between different days with a range between 4.1 and 5.4% for F_{max}, 1.2 and 2.8% for CT and 6 and 11.1% for FT.

For the same variables, the Pedar-X showed overall excellent reliability (ICC ≥ 0.9) for F_{max}, registering ICC's between 0.93 and 0.97, with the SEM% between 2.2% and 3.2%. The ICC values for FT and CT were similar to the Zebris FDM-THQ with values ranging from an acceptable ICC = 0.74 to excellent ICC = 0.93. The SEM% registered between 1.3 and 3.9% for CT and 6.2 and 7.8% for FT.

The coefficient of variation reported for F_{max} registered by the Zebris system at 10 and 15 km/hr ranged between 2.0 and 3.6% while for the Pedar-X system the range was between 1.1 and 2.5% for the same measurements. The coefficient of variance for FT at 10 km/hr had a much higher variability to the mean for both systems with values between 4.0 and 8.1%.

Validity

Table 3 shows the mean differences (Zebris FDM-THQ–Pedar-X) as well as the 95% limits of agreement between the two systems. All reported mean differences were significant ($p \leq 0.001$). Overall, the Zebris FDM-THQ reported a lower mean F_{max}, longer CT and shorter FT when compared with the Pedar-X system.

When examining the mean differences across treadmill speed for F_{max} during all testing sessions, these were determined to be -55 to -108 N, -566 to -642 N and -598 to -681 N for 5, 10 and 15 km/h conditions, respectively. A general trend of increasing mean differences (i.e., Zebris FDM-THQ underestimating Pedar-X values) with increasing treadmill speed can be seen in the Bland-Altman-like plot shown in Figure 1. No such trend of increasing (or decreasing) mean difference with increasing treadmill speed was apparent for CT or FT. Further *post hoc* Pearson correlation analysis demonstrated that the participant's body weight is positively correlated ($p < 0.015$) with the bias between Zebris and Pedar-X. However, if the maximal vertical force is normalised for body weight, then the positive correlation with the bias is significant during walking with r values between 0.45 and 0.68. The correlation with the bias in running speeds is less significant with r values between 0.15

Table 2. Within- and between-day reliability indices for each testing condition for the Zebris and Pedar-X system.

	10 km/hr								15 km/hr							
	ICC*(95%CI)*		SEM%		SDD		CV%		ICC*(95%CI)*		SEM%		SDD		CV%	
	Zebris	Pedar	Zebris	Pedar	Zebris	Pedar	Zebris	Pedar	Zebris	Pedar	Zebris	Pedar	Zebris	Pedar	Zebris	Pedar
Within-day [Left]																
F_{max} [N]	0.74 *(0.60–0.86)*	0.95 *(0.92–0.98)*	4.6	2.2	141 N	105 N	2.6	1.4	0.70 *(0.55–0.84)*	0.94 *(0.90–0.97)*	4.7	2.6	167 N	135 N	2.6	1.4
CT [s]	0.90 *(0.84–0.95)*	0.92 *(0.86–0.96)*	2.7	2.7	0.021s	0.020s	1.9	1.7	0.91 *(0.85–0.96)*	0.91 *(0.84–0.95)*	2.7	3.1	0.017s	0.018s	1.4	1.7
FT [s]	0.75 *(0.62–0.87)*	0.77 *(0.64–0.88)*	11.3	7.8	0.028s	0.024s	7.0	4.0	0.81 *(0.70–0.90)*	0.74 *(0.61–0.87)*	6.3	6.7	0.022s	0.026s	2.8	2.7
Within-day [Right]																
F_{max} [N]	0.77 *(0.65–0.88)*	0.97 *(0.94–0.98)*	4.7	2.3	143 N	108 N	2.1	1.6	0.77 *(0.65–0.88)*	0.97 *(0.94–0.99)*	4.8	2.2	169 N	119 N	2.8	1.1
CT [s]	0.88 *(0.80–0.94)*	0.91 *(0.84–0.96)*	2.9	2.7	0.023s	0.020s	1.9	1.7	0.92 *(0.86–0.96)*	0.90 *(0.83–0.95)*	2.7	3.2	0.017s	0.019s	1.2	1.1
FT [s]	0.80 *(0.68–0.90)*	0.80 *(0.68–0.90)*	10	7.5	0.026s	0.023s	6.6	4.4	0.81 *(0.70–0.90)*	0.83 *(0.72–0.91)*	6.4	5.5	0.022s	0.021s	3.0	2.7
Between-day [Left]																
F_{max} [N]	0.74 *(0.61–0.86)*	0.93 *(0.87–0.97)*	4.5	2.8	140 N	133 N	2.0	2.5	0.78 *(0.66–0.89)*	0.93 *(0.88–0.97)*	4.1	2.8	150 N	148 N	2.0	2.2
CT [s]	0.92 *(0.86–0.96)*	0.91 *(0.85–0.96)*	2.3	2.6	0.019s	0.019s	1.2	1.6	0.88 *(0.79–0.94)*	0.90 *(0.83–0.95)*	2.9	2.9	0.018s	0.017s	1.5	1.6
FT [s]	0.73 *(0.60–0.86)*	0.79 *(0.63–0.87)*	11.1	7.7	0.028s	0.025s	8.1	5.4	0.87 *(0.75–0.92)*	0.82 *(0.69–0.90)*	6	6.2	0.021s	0.025s	2.6	2.3
Between-day [Right]																
F_{max} [N]	0.70 *(0.56–0.84)*	0.95 *(0.91–0.97)*	5.4	2.9	168 N	138 N	3.6	2.4	0.75 (0.71–0.91)	0.96 *(0.93–0.98)*	4.6	2.3	162 N	125 N	2.1	1.7
CT [s]	0.91 *(0.84–0.96)*	0.90 *(0.93–0.95)*	2.5	2.8	0.020s	0.020s	1.6	1.8	0.90 (0.82–0.95)	0.85 *(0.76–0.93)*	2.8	3.9	0.018s	0.023s	1.6	2.3
FT [s]	0.81 *(0.70–0.90)*	0.79 *(0.68–0.90)*	9.2	7.7	0.024s	0.024s	6.5	5.8	0.82 (0.71–0.91)	0.82 *(0.71–0.91)*	6.2	6.2	0.022s	0.023s	2.3	3.4

Intraclass correlation coefficient [ICC]; 95% confidence interval [95% CI]; smallest detectable difference [SDD], relative standard error of measurement [SEM%]; maximal vertical plantar pressure [F_{max}]; contact time [CT]; flight time [FT]; coefficient of variation [CV%]. The italic values are related to the 95% CI.

and 0.54. The general trend of increasing mean differences with increasing treadmill speed as shown in the Bland-Altman-like plot does not change significantly when normalising for body weight (Figure 1(a) and (b)).

Discussion and implications

This study evaluated the within-day and between-day reliability and validity of selected temporal and kinetic gait parameters measured by the Zebris FDM-THQ instrumented treadmill in a group of healthy males with a focus on running speeds. By way of comparison, the Pedar-X Even though the determination of within-session intra-participant step-to-step variability was not an aim of the study, it is important to know there was a good reliability within steps before they were averaged.

Reliability of the Zebris FDM-THQ

As stated in Hopkins (2000) and Atkinson and Nevill (1998), more than one measure of reliability should be provided when conducting reliability studies. We utilised ICC as a measure of relative reliability while our SEM and SDD assessed the absolute reliability between our different measurements (Atkinson & Nevill, 1998; Hopkins, 2000). Within-day and between-day ICC values for the Zebris FDM-THQ system for F_{max} were acceptable while CT and FT were predominantly good to excellent. However, from examining the 95% CI's and point estimates of ICC's, the Pedar-X system showed superior reliability. Interestingly, the 95% CI's for the F_{max} ICC values for the Pedar-X system never overlapped the point estimates for ICC for the Zebris FDM-THQ system.

Similar to previous research, the SEM% values for F_{max} were less than 5% for within-day and between-day comparison, while the SDD's for the treadmill can detect are considered low in walking conditions (Faude et al., 2012; Lee et al., 2014; Reed et al., 2013). To our knowledge, there is no previous reporting on the reliability and SDD's of the Zebris FDMTHQ for running conditions.

Validity of the Zebris FDM-THQ for registering maximal vertical force

Concurrent validity measures for all F_{max} mean differences showed negative values indicating that the Pedar-X registered higher F_{max} for all speeds (Table 3, Figure 1).

Previous research by Castro and co-workers showed that deriving F_{max} from in-shoe pressure measurements registers higher vertical ground reaction forces than pressure plates (Castro, Soares, & Machado, 2011). They reported a range difference of -498.1 to 208.6 N in their set-up without control for walking speed. However, both pressure systems recorded lower F_{max} values when compared to vertical forces registered by a force plate as traditionally accepted gold standard.

Both systems derive F_{max} from measured plantar pressure, but at different levels under the foot. Pedar-X measured plantar pressure between the foot and the midsole of the shoe, while the Zebris FDM-THQ measured the pressure produced between the surface of the treadmill and the outsole of the shoe. As the foot progresses from initial heel contact to toe-off, the Pedar-X in-shoe system stays generally parallel to the plantar surface of the foot, allowing to register a more perpendicular force that is relative to the supporting surface

Table 3. mean difference and 95% limits of agreement (lower and upper Limit) between Zebris and pedar-X system for each testing condition and variable.

		10Km/hr			15 km/hr		
		D1	D2T1	D2T2	D1	D2T1	D2T2
		Δ *(95%LoA)*	Δ *(95%LoA)*	Δ *(95%LoA)*	Δ *(95%LoA)*	Δ *(95%LoA)*	Δ *(95%LoA)*
F_{max} [n]	L	-586	-566	−606	-625	-598	-638
		(-910,-261)	*(-887,-244)*	*(-925,-286)*	*(-987,-265)*	*(-965,-230)*	*(-1,010,-267)*
	r	-601	-607	-642	-644	-634	-681
		(-929,-272)	*(-997,-236)*	*(-1,031,-253)*	*(-1,035,-253)*	*(-1,039,-229)*	*(-1,107,-255)*
ct [s]	L	0.019	0.019	0.021	0.014	0.014	0.015
		(0.000, 0.038)	*(0.000, 0.038)*	*(0.000, 0.042)*	*(-0.003, 0.031)*	*(-0.002, 0.029)*	*(-0.004, 0.033)*
	r	0.020	0.022	0.022	0.011	0.015	0.013
		(-0.001, 0.041)	*(0.003, 0.041)*	*(0.002, 0.042)*	*(-0.015, 0.036)*	*(-0.007, 0.036)*	*(-0.006, 0.032)*
Ft [s]	L	−0.019	−0.022	−0.023	−0.013	−0.016	−0.015
		(-0.039,0.000)	*(-0.043, 0.000)*	*(-0.046, 0.000)*	*(-0.031, 0.005)*	*(-0.035, 0.004)*	*(-0.036, 0.006)*
	r	−0.019	−0.018	−0.019	−0.012	−0.013	−0.013
		(-0.040, 0.002)	*(-0.039, 0.002)*	*(-0.043, 0.005)*	*(-0.037, 0.016)*	*(-0.035, 0.009)*	*(-0.037,0.011)*

Day 1[D1]; Day 2, test 1[D2t1]; Day 2, immediate retest [D2t2]; mean difference [Δ]; 95% Limits of agreement [95%Loa]; maximal vertical plantar pressure [F_{max}]; contact time [ct]; flight time [Ft]; Left foot [L]; right foot [r]; mean difference is significant with $p \leq 0.001$ in all cases; negative difference value indicates pedar system measures higher values than Zebris system. the italic values are related to the 95% ci.

of the shoe (Orlin & McPoil, 2000). As the Zebris FDM-THQ is fixed to the treadmill, the lower limb/foot has an increased angle of contact during heel contact and push-off. As the angle of applied force on the pressure sensor increases, the vertical force derived from that sensor decreases, limiting the accuracy of measurement (Spooner, Smith, & Kirby, 2010).

Maximal vertical force during running

From Figure 1(c) and (d), which displays a Bland-Altman-type plots for F_{max} for the left and right foot, a distinctive bias with increasing running speed is evident. With increasing speed, the F_{max} differences and scatter between the Zebris FDM-THQ and the Pedar-X increases progressively (Ludbrook, 2010). Even though the participant's body weight is positively correlated ($p < 0.02$) with the bias between Zebris and Pedar-X, the speed is the main defining factor in the bias between both systems, the body weight acts as a modifier to the bias and further increases it (see Figure 1).

This finding was unexpected as the Zebris has a smaller sensor size and higher spatial resolution (1.4 per cm^2 vs. 0.57–0.78 per cm^2), which both are known specifications for accurate measurement of true peak pressure (Pataky, 2012; Razak et al., 2012). A potential cause for underestimating F_{max} measurements, specifically related to instrumented treadmills, maybe due to bending of the compliant treadmill structure, this has been shown to increase a non-linearity between exerted and measured forces (Sloot, Houdijk, & Harlaar, 2015).

Also, differences might possibly be attributed to shear friction. The Zebris FDM-THQ instrumented treadmill has a fixed pressure plate, similar to plates embedded in walkways, built-in under the running belt. Contrary to the classic rollover registration, the foot is pulled backwards (at the determined walking- or running speed) over the pressure plate by the running belt, while a forward rollover from initial heel contact to toe-off is registered. General capacitive sensors, used in both systems, are unable to measure shear force well (Orlin & McPoil, 2000). With the increased speed, friction becomes higher, possibly making it more difficult to have an accurate reading.

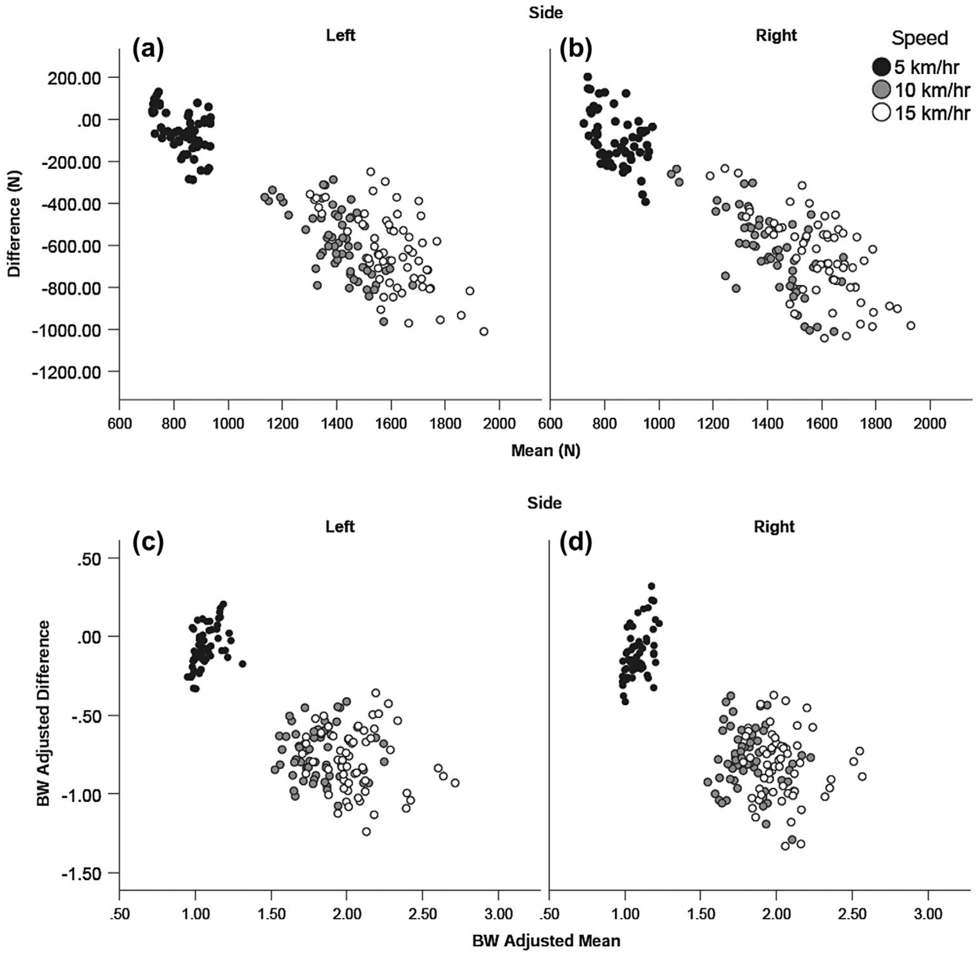

Figure 1. plot for the three different speeds (5, 10 and 15 km/hr) of the differences between Zebris and pedar-X vs. the mean of the two measurements for the maximal vertical force left (a) and right (b) foot and maximal vertical force normalised to bodyweight for the left (c) and right (d) foot.

Another possible explanation of this negative bias might be that the sensors of the Zebris FDM-THQ treadmill may become less accurate at the upper range of the calibrated measuring range of 1–120 N/cm² as the lower registered values compare much better with the Pedar-X.

Validity of the Zebris FDM-THQ for registering temporal parameters

Longer CT and shorter FT were recorded in all conditions by the Zebris FDM-THQ in comparison to the Pedar-X. The difference in temporal parameters maybe attributed to the differences in-shoe length (measured by the Zebris FDM-THQ) vs. the actual foot length (measured by the Pedar-X). When the Zebris FDM-THQ was compared with an OPTOGait system during barefoot walking, there was a very good correlation regarding CT during walking (Lee et al., 2014).

Limitations of the study

This study has a number of limitations that need to be considered. First, the sample was restricted to healthy male participants therefore, it is unknown whether these findings extend to other groups (i.e., women, children, elderly or injured individuals) or different walking / running speeds.

Secondly, the sampling rate chosen for both data collection systems in this study was 100 Hz due the fact that this is the highest possible sample frequency for the Pedar-X system. Higher sampling frequencies are recommended for determining maximal vertical force in running trial trials (Orlin & McPoil, 2000). With lower sampling frequencies, actual maximal peaks particularly at faster running speeds could be missed when the contact times are shorter.

Thirdly, the Pedar-X insoles were calibrated once at the start of the study. During the three-week duration of the data collection, accuracy was only confirmed by checking the participant's bodyweight (Seitz & Kalpen, 2014). However, for the most accurate determination of ground reaction forces derived from pressure measurements, the insoles should perhaps be calibrated on a daily basis (Kraus & Odenwald, 2008). Hurkmans, Bussmann, Benda et al. (2006) published results on the drift that was apparent after 1 h. Our protocol was much shorter (about 15 min) with each measurement being 20 s–so if there would be any drift–we deem it would indeed be minimal.

Further, treadmill running when compared with overground running has been shown to alter temporal parameters such as CT. Therefore, extending the conclusions to overground walking or running should be avoided (Parvataneni, Ploeg, Olney, & Brouwer, 2009; Wearing, Reed, & Urry, 2013). Only 10 km/h (2.78 m/s) and 15 km/h (4.17 m/s) were chosen for running speeds, where measurements at more different speeds would have given a more detailed picture of the validity of this treadmill.

Finally, the non-randomised nature of the protocol, while mimicking a protocol used in day-to-day clinical practice, maybe considered a potential limitation of the study.

Conclusion

This study confirms the first hypothesis as the Zebris FDM-THQ instrumented treadmill acceptably (ICC ≥ 0.7) reproduced the maximal vertical force measurements with a maximum 5.4% standard error. Further, it showed predominantly good (ICC ≥ 0.8) to excellent (ICC ≥ 0.9) reliability for temporal parameters (contact time and flight time) with a maximum of 11.3% standard error in this study. However, the authors partly reject the second hypothesis as its concurrent validity was inferior to the Pedar-X system. A significant bias effect existed for the Zebris FDM-THQ system measuring maximal vertical force when compared with the Pedar-X during running trials. The data presented seems to indicate a trade-off between reliability/validity and clinical ease of use. The Zebris FDM-THQ system is an easy to use instrumented treadmill and might allow for analysis of a large number of steps at fixed speeds in bigger cohorts. Therefore, it might be more appropriate for the comparison of different conditions rather than establishing accurate absolute values such as maximal vertical force. Future research should focus on determining what the individual clinical important range might be for the smallest detectable difference for the kinetic and spatio-temporal parameters when performing test-retest protocols in clinical trials.

Disclosure statement

No potential conflict of interest was reported by the authors.

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