The internal and external demands of multi-directional running and the subsequent effect on side cut biomechanics in male and female team sport athletes

Thesis submitted in accordance with the requirements of the University of Chester for the degree of Doctor of Philosophy

By Chelsea Oxendale

Abstract

The aim of this thesis was to examine the physiological and biomechanical responses to multi-directional running in male and female team sport athletes. Chapter 4 compared measures of energy expenditure derived from indirect calorimetry and microtechnology, as well as high power and high-speed activity, during linear and multi-directional running. Measured energy expenditure was higher during the multi-directional trial (9.0 ± 2.0 *cf.* 5.9 ± 1.4 $\text{kcal}\cdot\text{min}^{-1}$), whereas estimated energy expenditure was higher during the linear trial (8.7 ± 2.1 *cf*. 6.5 ± 1.5 $\text{kcal}\cdot\text{min}^{-1}$). Whilst measures of energy expenditure were strongly related ($r > 0.89$, $p < 0.001$), metabolic power underestimated energy expenditure by 52% (95% LoA: 20-93%) and 34% (95% LoA: 12-59%) during the multi-directional and linear trial, respectively. Time at high power was 41% (95% LoA: 4-92%) greater than time at high speed during the multi-directional trial, whereas time at high power was 5% (95% LoA: -17-9%) lower than time at high speed during the linear trial. Chapter 5 explored the internal and external responses to linear and multi-directional running, specifically examining if measures of high speed and high power reflect changes in internal load. High speed distance ($p < 0.001$) was higher during the linear trial, whereas time at high power ($p = 0.046$) and accelerations performed ($p < 0.001$) were higher during the multi-directional trial. Summated HR (-0.8; ±0.5, $p = 0.003$), B[La] (-0.9; ±0.6, $p = 0.002$) and RPE (-0.7; ±0.6, $p = 0.024$) were higher during the multi-directional trial. There was a large difference in the ratio of high speed:summated HR (1.5; ±0.5, $p = 0.001$) and high speed:total $\dot{V}O_2$ (2.6; ±1.2, $p < 0.001$) between linear and multi-directional running, whilst high power:summated HR (0.3; ±0.5, $p = 0.246$) and high power:total $\dot{V}O_2$ (0.1; ±0.8, $p = 0.727$) were similar. A small decrement in knee flexor torque was observed after the multi-directional (0.4; ±0.4, $p = 0.017$) and linear (0.2; ±0.3, $p = 0.077$) trials, respectively. Collectively, Chapters 4 and 5 reveal that more directional changes induce a greater internal response, despite reducing the high-speed distance someone is likely to cover. High power better reflects internal responses to multi-directional running than high speed, but microtechnology cannot be used to determine the absolute energy cost of multi-directional running.

Chapters 6 and 7 explored alterations in side cut biomechanics in males and females immediately (Chapter 6) and 48 h (Chapter 7) after multi-directional running. In Chapter 6, 20 m sprint time was higher (ES: 0.65 – 1.17, $p < 0.001$) after multi-directional running, indicating the presence of fatigue. Males and females displayed trivial to moderate changes in trunk flexion (0.16 – 0.28, $p = 0.082$), peak hip internal rotation (0.46 – 0.54, $p = 0.090$), and knee flexion (0.17 – 0.41, $p = 0.055$) and higher knee abduction (0.40 – 0.51, $p = 0.045$) and internal rotation (0.59 – 0.81, $p = 0.038$) angular velocities, during the weight acceptance phase of side cuts after multi-directional running. Peak hip extensor (0.19 – 0.29, $p = 0.055$) and knee internal rotation moment (0.22 – 0.34, $p = 0.052$) displayed trivial to small increases after multi-directional running, whereas peak hip external rotation (0.44 – 0.57, $p = 0.011$), knee extensor (0.33 – 0.45, $p = 0.003$) moment and knee to hip extensor ratio (0.15 – 0.45, $p = 0.005$) were lower. In addition, IGRF displayed trivial to moderate changes (0.04 – 0.79, $p = 0.066$) and lateral GRF was lower (0.29 – 0.85, $p = 0.002$) after multi-directional running. In Chapter 7, CK concentration (2.4 – 4.94, $p = 0.009$), perceived muscle soreness (4.2 – 4.8, $p < 0.001$) and 20 m sprint time (0.6 – 0.9, $p < 0.001$) were higher 48 h after multi-directional running, indicating the presence of EIMD. Males and females displayed trivial to moderate changes in peak torso flexion (0.13 – 0.35, $p = 0.055$), hip internal rotation angular velocity (0.43 – 0.64, $p = 0.073$) and more knee internal rotation (0.31 – 0.5, *p* = 0.009) 48 h after multi-directional running. A tendency for an interaction between sex and time was noted for peak knee flexion (*p* = 0.068) and internal rotation angular velocity (*p* = 0.057), with males only displaying a moderate increase. Males and females also displayed a lower peak knee extensor moment (0.43 – 0.56, *p* = 0.001) and a small increase in extensor moment (0.21 – 0.46, *p* = 0.066) and knee external rotation moment (0.34 – 0.78, *p* = 0.062). An interaction between sex and time was noted for IGRF (*p* = 0.037); there was a large increase in IGRF at 48 h in females (1.4) but not males (0.08). For the first time, these data highlight multi-directional running which elicits fatigue and EIMD causes alterations in side cut biomechanics which can persist for at least 48 h. Specifically, both males and females performed side cuts in a more extended position, with higher peak angular velocities, and peak knee external rotation moments and less knee extensor moments both immediately and 48 h after multi-directional running.

Acknowledgements

I have been extremely lucky to have such an amazing support network around me who have made the completion of a PhD possible. To all my supervisors, friends, family and participants, I am forever grateful for your help and support through this process.

First and foremost, I owe many of my life successes to my parents Colin and Susan Oxendale. I have been very blessed to have two amazing parents, who have supported me throughout all my life pursuits. Your hard work and perseverance in developing your own company from scratch has really bestowed on me that if you are willing to work hard, you can achieve great things. Words cannot express how grateful I am for your unconditional love, support and guidance you have given me throughout my life, which has been essential during my PhD. And if that wasn’t enough, you both helped completely renovate my house into a home. You have made me the woman I am today, and I hope I have made you proud. Mum I do hope when I graduate with my doctorate you don’t sneak off too early for a wine in the pub this time!

To my supervisors, Dr Grace Smith, Dr Jamie Highton and Prof Craig Twist, thank you for going above and beyond with your support, guidance and expertise throughout my PhD. During the 5 years I have worked on my PhD, you have all been there for me, through the highs and lows. Grace, thanks for your biomechanical expertise when I struggled to get my head around the literature. Jamie, there have been countless times I have wandered over to your office and asked for 5 minutes of your time, which have ended up being a 1 hour discussion! Thanks for listening and offering your expertise on the issues I encountered throughout the research process. Craig, thank you for your extensive comments and feedback which has undoubtedly improved the quality of my work. I am very lucky to have completed my PhD with such great academics, and above all else, lovely people. Finally, thank you to Prof Ken Green who has been extremely supportive and conscious of my PhD work, whilst working as a part time Senior Lecturer. Ken you are a fantastic manager, and I am very blessed to work in a department with such amazing people.

To my fellow PhD students, John Fernandes, Jonty Norris, Thomas Mullen and Edd Stanley. Working with you all in the PhD office made the process of doing a PhD more enjoyable, and on reflection, having that support network really helped my development as a researcher. Thanks for answering my ‘stupid questions’ and listening to my rants, which were often about data processing. I have learnt a lot from all of you and will look back fondly at our time in Tower 605. I would also like to thank my friends Vicky Beaumont and Ruth Hanson, who I met at Chester Uni. It is great to have friends who constantly lift each other up, celebrate in each other’s triumphs and support each other through challenging times. Thanks for your support during my PhD.

To my fiancée and future husband, Thomas Hughes. Thank you for being there for me always and unconditionally. You have supported me through the highs of my PhD and the low points, and to that end, literally been a shoulder to cry on. Thanks for genuinely showing an interest in my work, for your patience when I’ve been working long hours and for being a pilot testing Guinea pig. My life is so much brighter, happier and fun with you in it, and that positivity has been a blessing throughout my PhD. I really appreciate all you do for us, and I can’t wait to become your wife. I love you.

And finally, a huge thanks to all the participants who took part in the studies.

Declaration

This work is original and has not been previously submitted
in support of a Degree qualification or any other course

Signed:

Date: 26/04/2021

Publications

Oxendale, C. L., Highton, J., & Twist, C. (2017). Energy expenditure, metabolic power and high speed activity during linear and multi-directional running. *Journal of Science and Medicine in Sport, 20*(10), 957-961

Conference Proceedings

Oxendale, C. L., Highton, J., Twist, C., & Smith, G. (2019). Effect of running-induced fatigue on the biomechanics of side cutting manoeuvres. Paper presented at the European College of Sport Science, Prague, Czech Republic

Oxendale, C. L., Highton, J., Twist, C., & Smith, G. (2019). Effect of running-induced fatigue on the biomechanics of side cutting manoeuvres. Paper presented at the British Association of Sport and Exercise Sciences conference, Huddersfield, UK

Oxendale, C. L., Highton, J., & Twist, C. (2017). Internal and external responses to linear versus multi-directional running. Paper presented at the British Association of Sport and Exercise Sciences conference, Nottingham, UK

Contents

Chapter 1 Introduction

Chapter 2 Literature Review

Chapter 3 General Methods

Chapter 4 Energy expenditure, metabolic power and high-speed activity during linear and multi-directional running

Chapter 5 Can player tracking devices monitor changes in internal load during multi-directional running? A comparison of high speed and high metabolic power

Chapter 6 Effect of multidirectional running on the biomechanics of side cuts in males and females

Chapter 7 The effect of exercise-induced muscle damage on the biomechanics of side cuts in males and females

List of Figures

List of Tables

Table title **Page no.**

List of Abbreviations

2D	Two dimensional
3D	Three dimensional
ANOVA	A two-way analysis of variance
ACL	Anterior cruciate ligament
ADP	Adenosine diphosphate
ATP	Adenosine triphosphate
AU	Arbitrary unit
B[La]	Blood lactate concentration
Ca^{2+}	Calcium
CD	Compact disc
CI	Confidence interval
CK	Creatine kinase
CMJ	Counter-movement jump
CNS	Central nervous system
COM	Centre of mass
CV	Coefficient of variation
DOMS	Delayed onset muscle soreness
E-C	Excitation-contraction
EE	Energy expenditure
EIMD	Exercise-induced muscle damage
EMG	Electromyography
EPOC	Excess post-exercise oxygen consumption
ES	Effect size
GPS	Global positioning system
GRF	Ground reaction force
H^+	Hydrogen
HR	Heart rate
HP	High power
HS	High speed
IC	Initial contact
ICC	Intraclass correlation
IGRF	Vertical ground reaction force impulse
iTRIMP	Individualized training impulse
K^+	Potassium
LoA	Limits of agreement
MP	Metabolic power
MVC	Maximum voluntary contraction
Na^+	Sodium
PCr	Phosphocreatine
Pi	Inorganic phosphate
PL	PlayerLoad™
RPE	Rating of perceived exertion
SD	Standard deviation
SEM	Standard error of measurement
TO	Toe off
$\dot{V}O_2$	Oxygen consumption

Chapter 1

Introduction

1.1 The characteristics of team sports training and competition

Team sport athletes typically cover 3 – 12 km during training and match-play. This incorporates numerous high-intensity movements, such as accelerations (33 - 656), decelerations (49 - 612) and high-speed runs (119 – 930 m), interspersed with prolonged periods of low-intensity movements (Akenhead, Hayes, Thompson, & French, 2013; Dalen, Jørgen, Gertian, Geir Havard, & Ulrik, 2016; Gabbett, Jenkins, & Abernethy, 2012; Kempton, Sirotic, Rampinini, & Coutts, 2015; Russell et al., 2016; Springham et al., 2020; Strauss, Sparks, & Pienaar, 2019; Tierney, Young, Clarke, & Duncan, 2016; Trewin, Meylan, Varley, & Cronin, 2018; Varley, Gabbett, & Aughey, 2014; Waldron, Twist, Highton, Worsfold, & Daniels, 2011). The movements and activities performed by team sport athletes evoke acute psychophysiological responses such as an elevated heart rate (~80-88% of maximum heart rate; Aslan et al., 2012; Cunniffe et al., 2009; Dubois et al., 2017; Iacono, Martone, Cular, Milic, & Padulo, 2017; Lythe & Kilding, 2011; Waldron et al., 2011), blood lactate concentration (3 – 8 $mmol \cdot L^{-1}$; Aslan et al., 2012; Coutts et al., 2003; Deutsch, Maw, Jenkins & Reaburn, 1998; Krustrup et al., 2010; Krustrup et al., 2006), rating of perceived exertion (10.4 – 14.8; Aslan et al., 2012; Roberts et al., 2010) and oxygen consumption (70-80% of $\dot{V}O_{2max}$; Bangsbo, Mohr & Krustrup, 2006; Coutts et al., 2003), which indicate a high reliance on both aerobic and anaerobic metabolism.

Mechanical stresses imposed from team sport activity also elicit structural damage and soreness to the musculoskeletal system immediately, and in the days after, team sport activity (Keane, Salicki, Goodall, Thomas, & Howatson, 2015; Nedelec et al., 2014; Oxendale, Twist, Daniels, & Highton, 2016; Russell et al., 2016; Varley, Lewin, Needham, Thorpe & Burbeary, 2017). These psychophysiological responses are specific to the nature, intensity and duration of the task, and provide the stimulus for acute and chronic performance adaptations after single and repeated bouts of activity, respectively (Impellizzeri, Marcora & Coutts, 2019). However, exposure to such stimuli might increase the likelihood of fatigue and injury (Halson, 2014; Gabbett, 2016). Accordingly, consideration of both the movements and activities performed by athletes and their resulting psychophysiological responses are required to better control and optimize an individual's adaptive response.

1.2 Monitoring internal and external load in team sports

The movements and activities performed by team sport athletes and the resulting psychophysiological response comprise loads that can be classified as external and internal. External load represents the physical work done during a training session or match (e.g. distance covered) and the internal load represents the psychophysiological and biomechanical response (Impellizzeri et al., 2019; Impellizzeri, Rampinini, & Marcora, 2005; McLaren et al., 2018; Vanrenterghem, Nedergaard, Robinson, & Drust, 2017). Quantifying external loads provides the coach with valuable information on the organisation, quality and quantity of exercise, that helps to understand the prescribed training and monitor physical adaptations (Cummins et al., 2013; Impellizzeri et al., 2019). This external load might also be used to assess the risk of overtraining and maladaptation, as greater amounts of high-speed running (Gabbett & Ullah, 2012) and accelerations performed (Bowen, Gross, Gimpel & Li, 2017) have been associated with an increased risk of non-contact soft-tissue injuries. The internal load is dependent on the training/fitness, nutritional and psychological status of an individual (Delaney, Duthie, Thornton & Pyne, 2018; Impellizzeri et al., 2019) and their sex (Harmer et al., 2014; Hunter, 2016; Hunter, 2014; Yoon, Doverl, Widule & Hunter, 2015). Due to the lack of a single or gold-standard measure of external and internal load, these are quantified using a range of variables which describe an individual's response to exercise (Impellizzeri et al., 2019).

Acute and chronic training adaptations are ultimately determined by the internal rather than the external load, and therefore internal load should be monitored (Impellizzeri et al., 2019; McLaren et al., 2018). However, in practice it is not always possible to measure internal load directly, due to the lack of readily available valid indicators (Impellizzeri et al., 2019) and/or the practical and methodological issues of quantifying these loads in applied contexts (Osgnach, Poser, Bernardini, Rinaldo, & di Prampero, 2010). A greater external load often results in a greater internal load (Delaney et al., 2018; Gaudino et al., 2015; Polglaze et al., 2018b). This forms the basis of the acute dose – response paradigm (Impellizzeri et al., 2005) whereby the dose represents the external load, and the response represents the internal load. Attention has therefore shifted into the assessment of external load using wearable microtechnology (global positioning systems [GPS] incorporating accelerometers, gyroscopes and magnetometers), which has become commonplace in running-based team sports (Akenhead, Hayes, Thompson & French, 2013; Cunningham et al., 2018; Dalen et al., 2016; Hulin et al., 2015; Oxendale et al., 2016; Russell et al., 2016; Springham et al., 2020; Strauss et al., 2019; Tee, Lambert, & Coopoo, 2016; Varley et al., 2014; Vescovi, 2016). These devices provide reliable (Johnston et al., 2014; Varley, Fairweather & Aughey, 2012) and valid (Jennings, Cormack, Cutts, Boyd & Aughey, 2010; Johnston et al., 2014; Nikolaidis, Clemente, van der Linden, Rosemann & Knechtle, 2018; Rampinini et al., 2015) assessment of distance and velocity-based variables below ~ 20 $km{\cdot}h^{-1}$, and have some physiological relevance, as the energy cost of constant speed running is influenced by distance covered (Brueckner et al., 1991). However, the common use of arbitrary speed zones underestimates a significant proportion of distance covered by sprinting, compared with individualised speed zones (Hunter et al., 2015; Rago, Brito, Figueiredo, Krustrup, & Rebelo, 2020), which could impair the coach's ability to make informed decisions on external training dose prescription. The assessment of external load using distance covered in speed zones only (e.g. Cunningham et al., 2018; Strauss et al., 2019) also fails to account for the numerous accelerations and decelerations performed during team sports. Such actions elicit a greater physiological response than constant speed running, such as a higher blood lactate concentration (Ashton & Twist, 2015; Buchheit, Bishop, Haydar, Nakamura, & Ahmaidi, 2010), oxygen consumption (Hatamoto et al., 2014) and heart rate (Akenhead, French, Thompson, & Hayes, 2014) in male and female team sport athletes. Measurement of accelerations and decelerations are therefore necessary for the accurate quantification of external load, which will subsequently affect an individual's response to exercise (i.e. their internal load).

Estimating the internal load of team sports from microtechnology derived accelerations and metabolic power equations has received recent attention (di Prampero & Osgnach, 2018; Osgnach et al., 2010). Briefly, metabolic power is a mathematically derived marker of external load (see Appendix 1.1 for calculation) based on the speed-time profile of the athlete, and the assumption that estimated energy cost of accelerated/decelerated running on a flat terrain is equivalent to constant speed running uphill/downhill (di Prampero et al., 2005; Osgnach et al., 2010). Measurements of internal load have demonstrated stronger associations with metabolic power derived variables (i.e. time/distance over high metabolic power threshold [$>20\ \mathrm{W \cdot kg^{-1}}$]), in comparison to distance-based metrics (Delaney et al., 2018; Polglaze et al., 2018b). For example, Delaney et al. (2018) reported a stronger correlation between heart rate derived internal load and distance covered at high metabolic power during rugby league training, in comparison to distance covered at high speed ($r = 0.92$ *cf.* $r = 0.67$, respectively). Whilst this suggests metabolic power derived variables can better reflect internal load compared with traditional speed thresholds, the validity of metabolic power has been questioned (Brown, Dwyer, Robertson & Gastin, 2016; Buchheit et al., 2015; Highton, et al., 2017; Stevens et al., 2015). Specifically, underestimations between estimated energy expenditure derived using the metabolic power approach with energy expenditure (EE) derived from $\dot{V}O_2$ during team sport activity have been reported (~15 – 85%; Brown et al., 2016; Buchheit et al., 2015; Highton et al., 2017; Stevens et al., 2015). The variation in underestimation reported likely reflects the non-uniformity of protocols used, the use of inferior tracking devices below 10 Hz (Buchheit et al., 2015) that leads to questionable acceleration data (di Prampero & Osgnach, 2018), and the inappropriate comparison of measured $\dot{V}O_2$ (which includes the oxygen consumption value at rest) with the net estimated energy cost using metabolic power (above rest) (Osgnach et al., 2016). Previous comparisons of energy expenditure derived using the metabolic power approach and $\dot{V}O_2$ are therefore limited and contrast the strong associations between metabolic power and internal load. A more in-depth assessment of the validity of metabolic power during team sport activity and evaluation of causation between externally derived metabolic power and internal load is required to fully understand its utility in the monitoring and assessment of team sport activity.

1.3 Recovery after team sport activity

An individual's internal response to team sport activity can elicit fatigue and exercise-induced muscle damage (EIMD) before returning to normal, collectively referred to as the recovery phase. Fatigue is characterised by an objective decline in performance (e.g. peak torque, CMJ/sprint performance) over a discrete period of time, whether or not the task can be continued (Bishop, 2012; Enoka & Duchateau, 2008, Enoka & Duchateau, 2016), whilst EIMD is characterised by stiffness and swelling of the muscles, a decreased force of muscular contraction and delayed onset muscle soreness (Byrne, Twist, & Eston, 2004). After team sport activity, symptoms of fatigue (Ashton & Twist, 2015; Behan, Willis, Pain, & Folland, 2018; Brownstein et al., 2017; Duffield et al., 2019; Goodall et al., 2017; Goodall, Charlton, Howatson, & Thomas, 2015; Johnston, Gabbett, Jenkins & Hulin, 2015; Mullen, Twist, & Highton, 2019; Rampinini et al., 2011) and EIMD (de Hoyo et al., 2016; Gastin, Hunkin, Fahrner, & Robertson, 2019; Keane, Salicki, Goodall, Thomas, & Hotwatson, 2015; Nedelec et al., 2014; Oxendale et al., 2016; Russell et al., 2016; Souglis, Bogdanis, Chryssanthopoulos, Apostolidis, & Geladas, 2018; Twist, Waldron, Highton, Burt, & Daniels, 2012; Varley et al., 2017; Wiig, Raastad, Luteberget, Ims, & Spencer, 2019) are common in athletes immediately and for up to several days after team sport activity. Recovery from team sport activity is therefore considered biphasic (Garrett et al., 2019), with the immediate fatigue largely owing to a combination of central and peripheral factors (Minett & Duffield, 2014), and EIMD symptoms peaking at approximately 48 h post-exercise due to structural damage to myofibrils, disrupted calcium homeostasis and inflammation (Hydahl & Hubal, 2014; Owens, Twist, Cobley, Howatson, & Close, 2019; Peake, Neubauer, Della Gatta, & Nosaka, 2017).

Markers of fatigue and EIMD are known to be related to the external movements (i.e. total distance, high-speed distance, accelerations and changes of direction) performed by athletes during the initial exercise bout (Ashton & Twist, 2015; de Hoyo et al., 2016; Hader, Mendez-Villanueva, Ahmaidi, Williams, & Buchheit, 2014; Jones et al., 2014; Nedelec et al., 2014; Oxendale et al., 2016; Varley et al., 2017). For example, running with more changes of direction and accelerations can induce a more pronounced on-set of fatigue (Ashton & Twist, 2015; Hader et al., 2014) and the magnitude of change in markers associated with EIMD has been positively associated with the number of sprints (Coppalle et al., 2019; Oxendale et al., 2016; Thorpe & Sunderland, 2012; Varley et al., 2017), accelerations (de Hoyo et al., 2016; Oxendale et al., 2016; Varley et al., 2017) and decelerations (de Hoyo et al., 2016; Oxendale et al., 2016) performed during the initial insult. Sex can also affect markers of fatigue as females have been reported to be less fatigable than males (Harmer et al., 2014; Hunter, 2016; Hunter, 2014; Yoon et al., 2015). Conversely, sex has little to no effect on markers associated with EIMD (Hicks, Onambele, Winwood & Morse, 2017; Hubal & Clarkson, 2009).

Studies which assess an individual’s response after team sport activity often use simulation protocols (e.g. Goodall et al., 2017; Twist & Sykes, 2011), given the high variability in high-speed running, accelerations and decelerations reported during team sports (Gregson, Drust, Atkinson, & Di Salvo, 2010; Harper, Carling, & Kiely, 2019; Kempton, Sirotic, & Coutts, 2014). Whilst this provides some insight into an individual’s response to team sport activity, the protocols used are often based on distance covered in arbitrary speed thresholds during team sports (Russell, Rees, Benton, & Kingsley, 2011; Savage, Lay, Wills, Lloyd, & Doyle, 2018; Sykes, Nicholas, Lamb, & Twist, 2013). As a result, such protocols might not adequately mimic the acceleration and deceleration demands of team sports, and therefore markers of fatigue and EIMD observed in the days after. The high variation in the number of accelerations and decelerations performed during team sports (Harper et al., 2019), also demonstrate further work is required to better understand how the systematic manipulation of the number of accelerations and decelerations influences an individual's response to team sport activity.

1.4 Acute physiological and biomechanical responses from team sport activity

Impaired neuromuscular performance, i.e., lower CMJ height and slower sprint times, are evident in males (Behan et al., 2018; Brownstein et al., 2017; Duffield et al., 2019; Goodall et al., 2017; Lovell, Midgley, Barrett, Carter & Small, 2011; Rampinini et al., 2011) and females (Andersson et al., 2008; Ashton & Twist, 2015; Krustrup, Zebis, Jensen & Mohr, 2010) after team sport activity. Given congested schedules, team sport athletes are therefore required to train or compete before a full recovery is achieved (Dupont et al., 2010; Johnston, Gabbett & Jenkins, 2013; Mohr et al., 2015). During this time, athletes might be most vulnerable to non-functional over-reaching and injury (Hogarth, Burkett, & McKean, 2015; Jones, Griffiths, & Mellalieu, 2017). Indeed, injuries are already a common occurrence in team sports, accounting for 7.7 – 37.3 injuries per 1000 hours of match exposure (Lopez-Valenciano et al., 2020; Stovitz & Shrier, 2012). The most commonly injured anatomical region is the knee joint (Lopez-Valenciano et al., 2020; Yeomans et al., 2018) and injury to the anterior cruciate ligament (ACL) accounts for a considerable proportion of injuries to the knee

(20 – 25%; Joseph et al., 2013; Majewski, Susanne, & Klaus, 2006; Swenson et al., 2013). ACL tears and ruptures are considered the most severe knee injury; accounting for the longest time to return to play (~236 days; Awwad, Coleman, Dunkley, & Dewar, 2019). The rate of ACL injuries per exposure are also ~2 – 6 fold higher in females compared with males (Gray et al., 2019; Hewett et al., 2005; Stanley et al., 2016).

Epidemiology studies demonstrate most ACL injuries occur during a non-contact side cutting manoeuvre (Koga et al., 2010; Olsen et al., 2004; Walden et al., 2015), and the risk of sustaining an ACL injury is partly related to an individual's side cut biomechanics (Bencke et al., 2013; Besier, Lloyd, Cochrane, & Ackland, 2001; Collins, Almonroeder, Ebersole, & O'Connor, 2016; Dai et al., 2015; Iguchi, Tateuchi, Taniguchi, & Ichihashi, 2014; Imwalle, Myer, Ford, & Hewett, 2009; Kipp, McLean, & Palmieri-Smith, 2011; McLean, Huang, Su, & van den Bogert, 2004; Sanna & O'Connor, 2008). Briefly, limited trunk and lower limb flexion angles (Blackburn & Padua, 2009; Kipp et al., 2011; Walden et al., 2015), an abducted and internally rotated knee position (Kobayashi et al., 2010; Koga et al., 2010; Olsen et al., 2004; Walden et al., 2015), and knee abduction and internal tibial rotation moments (Kiapour et al., 2014; Myer et al., 2015; Shin, Chaudhari & Andriacchi, 2011) are key biomechanical factors contributing to ACL injury. Females have displayed less knee flexion (McLean, Lipfert & Van den Bogert, 2004; Weinhandl, Irmischer, Sievert & Fontenot, 2017) and higher knee abduction moments (Sigward & Powers, 2006; Weinhandl et al., 2017) compared with males during a side cut, which partly explain the greater prevalence of ACL injuries in females (Stanley et al., 2016). Practically, these data can be used to help identify athletes who are at greater risk of sustaining an ACL injury and to inform ACL injury preventative interventions.

Fatigue can influence the biomechanics of side cuts and could therefore be considered a mechanism of ACL injury. Specifically, athletes can adopt a more upright side cutting position when fatigued (Cortes et al., 2013; Khalid et al., 2015; Lucci, Cortes, Van Lunen, Ringleb, & Onate, 2011; McGovern et al., 2015; Raja Azidin, Sankey, Drust, Robinson & Vanrenterghem, 2015) and can display changes in vertical ground reaction force (GRF) and sagittal joint loading (Iguchi et al., 2014; Khalid et al., 2015; Savage et al., 2018). Whilst some have reported fatigue-induced alterations in frontal plane biomechanics (Collins et al., 2016; Tsai, Sigward, Ollard, Fletcher & Powers, 2008), others have reported no change (Raja Azidin et al., 2015; Sanna & O'Connor, 2008). Similarly, it is not clear if transverse plane biomechanics are affected by fatigue (Lucci et al., 2011; Tsai, et al., 2008) or not (Collins et al., 2016; Savage et al., 2018) during a side cut. While thought to provide a role, how fatigue specifically influences the biomechanics of side cuts and subsequent ACL injury risk remains unclear. Furthermore, few studies have assessed the interaction between sex and fatigue on side cut biomechanics (Iguchi et al., 2014; Khalid, Sujae, Loke, Hamill, & Xingda, 2015; McGovern et al., 2015), so it is unclear if consistent interactions between sex and fatigue exist. Discrepancies amongst the literature likely reflect the non-uniformity of fatigue protocols, ranging from repetitive explosive movements such as vertical jumps combined with sprints (Lucci et al., 2011; Tsai et al., 2008) to 60 minutes of intermittent shuttle running over 20 m (Collins et al., 2016; Sanna et al., 2008). Few studies have used protocols which incorporate numerous accelerations and decelerations that occur during team sports (Akenhead et al., 2013; Russell et al., 2016; Springham et al., 2020; Varley et al., 2014). As recovery after team sport activity is dependent on the external movements performed (de Hoyo et al., 2016; Jones et al., 2014; Nedelec et al., 2014; Oxendale et al., 2016; Varley et al., 2017), research utilising fatigue protocols which mimic the external movements of team sports are warranted to fully understand how side cut mechanics are altered after team sport activity. This is important because critical information on fatigue-induced alterations to side cut biomechanics after team sport activity can help inform ACL screening and preventative programmes, with the ultimate goal of reducing ACL incidence rates.

Few studies have examined if side cut mechanics are altered in the days after team sport activity when athletes experience symptoms of EIMD. During this time, decrements in hamstring torque are common (Draganidis et al., 2015; Twist & Sykes, 2011; Wollin, Thorborg & Pizzari, 2017) and could increase risk of an ACL injury, as the hamstrings play a crucial role in stabilising the knee joint during valgus and internal rotation moments (Besier, Lloyd & Ackland, 2003). Indeed, alterations to sagittal plane walking and running biomechanics after EIMD are evident (Chen, Nosaka, Lin, Chen & Wu, 2009; Dutto & Braun, 2004; Paquette, Peel, Schilling, Melcher & Bloomer, 2017; Tsatalas et al., 2013a; Tsatalas et al., 2013b; Paschalis et al., 2007a). However, cutting manoeuvres place a greater emphasis on transverse and frontal mechanics compared with straight running (Besier et al., 2001), and running does not place sufficient loading on the ACL required to identify ACL injury mechanisms (Vanrenterghem et al., 2012). To date, only one study has explored the effect of EIMD on side cut mechanics (Snyder, Hutchison, Mills, & Parsons, 2019), reporting an increase in posterior GRF and anterior tibial shear force after muscle damaging exercise. Whilst this suggests EIMD could have implications for ACL injury risk, a more in-depth assessment of side cut biomechanics in the days after team sport activity, when symptoms of EIMD exist, would develop current knowledge on how EIMD alters side cut biomechanics. This might also help identify whether or not EIMD indirectly contributes to ACL injury risk.

1.5 Summary

Team sports are multi-directional and involve repeated high-intensity efforts performed over short distances. Therefore, measurements of distance covered in arbitrary defined speed zones fail to account for the numerous accelerations and decelerations performed during team sports, which also elicit a greater psychophysiological response. Further consideration over the assessment of external load, and how this affects an individual's response to exercise is required to improve the assessment of external load. Measurements of metabolic power, in particular, have demonstrated stronger relationships with an athlete's internal response when compared with high speed distance covered. Metabolic power might therefore better reflect multi-directional movements than high speed distance covered, yet further investigation of its utility to reflect an individual's internal response is still required. The specific external movements performed by athletes are also related to the magnitude of fatigue and EIMD experienced during the biphasic recovery period after team sport activity. During this time, athletes might be more susceptible to severe injuries, with injuries to the knee joint, specifically the ACL during a side cut, being a common occurrence in team sport athletes. Indeed, exercise-induced fatigue can cause alterations in the biomechanics of side cuts, but discrepancies in the literature still exist, due to the non-uniformity of fatigue protocols used. The effect of EIMD on side cut biomechanics has also received limited attention, but might provide further insight into ACL injury mechanisms, given that EIMD persists in the days after team sport activity and can impair neuromuscular function and alter walking and running biomechanics. A summary of the current understanding (black text) of how the external and internal demands of team sports interact, and the physiological and biomechanical responses during the recovery process are presented in Figure 1.1. The red text denotes areas where the current thesis will attempt to contribute new knowledge to the topic area.

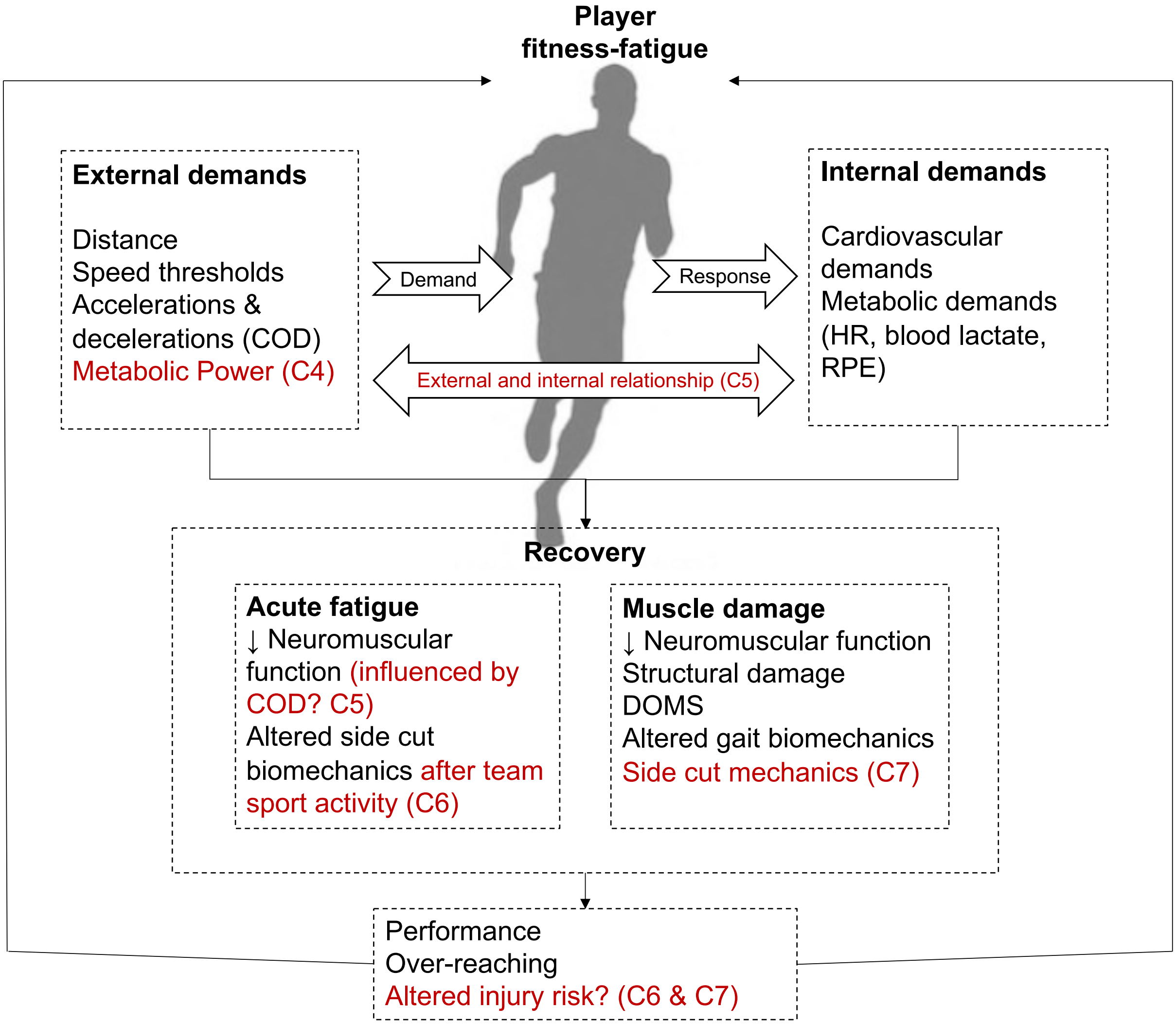


Figure 1.1 Proposed framework of the internal and external demands of team sports, and the subsequent acute physiological and biomechanical responses during the recovery process, in relation to anterior cruciate ligament (ACL) injury risk. The red ink denotes topic areas the thesis will explore and which chapter of the thesis each area has been explored (i.e. C4 represents Chapter 4). COD = change of direction, DOMS = delayed on-set of muscle soreness, HR = heart rate, RPE = rating of perceived exertion ↓ = decrease

1.6 Aims

This thesis focuses on the central theme of understanding the physiological and biomechanical responses to multi-directional running in male and female team sport players. The aims were: (1) to assess the utility of metabolic power compared with traditional speed based thresholds to quantify the external movements of linear and multi-directional running; (2) to examine how the systematic manipulation of the number of directional changes performed during running influences the internal load, the utility of metabolic power using integrated ratios, and neuromuscular function immediately after; (3) to examine the acute biomechanical adaptations in side cut mechanics as a result of fatigue in males and females; and (4) to examine how EIMD after multi-directional running alters the biomechanics of side cuts in males and females.

1.7 Organisation of the thesis

Chapter 2 of this thesis offers a review of the literature relating to the internal and external demands of team sports, fatigue and muscle damage after team sport activity, the biomechanical mechanisms and assessment of ACL injuries and the effect of fatigue and muscle damage on ACL injury risk in both males and females. Chapter 3 is a General Methods that details common procedures used throughout the four empirical data chapters. Thereafter, four empirical chapters are presented that seek to address the aforementioned aims of this body of work (see section 1.6). Chapter 4 examines the assessment of external load during linear and multi-directional running and Chapter 5 examines whether changes in external load can reflect changes in internal load between linear and multi-directional running, using integrated ratios. Chapters 6 and 7 assess the biomechanics of side cuts using 3D motion capture after multi-directional running induced fatigue (Chapter 6) and with symptoms of EIMD (Chapter 7). Finally, Chapter 8 presents conclusions on how the external and internal demands of linear and multi-directional running are related, and the implications for ACL injury risk during recovery from multi-directional running, detailing the implications for practitioners and recommendations for future research.

Chapter 2

Literature Review

2.1 Introduction

The purpose of this Chapter was threefold. Firstly, to review the literature describing the external and internal demands of team sports; secondly, to review markers of fatigue and muscle damage after team sport activity; and finally, to evaluate the effect of fatigue and muscle damage from team sport activity on ACL injury risk.

2.2 The internal and external demands of team sport activity

The use of GPS incorporating accelerometers, gyroscopes and magnetometers (collectively referred to as microtechnology) to quantify the movements of team sports is routine in research and applied practice. Data on durations, player velocities, distances covered, accelerations and sport specific actions can be calculated. This information allows for greater understanding of the physical demands of match-play (Dalen et al., 2016), which can be used to profile successful performance (Gabbett, 2013) and minimise injury risk (Gabbett, 2016). However, external demands used in isolation do not provide an indication of an individual's psychophysiological response to training (Delaney et al., 2018). Internal measures such as heart rate (HR) (Cunniffe, Proctor, Baker & Davies, 2009; Lythe & Kilding, 2011) and blood lactate concentration (B[La]) (Aslan et al., 2012; Krustrup, Zebis, Jensen & Mohr, 2010) have therefore been quantified during team sport activity. Given the practical and methodological issues of taking internal measures during competition (e.g. Alexandre et al., 2012), methods of estimating the internal demands of sport from external load has received recent attention (di Prampero & Osgnach, 2018; Osgnach et al., 2010). Yet, it is unclear whether the external demands of team sport activity reflect the internal demand imposed on athletes. Therefore, the following sections of this Chapter will detail the internal and external demands of team sports, as well as their relationship.

2.2.1 External movement demands of team sports

The movements of team sports using microtechnology have been extensively researched (see reviews by Cummins, Orr, O'Connor & West, 2013; Hausler, Halaki & Orr, 2016) and are therefore discussed briefly here. Team sports involve frequent bouts of high intensity activity interspersed with prolonged periods of low intensity activity. The total distance covered typically ranges between 3 – 12 km, equating to 53 – 131 $m \cdot min^{-1}$ (Table 2.1). Approximately 200 – 1,800 m (1.4 – 10 $m \cdot min^{-1}$) are performed at high speed, which can exceed 20 $m \cdot min^{-1}$ (Table 2.1) and occur during pivotal moments during a match (Faude, Koch, & Meyer, 2012). The range of values reported is likely explained by differences in rules for each sport (Varley et al., 2014), differences in position specific demands (e.g. Dalen et al., 2016; Jones, West, Crewther, Cook, & Kilduff, 2015), field position (Gabbett, Polley, Dwyer, Kearney, & Corvo, 2013), formation (Tierney, Young, Clarke, & Duncan, 2016), the classification of high speed running (> 4 – 5.8 $m \cdot s^{-1}$; Table 1) and differences in playing time (e.g. soccer: 95.3 ± 1.8 *cf.* rugby league: 64.9 ± 18.8 min; Varley et al., 2014). Given the latter, reporting relative distances covered allows for more appropriate comparisons between sports (Cummins et al., 2013), and might be more representative of a player's actual workload (Aughey, 2010). However, factors such as formation and field position can still change from match-to-match and might partly explain the high variability in high speed running and sprinting reported during team sports (CV: 13.3 – 30.8 %; Gregson et al., 2010; Kempton et al., 2014).

The number of accelerations and decelerations performed during team sports has been quantified, given that these actions are an important aspect of team sport performance (Brughelli, Cronin, Levin & Chaouachi, 2008). A wide range of accelerations (5 – 650; Table 2.1), decelerations (8 – 610; Table 2.1) and changes of direction (~12 ± 5 – 727 ± 203; Bloomfield, Polman, & O'Donoghue, 2007; Nedelec et al., 2014) have been reported, which likely reflects the varied classifications of acceleration actions (> 0.5 – > 3 $m \cdot s^{-2}$; Table 2.1). The high frequency of accelerations demonstrates the intermittent nature of team sports, which is associated with an increased physiological strain (Akenhead et al., 2014). Measures of high speed and accelerations might therefore provide a more comprehensive indication of the high intensity demands of team sports than measures of high speed alone (Dubois et al., 2017). In agreement, recent studies have demonstrated speed-based parameters are not appropriate for the classification of team sport activity, and instead suggest the use of metabolic power derived variables, such as distance covered at high metabolic power threshold (Polglaze et al., 2018b). Collectively, these data highlight the overall work-rate, high speed and accelerations demands of team sports, which provide useful guidelines for practitioners to follow when designing conditioning programmes (Waldron et al., 2011).

Table 2.1 The external demands of team sports using microtechnology

Study	Total distance (m) (Relative distance; m·min^{-1})	High speed (HS) distance (m) (Relative distance; m·min^{-1})	Accelerations (n) (Relative accelerations; n ·min^{-1})	Decelerations (n) (Relative decelerations; n ·min^{-1})	Comments
Football					
Akenhead et al. (2013)	10,451 ± 760	505 ± 209	178 ± 38	162 ± 29	10 Hz GPS, HS > 5.8 m·s^{-1}. Accelerations >3 m·s^{-2}
Wehbe et al. (2014)	~9,642.6 – 10,769.6 (~104.7 - 116.1)	~589.1 - 716.7	Medium accels: ~79.8 - 114.4 High accels: ~4.8 - 8.0	Medium decels: ~101.6 - 136.3 High decels: ~16.0 - 32.1	5 Hz GPS, HS > 19.8 km·h^{-1}. Medium accelerations = 2.5 - 4 m·s^{-2}. High accelerations > 4 m·s^{-1}
Varley et al. (2014)	10,274 ± 946 (104 ± 10)	517 ± 239 (5.42 ± 2.49)	65 ± 21 (0.68 ± 0.22)	-	5 Hz GPS, HS > 5.5 m·s^{-1}. Accelerations > 2.78 m·s^{-2}
Suarez-Arrones et al. (2015)	(~103.7 - 127.7)	HS: (~7.6 - 15.7) Sprint: (~3.3 - 7.6)	-	-	Data is during the first half only, 5 Hz GPS. HS > 18 km·h^{-1}, Sprint > 21 km·h^{-1}
Dalen et al. (2016)	11,046 ± 1,015	HS: 847 ± 349 Sprint: 214 ± 130	76 ± 22	54 ± 16	20 Hz RadioEye sensor, HS = 19.8 – 25.2 km·h^{-1}, Sprint > 25.2 km·h^{-1}. Accelerations > 2 m·s^{-2}
Russell et al. (2016)	~ 9,457 (~103)	~487	Total: ~656 HI accels: ~26	Total: ~612 HI decels: ~43	10 Hz GPS, HS > 5.5 m·s^{-1}. Accelerations > 0.5 m·s^{-2} and HI accelerations > 3 m·s^{-2}

Continued on next page

Table 2.1. Continued

Study	Total distance (Relative distance; m·min^{-1})	High speed (HS) distance (m) (Relative distance; m·min^{-1})	Accelerations (n) (Relative accelerations; n ·min^{-1})	Decelerations (n) (Relative decelerations; n ·min^{-1})	Comments
Tierney et al. (2016)	10,131 ± 583	497 ± 175	33 ± 10	49 ± 14	Based on a 4-4-2 playing formation, 10 Hz GPS HS > 19.8 km·h^{-1} and accelerations > 3 m·s^{-2}
Springham et al. (2020)	10,604 ± 1,180	752 ± 237.1	101 ± 25.6	112 ± 28.5	HS = distance covered between 5.5 m·s^{-1} and 80% of individual max speed. Accelerations > 3 m·s^{-2}
Female football					
Trewin et al. (2018)	10,368 ± 952 (108 ± 10)	930 ± 348 (9.7 ± 3.7)	174 ± 33 (1.82 ± 0.35)	-	10 Hz GPS, HS > 4.58 m·s^{-1} and accelerations > 2.26 m·s^{-2}
Strauss et al. (2019)	5,567 – 6,065 (74 – 87)	(3.6 – 5.7)	-	-	10 Hz GPS, HS > 4.4 m·s^{-1}
Rugby League					
Waldron et al. (2011)	4,181 – 6,917 (89-95)	119 - 316	-	-	5 Hz GPS, HS > 21 m·s^{-1}
Gabbett et al. (2012)	3,569 – 6,819 (93-101)	235 - 583	-	-	5 Hz GPS, HS > 5 m·s^{-1}
Austin & Kelly (2013)	4,597 – 8,500 (82 - 102)	432 - 749	-	-	5 Hz GPS, HS > 18 km·h^{-1}

Continued on next page

Table 2.1. Continued

Study	Total distance (m) (Relative distance; m·min^{-1})	High speed (HS) distance (m) (Relative distance; m·min^{-1})	Accelerations (n) (Relative accelerations; n ·min^{-1})	Decelerations (n) (Relative decelerations; n ·min^{-1})	Comments
Varley et al. (2014)	6,276 ± 1,950 (97 ± 16)	327 ± 168 (4.9 ± 2.1)	71 ± 38 (1.1 ± 0.56)	-	5 Hz GPS, HS > 5.5 m·s^{-1}. Accelerations > 2.78 m·s^{-2}
Kempton et al. (2015)	~4,289 – 7,298 (~83 - 91)	~274 - 695	~51.6 - 78.3	~59.6 - 93.3	5 Hz GPS, HS > 18.1 km·h^{-1}. Accelerations > 2.78 m·s^{-2}
Hulin et al. (2015)	Successful: (~67 - 68) Unsuccessful: (~88 - 92)	Successful: (~2 - 5) Unsuccessful: (~6 - 7)	-	-	10 Hz GPS, HS > 5 m·s^{-1}
Oxendale et al. (2016)	~4,675 – 5,640 (~81.9 – 83.2)	~306.5 – 481.4 (~5.1-6.6)	~4.7 – 9.1	~8.4 – 9.6	10 Hz GPS, HS > 18 km·h^{-1}. Accelerations > 2.79 m·s^{-2}
Rugby Union					
Jones et al. (2015)	~4,746 – 6,436 (~52.7 – 71.7)	~102 – 642 (~1.4 – 6.8)	~ 93.8	~ 54.2	10 Hz GPS, HS > 5 m·s^{-1}. Accelerations > 3 m·s^{-2}
Reardon et al. (2015)	~5,638.6 – 6,171.3 (~71.6 – 81.0)	~290.4 – 672.6 (~3.77 – 8.67)	-	-	10 Hz GPS, HS > 5 m·s^{-1}
Tee et al. (2016)	5,050 ± 1,636 (69 ± 8)	Striding: (10 ± 4) Sprinting: (2.4 ± 1.9)	1 every 6 ± 10 min		5 Hz GPS, Striding: 4-6 m·s^{-1}, Sprinting > 6 m·s^{-1}. Accelerations > 2.75 m·s^{-2}
Cunningham et al. (2018)	(106.7 ± 15.0)	(20.9 ± 13.5)	-	-	10 Hz GPS, HS > 5 m·s^{-1} Worst case scenario over 240 s period

Continued on next page

Table 2.1. Continued

Study	Total distance (m) (Relative distance; m·min^{-1})	High speed (HS) distance (m) (Relative distance; m·min^{-1})	Accelerations (n) (Relative accelerations; n ·min^{-1})	Decelerations (n) (Relative decelerations; n ·min^{-1})	Comments
Hockey					
Jennings et al. (2012)	~9,453 – 10,160	~1,734 – 2,554	-	-	5 Hz GPS, HS > 4.17 m·s^{-1}
Polglaze et al. (2015)	6,095 ± 938 (131 ± 11)	-	-	-	10 Hz GPS
Female Hockey					
Vescovi (2016)	2,817 – 5,626 (97 - 116)	HS: 310 – 580 Sprinting: 62 - 134	-	-	5 Hz GPS, HS = 16.1 – 20 km·h^{-1}. Sprinting > 20.1 km·h^{-1}

GPS = global positioning system, HS = high speed, HI = high intensity, accels = accelerations, decels = decelerations.

2.2.2 Validity and reliability of external movement demands assessed using microtechnology

The first commercially available GPS units, sampling at 1 Hz, demonstrated high between trial variance for high speed movements (CV: 11.2 – 32.4 %; Coutts & Duffield, 2010) and high errors (CV: 9.6 – 32.4 %) during shorter movement distances ranging from 10 to 40 m (Jennings, Cormack, Cutts, Boyd & Aughey, 2010), and are therefore not discussed further.

Measures of total distance have demonstrated an acceptable level of accuracy (CV: 1.3 – 2.8 %) using 5 and 10 Hz GPS units (Nikolaidis et al., 2018; Rampinini et al., 2015). However, 10 Hz GPS units have demonstrated superior accuracy for measuring distance covered at high speed (CV: 4.7 *cf.* 7.5 %; Rampinini et al., 2015), instantaneous speed during constant velocity running (CV: 3.1 – 8.3 % *cf.* 3.6 – 11.1 %; Varley, Fairweather & Aughey, 2012) and accelerations (CV: 3.6 – 5.9 % *cf.* 7.1 – 14.9 %; Varley, et al., 2012) in comparison to 5 Hz devices. In addition, 10 Hz devices are up to six-fold more reliable (CV: 1.9 – 6.0 %) than 5 Hz devices (CV: 6.3 – 31.8 %) for assessing instantaneous speed (Varley et al., 2012). Whilst these data reaffirm the sampling rate limits the accuracy of reported distances and running velocities (Jennings et al., 2010), it is noteworthy that Johnston et al. (2014) reported 10 Hz Catapult units demonstrated greater reliability for distances covered at low to high speeds (CV: 1.7 – 4.8 %) in comparison to 15 Hz GPSport devices (CV 2.0 – 7.6 %). GPS units sampling at 10 – 15 Hz have also demonstrated less than favourable reliability (CV: 11.5 – 12.1 %; Johnston et al., 2014) and validity (CV: 10.5 %; Rampinini et al., 2015) during high speed running over 20 km$\cdot$h^{-1}. Collectively, whilst a higher sampling rate can typically improve the reliability and validity of GPS metrics, factors such as model of device should be considered (Johnston et al., 2014). Moreover, it might be beneficial to classify the lower band of high-speed running as less than 20 $km \cdot h^{-1}$ to improve the reliability and validity of these movements measured using microtechnology.

The validity of GPS distance and speed metrics are also dependent on the number of directional changes during running. Specifically, the validity (CV: 2 – 3.9 % *cf.* CV: 1.3 – 2.2 %; Nikolaidis et al., 2018) and reliability (CV: 4.6 – 5.3 *cf.* 5.3 – 6.7 %; Portas, Harley, Barnes & Rush, 2010) of GPS distance measurements can be reduced during running with more directional changes. Movement over shorter (5 – 15 m) compared with longer (20 – 30 m) distances can also reduce the accuracy of GPS distance (CV: 10.9 *cf.* 5.1 %; Castellano, Casamichana, Calleja-Gonzalez, San Roman & Ostojic, 2011) and speed metrics (11.9 ± 11.3 % *cf.* 6.6 ± 3.5 %; Beato, Bartolini, Ghia & Zamparo, 2016). However, the mean difference between actual and 10 Hz GPS distances during running with changes of direction (-2.16 – 2.13 m; Nikolaidis et al., 2018; Rawstorn et al., 2014) is deemed acceptable for monitoring training and performance.

GPS housed accelerometers have demonstrated a favourable level of reliability for measuring PlayerLoad^{TM} during dynamic tasks (CV: 0.9 – 1.9 %; Boyd, Ball & Aughey, 2011) and peak gravitational accelerations during impacts (CV: 1.9 – 2.2 %; Kelly, Murphy, Watsford, Austin & Rennie, 2015). Accordingly, accelerometers can be used to detect changes in activity with confidence (Scott, Scott & Kelly, 2016). However, the validity of accelerometers to measure peak acceleration during high frequency movements is less favourable (CV: 28 – 35 %; Kelly et al., 2015), and consistently measured a lower magnitude of acceleration during both static and dynamic testing, compared with a criterion. Whilst caution is recommended when measuring the absolute magnitude of peak acceleration, future research exploring the agreement between accelerometer and criterion derived acceleration could inform the possibility of a correction equation to improve the validity of peak acceleration.

2.2.3 Comtemporary metrics used to monitor external load

2.2.3.1 PlayerLoad^{TM}

PlayerLoad^{TM} (also referred to as Body Load or Dynamic Stress Load) provides a summative measure of acceleration, from a tri-axial accelerometer which typically operates at 100 Hz (Vanrenterghem et al., 2017). Recent studies used PlayerLoad^{TM} to quantify typical profiles during team sports. Specifically, values ranging from 544 to 717 AU, equating to ~8.7 – 13.2 $PL{\cdot}min^{-1}$, have been reported (Gabbett, 2015; Polglaze, Dawson, Hiscock & Peeling, 2015; McLaren, Weston, Smith, Cramb & Portas, 2015). Whilst Dalen and colleagues (2016) reported higher PlayerLoad^{TM} values during football (13,327 ± 2,197 AU), differences in the calculation of PlayerLoad^{TM} (see Appendix 2.1) partly explain such differences.

Studies have demonstrated total distance covered (R^2 = 52 – 74 %; Polglaze et al., 2015; Casamichana, Castellano, Calleja-Gonzalez, San Roman & Castagna, 2013), accelerations (R^2 = 7 – 10 %; Dalen et al., 2016) and decelerations (R^2 = 5 – 7 %; Dalen et al., 2016) explain a considerable proportion of the variance in total PlayerLoad^{TM}. Decrements in total PlayerLoad^{TM} are also evident from the first half to the second half of match-play (Dalen et al., 2016), which is consistent with between-half decrements in high speed running and accelerations (Russell et al., 2016). These data demonstrate the utility of PlayerLoad^{TM} to estimate the biomechanical load of the whole body (Vanrenterghem et al., 2017), which can discriminate between different playing standards (Cormack, Smith, Mooney, Young & O'Brien, 2014). However, the ability of PlayerLoad^{TM} to reflect whole-body external load is dependent on the approach speed and angle of directional changes (Nedergaard et al., 2017), which might make comparisons of PlayerLoad^{TM} between different movement patterns inappropriate.

2.2.3.2 Metabolic Power

Metabolic power assumes that energy expenditure can be estimated based on the equivalence of an accelerating frame of reference (i.e. a runner's centre of mass) with the Earth's gravitational field (di Prampero et al., 2005). This is calculated on the assumption that the energetic cost of accelerative running is equivalent to constant speed running, up an equivalent slope, while carrying an additional mass (di Prampero et al., 2005), as detailed in Appendix 1.1.

Recently, metabolic power derived variables have been used to quantify the demands of team sports, as it can estimate the metabolic requirement of activities where speed is constantly changing (Osgnach et al., 2010). Estimated energy expenditure using metabolic power ranges from 14.4 to 65.6 $kJ \cdot kg^{-1}$ during team sport match-play (Coutts et al., 2015; Dubois et al., 2017; Kempton, Sirotic, Rampinini, & Coutts, 2015; Polglaze, Dawson, Buttfield, & Peeling, 2018a; Vescovi, 2016; Walker, McAinch, Sweeting, & Aughey, 2016). The range of values likely reflects sport and position specific movements (see section 2.2.1), and the higher metabolic requirement of collision-based activities (Highton, Mullen, Norris, Oxendale, & Twist, 2017).

Measures of average metabolic power (~5 – 11 W·kg^{-1}; Coutts et al., 2015; Dubois et al., 2017; Kempton et al., 2015; Polglaze et al., 2018a; Vescovi, 2016) and time (5.0 – 12.2 min; Coutts et al., 2015; Kempton et al., 2015; Polglaze et al., 2018a) or distance covered (571 – 1745; Dubois et al., 2017; Kempton et al., 2015; Polglaze et al., 2018a) at high metabolic power (> 20 W·kg^{-1}) have also been reported to provide an indication of the average and high-intensity energetic demands of team sports. These data reaffirm the intermittent nature of team sports and provide information on the total contribution of high intensity efforts during match-play. When comparing metabolic power to traditional variables, high metabolic power is ~ 27 – 62 % higher than high speed distance covered (Dubois et al., 2017; Hoppe, Baumgart, Slomka, Polglaze, & Freiwald, 2017; Kempton et al., 2015; Polglaze et al., 2018a), which suggests velocity categories might underestimate the high intensity demands of team sports (Gaudino et al., 2013). Accordingly, measures of metabolic power might provide a more informative alternative to analyse high intensity activity (Dubois et al., 2017; Gaudino et al., 2013). However, the validity of metabolic power may question its use within team sports.

2.2.3.3 Validity of metabolic power

Several studies have reported varying underestimations between estimated energy expenditure derived using the metabolic power approach with energy expenditure (EE) derived from $\dot{V}O_2$ during team sport activity (~15 – 57 %; Brown, Dwyer, Robertson, & Gastin, 2016; Highton, et al., 2017; Stevens et al., 2015). This variation in underestimation likely reflects differences in the intermittent nature of protocols used, as Buchheit and colleagues (2015) found the underestimation of EE was particularly prevalent during stationary recovery periods (~85 %; Buchheit, Manouvrier, Cassiram, & Morin, 2015). In theory, when athletes are stationary metabolic power derived EE would be zero as forward acceleration would be zero. This fails to consider the contribution of excess post-exercise oxygen consumption (EPOC) to the overall energy cost of exercise during stationary periods (Tabata et al., 1997). Conversely, overestimations in metabolic power derived EE have been reported during continuous constant speed running (6 – 11 %; Stevens et al., 2015), emphasising that metabolic power derived energy expenditure only accounts for the EE attributable to locomotion (Polglaze & Hoppe, 2019) and is influenced by the intermittentness of protocols. However, it is not clear how the systematic manipulation of directional changes can influence the agreement of estimated and measured EE. Furthermore, whilst time at high metabolic power has demonstrated stronger associations with an individual's internal response to exercise, compared with measures of high speed (see section 2.2.5 and Table 2.2), further research is required to investigate whether high metabolic power better reflects the internal response to running in comparison to high speed.

2.2.4 Internal demands of team sports

Average HR ranges from 156 to 172 $b \cdot min^{-1}$ during football (Aslan et al., 2012; Coelho, et al., 2010; Eniseler, 2005; Thatcher & Batterham, 2004), hockey (Lythe & Kilding, 2011), rugby league (Coutts, Reaburn & Abt, 2003; Waldron et al., 2011) and rugby union (Cunniffe et al., 2009). This equates to ~80-88 % of maximum heart rate (HR_{max}) (Aslan et al., 2012; Cunniffe et al., 2009; Dubois et al., 2017; Iacono, Martone, Cular, Milic & Padulo, 2017; Lythe & Kilding, 2011; Waldron et al., 2011) and 70-80 % of $\dot{V}O_{2max}$ (Bangsbo, Mohr & Krustrup, 2006; Coutts et al., 2003), based on the linear relationship between HR and oxygen uptake (Coelho et al., 2010). These data indicate a high reliance on aerobic metabolism during team sports.

Studies which have assessed HR in accordance with pre-defined zones have demonstrated HR typically remains above 70 % HR_{max}, whilst players spend ~19 – 51% of match time above 85 % HR_{max} (Coelho et al., 2011; Coutts et al., 2003; Dubois et al., 2017), which corresponds to the anaerobic threshold (Coelho et al., 2011; Stolen, Chamari, Castagna & Wisloff, 2005). Others have reported summated HR (e.g., 242 – 435 AU; Waldron et al., 2011), which places greater weighting on higher HRs. Measures of estimated energy expenditure based on HR have also been reported during team sports ranging from 1100 to 2000 kcal (Coelho et al., 2010; Coutts et al., 2003; Cunniffe et al., 2009; Osgnach et al., 2010). Collectively, these findings suggest team sports incur a high metabolic cost. However, estimated energy expenditure derived from GPS was lower than those reported using HR (Coutts et al., 2003; Cunniffe et al., 2009), indicating metabolic variables derived from GPS might underestimate the actual energy cost of team sport activity (see section 2.2.3.3).

Blood lactate concentration (B[La]), both during and after team sports has been reported to assess the metabolic demands from anaerobic glycolysis. Studies have documented average B[La] values between 3 – 8 $mmol{\cdot}L^{-1}$ during team sports (Aslan et al., 2012; Coutts et al., 2003; Deutsch, Maw, Jenkins & Reaburn, 1998; Krustrup et al., 2010; Krustrup et al., 2006). Typically, B[La] is lower during the second half of a match compared with the first half (2.7 – 5.9 *cf.* 4.5 – 8.4 $mmol{\cdot}L^{-1}$; Aslan et al., 2012; Coutts et al., 2003; Krustrup et al., 2010; Krustrup et al, 2006) which might be indicative of a limited availability of muscle glycogen, compromising energy turnover from glycolysis (Nielsen et al., 2012). B[La] responses after team sport activity are also dependent on position. Specifically, B[La] responses after rugby league were higher in forwards compared to backs (8.5 *cf.* 6.5 $\text{mmol}\cdot\text{L}^{-1}$; Coutts et al., 2003) and values of 3.2, 4.0 and 4.6 $\text{mmol}\cdot\text{L}^{-1}$ have been reported during a football match for the defenders, midfielders and forwards, respectively (Aslan et al., 2012). These findings reflect the differences in movement demands for specific positions within team sports (see section 2.2.1) and indicate the rate of anaerobic glycolysis during field-based team sports is high.

Borg's rating of perceived exertion (RPE) scale, ranging from 6 – 20 (Borg, 1970), and the modified session RPE scale, ranging from 0 – 10 (Foster et al. 1995), have been implemented to assess the global physical and psychological stress of the most recent exercise intensity and the whole session, respectively (Impellizzeri, Rampinini, Coutts, Sassi, & Marcora, 2004). RPE and session RPE values during team sport activity range from 10.4 – 14.8 and 4 – 7 AU, respectively (Aslan et al., 2012; Casamichana, Castellano, Calleja-Gonzalez, San Roman, & Castagna, 2013; Impellizzeri et al., 2004; Roberts et al., 2010) which corresponds to "light – hard" perceived intensity. Interestingly, a progressive increase in RPE from the first 15 minutes (10.4) to the last 15 minutes (14.5) during a football match (Aslan et al., 2012) indicates players perceived the progressive periods of the match as "harder" despite being less active in the latter periods (Russell et al., 2016). Thus, RPE values might provide a practical indication to the accumulation of fatigue during intermittent prolonged activity (Martin & Andersen, 2000), particularly given the strong associations between RPE and HR ($r = 0.74$) and RPE and B[La] ($r = 0.83$) (Scherr et al., 2013).

2.2.5 The relationship between internal and external demands

The relationship between internal and external loads in team sports has received much attention (see review by McLaren et al., 2018). Total distance covered demonstrates the strongest association with measures of session RPE (r = 0.75 – 0.81; Table 2.2) and HR (r = 0.87; Table 2.2). This likely reflects the increased metabolic energy cost required to run a greater distance (Wallace, Slattery & Coutts, 2014). Conversely, Casamichana and Castellano (2015) reported weak associations between total distance and session RPE (r = 0.24; Table 2.2), which might be explained by the use of intensity based external measures (session RPE and mean HR), compared to measures of load (which integrate intensity and duration). Specifically, a single measure of exercise intensity might underrepresent the stochastic nature of team sport movement patterns which affect perceived effort (Drust, Reilly, & Cable, 2000), whereas multiplying session RPE by duration provides a more robust index of internal load (Gaudino et al., 2015).

High speed distance covered displayed a range of associations with session RPE (r = 0.34 – 0.75; Table 2.2) and HR (r = 0.44 – 0.72; Table 2.2), which might reflect the limited ability of session RPE and HR to reflect efforts performed at supramaximal intensity (Casamichana et al., 2013; Alexandre et al., 2012). Indeed, as the duration between high speed efforts can influence HR (Brown & Glaister, 2014), and perceived effort (Little & Williams, 2007), the intermittent nature of exercise has demonstrated some ability to modulate the relationship between internal and external demands (see Table 2.2; McLaren et al., 2018). Conversely, acceleration-based metrics (i.e. number of accelerations, metabolic power and PlayerLoad^{TM}) demonstrated stronger associations with internal metrics (r = 0.63 – 0.92; Table 2.2) when compared with high speed distance covered. Recent studies have shown high speed metrics can underestimate the high intensity demands of team sports (Akenhead et al., 2014; Gaudino et al., 2013), given the numerous acceleration and deceleration actions performed (see section 2.2.1). In addition, running with an increased number of directional changes and accelerations increases B[La] (20.3 – 32.7 %; Ashton & Twist, 2015; Dellal et al., 2009), RPE (9.4 – 66.7 %; Ashton & Twist, 2015; Dellal et al., 2009; Tang et al., 2018), HR (Tang et al., 2018) and $\dot{V}O_2$ ($R^2 = 0.95$; Hatamoto et al., 2013) in comparison to in-line running with fewer directional changes. The large propulsive and braking forces applied by the lower limbs to the ground during directional changes (Hewit, Cronin, Button & Hume, 2011), result in a greater muscle activation during accelerations/decelerations (Besier et al., 2003) and might explain the higher metabolic demands associated with an increased number of accelerations. These data highlight the potential application of acceleration-based metrics to reflect the internal demands of team sport activity. However, the ability of PlayerLoad^{TM} to reflect internal physiological load (Vanrenterghem et al., 2017) and the accuracy of metabolic power derived variables (see section 2.2.3.3) remains unclear. Thus, further research examining the ability of accelerometer-based metrics to reflect internal load are warranted.

Table 2.2 Relationship between internal and external load during team sports

Study	Total distance (m)	High speed (HS) distance (m)	Accelerations/ decelerations (n)	Metabolic power/ PlayerLoad^{TM} (MP/PL)	Comments
Session RPE					
Casamichana et al. (2013)	*r* = 0.74*	*r* = 0.64*		PL: *r* = 0.76*	Correlated with sRPE during soccer training
Scott et al. (2013)	*r* = 0.81*	*r* = 0.71*	-	PL: *r* = 0.83*	Correlated with sRPE x training duration during soccer training.
Weaving et al. (2014)	-	*r* = 0.75* (SSG) *r* = 0.34 (CON)	-	-	Correlated with sRPE x training duration during rugby league small sided games (SSG) and conditioning (CON)
Casamichana & Castellano (2015)	*r* = 0.24	*r* = 0.13		PL: *r* = 0.14	Correlate with sRPE during 7 v 7 SSG soccer
Gaudino et al. (2015)	-	*r* = 0.61*	*r* = 0.631*	-	Correlated with sRPE x training duration during soccer training
Bartlett et al. (2017)	ρ = 0.77*	ρ = 0.69*	-	-	Correlated with sRPE during Australian football.
Delaney et al. (2018)	*r* = 0.75 ± 0.06	*r* = 0.61 ± 0.22	*r* = 0.79 ± 0.07	HP: *r* = 0.77 ± 0.09	Correlated with sRPE x training duration during rugby league training

Continued on next page

Table 2.2 Continued

Study	Total distance (m)	High speed (HS) distance (m)	Accelerations/ decelerations (n)	Metabolic power/ PlayerLoad^{TM} (MP/PL)	Comments
Jaspers et al. (2018)		IS = 0.507	Accels: IS = 0.515 Decels: IS = 0.51	PL: IS = 0.487	IS derived from advanced linear regression, to predict sRPE
HR					
Casamichana et al. (2013)	-	r = 0.37	-	PL: r = 0.72	Correlated with Edwards summated HR during soccer training
Weaving et al. (2014)	-	r = 0.52* (SSG) r = 0.44 (CON)	-	-	Correlated with iTRIMP during rugby league small sided games (SSG) and conditioning (CON)
Casamichana & Castellano (2015)	r = 0.267	r = 0.21	-	PL: r = 0.14	Correlated with average HR during 7 v 7 SSG soccer
Delaney et al. (2018)	r = 0.87 ± 0.06	r = 0.67 ± 0.24	r = 0.88 ± 0.06	HP: r = 0.92 ± 0.09	Correlated with iTRIMP during rugby league training.
Polglaze et al. (2018b)	-	CS: r = 0.719*		CP: r = 0.867*	Correlated with time above 85% HRmax during hockey matches.

r denotes a correlation coefficient, HP = high metabolic power, ρ = Spearmans rank correlation matrix, IS = Importance score, CS = critical speed and CP = critical power, accels = accelerations, decels = decelerations, sRPE = session RPE, iTRIMP = individual training impulse, SSG = small sided games, CON = conditioning, HRmax = maximum heart rate, MP = metabolic power, PL = PlayerLoad^{TM}

Given the relationship between external and internal load, integrated ratios (i.e. external load divided by internal load), also referred to as the efficiency index (Torreño et al., 2016), have been used to assess the dose-response relationship between training and psychophysiological responses (Akubat, Barrett & Abt, 2014). Aerobic capacity during football has demonstrated stronger associations with the ratio of internal (HR) to external (high speed distance) load (r = 0.58 – 0.69) compared with external markers alone (r = 0.14 – 0.28). Similarly, the ratio of internal (HR) to external (high speed, PlayerLoad^{TM} and high metabolic power) load demonstrated moderate to strong associations (r = 0.54 – 0.72; Akubat, Barrett, Sagarra & Abt, 2018; Delaney et al., 2018; Taylor, Sanders, Myers & Akubat, 2017) with changes in aerobic capacity. The ratio of external to internal load can also detect changes in physical performance over the course of a match and between different playing positions (Torreño et al., 2016). The use of an external to internal ratio has therefore been advocated to assess an individual's responses to prescribed training (Delaney et al., 2018; Akubat et al., 2018), but might also be useful to examine the extent external load reflects internal load between exercise modalities. For example, an increase in HR during a small-sided game compared to sprint interval training might also be accompanied by an increase in accelerations, and therefore the ratio between these two exercise modalities should not be different.

2.3 Mechanisms and symptoms of fatigue and muscle damage in team sports

Due to the high-intensity, intermittent nature of team sport activity (see section 2.2.1), fatigue, characterised by a reversible reduction in maximal force, power or speed that is associated with a decline in performance, can occur whether or not the task can be continued (Bishop, 2012; Enoka & Duchateau, 2008). In team sports, fatigue occurs temporarily after short intense periods (Black, Gabbett, Naughton & McLean, 2016), towards the end of a match (Akenhead et al., 2013) and immediately afterwards (McLellan, Lovell & Gass, 2011; Rampinini et al., 2011). Fatigue can recover quickly (within hours) after team sport activity (Carroll, Taylor & Gandevia, 2017), whereas muscle damage; accompanied by myofibrillar structural damage, takes longer (Finsterer, 2012) and is therefore discussed separately (see section 2.3.2). The cause of fatigue cannot be attributed to one factor; instead, it is because of several central and peripheral mechanisms, which relate to fatigue through processes proximal and distal to the neuromuscular junction, respectively (Minett & Duffield, 2014). This can range from a reduced central motor drive, limiting the ability to recruit available motor units, to the accumulation of metabolites within the muscle, reducing the muscle's ability to perform work (Girard, Mendez-Villanueva & Bishop, 2011). The possible mechanisms of fatigue that accompany team sport activity have been reviewed extensively (see Girard et al., 2011; Minett & Duffield, 2014; Waldron & Highton, 2014), therefore this section briefly details these mechanisms.

2.3.1 Fatigue

2.3.1.1 Mechanisms of fatigue

2.3.1.1.1 Central factors

The central nervous system (CNS) plays a vital role in regulating muscle contraction (Noakes, Gibson & Lambert, 2005). Fatigue associated with a failure of the physiological systems proximal to the neuromuscular junction (i.e. the CNS), is termed 'central fatigue' (Gandevia, 2001). Muscle contraction associated with sprint exercise requires an increased neural drive (Ross, Leveritt & Riek, 2001); therefore, a reduction in neural drive will impair neuromuscular function and performance (Girard, Lattier, Maffiuletti, Micallef & Millet, 2008). Typically, researchers have measured a decline in maximal voluntary contraction torque compared to that elicited by peripheral electrical stimulation (Goodall, Charlton, Howatson, & Thomas, 2015; Minett et al., 2014; Tomazin, Morin, & Millet, 2017), and/or a reduced electromyography signal amplitude (Medez-Villanueva, Hamer, & Bishop, 2008; Medez-Villanueva, Hamer, & Bishop, 2007) to demonstrate reduced central drive and therefore central fatigue, after repeated sprint exercise (~6 – 8%; Table 2.3). Some studies have also assessed EMG responses to transcranial magnetic stimulation and have reported no differences after repeated sprint running exercise (Brownstein et al., 2017; Goodall et al., 2015), whereas reductions in voluntary activation with transcranial magnetic stimulation have been reported (~9%; Goodall et al., 2015). Whilst the current mechanisms of central fatigue remain unclear, these data suggest central fatigue after repeated sprint exercise is due to spinal factors (i.e. inhibition of motor neurons' excitability due to neutrally transmitted afferent feedback from the muscles; Davis & Bailey, 1997) and to a lesser extent, supraspinal factors (i.e. corticospinal excitability; Collins, Pearcey, Buckle, Power, & Button, 2018). Compared with peripheral fatigue, central fatigue tends to occur later during repeated sprint exercise (Goodall et al., 2015; Monks, Compton, Yetman, Power, & Button, 2017) and may act as a protective mechanism to limit further increases in peripheral fatigue.

2.3.1.1.2 Peripheral fatigue

Fatigue through processes at or distal to the neuromuscular junction is typically referred to as peripheral fatigue (Gandevia, 2001). After intense exercise, marked disturbances in intracellular sodium (Na^+) and both intracellular and extracellular potassium (K^+) concentration have been associated with muscle fatigue (Allen, Lamb,

& Westerblad, 2008a; Cairns & Lindinger, 2008; Fowles, Green, Tupling, O'Brain, & Roy, 2002). Specifically, the Na^+/K^+ pump is unable to reverse the K^+ efflux from the working muscles, leading to a two-fold increase in the extracellular K^+ (Cairns & Lindinger, 2008; Juel, Pilegaard, Nielsen, & Bangsbo, 2000). These disturbances produce a depolarization and reduce the chemical gradient of Na^+, which can lead to an inactivation of voltage gated Na^+ channels and reduce the amplitude of action potentials (Nielsen & Calusen, 2000) and corresponding M-wave amplitude (evoked by stimulus to the motor nerve). Whilst some have reported an increase in M-wave amplitude after team sport activity (Perrey, Racinais, Saimouaa & Girard, 2010), most report no change (Brownstein et al., 2017; Girard et al., 2008; Thomas, Dent, Howatson, & Goodall, 2017; Tomazin et al., 2017) indicating sarcolemma excitability plays little role in fatigue after team sport activity. Conversely, reductions in evoked twitch torque after repeated sprint running (Girard et al., 2008; Thomas et al., 2017; Tomazin, Morin, & Millet, 2017) highlight a failure of excitation-contraction coupling, likely related to impaired sarcoplasmic reticulum activity (Mador, Kufel, Pineda, & Sharma, 2000) and/or the accumulation of intramuscular metabolites (e.g. Pi and H+; Fitts, 1994). Whilst the specific mechanism is still debated, the accumulation of intracellular hydrogen ions (H^+) and lactate, because of glycolytic ATP re-synthesis has been associated with fatigue (Kayser, 2010), lowers the muscle pH and might reduce muscle force by decreasing calcium (Ca^2) release from the sarcoplasmic reticulum, decreasing the sensitivity of troponin to Ca^{2+} and interfering with cross-bridge cycling (Stackhourse, Reisman, & Binder-Macleod, 2001). Increases in inorganic phosphate (Pi), caused by the increased breakdown of phosphocreatine (PCr), can also reduce sarcoplasmic reticulum Ca^{2+} release and Ca^{2+} sensitivity (Allen et al., 2008a), resulting in less active cross-bridges and subsequent a decline in muscle function (Allen et al., 2008b). The accumulation of Pi is therefore considered a major contributor towards muscular fatigue during and after repeated sprint running (Glaister, 2005; Westerblad, Allen & Lannergren, 2002). Limited availability of PCr stores used to re-synthesis ATP have also been suggested to limit repeated sprint performance (Bishop, 2012; Mendez-Villanueva, Edge, Suriano, Hamer, & Bishop, 2012), albeit this has largely been assessed during cycling.

2.3.1.2 Sex-related differences in fatigue

During isometric and slow velocity dynamic contractions, females are typically less fatigable than males (Ansdell et al., 2020; Harmer et al., 2014; Hunter, 2016; Hunter, 2014; Yoon et al., 2015). The specific mechanism is related to sex differences in muscle Ca^{2+} regulation; as females possess a greater proportional area of type 1 muscle fibres than males (Miller, MacDougall, Tarnopolsky, & Sale, 1993) and slower rates of sarcoplasmic reticulum Ca^{2+} reuptake compared with males (Harmer et al., 2014; Hunter, 2014; Yoon et al., 2015), causing a slower rate of relaxation in females. Large absolute contractions exerted by males can also limit blood flow (and therefore oxygen supply) more rapidly in males leading to a more rapid accumulation of metabolites and rate of muscle fatigue (Hunter 2016; Hunter, 2009). Conversely, supraspinal fatigue (measured from motor evoked potentials from transcranial magnetic stimulation) is similar between males and females, which suggests activation of the motor neuron pool are similar in males and females with fatigue (Temesi et al., 2015; Yoon et al., 2015). During high velocity dynamic contractions, differences in fatigue between the sexes are diminished (Senefeld, Yoon, Bement, & Hunter, 2013). A possible explanation is differences in energy utilization as the greater proportion of type 1 muscle fibres in females require larger increases in energy utilization compared with type 2 muscle fibres (Hunter, 2016). These data highlight males and females can respond differently to a fatiguing task at the same relative intensity during isometric and slow velocity contractions, largely via peripheral compared with central mechanisms, and that generally females are less fatigable than males. More studies using females to assess muscle fatigability and performance under differing task conditions are warranted given, to date, many studies assessing fatigue have used proportionally more males than females (Hunter, 2014).

2.3.1.3 Markers of fatigue after team sport activity

A variety of markers have been used to monitor fatigue after team sport activity (Nedelec et al., 2012). Whilst it has been recommended that practitioners assess a combination of these markers regularly to accurately monitor individual responses to a given training stimulus (Wiewelhove et al., 2015), measures of neuromuscular function are typically used within a team sport environment (Twist & Highton, 2013). Specifically, measures of sprint performance (Brownstein et al., 2017; Duffield et al., 2019; Lovell, Midgley, Barrett, Carter & Small, 2011; Rampinini et al., 2011), CMJ (Brownstein et al., 2017; Duffield et al., 2019) and isolated maximal voluntary strength (Behan et al., 2018; Brownstein et al., 2017; Goodall et al., 2017; Nedelec et al., 2012) are often used to monitor fatigue after team sport activity (see Table 2.3), which are briefly discussed below.

2.3.1.3.1 Sprint and CMJ performance

A ~3 – 7 % impairment in sprint performance is evident after prolonged intermittent activity (see Table 2.3). Typically, short sprint distances of 20 m are assessed given that short sprint performance is an important aspect of success in team sports

(Nedelec et al., 2012), and can provide insight into task-specific fatigue (Gathercole, Sporer, Stellingwerff, & Sleivert, 2015; Twist & Highton, 2013). Furthermore, sprint performance assessed with infrared timing gates over short distances (10 – 30 m) offers a reliable measurement (CV = 1.0 – 1.5 %; Waldron, Worsfold, Twist & Lamb, 2011), meaning small decrements in neuromuscular function because of fatigue can be accurately monitored before and after team sport activity. Similar reductions (~3 – 4 %) in repeated sprint performance are also evident after team sport activity (see Table 2.3). However, given that repeated sprint tests can be physically exhausting, previous research has typically incorporated fewer sprints than those implemented within repeated sprint tests to allow for easy implementation during the recovery process (Nedelec et al., 2012).

In contrast to the narrow range of changes observed in sprint performance, the reported decrements observed in CMJ peak power (no change to a 41 % reduction) and CMJ height (2 – 12 % reduction) after team sport activity are varied (see Table 2.3). Such variation might be indicative of the ‘task dependency’ of fatigue, i.e., the degree of fatigue experienced is dependent on the task performed (Girard et al., 2011). Discrepancies amongst the literature might also be partly due to differences in the CMJ protocol used. For example, systematic overestimations in jump height have been reported when using a jump mat compared with a force platform (Dobbin, Hunwicks, Highton, & Twist, 2017; Rogan, Radlinger, Imhasly, Kneubuehler, & Hilfiker, 2015), suggesting CMJ values obtained using different equipment are not interchangeable. When fatigue markers are compared, measures of 20 m sprint performance are more repeatable than CMJ performance (CV: ~1 – 3 % *cf.* ~3 – 5 %; Carr, McMahon, & Comfort, 2015; Gathercole et al., 2015).

2.3.1.3.2 Maximal voluntary contraction

Typically, reductions of 7 – 14 % in maximal isometric strength, 7 – 17 % in concentric strength and 15 – 31 % in eccentric strength have been reported after team sport activity (see Table 2.3). Notably, the hamstrings are more susceptible to decrements in strength after team sport activity compared to the quadriceps (see Table 2.3; Ashton & Twist, 2015; Delextrat et al., 2010; Magalhães et al., 2010). Decrements in MVC are also largely dependent on the task being performed, as greater reductions in MVC have been observed from studies incorporating a greater volume of high-speed running (e.g. Magalhães et al., 2010 *cf.* Ashton & Twist, 2015), more time spent on the field (r = -0.5; Duffield et al., 2012) and running with more directional changes (~17.9 % *cf.* ~5.9 %; Ashton & Twist, 2015).

Table 2.3 Measures of neuromuscular fatigue after team sport activity

Study	Sport/Exercise	Participants	Pre to post change in marker		
			Sprint performance	CMJ	MVC at knee joint
Ronglan et al. (2006)	Handball match	7 elite females	~4 % ↑ in 20 m sprint time	8.4% ↓ in CMJ height	6.9 % ↓ in peak CON extensor torque at 60 º·s^{-1}
Ascensão et al. (2008)	Soccer match	16 elite males	~7 % ↑ in 20 m sprint time	-	~ 10 % ↓ in peak CON extensor torque at 90 º·s^{-1}
Delextrat et al. (2010)	LIST	8 male University level soccer players	-	-	16.6 % ↓ in peak CON extensor torque 17.7 % ↓ in peak CON flexor torque 31.4 % ↓ in peak ECC flexor torque at 60 º·s^{-1}
Krustrup et al. (2010)	Soccer match	14 elite females	~4 % ↑ in 3 x 20 m sprint time with 25 s rest	NS	-
Magalhães et al. (2010)	LIST	16 elite male soccer players	~5 % ↑ in 20 m sprint time	~12 % ↓ in CMJ height	~15 % ↓ in peak CON flexor torque and ~11 % ↓ in peak CON extensor torque at 90 º·s^{-1}
Small et al. (2010)	SAFT^{90}	16 semi-professional males	-	-	16.8 % ↓ in peak ECC flexor torque NS change in peak CON flexor and extensor torque
Thorlund et al. (2010)	Soccer match	9 young elite males	-	2.1 % ↓ in CMJ height	~11 % ↓ in peak ISO extensor torque and ~7 % ↓ in peak flexor torque at 70º

Continued on next page

Table 2.3 Continued

Study	Sport/Exercise	Participants	Pre to post change in marker		
			Sprint performance	CMJ	MVC at knee joint
McLellan et al. (2011)	Rugby league	17 elite males	-	~23 % ↓ in peak force and ~41 % ↓ in peak power	
Rampinini et al. (2011)	Soccer match	22 young elite males	~3 % ↑ in 2 x 20 m sprint time	-	~11 % ↓ in peak ISO extensor torque at 90º and ~8 % ↓ in %VA using electrically evoked stimuli
Twist & Sykes (2011)	Simulated rugby league match	10 University level males	-	~10 % ↓ in CMJ height	13.6 $N{\cdot}m^{-1}$ ↓ in CON peak flexor torque and 26.2 $N{\cdot}m^{-1}$ ↓ in peak CON extensor torque at 60 $^{o}{\cdot}s^{-1}$
Duffield et al. (2012)	Rugby league match	11 amateur males	-	4.8 % ↓ in CMJ height	8.4 % ↓ in peak ISO extensor torque at 90º flexion
Dittrich et al. (2013)	40 min of intermittent treadmill running	12 male trained endurance athletes	-	-	~14 % ↓ in peak ISO extensor torque at 60º
Timmins et al. (2014)	3 sets of 6 x 20 m sprints	17 recreationally active men	-	-	~15 % ↓ in ECC peak flexor torque from 90 to 5º and ~10 % ↓ in CON peak flexor torque from 5 to 90º
Ashton & Twist (2015)	30 min of LIST over 10 m shuttles	10 female university level netball players	~4.9 % ↑ in 20 m sprint time	-	~17.9 % ↓ in peak CON flexor torque at 60 $^{o}{\cdot}s^{-1}$. NS change in peak CON extensor torque

Continued on next page

Table 2.3 Continued

Study	Sport/Exercise	Participants	Pre to post change in marker		
			Sprint performance	CMJ	MVC at knee joint
Johnston et al. (2015)	Rugby league match	21 sub-elite youth males	-	~5 – 7 % ↓ in CMJ peak power	-
Goodall et al. (2015)	12 x 30 m sprints	12 males intermittent sprint sport players			~12 % ↓ in peak isometric extensor torque. ~23 % ↓ potentiated twitch force and ~9 % ↓ in VA with transcutaneous muscle stimulation. ~ 15 % ↓ in potentiated quadricep twitch force
Brownstein et al. (2017)	Competitive soccer match	16 semi-professional soccer players	~4 % ↑ in 20 m sprint time	~5 % ↓ in CMJ height	~14 % ↓ in peak isometric extensor torque. ~7% ↓ in VA with motor nerve stimulation and ~5 % ↓ in VA with motor cortical stimulation. ~14 % ↓ in potentiated quadricep twitch force
Goodall et al. (2017)	Simulated soccer exercise	10 amateur football players	-	-	~11 % and ~20 % ↓ in extensor MVC at half time and full time, respectively.
Behan et al. (2018)	90 min of LIST	15 male team sport players	-	-	~12 % ↓ in peak isometric extensor torque and ~15 % in peak flexor torque
Duffield et al. (2019)	Rugby union match	22 professional male rugby union players	~3 % ↓ in 30 m sprint speed	~10 % ↓ in CMJ height	-

Continued on next page

Table 2.3 Continued

Study	Sport/Exercise	Participants	Pre to post change in marker		
			Sprint performance	CMJ	MVC at knee joint
Mullen et al. (2019)	23 min rugby movement simulation	20 male rugby players	-	-	~12 % ↓ in peak isometric extensor torque and ~6 % ↓ in %VA using electrically evoked stimuli

CMJ = counter-movement jump, MVC = maximum voluntary contraction, CON = concentric, ISO = isometric, VA = voluntary activation, NS = non-significant, LIST = Loughborough intermittent shuttle test, SAFT^{90} = soccer-specific aerobic field test, ↑ = increase, ↓ = decrease

Marked reductions in voluntary activation using electrically evoked stimuli to the muscle (~6 – 8 %) and using transcranial magnetic stimulation (~5 – 9 %) have been reported after team sport activity (see Table 2.3). These data suggest substantial deficits in CNS function are evident after team sport activity (Rampinini et al., 2011; Thorlund, Michalsik, Madsen & Aagaard, 2008), which can be attributed to spinal and supraspinal fatigue assessed by electrical stimulation of the muscle and transcranial stimulation, respectively. The observed decrease in force output of the muscle in response to electrical stimulation (~14 – 15 %; Brownstein et al., 2017; Goodall et al. 2015), also indicates the presence of peripheral fatigue. Taken together, fatigue after team sport activity, evident by reductions in MVC, CMJ and sprint performance, can be attributed to both central and peripheral factors.

Whilst the use of isometric and isokinetic dynamometry to assess neuromuscular function after team sport performance has been criticized for a lack of ecological validity (Twist & Highton, 2013), it can provide a favourable level of relative reliability for measurements of peak torque at the knee (ICC: 0.85 – 0.93; Hartmann, Knols, Murer, & de Bruin, 2009; Lund et al., 2005; Symons, Vandervoort, Rice, Overend, & Marsh, 2005; Timmins et al., 2014) and an acceptable coefficient of variation (CV: 3.8 – 6.1 %) for isometric and isokinetic contractions at a variety of speeds (Almosnino, Stevenson, Bardana, Diaconescu, & Dvir, 2012; Ferri-Morales, Alegre, Basco, & Aguado, 2014). Measurements of neuromuscular function using dynamometry before and after exercise can therefore be used to assess neuromuscular fatigue (Minshull, Gleeson, Walters-Edwards, Eston, & Rees, 2007), but might be difficult to implement in applied practice (see section 2.3.3).

2.3.2 Exercise-induced muscle damage

Exercise-induced muscle damage (EIMD) is a common phenomenon that typically occurs both immediately and for several days after team sport activity (Gastin, Hunkin, Fahrner, & Robertson, 2019; Howatson & Milak; 2009; Nedelec et al., 2014; Oxendale et al., 2016; Twist & Sykes, 2011). The symptoms of EIMD include stiffness and swelling of the muscles, a decreased force of muscular contraction and delayed onset muscle soreness (Byrne, Twist, & Eston, 2004). Whilst the exact mechanisms that contribute to EIMD are not fully understood, previous research has divided this phenomenon into two general areas; the initial primary damage, both metabolic and mechanical, and secondary damage associated with the inflammatory response (Hydahl & Hubal, 2014; Owens, Twist, Cobley, Howatson, & Close, 2019; Peake, Neubauer, Della Gatta, & Nosaka, 2017; Tee, Bosch & Lambert, 2007). This section briefly details the current known mechanisms of muscle damage and neuromuscular markers which have been used to assess the magnitude of damage after team sport activity.

2.3.2.1 Mechanisms of muscle damage

Mechanical disruption relates to damage that occurs from mechanical loading on the myofibers (Howatson & Van Someren, 2008; Hydahl & Hubal, 2014; Peake et al., 2017). The weakest sarcomeres are located at different regions of each myofibril, and it is believed the non-uniform lengthening of these sarcomeres during eccentric muscle contractions results in some myofibers being over-stretched and thus are no longer able to overlap (Talbot & Morgan, 1996). Consequently, the longest sarcomeres become weaker, and passive structures assume more tension (Howatson & Van Someren, 2008) and undergo what is termed ‘popping’ (Morgan, 1990). This encompasses a shearing of myofibrils, exposing membranes, especially t-tubules, to large deformations (Morgan & Proske, 2004) causing Z-line streaming (Fridén, Sjöström, & Ekblom, 1983; Newham, McPhail, Mills, & Edwards, 1983). This leads to disruption of myofiber damage, membrane disruption, opening of stretch activated channels and subsequently excitation-contraction (E-C) coupling dysfunction (see Figure 2.1; Hydahl & Hubal, 2014; Owens et al., 2019; Peake et al., 2016). E-C coupling involves a sequence of events that starts with the release of acetylcholine at the neuromuscular junction and ends with the release of Ca^{2+} from the sarcoplasmic reticulum (Warren, Ingalls, Lowe, & Armstrong, 2001). Increased influx of Ca^{2+} into the muscle cell through stretch-activated channels stimulate calpain (Zhang, Yeung, Allen, Qin, & Yeung, 2008) which degrades contractile or excitation-contraction coupling proteins (i.e. desmin; Peake et al., 2017) resulting in inhibition of the interaction of actin and myosin (Szent-Györgyi, 1975) and prolonged loss of muscle strength (Hydahl & Hubal, 2014). Specifically, E-C coupling failure is thought to account for 57 – 75% of strength loss after muscle damaging exercise (Warren et al., 2001).

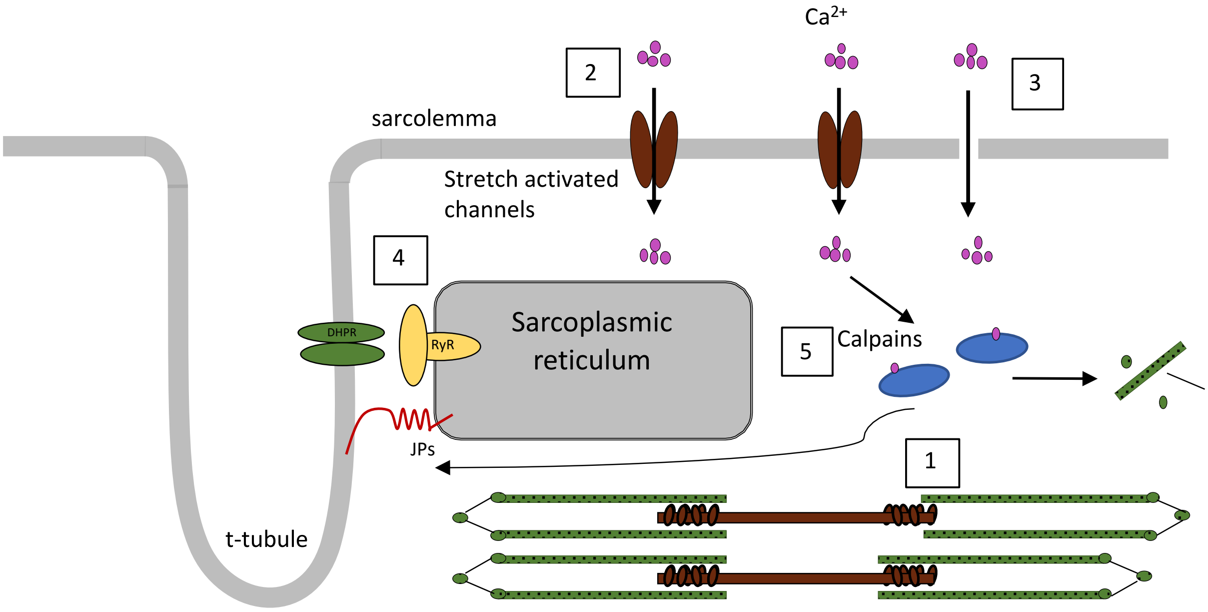


Figure 2.1. Potential molecular mechanisms of muscle damage after eccentric actions (Adapted from Hydahl & Hubal, 2014). (1) Overstretched sarcomeres, (2) opening of stretch activated channels, (3) EC coupling dysfunction, (4) influx of extracellular calcium and (5) calcium activated calpains.

The metabolic stress model proposes that the initial events of muscle damage are caused by metabolic deficiencies within the working muscle. During exercise, metabolic flux through the glycolytic and oxidative metabolic pathways is increased to match the increased rate of adenosine triphosphate (ATP) synthesis (Krisanda, Moreland, & Kushmerick, 1988). However, ATP concentrations could decrease to concentrations sufficiently low enough to induce muscle damage, particularly in the presence of glycogen depletion (Tee et al., 2007). The proposed mechanism for metabolic muscle injury would be a decreased action of the calcium adenosine triphosphatase (ATPase), compromising the removal of calcium (Tee et al., 2007). An increase in hydrogen ions, affecting the ability of the sarcoplasmic reticulum to take up calcium (Kendall & Eston, 2002), insufficient mitochondrial respiration and oxygen free radial production (Armstrong, 1990) have also been proposed to cause the initial stimulus for damage. However, metabolic factors are unlikely causes of muscle damage after eccentrically biased exercise, which have a lower metabolic cost when compared with concentric actions (Howatson & Van Someren, 2008). Furthermore, EIMD is minimal after concentric vs. eccentric contractions (Lavender & Nosaka, 2006; Newham, McPhail, Mills, & Edwards, 1983). Accordingly, mechanical loading is more likely responsible for EIMD (Owen et al., 2019; Proske & Morgan, 2001).

The secondary phase of muscle damage is initiated by the aforementioned disruption of intracellular calcium homeostasis (Howatson & Someren, 2008). This can trigger proteolysis (the breakdown of structural proteins) and facilitate breakdown of the damaged fibres (Gissel, 2005; Proske & Allen, 2005). The subsequent inflammatory cascade, in which damaged areas are invaded by leucocytes, in particular neutrophils and macrophages (Tidball, 2004), is necessary to clear damaged tissue and initiate tissue repair and adaptation (Chazaud, 2016). Specifically, leucocytes primarily perform three functions: attack and breakdown of debris, removal of cellular debris and regeneration of cells (Kendall & Eston, 2002; Paulsen, Mikkelsen, Raastad, & Peake, 2012). In doing so, neutrophil activation can release high concentrations of cytolytic and cytotoxic molecules that can exacerbate existing muscle damage; and is hence, a secondary damage process (Nguyen & Tidball, 2003; Tiddus, 1998). It is commonly believed that micro trauma of myofibers and the subsequent inflammation is responsible for delayed on-set muscle soreness (DOMS) (Damas, Nosaka, Libardi, Chen & Ugrinowitsch, 2016; Peak et al., 2017; Proske & Allen, 2005). Recent reviews have also highlighted a new potential mechanism for DOMS, in which activation of nerve growth factor and glial cell-lined-derived neurotrophic factor produced by muscle fibres and/or satellite cells, directly or in-directly stimulate nociceptors (Mizumura & Taguchi, 2016; Peak et al., 2017).

2.3.2.2 Sex-related differences in EIMD

Females might have some resistance to EIMD compared with males, due to the mitigating effect of oestrogen on muscle damage, disruption and inflammation (Tiidis, 2005). Specifically, oestrogen is a strong antioxidant and has the potential to stabilize the membrane of skeletal muscle cells during exercise, which could help protect females from EIMD and promote repair (Hubal & Clarkson, 2009). However, studies have reported no sex differences in muscle function after muscle damaging exercise (Borsa & Sauers, 2000; Sayer & Clarkson, 2001), and no differences in markers of EIMD in female oral contraceptive pill users (who displayed lower oestrogen concentrations) compared with female non-contraceptive pill users (Hicks, Onambele, Winwood & Morse, 2017). Taken together, current literature would suggest sex does not influence post-exercise indices of muscle damage (Hubal & Clarkson, 2009).

2.3.2.3 Markers of muscle damage after team sport activity

The symptoms of EIMD can persist up to 7 days after team sport activity (Gastin et al., 2019; Hughes, Denton, Lloyd, Oliver & De Ste Croix, 2018; Keane et al., 2015; McLellan et al., 2011; Oxendale et al., 2016; Souglis, Bogdanis, Chryssanthopoulos, Apostolidis, & Geladas, 2018), the magnitude of which is dependent on match demands, such as the number of sprints (Coppalle et al., 2019; Oxendale et al., 2016; Thorpe & Sunderland, 2012; Varley et al., 2017), accelerations (de Hoyo et al., 2016; Oxendale et al., 2016; Varley et al., 2017) and decelerations (de Hoyo et al., 2016; Oxendale et al., 2016). Direct measurements of muscle damage using electron or light microscopy to analyse myofibrillar disruption of a muscle biopsy sample (Gibala et al., 2000; Stupka, Tarnopolsky, Yardley, & Phillips, 2000) are typically used as a gold standard measure of muscle damage (Paulsen et al., 2010). However, given the invasive nature of a muscle biopsy, markers of DOMS, biochemical blood markers and measurements of muscle function, have been used to indirectly measure the magnitude and time course of muscle damage after team sport activity (see Table 2.4), which typically peaks after 24 – 48 h (Howatson & Milak, 2009; Keane et al., 2015; Leeder et al., 2014; Nedelec et al., 2014).

Measurements of MVC have been advocated to provide the most effective in-direct method of assessing the magnitude and duration of EIMD (Damas et al., 2016; Warren, Lowe, & Armstrong, 1999). However, the assessment of MVC can be impractical and can lack ecological validity, as the angular speeds used to assessed MVC are much lower than those observed during multi-joint actions like sprinting (60-300 *cf.* $970°\cdot s^{-1}$; Nedelec et al., 2012). Instead, the use of dynamic movements utilising the stretch-shortening cycle (i.e. CMJ and 20 m sprint performance) have been recommended for the routine assessment of muscle damage after sport specific exercise (Wiewelhove et al., 2015), given the utility, specificity and reliability of these measurements (Twist & Highton, 2013; Komi, 2000). Specifically, 20 m sprint performance has demonstrated greater reliability when compared with CMJ performance (CV: 0.9 ± 0.1 *cf.* 3.0 ± 1.1 %; Gathercole et al., 2015) and might therefore be more sensitive to small changes in neuromuscular function. Creatine kinase (CK) concentration is a simple diagnostic marker of EIMD and DOMS provides a reflection of inflammation within the extracellular matrix, and is associated with EIMD (Damas et al., 2016; Peake et al., 2017; Silva et al., 2018; Wiewelhove et al., 2015). Specifically, DOMS is easy to use, cost effective and sensitive to inflammatory responses to muscle damage (Peak et al., 2017; Silva et al., 2018) and CK reflects mechanical sarcomere damage in the muscle (Brancaccio, Maffulli & Limongelli, 2007; Wiewelhove et al., 2015). Accordingly, the subsequent section briefly details in-direct markers of muscle damage (consisting of sprint performance, CK concentration and muscle soreness) 24 – 48 h after over-ground team sport activity, to identify what factors (if any) mediate muscle damage after team sport activity. More extensive recent reviews documenting muscle damage after team sport activity are available elsewhere (Doeven, Brink, Kosse, & Lemmink, 2018; Hagstrom & Shorter, 2018).

2.3.2.3.1 Sprint and CMJ performance

An impairment of ~1 – 5 % in short sprint performance was evident 24 – 48 h after team sport activity in most studies (see Table 2.4). A loss of muscle strength (Khan et al., 2016) and a reduced reflex sensitivity during the stretch-shortening cycle (Avela, Kyröläinen, Komi, & Rama, 1999) likely explain the reduced sprint performance. Yet, two studies indicated no change in sprint performance at 24 h (Table 4), which might in part be explained by the high between match variation in high intensity actions performed during a soccer match (CV: 16.2 – 30.8 %; Gregson et al., 2010) and the association between markers of muscle damage and high intensity actions performed during a team sport match (Jones et al., 2014; Oxendale et al., 2016). Similarly, whilst small improvements in CMJ performance at 24 h were observed in comparison to measurements made immediately after match-play (McLellan et al., 2011; Magalhäes et al., 2010; Twist & Sykes, 2011), decrements in CMJ performance were evident at 24 h (4 – 27 %; Table 2.4). Whilst this suggests rapid stretch-shortening cycle movements can be impaired after intermittent team sport activity, Byrne and Eston

(2002) showed a squat jump was affected to a greater extent than a CMJ after EIMD (91.6 *cf.* 95.2 % of pre-exercise values). These data demonstrate stretch-shortening cycle movements can attenuate the effect of EIMD (Byrne & Eston, 2002) and might partly explain the small improvement in CMJ performance at 24 h (Table 2.4). The range of decrements in CMJ performance observed can be attributed to the different demands of team sport matches. Specifically, moderate relationships between the number of hard changes of direction ($r = -0.47$; Nedelec et al., 2014) and decelerations ($r = -0.47$; de Hoyo et al., 2016) performed during a soccer match with CMJ performance decrement at 24 – 48 h, have been reported. Collectively, these findings suggest an increase in the number of high intensity actions performed during team sport activity can cause greater decrements in explosive movements of sprinting and jumping in the days after.

2.3.2.3.2 Creatine kinase concentration

Creatine kinase-MM (an isoform of the enzyme located in the sarcomere) catalyses the reversible exchange of high energy phosphate bonds between phosphocreatine and ADP to regenerate ATP (Brancaccio, Maffulli & Limongelli, 2007). High serum concentrations of CK reflect sarcomere damage arising from strenuous exercise or muscular pathology (Brancaccio et al., 2007). Indeed, elevations in CK concentration from 39 – 391 % (see Table 2.4) have been reported after sport-specific running. The range of values reported partly reflect the individual variability in CK concentration due to sex, training status and distribution of fibre types in skeletal muscles (Heled, Bloom, Wu, Stephens, & Deuster, 2007; Oosthuyse & Bosch, 2017; Magal et al., 2010; Souglis et al., 2018). Specifically, several studies have reported strong associations between sprinting metrics ($r = 0.39 – 0.76$; Jones et al., 2014; Oxendale et al., 2016;

Varley et al, 2017), accelerations (*r* = 0.44 – 0.48; Varley et al., 2017; de Hoyo et al., 2016; Oxendale et al., 2016), decelerations (*r* = 0.48 – 0.71; de Hoyo et al., 2016; Oxendale et al., 2016) and collisions (*r* = 0.64 - 0.67; Jones et al., 2014; Oxendale et al., 2016) with CK responses at 12 – 48 h post-exercise. The high-intensity muscle contractions and ground reaction force associated with sprinting (Kyröläinen, Avela, & Komi, 2005) and the intense eccentric contractions performed during deceleration actions (Savage, Fantini & Brüggemann, 2011), which can increase muscle activation to stabilise the knee joint (Besier et al., 2003), partly explain the muscle damage observed in the aforementioned studies. Such mechanical loading presumably places high strain on weak sarcomeres and/or the extracellular matrix surrounding the muscle fibres, inducing muscle damage (Morgan & Proske, 2006). Indeed, Grazioli et al. (2019) reported no changes in muscle damage markers after performing linear sprints with no rapid deceleration, which has been shown to induce muscle damage in similar exercise protocols (e.g. Howatson & Milak, 2009). Taken together, these data emphasise the movements patterns associated with EIMD discussed in section 2.3.3.1.

Table 2.4. Indirect markers of muscle damage 24 – 48 h after team sport activity

Study	Sport/Exercise	Participants	24 - 48 h change in marker		
			Sprint/CMJ performance	CK	Perceived muscle soreness
Ascensão et al. (2008)	Football match	16 male professional football players	~5 % ↑ in 20 m sprint time (24-48 h)	↑ (24 and 48 h, values not reported)	↑ (24 and 48 h, values not reported)
Howatson & Milak (2009)	Repeated sprints 15 x 30 m sprints	20 male collegiate team sport players	-	391 % ↑ (24 h)	↑ (24-72 h post exercise, values not reported)
Magalhães et al. (2010)	LIST	16 elite male football players	~ 1 % ↑ in 20 m sprint time. ~8 % ↓ in CMJ height	↑ (24 and 48 h, values not reported)	↑ (24 and 48 h, values not reported).
McLellan et al. (2011)	Rugby league match	17 elite rugby league players	~10 % ↓ in CMJ peak force (24 h). 3 % ↓ (48 h)	267 % ↑ (24 h) 131 % ↑ (48 h)	-
Rampinini et al. (2011)	Football match	20 male professional football players	~1 % ↑ in 40 m sprint time (24 h)	~224 % ↑ (24 h) ~160 % ↑ (48 h)	↑ (24 h, values not reported).
Singh et al. (2011)	Non-contact team sport circuit	11 male team sport athletes	No change in sprint performance. CMJ height ↓ at 48 h (values not reported)	↑ (value not reported, 24 h)	~ 200 % ↑ (24 and 48 h)
Twist & Sykes (2011)	Simulated rugby league match	10 university males	~5 % ↓ in CMJ height	S ↑ (24 h, values not reported)	~ 500 % ↑ (24 h)

Continued on next page

Table 2.4. Continued

Study	Sport/Exercise	Participants	24 - 48 h change in marker		
			Sprint/CMJ performance	CK	Perceived muscle soreness
Twist et al. (2012)	Rugby League match	23 male professional rugby league players	↓ in CMJ height (24 and 48 h)	↑ (ES = 1.7 – 2.3; 24 h and ES = 1.2 – 1.3; 48 h)	~150 – 160 % ↑ (24 h) ~140 – 165 % ↑ (48 h)
Silva et al. (2013)	Football match	7 professional males	NS change in 5 and 30 m sprint. ~7 % ↓ in CMJ height	~87 % ↑ (48 h)	
Nedelec et al. (2014)	Football match	10 professional football players	~5 % ↓ in peak speed during a 6 s sprint. ~ 7 % ↓ in CMJ height (48 h)	105 % ↑ (48 h)	~80 % ↑ (48 h)
Leeder et al. (2014)	LIST	8 well trained male team sport athletes	~-6 % ↓ in CMJ performance (at 24 h)	194 % ↑ (48 h)	↑ (value not reported)
Keane et al. (2015)	Repeated sprint activity (15 x 30 m sprints)	11 well-trained females	~6 % ↑ in 30 m sprint time. ~ 10% ↓ in CMJ height (48 h)	↑ (318 % at 24 h)	↑ (value not reported)
de Hoyo et al. (2016)	Football match	15 U-19 elite males	~13 % ↓ in CMJ height (24 h)	↑ ~52 % (24 h)	-
Oxendale et al. (2016)	Rugby league match	17 elite males	~4.7 % ↓ in CMJ flight time (at 36 h)	↑ ~178 % (36 h)	~17 % ↑ (36 h)

Continued on next page

Table 2.4. Continued

Study	Sport/Exercise	Participants	24 - 48 h change in marker		
			Sprint/CMJ performance	CK	Perceived muscle soreness
Russell et al. (2016)	Football match-play	15 elite males	~3 % ↓ in CMJ peak power output (48 h)	↑ ~39 % (48 h)	-
Varley et al. (2017)	Football match-play	16 elite soccer players	No change in CMJ performance	↑ (ES = 1.11; 40 h)	↑ (ES = 0.73; 40 h)
Souglis et al. (2018)	Football match-play	30 male and 30 female professional players	-	↑ at 24 and 48 h (value not reported)	-
Gastin et al. (2019)	Australian Football match-play	26 male professional players	-	↑ ~129 % (34 – 40 h)	-
Grazioli et al. (2019)	15 x 20 m sprints	30 well trained collegiate athletes	No change in CMJ height	No change	No change
Wiig et al. (2019)	Football match	75 semi-professional football players	↓ in CMJ height (ES = 0.68 at 24 and 48 h)	↑ (ES = 1.2; 24 h and ES = 0.67; 48 h)	-

CMJ = counter-movement jump, CK = creatine kinase, NS = non-significant, ES = effect size, LIST = Loughborough intermittent shuttle test, ↑ = increase, ↓ = decrease

2.3.2.3.3. Perceived muscle soreness (DOMS)

It is widely accepted that EIMD results in delayed onset muscle soreness, which typically peaks 24 – 72 h after exercise (Cheung, Hume & Maxwell, 2003). In agreement, elevations (80 – 500 %; Table 2.4) in perceived muscle soreness have been reported in the days after team sport activity. Nedelec et al. (2014) reported a strong association between the number of short sprints performed (<5 m) and muscle soreness 48 h after a football match (r = 0.74), reflecting the rapid deceleration associated with short sprints that can lead to muscle damage in the days after (de Hoyo et al., 2016; Howatson & Milak, 2009; Oxendale et al., 2016). Furthermore, whilst DOMS is assessed subjectively and interpretation can be easily manipulated by athletes (Twist & Highton, 2013), it is strongly correlated with circulating myocellular proteins (r = 0.67 – 0.73; Kanda et al., 2013) and inflammation-related biomarkers (r = 0.46 – 0.59; Kawamura et al., 2018) resulting from muscle damage.

2.3.3 Contemporary issues with monitoring fatigue and EIMD after team sport activity

Whilst the aforementioned sections highlight the use of fatigue and in-direct markers of EIMD, some noteworthy issues warrant acknowledgement. The notion of central and peripheral fatigue as separate mechanisms of fatigue has recently been critiqued (Enoka & Duchateau, 2016). Specifically, Enoka and Duchateau (2016) suggest the neuromuscular activity needed to counteract an exercise-induced decrease in force capacity is not independent from those involved in generating the accompanying sensations, and thus the aetiology of fatigue (i.e. central or peripheral) cannot be definitively determined. Instead, Kluger, Krupp and Enoka (2013) propose the concept of fatigue in two attributes: performance fatigue and perceived fatigue. This concept of fatigue highlights the need to assess contractile capabilities/activation of the involved muscle as well as the perceived rate of change in sensations and acknowledges that most voluntary actions performed by humans involve significant interactions between the two domains (i.e. performance and perceived fatigue; Enoka & Duchateau, 2016). However, the assessment of muscle function is unlikely to be routinely and simultaneously employed in a large squad of players (Carling et al., 2018), and therefore lacks practicality. The use of CMJ and/or single sprint efforts provide a more pragmatic means of determining neuromuscular fatigue (Carling et al., 2018). Sprint efforts occur during pivotal moments during a match (Faude et al., 2012), and therefore a decrement in sprint performance has relevance and ecological validity in a team sport context (Enoka & Duchateau, 2016).

It remains unclear if elevations in CK concentration after exercise represent a degree of actual muscle damage or some form of disruption in energy control processes or other molecular reaction mechanism (Baird, Graham, Baker, & Bickerstaff, 2012). The ability of CK concentration to reflect EIMD has therefore been questioned. Specifically, CK concentration is highly variable between individuals (Brancaccio et al., 2007) and has demonstrated less than favourable reliability (CV: 26 %; Roe et al., 2016). However, such individual variation can be partly accounted for by assessing individual resting values and consideration of the reliability of CK concentration when determining a meaningful change can help overcome some of the issues with this indirect marker of muscle damage. The specific mechanism of where DOMS originates is also still debated (Mizumura & Taguchi, 2016; Peake et al., 2017). Neurotrophic factor-mediated mechanisms, as opposed to inflammatory changes caused by myofiber damage, have recently been suggested as a mechanism of DOMS (Hayashi et al., 2017; Peake et al., 2017), as studies have reported changes in muscle function, myofibrillar damage and/or inflammation were not related to DOMS (Paulsen et al., 2010a; Paulson et al., 2010b). Accordingly, DOMS is a common symptom of EIMD (Paulson et al., 2012) but not an indicator of muscle damage. Based on the aforementioned issues, caution should be taken when assessing muscle damage magnitude based on DOMS and CK concentration (Damas et al., 2016). Instead, it is recommended in the assessment of EIMD a multidimensional approach is employed using a variety of in-direct markers (Heidari et al., 2019).

2.4. Mechanisms of ACL injury risk

Injury and rupture to the ACL is a common occurrence in team sports such as football, netball and rugby (Agel, Rockwood, & Klossner, 2016), and accounts for 65% of total ACL injuries resulting in surgery (Gianotti, Marshall, Hume, & Bunt, 2009). Most occurrences are non-contact in nature (Boden, Dean, Feagin, & Garrett, 2000; Walden et al., 2015) and often happen during a 30 – 90° side cut in males (Grassi et al., 2017; Walden et al., 2015) and females (Koga et al., 2010). Whilst it is unclear if ACL incidence rates differ between halves of match-play (Grassi et al., 2017; Hawkins, Hulse, Wilkinson, Hodson, & Gibson, 2001), in vivo studies have demonstrated the ACL is susceptible to fatigue (Wojtys, Beaulieu, & Ashton-Miller, 2016). Previous research has also reported fatigue-induced modifications in side cut kinematics and kinetics that could increase the risk of a non-contact ACL injury (Collins et al., 2016; Khalid, Harris, Michael, Joseph & Qu, 2015; McLean et al., 2007; Savage et al., 2018). Furthermore, whilst changes in gait biomechanics after EIMD have been reported (Paquette et al., 2017; Tsatalas et al., 2013a; Tsatalas et al., 2013b; Paschalis et al., 2007a), the effect of EIMD on ACL injury risk has received limited attention. The purpose of this section is to briefly review the biomechanical mechanisms of ACL injury risk, before discussing the effect of fatigue and EIMD on ACL injury risk.

2.4.1 Biomechanical mechanisms of ACL injury

2.4.1.1. Sagittal plane kinematics

Landing and/or cutting with an extended trunk (Blackburn & Padua, 2009; Davis, Hinshaw, Critchley, & Dai, 2019; Podraza & White, 2012), reduced hip (Kipp, McLean, & Palmieri-Smith, 2011) and knee flexion angles (~20°; Koga et al., 2010; Walden et al., 2015; Weiss & Whatman, 2015) and reduced hip and knee angular velocities (Bakker et al., 2016) are associated with an increased risk of ACL injury/ACL strain. Reduced flexion angles increase quadriceps loading (DeMorat, Weinhold, Blackburn, Chudik, & Garrett, 2004; Fujiya, Kousa, Fleming, Churchill, & Beynnon, 2011) leading to insufficient hamstring activation (Yanagawa, Shelburne, Serpas, & Pandy, 2002), which elicits higher anterior tibial shear loads and therefore ACL strain. Reduced hip and trunk flexion angles have also been reported to best predict maximum ACL strain (Bakker et al., 2016), and a reduced trunk angle has been observed in ACL injured participants compared to a control group (Sheehan, Sipprell & Boden, 2012). Trunk position therefore plays a key role in ACL injury risk, yet it is often not assessed in studies assessing ACL injury risk (e.g. Benjaminse et al., 2008; Cortes, Greska, Kollock, Ambegaonkar, & Onate, 2013; Iguchi et al., 2014; McGovern et al., 2015; Savage et al., 2018). Notable differences between sexes are also evident. Typically, females exhibit smaller hip (~39 – 49 *cf*. 44 – 54°; Landry, McKean, Hubley-Kozey, Stanish, & Deluzio, 2007; Pollard, Sigward, & Powers, 2007) and knee (~3 – 16°; Chappell et al., 2007; Dai et al., 2015; Decker, Torry, Wyland, Sterett, & Steadman, 2003; McGovern et al., 2015; Yu et al., 2006) flexion angles compared to males during a side cutting manoeuvre and therefore could be at greater risk of ACL injury.

2.4.1.2 Sagittal plane kinetics

Landing with an erect posture increases vertical GRF (Podraza & White, 2012) associated with increased ACL injury risk (Hewett, 2000; Kirkendall & Garrett, 2000), and decreases hip extensor moment (Shimokochi, Ambegaonkar, Mayer, Lee, & Shultz, 2013; Kulas et al., 2008), suggesting a reduced ability of the hip extensors to produce work. This can increase knee extensor moments (Kulas et al., 2008), which are associated with an increased ACL strain ($r > 0.86$; Yu, Lin & Garrett, 2006) and a reduced time to peak ACL strain ($r = -0.38$; Bakker et al., 2016) and can distinguish individuals who go on to sustain an ACL injury (Leppänen et al., 2017). Whilst Bakker et al. (2016) reported maximum hip extensor moment was more associated with ACL strain than knee extensor moment, Leppänen et al. (2017) reported hip extensor moment was not associated with ACL injury risk, in a prospective study. Furthermore, an increase in hip extensor moment might reflect a change in work distribution (between the hip and knee) to help absorb mechanical energy (Coventry, O'Connor, Hart, Earl, & Ebersole, 2006). Females also exhibit smaller hip extensor moments compared to males during a side cutting manoeuvre (Landry et al., 2007; Pollard et al., 2007). This indicates a reduced strength of the hip extensors in females, (which is required to decelerate in the sagittal plane), resulting in greater exploitation of the frontal and transverse planes (Pollard et al., 2007), such as an increase knee internal rotation moment in females (Kipp, McLean, & Palmieri-Smith, 2011). Whilst the subsequent effect of sagittal hip moments might be a risk factor for the ACL, sagittal hip moments alone play a limited role in ACL injuries (Leppänen et al., 2017; Mclean, Huang, Su, & van den Bogert, 2004).

Higher peak vertical GRF (> 3/4 x BW; Bakker et al., 2016; Hewett et al., 2005; Koga et al., 2010; Yu & Garrett, 2007), reduced time to peak vertical GRF (Bates, Ford, Myer & Hewett, 2013) and high impulses (Bates et al., 2013) can increase ACL injury risk. Stiff landings (characterised by reduced lower limb flexion angles) produce larger vertical GRF (Ali, Robertson & Rouhi, 2014; Myer et al., 2011) and are therefore related to ACL injury risk. Specifically, higher range of motion of hip and knee flexion when landing, play a more important role in reducing impact forces (Yin, Sun, Mei, Gu, Baker, & Feng, 2015) and increasing time to peak ACL strain (Bakker et al., 2016) in comparison to joint positions at initial contact.

2.4.1.3. Frontal plane kinematics

Lateral flexion of the trunk in the opposite direction of a side cutting manoeuvre (Dempsey et al., 2007; Hewett, Torg & Boden, 2009) and high knee abduction angles (9 – 12º) during landing and cutting manoeuvres have been associated with ACL injuries (Hewett et al., 2009; Hewett et al., 2005; Koga et al., 2010; Myer et al., 2015). Specifically, epidemiology studies have observed lateral displacement of the trunk (Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007) and knee abduction/ knee valgus (categorized by knee abduction and internal rotation; Hewett et al., 2009; Hewett et al., 2005; Grassi et al., 2017; Stuelcken, Mellifont, Gorman, & Sayers, 2016; Walden et al., 2015) in the majority of ACL injuries analysed. Females have also demonstrated greater knee abduction angles (8º *cf.* 4º) during a side cut (Ford, Myer, Toms, & Hewett, 2005) and landing (Hewett et al., 2009; Krosshaug et al., 2007) and a greater tendency towards lateral trunk flexion during a side cut (Figure 2.2; Pollard et al., 2007), compared with males. Valgus collapse (characterised by high knee abduction angular velocities) also appears to be a key mechanism in females (Krosshaug et al., 2007; Stuelcken et al., 2016) but less so in males (Walden et al., 2015), which collectively suggests females could be at greater risk of ACL injury.

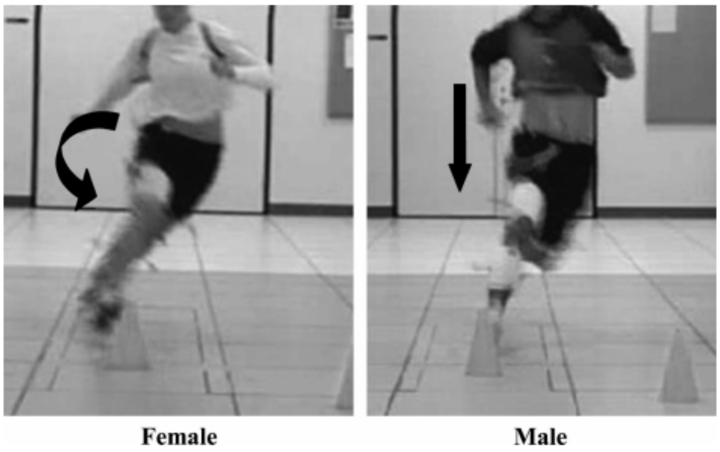


Figure 2.2 An example of how females tended to lean their trunk over their stance leg when performing a cutting manoeuvre (taken from Pollard et al., 2007).

The contribution of frontal plane hip mechanics to ACL injury risk has been disputed. Specifically, hip abduction has been reported in females with increased knee valgus moments (Sigward & Powers, 2007) and could move the body's centre of mass (COM) resulting in GRF acting on the lateral side of the knee joint, straining the ACL (Weiss & Wahtmann, 2015). Yet, hip adduction has been reported as a common mechanism during ACL injuries (Grassi et al., 2017; Hewett et al., 2005). Increased hip adduction results in medial translation of the knee joint centre relative to the foot (Hewett et al., 2005) and is therefore associated with increased knee abduction angle in females during a side cut (r = 0.49; Imwalle, Myer, Ford, & Hewett, 2009). Accordingly, hip adduction is likely a secondary mechanism of ACL injury risk.

2.4.1.4 Frontal plane kinetics

Lateral flexion of the trunk in the opposite direction of a side cut can place excessive loading on the knee joint (Dempsey et al., 2007), increase knee abduction moment (Jamison, Pan & Chaudhari, 2012; Kristianslund et al., 2014) and is associated with an increased ACL injury risk using in vivo data within a simulation model (Shin, Chaudhari & Andriacchi, 2011). Conversely, both hip adduction (Frank et al., 2013; Hewett et al., 2005) and hip abduction moments (Kristianslund, Faul, Bahr, Myklebust & Krosshaug, 2014) have been associated with knee valgus moment; an important mechanism of ACL injury (Kristianslund et al., 2014). Inconsistencies in the literature might reflect the definition of joint moments (i.e. internal or external) and the influence of lateral trunk flexion on frontal plane hip motion (Havens & Sigward, 2015), which highlights the need to consider key variables collectively when assessing ACL injury risk.

High peak knee abduction moments (>25 / 45 ± 29 N·m) during both landing and side cuts are key mechanisms of ACL injuries (Hewett et al., 2005; Koga et al., 2010; Myer et al., 2015). Specifically, high external knee abduction / knee valgus moments are strongly correlated to ACL force (r = 0.82; Navacchia, Bates, Schilaty, Krych, & Hewett, 2019) and are associated with peak vertical GRF (r = 0.74 and r = 0.67, respectively; Hewett et al., 2005) and an increased lateral GRF (1.5 ± 0.9 $\mathrm{N{\cdot}kg^{-1}}$; Sigward & Powers, 2007), which increase the strain on the ACL. Hewett et al. (2005) also found knee abduction / knee valgus moment was the most significant predictor of ACL injury in females compared with other biomechanical variables and could predict ACL injury status with 73% specificity and 78% sensitivity. Females have also demonstrated higher knee abduction moments than males during a landing task (Chappell, Yu, Kirkendall, & Garrett, 2002) and side cut (Sigward, Cesar, & Havens, 2015). These data collectively suggest knee abduction / knee valgus moments are key mechanisms of ACL injury and females are potentially more susceptible to ACL injury risk, due to altered frontal plane knee mechanics.

2.4.1.5 Transverse plane kinematics

Trunk rotation towards the uninjured leg (Stuelcken et al., 2016; Walden et al., 2015) and internal rotation at the hip (Boden, Torg, Knowles, & Hewett, 2009; Krosshaug et al., 2007) have been observed during ACL injuries. An increase in hip internal rotation increases peak valgus moments in males (r = ~0.75) and females (r = ~0.77) during a side cutting manoeuvre (McLean et al., 2005). Whilst research has also highlighted a correlation between external hip rotation and increased knee valgus (Weltin, Gollhofer, & Mornieux, 2016), the use of a lateral reactive jump (Weiltin et al., 2016), compared with a side cut which elicits greater hip internal rotation (Pollard, Sigward, & Powers, 2007), partly explain differences in the contribution of hip rotation to knee loading. These data suggest internal hip rotation is a mechanism of ACL injury during a side cut task.

Whilst both internal (5 – 12º) and external rotation of the tibia (5 – 15º) have been observed during ACL injuries (Grassi et al., 2017; Koga et al., 2010; Olsen, Myklebust, Engebretsen, & Bahr, 2004), internal rotation is more associated with ACL injury risk. Specifically, combined knee abduction and internal tibial rotation increases ACL strain more than any individual degree of freedom in vitro (Bates, Nesbitt, Shearn, Myer, & Hewett, 2017) and internal tibial rotation was evident in most non-contact ACL injuries from an extensive study of 1700 cases (Kobayashi et al., 2010). Upon landing, the tibia is characteristically externally rotated at initial contact and then undergoes internal tibial rotation during the first 40 ms (Koga et al., 2010; Olsen et al., 2004), which is when ACL strain reaches peak values (Shin, Chaudhari & Andriacchi, 2007). Thus, inconsistencies amongst the literature might be dependent on the timing of reported variables.

2.4.1.6 Transverse plane kinetics

Despite the limited research examining the influence of trunk rotation moments on ACL injury risk, internal hip rotation moments have been reported to coincide with knee valgus moment during a side cutting manoeuvre (Jesper et al., 2013). An increased hip internal rotation moment has also been associated with increased knee abduction load (McLean & Samorezov, 2009), suggesting a possible link between internal hip rotation moment and ACL injury risk.

Internal tibial rotation moments have been reported to increase the strain placed on the ACL more so than external tibial rotation moments (Fleming et al., 2001; Oh, Lipps, Ashton-Miller, & Wojtys, 2012). Whilst internal tibial rotation moments are strongly correlated to ACL force ($r = 0.78$; Navacchia et al., 2019), in vivo cadaver models have demonstrated internal tibial rotation moments alone are not enough to rupture the ACL (Shin et al., 2011). However, the coupled effect of knee abduction/valgus and internal tibial rotation moment can increase stain on the ACL and potentially cause a rupture (Kiapour et al., 2015; Navacchia et al., 2019; Shin et al., 2011). These data suggest both knee valgus and internal tibial moments contribute to increased ACL strain, yet knee abduction/valgus has the ultimate impact on ACL integrity.

2.4.1.7 Movement variability

Movement variability, defined as normal variations in motor performance over multiple trials (Stergiou & Decker, 2011), has been linked with acute and overuse injuries (Bartlett, Wheat & Robins, 2007; James, 2004; Nordin & Dufek, 2019). The variability-overuse hypothesis suggests an increased movement variability might allow individuals to adapt to environmental perturbations and reduce the risk of overuse injuries (James, 2004; James, Dufek & Bates, 2000; Nordin & Dufek, 2019). However, acute injuries are associated with a single traumatic loading event which exceeds the threshold of musculoskeletal tissues (Nordin & Dufek, 2019), therefore an increase in movement variability might increase ACL injury risk. Specifically, McLean et al. (2004) reported females exhibited greater variability in knee abduction angle compared with males, and increased knee abduction angles are associated with ACL loading/ACL injury risk (Donelon, Dos'Santos, Pitchers, Brown & Jones, 2020; Hewett et al., 2005). Taken together, whilst an increase in movement variability can reduce the risk of overuse injuries, it can increase the risk of extreme movement patterns, such as knee abduction angle, and could increase ACL injury risk.

2.4.2 Assessment of ACL injury risk

2.4.2.1 Functional tasks

Given the mechanisms of ACL injury risk, both side cutting manoeuvres and single leg landings have typically been used to assess ACL injury risk. Yet, most ACL injuries during team sports occur during a side cutting manoeuvre in both males (Walden et al., 2015) and females (Koga et al., 2010; Olsen et al., 2004). This could be associated with the high frequency of cutting manoeuvres performed during team sports (Bloomfield et al., 2007) and the position of the knee joint during cutting manoeuvres.

Specifically, decreases in knee flexion (20.9º *cf.* 31.5º) and increases in knee valgus angle (11.5º *cf*. 5.6º) as well as knee abduction moment (1.58 $Nm{\cdot}kg^{-1}$ *cf.* 0.25 $Nm{\cdot}kg^{-1}$) have been reported during a side cutting manoeuvre in comparison to a single leg landing (Kristianslund & Krosshaug, 2013), all of which are associated with ACL injury risk (see section 2.4.1). Collectively, these data suggest a side cutting manoeuvre might provide a more sport specific assessment of ACL injury risk in team sport athletes.

2.4.2.2 Side cutting task achievement

Injury to the ACL typically occurs when players move forward at high speed and cut at an intended angle between 30 – 90° (Walden et al., 2015). Specifically, ACL strain reaches peak values during the weight acceptance phase of stance (0 – 25% of stance/ 0 – 83 ms after initial contact; Koga et al., 2010; Shin, Chaudhari, & Andriacchi, 2007; Sigward & Power, 2007), where there is a large deceleration component. Research has therefore typically utilized a 45° side cutting manoeuvre in the assessment of ACL injury mechanisms (Collins et al., 2016; Imwalle, Myer, Ford & Hewett, 2009; Jamison et al., 2012; Sanna & O'Connor, 2008) and focused on the weight acceptance phase of stance, as knee joint loading must be sufficiently close to knee loads associated with ACL injury to identify ACL injury mechanisms (Vanrenterghem, Venables, Pataky, & Robinson, 2012). A 45° cutting angle is acute enough to require a substantial deceleration, but shallow enough for a change of direction to be achieved during a single foot contact (Alenezi, Herrington, Jones, & Jones, 2016) with higher approach speeds. Specifically, Vanrenterghem et al. (2012) identified knee loading mechanisms during a side cutting manoeuvre only reached meaningful values from an approach speed of 4 $m{\cdot}s^{-1}$. Taken together, a 45° side cutting manoeuvre at an approach speed of at least 4 $m{\cdot}s^{-1}$ can be used to identify the mechanisms associated with ACL injury.

2.4.2.3 Biomechanical measurement variables

Previous research has examined joint kinematics and kinetics at 30 to 100 ms after initial contact (McGovern et al., 2015; Kristianslund et al., 2014), the loading phase of stance (0 – 50% of stance; Hanson, Padua, Blackburn, Prentice, & Hirth, 2008; Sigward & Powers, 2007), the weight acceptance phase (initial contact to peak knee flexion; Jamison et al., 2012) and peak values (Collins et al., 2016) during a side cut. Whilst examining data within discrete parameters can lead to severe reduction in the data and the loss of important information (Deluzio, Harrison, Coffey, & Caldwell, 2014), peak values (i.e. peak knee abduction moment and peak GRF) are directly related to ACL injury risk (Hewett et al., 2005). Accordingly, examining kinematic and kinetic variables over the whole of stance as well as relevant peak values, can provide an insight into ACL injury risk.

When undertaking movement analysis, it is important to consider the reliability of biomechanical variables to identify true changes after an intervention. Studies have reported interclass correlation coefficients (ICC) to indicate the relative agreement of biomechanical variables (e.g., Alenezi, et al., 2016). However, ICC values alone are not presented in the context of the original data, making it difficult to use practically to interpret the reliability of actual data (Sankey et al., 2015) and do not indicate the level of disagreement between measurements (Alenezi, et al., 2016). To help interpret whether a kinematic / kinetic change is meaningful, a standard error of measurement (an estimate of how much a measured kinematic/kinetic value are spread around the “true” value) should therefore be used when reporting 3D kinematics of the knee joint during side cutting manoeuvres (Benoit et al., 2006). Accordingly, only studies which report reliability data using the standard error of measurement (SEM) and/or markers of variability (e.g. standard deviation) are discussed.

During a side cutting manoeuvre, GRF has demonstrated a high level of relative agreement (SEM: 0.14 X BW) and less variability compared with kinematic and kinetic data (Alenezi, et al., 2016). Lower limb kinematic data has also demonstrated good reliability (~2-5°/<5% variability; Alenezi et al., 2016; Sankey et al., 2015), with hip adduction, internal rotation and knee internal rotation angle demonstrating the highest SEM within-day (3.37, 3.81 and 2.71° respectively; Alenezi et al., 2016). Whilst lower limb kinetic data has demonstrated greater variability in all three planes (16.9 – 31.8 N·m; Sankey et al., 2015), Alenezi et al. (2016) reported hip flexion (0.27 $N{\cdot}m{\cdot}kg^{-1}$), knee valgus (0.18 $N{\cdot}m{\cdot}kg^{-1}$), and knee flexion (0.16 $N{\cdot}m{\cdot}kg^{-1}$) moments demonstrated acceptable SEM and relative agreement (ICC > 0.82). Robinson and Vanrenterghem (2012) recommend maximum differences of <4º for frontal and sagittal plane knee angles and <10 N·m for sagittal knee moments and <8 N·m for frontal knee moments during a side cutting manoeuvre are unlikely to be meaningful differences. Collectively, these data suggest certain biomechanical variables show sufficient consistency, however some frontal and transverse motions would require considerable changes to identify effects from an intervention.

2.4.2.4 3D biomechanical analysis

The accuracy of 3D biomechanical data is influenced by marker configuration (Manal, McClay, Stanhope, Richards, & Galinat, 2000), which can be improved by using a functional method to define hip and knee joint centres (Besier, Sturnieks, Alderson, & Lloyd, 2003) and incorporating a point cluster technique (Ishii, Nangano, Ida, Fukubayashi, & Maruyama, 2011; Manal, McClay, Stanhope, Richards, & Galinat, 2000). Whilst previous marker models used to assess ACL injury risk typically incorporate these aspects (Dempsey et al., 2007; Khalid et al., 2015; Vanrenterghem, Gormley, Robinson & Lees, 2010), not all incorporate a functional method to assess the location of hip and knee joint centres (Frank et al., 2013; McGovern et al., 2015; Sanna & O’Connor, 2008). This is important given that Robinson and Vanrenterghem (2012) found the use of a function frame to define the knee axis can provide accurate knee biomechanics, in comparison to anatomical landmarks, during a side cutting manoeuvre. Furthermore, most studies assessing ACL injury risk during a side cut do not incorporate trunk markers to assess trunk position (e.g., Collins et al., 2016; Khalid et al., 2015; McGovern et al., 2015; Sanna et al., 2008), which can provide an important indication of ACL injury risk (see section 2.4.1). The Liverpool John Moores University (LJMU) lower limb and trunk model can provide an appropriate representation of the COM during a side cut (accounting for 82% of body mass; Vanrenterhem et al., 2010), which also incorporates a point cluster technique and a functional method for the assessment of hip and knee joint centres. This marker model has since been used to estimate COM variables (Sankey, Robinson & Vanrenterghem, 2020; Jamkrajang, Robinson, Limroongreungrat, & Vanrenterghem, 2017), which could provide further insight into the ACL injury risk. Specifically, the position of the whole-body centre of mass is associated with peak knee abduction moment (Donnelly, Lloyd, Elliott, & Reinbolt, 2012; Sankey et al., 2020), a key mechanism of ACL injury. Accordingly, the LJMU lower-limb and trunk model (Vanrenterhem et al., 2010), might provide a more accurate understanding of ACL injury risk during a side cutting manoeuvre.

The movement between surface markers and underlying bone, referred to as soft tissue artefact, can also influence the accuracy of biomechanical data (Benoit, Damsgaard & Anderson, 2015), regardless of the model used, as the digitised coordinates will still contain some random errors referred to as noise (Bartlett, 2014). Noise is typically lower in amplitude and can be removed using a low-pass filter (Sinclair, Taylor, & Hobbs, 2013), of which a fourth-order zero-lag Butterworth filter is frequently utilized within biomechanical analysis (Collins et al., 2016; Iguchi et al., 2014; Sanna & O'Connor, 2008). Butterworth filters yield a weighted average of data points across the kinematic waveform to determine the cut off frequency (Derrick, 2012). Determining the most appropriate cut off frequency is essential, given the influence on lower extremity kinematic data (Sinclair et al., 2013). Specifically, Fourier transformation and residual analysis have been deemed sufficiently reliable methods for determining cut-off frequencies (see Sinclair et al., 2013), yielding values of 10 – 15 Hz for 3D kinematic data during running and cutting manoeuvres (Collins et al., 2016; Sanna & O'Connor, 2008; Sinclair et al., 2013).

2.4.3 Effect of fatigue on ACL injury risk

Several authors have suggested an increased risk of ACL injury due to fatigue. Specifically, increases in hip extension (~4º; Borotikar, Newcomer, Koppes & McLean, 2008), hip internal rotation (~2º; Borotikar et al., 2008), knee abduction/knee valgus angles (~1 – 7º; Borotikar et al., 2008; McLean et al., 2007; Smith, Sizer, & James, 2009) and increases in peak knee internal rotation (~0.17 $N{\cdot}m{\cdot}kg^{-1}$), abduction moments (0.21 N·m·kg^{-1}; McLean et al., 2007), and increases in sagittal plane angular velocities (6%; Tamura et al., 2017) have been reported after fatiguing exercise during single leg landing activities. Similar fatigue induced modifications during side cutting manoeuvres such as decreases in knee flexion angle (~ 3º; Cortes et al., 2013; Lucci et al., 2011), and increases in peak knee abduction angles (~2º; Collins et al., 2016; Tsai, Sigward, Ollard, Fletcher & Powers, 2008) and moments (0.3 N·m·kg^{-1}; Tsai, et al., 2008), and knee internal rotation angle (~1 – 6º; Lucci et al., 2011; Tsai, et al., 2008) have also been reported. Notably, females exhibit an increased knee abduction/valgus moment, which is indicative of an increased ACL injury risk (Inguchi et al., 2014; McLean et al., 2007). However, others have reported no such differences in knee flexion angle (Inguchi et al., 2014; McLean et al., 2007) or increases in hip and knee flexion angle at initial contact (Coventry, O'Connor, Hart, Earl & Ebersole, 2006) during single leg landings and side cutting manoeuvres with fatigue. Changes in GRF with fatigue also appear to be equivocal (see review by Zadpoor & Nikooyan, 2012), suggesting further research examining the effect of fatigue on lower limb mechanics is warranted.

Discrepancies amongst the literature examining fatigue and ACL injury risk might partly be explained by the variety of fatigue protocols used and the use of male and/or female participants. Indeed, changes in vertical GRF impulse (Inguchi et al., 2014) and knee kinematics (Kernozek, Torry, & Iwasaki, 2008) under fatigue can be sex dependant, and fatigue responses during landing activities are highly dependent on which muscle has been fatigued (Kellis & Kouvelioti, 2009). For example, hip abductor fatigue caused no change to frontal plane hip and knee mechanics (Patrek, Kernozek, Willson, Wright, & Doberstein, 2011), whereas isolated hip rotator fatigue has been reported to increase hip internal rotation at initial contact during a single leg drop jump (Thomas, Palmieri-Smith, & McLean, 2009). The non-uniformity of fatigue protocols used in the literature, such as 4 minutes of jumping, stepping and bounding tasks (McLean et al., 2007), successive counter-movement jumps (Inguchi et al., 2014) and knee extensor and flexor contractions on a dynamometer (Kellis & Kouvelioti, 2009), make comparisons amongst the literature difficult. In addition, as these protocols do not mimic the specific movements of team sport activity, these findings are equivocal and lack ecological validity. Accordingly, the rest of this section focuses on lower limb mechanics after fatiguing exercise protocols which mimic the intermittent movement patterns typical of team sport activity (discussed in section 2.2.1).

Several studies have examined changes in lower limb kinematics and kinetics after intermittent activity (see Table 2.5). Typically, athletes adopt a more erected position, displaying less hip (~4°) and knee flexion (~4°) during a side cutting manoeuvre (Khalid et al., 2015; McGovern et al., 2015; Raja Azidin et al., 2015). Whilst this contrasts with Savage et al. (2018) who reported a ~7° increase in knee flexion angle, both Savage et al. (2018) and Khalid et al. (2015) reported increases in knee extensor moment, which has been linked to an increased eccentric action of the quadriceps. Of the studies reviewed, increases in knee internal rotation range of motion (Sanna & O’Connor, 2008), hip and knee external rotation at initial contact (Sanna & O’Connor, 2008) and a reduction in knee external rotation moment (Khalid et al., 2015) have been reported during a side cutting manoeuvre, whereas others have reported no such changes (Collins et al., 2016; McGovern et al., 2015). Thus, it is unclear whether transverse plane biomechanics are affected by fatigue.

Fatigue induced modifications in frontal plane kinematics have received limited attention and it remains unclear as to whether adduction and abduction motions change (see Table 2.5). Similarly, only one of the studies reviewed has reported changes in GRF, which found fatigue increased peak vertical and anterior/posterior GRF (Khalid et al., 2015). An increase in GRF following fatigue can be expected, given that athletes adopt a more erected position, and decreases in hip and knee flexion can significantly increase vertical GRF (Blackburn & Padua, 2009).

Sex dependant fatigue related modifications in lower limb kinematics and kinetics have been observed during a side cutting manoeuvre (Khalid et al., 2015; McGovern et al., 2015). Specifically, Khalid et al. (2015) reported males exhibited greater peak knee internal rotation moments and vertical GRF at initial contact in comparison to women. Conversely, McGovern et al. (2015) reported females performed side cut manoeuvres in a more erected position with less knee flexion and more internal hip rotation than males. Such discrepancies might be attributed to differences in the mechanisms of fatigue caused by different protocols. Indeed, Stern and colleagues reported females had greater quadriceps dominance after fatiguing exercise, as quadriceps torque remained unchanged whereas hamstring torque decreased by 5.7 % (Stern, Kuenze, Herman, Sauer, & Hart, 2012). Conversely, males had greater decrements in quadriceps torque (-8.5 %) in comparison to hamstring torque (-3.7 %). As quadriceps dominance is associated with increase ACL injury risk (Sigward & Powers, 2006), this would suggest fatigue increases the risk of ACL injury in females.

The contrasting literature regarding sex dependant fatigue modifications in lower limb kinematics and kinetics might also be explained by between subject aerobic fitness and within subject movement variability. Specifically, enhanced oxygen delivery to exercising muscles directly attenuates muscle fatigue (Wan, Qin, Wang, Sun, & Liu, 2017), so athletes with a greater aerobic capacity could display some tolerance to fatigue from the same task. Increased within subject movement variability (calculated as the average standard deviation of the joint angle) has also been reported after fatiguing exercise (Cowley & Gates, 2017; Scholes, McDonald, & Parker, 2012), and higher movement variability during a fatigue protocol were reported in a participant who sustained an ACL injury compared with a control group (Hamdan & Raja Azidin, 2020). Such increases in movement variability might be an attempt to help adapt movement patterns affected by fatigue (Cowley & Gates, 2017), but could increase the risk of extreme movement patterns. Conversely, Cortes et al. (2014) reported a decrease in mean variability of GRF and knee moments after fatiguing exercise, thus further research exploring how fatigue affects movement variability during a side cut task are warrented.

Table 2.5 Changes in lower limb kinematics and kinetics at the hip and knee joint, during a side cut (or similar action), after prolonged intermittent running activity

Study	Fatigue protocol	Participants	Sagittal	Frontal	Transverse	GRF
Sanna & O'Connor (2008)	60 minutes of 20 m shuttles	12 college female soccer players	No change	No change	↑ ~3.3° knee internal rotation ROM from IC to peak and NS ↑ 1.1-1.3° in hip and knee external rotation at IC	-
Schmitz et al. (2014)	90 minutes of intermittent running (soccer simulation)	30 male and 29 female collegiate and club sport athletes	↓ in hip flexion angle and hip loading at IC ↓ in knee loading (values not reported)	-	↓ in knee shear forces (values not reported)	-
Khalid et al. (2015)	Yo-yo intermittent recovery test	6 male and 6 female university soccer players	↑ 0.11 $N \cdot m \cdot kg^{-1}$ peak knee extension moment and ↑ ~3° knee extension angle at IC	-	↓ 0.06 $N \cdot m \cdot kg^{-1}$ peak knee external rotation moment	↑ 0.15 X BW vertical GRF and ↑ 0.08 X BW peak anterior/posterior GRF
McGovern et al. (2015)	Prolonged modified t test	10 male and 19 female university soccer players	↓ 4° hip and knee flexion angle	↑ ~3° hip adduction angle (males only)	No change	-

Continued on next page

Table 2.5 Continued

Study	Fatigue protocol	Participants	Sagittal	Frontal	Transverse	GRF
Raja Azidin et al. (2015)	Soccer match simulation	19 male recreational soccer players	↑ knee extension angle at IC (values not reported)	No change	-	-
Collins et al. (2016)	60 minutes of intermittent shuttle running	13 collegiate female soccer players	No change	↑ 2.4° peak knee abduction angle	No change	-
Savage et al. (2018)	4 x 20 minutes of intermittent non-motorised treadmill	8 male Australian football players	↑ ~7° knee flexion angle at IC and ↑ knee extensor moment (values not reported)	-	No change	-

IC = initial contact, ↑ = increase, ↓ = decrease, ROM = range of motion, GRF = ground reaction force, NS = non-significant

2.4.4 Effect of EIMD on ACL injury risk

The effect of EIMD on ACL injury risk has received limited attention, however several studies have examined the effect of EIMD on walking and running kinematics. Decreases in both hip (~2 – 7º; Tsatalas et al., 2013a) and knee (~1 – 10º; Chen, Nosaka, Lin, Chen & Wu, 2009; Dutto & Braun, 2004; Paquette et al., 2017; Paschalis et al., 2007a; Tsatalas et al., 2013a; Tsatalas et al., 2013b) range of motion during walking and running have been observed after muscle-damaging exercise. These findings were consistent with a decrease in stride length (Burt, Lamb, Nicholas & Twist, 2014; Chen et al., 2009; Tsatalas et al., 2013b) and an increase in stride rate during sub-maximal running after muscle-damaging exercise (Tsatalas et al., 2013a; Tsatalas et al., 2013b). Increasing stride rate has been associated with an increase in vertical leg stiffness (Farley & Gonzalez, 1996), which could increase risk of injury due to a reduction in shock absorption capabilities (Dutto & Braun, 2004). From these data, it would seem likely that knee flexion is reduced with EIMD, which is associated with ACL injury risk. However, during initial contact knee flexion has been found to increase (~1.4 – 3.7º; Tsatalas et al., 2013a; Tsatalas et al., 2013b) and decrease (~1.1 – 2º; Dutto & Braun, 2004; Paschalis et al., 2007a; Paquette et al., 2017) during walking and running activities. Such discrepancies are task dependant, given that increases in knee flexion were observed during walking (Tsatalas et al., 2013a; Tsatalas et al., 2013b) and decreases in knee flexion were observed during running (Dutto & Braun, 2004; Paschalis et al., 2007a; Paquette et al., 2017).

Changes in walking kinetics have also been reported after muscle-damaging exercise. Tsatalas et al. (2013a) reported decreases in peak hip flexor moment (-1.3 *cf.* -1.09 $N{\cdot}m{\cdot}kg^{-1}$) and increases in peak knee flexor moment (-0.09 *cf.* -0.15 $N{\cdot}m{\cdot}kg^{-1}$), which has been postulated as a protective mechanism to reduce loading on painful tissues. Furthermore, peak vertical (119.9 *cf.* 113.7 % BW) and posterior (-23.3 *cf.* -18.9 % BW) GRF decreased with EIMD, although the first minimum vertical GRF (72.1 cf. 82.0 % BW) was increased (Tsatalas et al., 2013a). These data suggest an increased loading during the weight acceptance phase of stance (Tsatalas et al., 2013a), which could increase injury risk. Collectively, whilst these data suggest an increased risk of injury with EIMD, the specific risk of injury to the ACL following EIMD cannot be determined, as running does not place sufficient loading on the ACL required to identify ACL injury mechanisms (Vanrenterghem et al., 2012). To the authors knowledge, only one study has assessed the effect of EIMD on side cut biomechanics (Snyder, Hutchison, Mills & Parsons, 2019). Specifically, Snyder et al. (2019) reported peak posterior GRF (0.77 *cf.* 0.87 xBW) and anterior tibial shear force (1.15 *cf*. 1.24 xBW) increased after muscle damaging exercise and such changes have been associated with an increased risk of ACL injury. Taken together, these findings highlight further research assessing the effect of EIMD on lower limb kinematics and kinetics during a side cut is warranted to fully understand the effect of EIMD on ACL injury risk.

2.5 Conclusion

Team sport athletes perform numerous high-speed efforts, accelerations and decelerations during match-play which elicit acute psychophysiological responses such as an elevated $\dot{V}O_2$, HR, B[La] and RPE. These psychophysiological responses are strongly correlated with specific movements performed by athletes (i.e. accelerations, decelerations and high-speed running). In particular, metabolic power has demonstrated the strongest associations with an athlete’s internal psychophysiological response in comparison to high speed running, and therefore has potential to reflect an individual’s internal response to team sport activity. However, the validity of metabolic power has been questioned and is influenced by the intermittentness of exercise. Further research is therefore required to investigate whether metabolic power better reflects the internal response to team sport activity, in comparison to high speed.

The movement characteristics of team sports cause symptoms of fatigue and muscle damage that appear immediately, and for days after exercise, and can be attributed to a combination of central and peripheral mechanisms. For example, decrements in MVC, CMJ and sprint performance have been reported after team sport activity and are associated with the amount of high-speed running and directional changes performed by the player. Similar associations between sprints, accelerations and decelerations with indirect markers of muscle damage have also been reported. It is therefore essential that research assessing fatigue and muscle damage after team sport activity incorporates key movement patterns that are performed frequently during match-play (see section 2.1.1).

Injury to the ACL often occurs during a side cut in team sport athletes. Whilst the mechanisms of ACL injury are multifaceted, knee abduction / valgus and internal tibial rotation motions and moments are key mechanisms reported during an ACL injury. Smaller flexion angles (at the trunk, hip and knee), hip adduction and trunk rotation are also common secondary mechanisms associated with ACL injuries. ACL injury risk also appears to be dependent on sex and fatigability. Specifically, under fatigue, females typically adopt a more erected side cut position which is associated with an increased risk of injury. However, discrepancies in reported modifications in frontal and transverse plane lower limb mechanics after fatigue are evident and potentially reflect the non-uniformity of fatigue protocols used. Further research is therefore warranted to assess how fatigability from team sport activity influences side cut biomechanics to help inform ACL injury risk after team sport activity, ACL screening and preventative programmes. Finally, the current literature on the effect of EIMD on side cut mechanics and ACL injury risk is minimal, but EIMD-induced changes in running mechanics are evident. As team sport athletes might have to perform whilst exhibiting symptoms of EIMD, these data highlight the need to assess side cut biomechanics after muscle damaging exercise, to help identify whether or not EIMD contributes to ACL injury risk.

Chapter 3

General Methods

This section details common procedures used in Chapters 4-7.

3.1 Multi-stage fitness test (Chapters 4,5,6 and 7)

The 20 m multi-stage fitness test (Ramsbottom, Brewer, & Williams, 1988) involved participants running back and forth along a 20 m indoor linear course. Movement speeds were controlled using an audio CD, with the initial speed starting at 8.5 $km \cdot h^{-1}$ and progressively increasing by 0.5 $km \cdot h^{-1}$ every ~60 s until volitional exhaustion. The calculation (Chapter 4 and 5) and estimation (Chapter 6 and 7) of the participant's $\dot{V}O_{2peak}$ is discussed further in the relevant chapters. The multi-stage fitness test has demonstrated favourable relative agreement with measured $\dot{V}O_{2max}$ (r = 0.87 - 0.92) with an estimated standard deviation of 3.5 $ml \cdot kg^{-1} \cdot min^{-1}$ and standard error of measurement of 4.1 $ml \cdot kg^{-1} \cdot min^{-1}$ (Paradisis et al., 2014; Ramsbottom et al., 1988). The multi-stage fitness test has also demonstrated high relative reliability (r = 0.95), however the absolute reliability is less favourable (95% limits of agreement (LoA: 0.0 ± 5.5; Lamb & Rogers, 2007). Taken together, these data suggest the multi-stage fitness test can be used to estimate $\dot{V}O_{2max,}$ but the repeatability is less favourable, as a participant with an estimated $\dot{V}O_{2max}$ of 55 $ml \cdot kg^{-1} \cdot min^{-1}$ might have an estimated value as high as 60.5 or as low as 49.5 $ml \cdot kg^{-1} \cdot min^{-1}$ in subsequent trials.

3.2 Multi-directional running protocol (Chapters 4,5,6 and 7)

The multi-directional trial comprised repeated bouts of ~60 s of intermittent activity (jogging and sprinting) followed by 120 s of passive rest, where participants covered 175 m during each bout. The specific number of bouts performed are detailed in the relevant chapters. The specific pattern of activity comprised of three 10 m sprints forward interspersed with a 5 m jog backwards. Thereafter, a 2.5 m lateral jog to the right and left was performed, followed by two 10 m sprints forward interspersed with a 5 m jog backwards. This was followed by a 10 m jog forwards, a 2.5 m lateral jog to the right and left into a 35 m sprint forward. Finally, a 5 m diagonal jog, a 15 m jog forwards, a 5 m jog backwards followed by a 20 m sprint forwards was performed during each bout (Figure 3.1). Reliability data for the multi-directional trial are provided in Chapter 4.

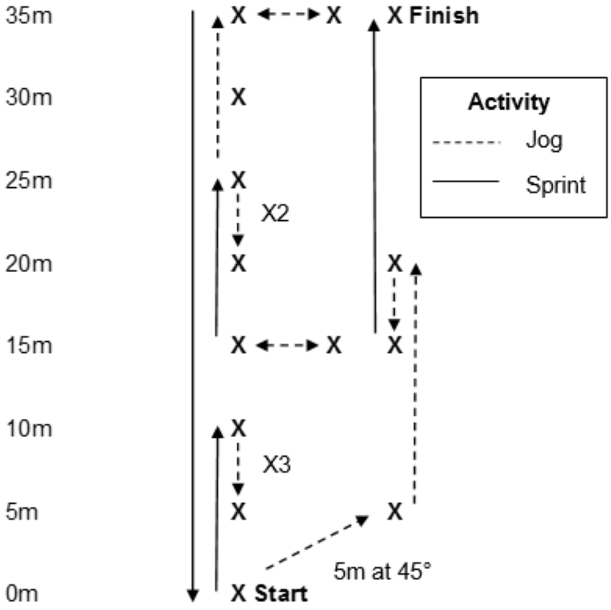


Figure 3.1. Schematic representation of the multi-directional running condition. Each X indicates a change of direction.

All participants completed a warm up consisting of two submaximal bouts of the multi-directional trial and three progressive accelerations over 10 m before commencing the protocol.

3.3 Linear running protocol (Chapters 4 and 5)

The linear trial comprised repeated bouts of ~60 s of intermittent activity (jogging and sprinting) followed by 120 s of passive rest, where participants covered 175 m during each bout. The specific activity pattern involved 3 x 35 m sprints interspersed with 2 x 35 m jogs along a linear course.

All participants completed a warm up consisting of two submaximal bouts of the linear trial and three progressive accelerations over 10 m before commencing the linear trial.

3.4 Sprint performance (Chapters 6 and 7)

Participants performed three single maximal 20 m sprints on an outdoor running track, with times recorded using four infrared timing gates (Brower Speed Trap 2; Brower, UT, USA). Timing gates were positioned at zero and 20 m, at a height of ~ 1 m, and all participants wore running trainers. Participants comenced each sprint from a standing start, positioned 0.5 m behind the initial timing gate, and were instructed to declerate only once they had passed the final timing gate. Each sprint was interspersed with a 2-minute passive recovery. The fastest 20 m sprint time was used for analysis. Single beam timing gates have demonstrated favourable between trial reliability (CV: 1%; Waldron et al., 2011) and favourable absolute agreement compared with high speed video analysis (95% LoA: 0.006 – 0.120 s; Altmann et al., 2017) over sprint distances of 20 – 30 m.

3.5 Three-dimensional motion capture of 45° side cuts (Chapters 6 and 7)

Twenty-eight reflective markers were placed on the trunk, pelvis and lower extremities in accordance with the Liverpool John Moores University (LJMU) lower-limb and trunk model (Vanrenterghem et al., 2010). Specifically, trunk markers were placed on the right and left acromion, proximal sternum, xiphoid process and vertebra C7 and T8. Pelvis markers were placed on the right and left iliac crest, anterior superior iliac spine, posterior superior iliac spine and greater trochanters. Lower limb markers were placed on the medial and lateral femoral epicondyles, medial and lateral malleoli and the heel, first and fifth metatarsal of each foot. In addition, non-collinear cluster markers, mounted on rigid plates were securely placed on the right and left thigh and shank (Figure 3.2). Thereafter a 3-second static calibration and a dynamic calibration for the right and left hip and knee was recorded to define functional joint centres. Three flexion and extension, abduction and adduction and circumduction movements were performed at the hip joint. For the knee joint participants performed three flexion and extension movements. After calibration, the medial malleolus, medial and lateral knee and left and right greater trochanters were removed, so only tracking markers remained (Vanrenterghem et al., 2010).

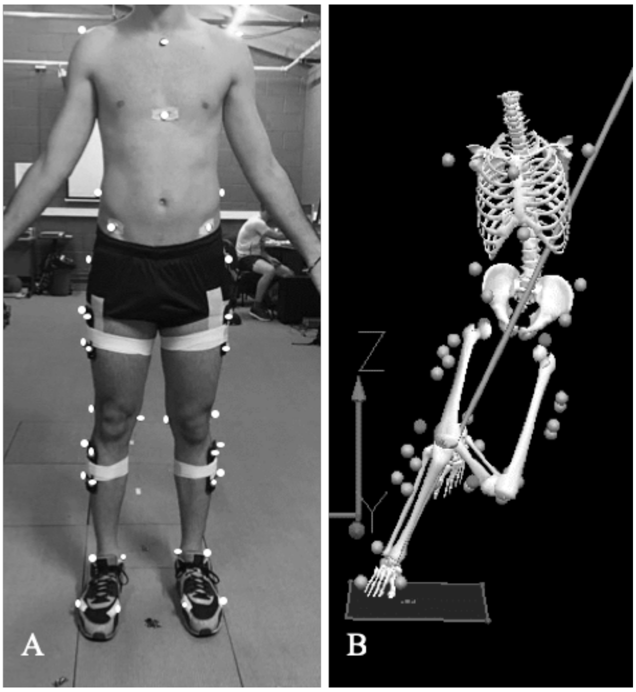


Figure 3.2 (A) Anterior view of the static marker model used and (B) Visual 3D representation of a particicpant performing a 45° side cut

Participants were permitted several practice attempts of the run and cutting manoeuvre. This involved 45° cutting manoeuvres at an approach speed of 4 – 4.5 m·s^{-1} (see section 2.4.2.2; Vanrenterghem et al., 2012) which was assessed using two infrared timing gates (Brower Speed Trap 2; Brower, UT, USA) located 1.5 m apart prior to the force platform, at a height of ~ 1 m (Figure 3.3). Thereafter participants performed five cutting maneouvers on the dominant side, interspersed with a 1-minute passive recovery. Successful trials were those in which the approach speed was maintained, the entire foot contacted the force platform and the cutting manoeuvre was performed the correct exit angle at 45°.

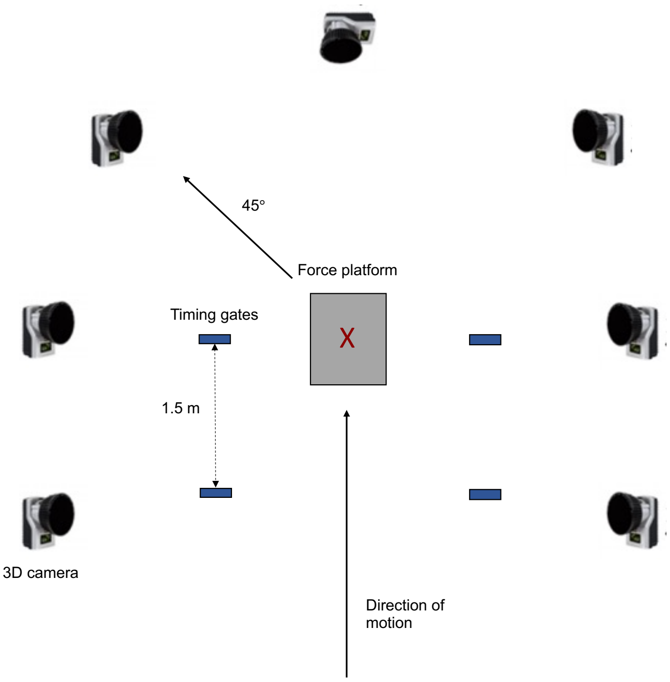


Figure 3.3 Schematic representation of the 3D motion capture data collection of 45° side cuts

Three-dimensional marker trajectories were recorded using seven three-dimensional cameras (Oqus 7, Qualisys, Sweden) sampling at 300 Hz. Simultaneous measurements of three-dimensional GRF were recorded on a force platform (Kistler, Switzerland), sampling at 900 Hz. All kinematic and kinetic data were captured using biomechanical software (Qualisys Track Manager 2.15, Qualisys, Sweden).

3.6 Data Analysis of 45° side cuts (Chapters 6 and 7)

Kinematic and kinetic calculations from tracked marker trajectories and GRF data were conducted using Visual3D^{TM} (version 5.1, C-Motion Inc., Rockville, USA). Trajectory data and GRF data were filtered using a fourth-order, zero-lag low-pass Butterworth filter at 12 Hz and 40 Hz, respectively, based on residual analysis (see appendix 3.1; Winter, 1990) and previous recommendations (Roewer, Ford, Myer & Hewett, 2014). A trunk and lower limb model (trunk, pelvis, 2 x thigh, 2 x shank, 2 x foot) was created for each participant from the standing calibration, which accounts for 82% of body mass and can therefore be used to estimate centre of mass variables (see section 2.4.2.4; Jamkrajang et al., 2017; Sankey et al., 2020). Participant-specific hip and knee functional joint centres were estimated from dynamic calibration, which provide a valid assessment of a fixed joint axis (Ehrig, Taylor, Duda & Heller, 2007) and accurate biomechancis compared with anatomical landmarks (Robinson & Vanrenterghem, 2012). Three-dimensional GRF was calculated and normalized to body weight (N·kg^{-1}). Joint motions (°) and angular velocities (°·s^{-1}) in all three planes were calculated using Cardan x-y-z rotation sequence. The hip and knee angle were measured relative to the next most proximal segment. Estimated whole-body centre of mass (COM) based on the LJMU lower limb and trunk model (Vanrenterghem et al., 2010) was used to calculate the extrapolated centre of mass (XCOM) in accordance with Hof (2008), as detailed below:

$$\mathrm{XCOM} = \mathrm{pCOM} + \frac{(\mathrm{vCOM})}{\sqrt{gl^{-1}}}$$

where *pCOM* is the medio-lateral position of the COM, *vCOM* is the medio-lateral velocity of the COM, *g* is gravity and *l* is the distance between the COM and the ankle (defined by the lateral malleolus marker) in the frontal plane (Hof, 2008; Sankey et al., 2020). The medio-lateral foot placement was then calculated as the medio-lateral distance from the XCOM relative to the base of support (BOS; defined by the fifth metatarsal head; Sankey et al., 2020).

Task achievement was evaluated using the first derivative of COM position to calculate COM velocity and cut angle. Three-dimensional hip and knee internal moments were calculated using Newton-Euler inverse dynamics procedures (Bresler & Frankel, 1950) and estimated body segment parameters from Dempster (1955). Specifically, hip adduction, extension and external rotation moment and knee adduction, extension and external rotation moments were calculated. The net internal joint moments produced by joints and ligaments are presented which counterbalance the external joint moments. For example, an external knee flexion moment, which tends to flex the knee, is counterbalanced by an internal knee extensor moment, generated by the quadriceps. In addition, the relationship between peak knee extensor and hip extensor moments were examined using the knee to hip extensor moment ratio (calculated by peak knee extensor moment divided by peak hip extensor moment). Using this ratio, a value greater than “1” would indicate increased knee extensor moments compared to hip extensor moments while a value of less than “1” would indicate increased hip extensor moments compared to knee extensor moments (Pollard, Sigward & Powers, 2010). The joint co-ordinate system was used as a reference frame for joint moments (Kristianslund, Krosshaug, Mok, McLean, & van den Bogert, 2014) and all joint moments were normalized to body mass ($N \cdot m \cdot kg^{-1}$). All data were time-normalized to

100% of stance, which was defined as the time vertical GRF exceeded 50 N (Collins et al., 2016). Peak kinematic and kinetic data during the weight acceptance phase of the cutting manoeuvre; defined as the interval between initial contact and peak knee flexion (Jamison et al., 2012) were quantified. Vertical GRF impulse (IGRF) during the weight acceptance phase was derived via integration of the vertical GRF over time (Caldwell, Robertson, & Whittlesey, 2014), normalized to body weight.

3.7 Statistical analysis approach (Chapters 4, 5, 6 and 7)

Traditional null hypothesis testing is the standard for quantitative research in sport science. However, the shortcomings and misinterpretations of null hypothesis testing and *p* values have recently been highlighted (Szuc & Ioannidis, 2017; Greenland et al., 2016). Briefly, the use of a global arbitrary cut off *p* value (i.e. $p < 0.05$ = a significant effect), which is not specific to the research question, does not provide a good measure of evidence regarding a hypothesis (Wasserstein & Lazar, 2016). A lone *p* value is also uninformative as it is prone to false positives and says nothing about the magnitude of the effect (Kruschke, 2010). Indeed, a review on the effect of fatigue on lower limb neuromuscular function highlighted only 22% of the reviewed studies provided effect sizes in addition to *p* values (Barber-Westin & Noyes, 2017). Here, the authors highlighted the need to assess the magnitude of the effect, particularly in small samples, as the use of statistically significant findings alone may have limited clinical relevance (Barber-Westin & Noyes, 2017).

Given the aforementioned issues with the lone *p* value and to adapt a practical approach to the analyses conducted in this thesis, the use of *p* values, effect sizes and accompanying 95% confidence intervals has been adopted throughout. Specific *p* values are reported for all analysis, to avoid the false belief of automatic statistical inference if $p < 0.05$ (Szuc & Ioannidis, 2017). The use of effect sizes and 95% confidence intervals are also included to aid comparisons amongst the literature discussed in the topic area (e.g. Ashton & Twist, 2015; Fox, Patterson & Waldron, 2017; Polglaze et al., 2017) and to indicate the magnitude of the effect, which is not possible with traditional hypothesis testing alone.

Chapter 4

Energy expenditure, metabolic power and high-speed activity during linear and multi-directional running

Rationale summary

The metabolic power approach, which accounts for the metabolic requirement of accelerations and decelerations, has the potential to provide a detailed profile of the metabolic demands of team sport activity. However, it is unclear how fluctuations in the number of directional changes performed affects the agreement between measured and estimated energy expenditure. This study therefore compared measurements of energy expenditure derived using microtechnology and indirect calorimetry during linear and multi-directional running.

4.1 Introduction

Assessing the physical demands of team sports has become common practice during training and match-play (Varley et al., 2014; Waldron et al., 2011). Typically, measures such as relative distance (Varley et al., 2014; Vigne, Gaudino, Rogowski, Alloatti & Hautier, 2010) and distance at high speed (Lythe & Kilding, 2011; Oxendale et al., 2016) have been used to describe match and training loads. This information can provide useful guidelines for practitioners when designing conditioning programmes specific to individual positions (Waldron et al., 2011) and performance profiles of successful compared with unsuccessful match outcomes (Gabbett, 2013). In addition, coaches can alter measured daily training load to allow for progressive improvements in player fitness, whilst minimizing injury risk (Gabbett & Ullah, 2012). However, the use of speed dependant time-motion data has recently been challenged (Osgnach et al., 2010; Varley & Aughey, 2013) because it does not account for the physiological load associated with accelerations that occur frequently (~650-1000) in team sports

(Russell et al., 2016; Akenhead et al., 2013). Consequently, the use of distance covered within a predefined speed threshold, such as high-speed running (>14.4 $km\cdot h^{-1}$; Rampinini, Coutts, Castagna, Sassi & Impellizzeri, 2007), is unlikely to accurately quantify an individual's external load.

The use of time-motion data to estimate energy expenditure of accelerated running (Osgnach et al., 2010) has the potential to address some of the practical and methodological issues associated with internal load measures. For example, HR recordings do not reflect the physiological demands of short duration, high intensity bouts (Achten & Jeukendrup, 2003) and blood lactate concentration largely depends on the activity undertaken in the 5 minutes before blood sampling (Stolen et al., 2005). Direct measurements of $\dot{V}O_2$ are also unfeasible during training sessions or matches (Osgnach et al., 2010). Therefore, estimations of energy expenditure are typically based on HR data, which is likely to overestimate energy expenditure by 15-20% (Achten & Jeukendrup, 2003; Rodríguez & Iglesias, 1998). Consequently, estimations of energy expenditure which assume that accelerative running on flat terrain is metabolically equivalent to constant speed running up an equivalent slope, have been advocated (Osgnach et al., 2010). Energy expenditure is then multiplied by instantaneous speed to calculate metabolic power (Osgnach et al., 2010). In contrast to traditional speed dependant zones, this approach accounts for the metabolic requirement of accelerations and decelerations, which can exceed the metabolic requirement of constant speed running (Akenhead et al., 2014). Indeed, several authors have reported that the distance covered at a high metabolic intensity (>20 $W\cdot kg^{-1}$) during team sport activity was nearly two times the distance covered at high speed (Gaudino et al., 2013; Kempton et al., 2015; Osgnach et al., 2010). Accordingly, the quantification of high metabolic power might provide a more suitable reflection of the high intensity demands of team sport activity, which can be used to design match-specific training programmes.

Given the growing interest in the metabolic demands of acceleration and deceleration associated with directional change (Ashton & Twist, 2015; Buchheit et al., 2010; Hader et al., 2014), recent studies have used this approach to measure energy expenditure and metabolic power during team sport activity. Specifically, measurements of energy expenditure (Brown et al., 2016; Coutts et al., 2015; Gaudino et al., 2013; Kempton et al., 2015; Walker et al., 2016), average metabolic power (Gaudino et al., 2013; Kempton et al., 2015; Vescovi, 2016) and time at high metabolic power (Coutts et al., 2015; Kempton et al., 2015) derived from microtechnology have been documented in several team sports to provide a profile of match and training load. Such measurements have also been strongly correlated with determinants of aerobic fitness ($r = 0.55 – 0.83$; Manzi, Impellizzeri & Castagna, 2014) and could therefore provide a more detailed profile of player physical performance, as well as the metabolic demands of training and match-play. However, the metabolic power approach overestimated energy expenditure during constant speed running (~8%; Stevens et al., 2015), whereas underestimations in energy expenditure and metabolic power were observed during shuttle running (~15%; Stevens et al., 2015) and a soccer specific drill (~29%; Buchheit et al., 2015), respectively. Changes in movement speed therefore appear to affect the agreement between estimated and measured energy expenditure. Whilst these studies question the validity of this approach, the potential effect of directional changes on estimated energy expenditure and metabolic power remains unclear. The metabolic power approach has the potential to estimate the energy expenditure of a directional change, as the acceleration phase accounts for >80% of the energy requirement of a change of direction (Hader, Mendez-Villanueva, Palazzi, Ahmaidi & Buchheit, 2016). Given the variation in accelerations and decelerations (Russell et al., 2016) and high-speed running (Carling, Bradley, McCall & Dupont, 2016) performed during match-play, assessing how fluctuations in directional changes influence estimated energy expenditure and metabolic power warrants further investigation.

The use of continuous (Stevens et al., 2015) and low speed movements protocols (Buchhiet et al., 2015; Stevens et al., 2015) are likely to under-represent the intense demands of team sport activity and cannot assess the agreement between activities at high metabolic power and high speed. The use of 4 Hz global positioning systems (GPS) to assess validity (Buchheit et al., 2015), which are unable to accurately detect instantaneous changes in speed (Varley et al., 2012), also warrants further investigation using microtechnology with higher sampling frequencies (Stevens et al., 2015). Thus, the purpose of this study was to compare measurements of energy expenditure derived using microtechnology and indirect calorimetry during linear and multi-directional running. The agreement between high speed and high metabolic power movement demands was also evaluated. It was hypothesized that the energy expenditure of multi-directional running would be higher than linear running. Furthermore, the agreement between measures of energy expenditure as well as high speed and high power activities would decrease when more changes of direction are performed.

4.2 Method

4.2.1 Participants

With institutional ethics approval (see Appendix 4.1), seven male and five female participants (age: 20.8 ± 2.7 y; stature: 176.0 ± 12.0 cm; mass: 73.3 ± 12.8 kg; $\dot{V}O_{2peak}$: 45.2 ± 2.9 $ml \cdot kg^{-1} \cdot min^{-1}$) were recruited from University-level team sports (rugby, football, hockey and netball). This sample size was based on a retrospective power calculation (Faul, Erdfelder, Buchner & Lang, 2009), using an effect size of 1.13 for differences between energy expenditure calculated from indirect calorimetry and microtechnology (see Appendix 4.2). All participants took part in team sport training sessions at least twice per week and competed in at least one match a month. Participants were briefed on all the procedures and provided written informed consent before participating in the study.

4.2.2 Design

In a repeated measures design, participants completed four sessions lasting approximately 60 minutes each. On the first visit, participants completed a multi-stage fitness test to ensure they met the inclusion criteria of an estimated maximal aerobic capacity above 40 $ml \cdot kg^{-1} \cdot min^{-1}$ for females (Vescovi, Brown & Murray, 2006) or 45 $ml \cdot kg^{\cdot -1} min^{-1}$ for males (Ostojic, 2004), based on the physiological characteristics of amateur team sport athletes. Thereafter, all participants were familiarized with the procedures and movements for each trial. In the second visit, participants completed the multi-directional trial to determine the reliability of the metabolic power derived measurements. Due to device malfunction, only 10 of the 12 participants' data were included in the reliability analysis. In the two subsequent visits participants completed the multi-directional and linear trials in a randomised order, separated by 3 – 7 days.

During both trials, energy expenditure was calculated using indirect calorimetry (EE_{VO2}) and estimated using microtechnology embedded within the GPS unit (EE_{GPS}). Measurements of high metabolic power and high-speed running were calculated for both trials, and the reliability of EE_{GPS}, time at high metabolic power and high speed were calculated for the multi-directional trial. Participants were required to abstain from performing any strenuous activity and consuming nutritional supplements 48 h before completing the multi-directional and linear trials.

4.2.3 Procedures

4.2.3.1 Multi-stage fitness test

During the test participants also wore a pre-calibrated portable gas analyser (Cosmed K4b2, Cosmrd S.r.I, Rome, Italy), so $\dot{V}O_{2peak}$ could be calculated as the highest value recorded over a 30 s period (Edgett et al., 2013). Please refer to General Methods section 3.2 for procedures.

4.2.3.2 Multi-directional and linear trials

The multi-directional and linear trials comprised eight bouts of ~60 s of intermittent activity (jogging and sprinting) followed by 120 s of passive rest. Please refer to General Methods section 3.3 and 3.4 for procedures.

Both trials were performed on an outdoor running track at a similar time of day (± 2 hours) to reduce the effects of diurnal variation. Mean temperature (p = 0.70) and humidity (p = 0.65) during the multi-directional (19.0 ± 4.2º and 32.5 ± 6.2%) and linear (19.6 ± 4.2º and 31.6 ± 3.7%) trials were similar. During each trial participants were instructed not to deviate from the prescribed running path.

4.2.3.3 Indirect calorimetry

Expired air was collected using a breath-by-breath portable gas analyser (Cosmed K4b2; Cosmed Slr, Rome, Italy), which was calibrated in accordance with the manufacturer's guidelines before each trial. Energy expenditure was calculated by the Cosmed K4b2 system from oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$), based on the equation (Weir, 1949):

$$EE = [3.801*(\dot{V}O_2 - \dot{V}O_{2\,p}) + 1.244*(\dot{V}CO_2 - \dot{V}CO_{2\,p})]*1440$$

Where $_p$ = protein

$\dot{V}O_2$ during the 120 s rest periods in each trial was included in the analysis to account for anaerobic contributions to total energy expenditure during exercise (Scott, 2006). Resting energy expenditure (assumed to be 1.29 $kcal{\cdot}min^{-1}$ for males and 1.03 $kcal{\cdot}min^{-1}$ for females; Thompson & Manore, 1996) was subtracted from total energy expenditure during each trial to provide net energy expenditure associated with exercise (EE_{VO2}; Osgnach, Paolini, Roberti, Vettor & di Prampero, 2016). Given its accuracy (Maiolo, Melchiorri, Iacopino, Masala & De Lorenzo, 2003), indirect calorimetry has been considered a gold standard to assess energy expenditure for the types of activities described here (Buchheit et al., 2015; Stevens et al., 2015).

4.2.3.4 Microtechnology

The movement characteristics of the multi-directional and linear trials were recorded using MinimaxX GPS units (Team 2.5, Catapult Innovations, Melbourne, Australia) sampling at 10 Hz. The same GPS device was used throughout the study for all participants to eliminate inter-device variability (Akenhead et al., 2013). Data was subsequently downloaded and analysed (Sprint, Version 5.1, Catapult Sports, VIC, Australia) to calculate EE_{GPS}. Calculations were based on the approach developed by

Osgnach et al. (2010), which assumes running on a flat terrain is energetically equivalent to uphill running at a constant speed. Accordingly, the following equation was used to calculate energy expenditure of accelerated running:

$$EE = (155.4ES^5 - 30.4ES^4 - 43.3ES^3 + 46.3ES^2 + 19.5ES + 3.6) \times EM \times KT$$

Where ES is the equivalent slope of accelerated running and EM is the additional force required to overcome acceleration. Calculations for these variables are detailed in di Prampero, Botter and Osgnach (2015). KT is the terrain constant of 1.29.

Metabolic power was calculated by multiplying energy expenditure with instantaneous speed (Osgnach et al., 2010). Time above high metabolic power were compared with time at high speed (> 14.4 $km \cdot h^{-1}$) and very high speed (> 16 $km \cdot h^{-1}$) to examine the differences in speed and metabolic power derived measurements of movement characteristics. Two definitions of high speed were used to compare a common high-speed definition used in previous literature comparing high speed and high power (> 14.4 $km \cdot h^{-1}$; Gaudino et al., 2013; Kempton et al., 2015) and the speed equivalent of high metabolic power, during constant-speed running (>16 $km \cdot h^{-1}$; Osgnach et al., 2010). The number of satellites detected by the GPS receiver and the horizontal dilution of precision was 13.7 ± 0.8 and 0.7 ± 0.1, respectively.

4.2.4 Statistical analysis

Descriptive statistics were calculated for EE_{VO2} , EE_{GPS}, metabolic power and speed measurements. A two-way analysis of variance (ANOVA) was used to determine differences between measurements of energy expenditure between trials and time at high speed, very high speed and high power between trials. Paired sample *t*-tests were used to determine any specific effects. Agreement between these measures were calculated using Pearson's product-moment correlation coefficient (*r*), the 95% confidence interval (CI) and the 95% limits of agreement (LoA: bias ± 1.96 x SD_{diff}). Due to the presence of heteroscedasticity, ratio LoA were calculated by applying natural logarithmic transformations to the data (Nevill & Atkinson, 1997). Pearson's product-moment correlation coefficient (*r*) was also calculated to assess the relationship between measurements of energy expenditure (EE_{VO2} and EE_{GPS}) and metabolic power with speed measurements. The coefficient of variation (CV), ratio LoA, intraclass correlation coefficient (ICC) and the 95% CI were calculated to determine the reliability of EE_{VO2}, EE_{GPS}, time at high power, high speed and very high speed during the multi-directional trial. Natural logarithmic transformations were applied to the data before ICC analysis (Atkinson & Nevill, 1998). Where appropriate, *p* values were reported. The reader should refer to General Method section 3.8 for further information regarding the statistical approach adopted.

4.3 Results

4.3.1 Energy expenditure

EE_{VO2} and EE_{GPS} during the multi-directional and linear trials are presented in Table 4.1. Whilst measurements of energy expenditure were strongly related ($r > 0.89$, $p < 0.001$), they were different ($F = 153.4$, $p < 0.001$). EE_{VO2} was higher during the multi-directional ($t = 10.9$, $p < 0.001$) and linear trials ($t = 9.1$, $p < 0.001$) when compared to EE_{GPS}. The ratio LoA for energy expenditure during the multi-directional trial demonstrated that EE_{GPS} underestimated EE_{VO2} by 52% (range: 20 – 93%). Similarly, EE_{GPS} during the linear trial was underestimated by 34% (range: 12% – 59%).

Table 4.1 Agreement between EE_{VO2} and EE_{GPS} during the multi-directional and linear trials

Trial	**EE_{VO2} kcal (kcal·min^{-1})**	**EE_{GPS} kcal (kcal·min^{-1})**	**Mean difference ± SD difference (kcal)**	***r***	**95% CI**	**Ratio LoA**
Multi-directional	213.5 ± 44.2 (9.0 ± 2.0)	140.9 ± 30.9 (5.9 ± 1.4)	72.6 ± 23.0	0.89*	0.69 to 0.99	1.52 x/÷ 1.27
Linear	199.9 ± 47.8 (8.7 ± 2.1)	148.9 ± 34.6 (6.5 ± 1.5)	51.0 ± 19.5	0.95*	0.86 to 0.99	1.34 x/÷ 1.19

** Denotes a significant correlation ($p < 0.001$). EE_{VO2} = energy expenditure from indirect calorimetry, EE_{GPS} = energy expenditure from GPS*

4.3.2 Metabolic power

Comparisons between the equivalent threshold for time at high speed, very high speed and high power during the multi-directional and linear trials are presented in Table 4.2 and 4.3. Whilst time at high speed and high power demonstrated a strong relationship (Table 4.2), there was a difference between time at high speed and high power ($F = 84.9$, $p < 0.001$) and a difference between trials ($F = 10.7$, $p = 0.007$). Time at high power was higher than time at high speed during the multi-directional trial ($t = 10.3$, $p < 0.001$). Conversely, time at high power was lower than time at high speed during the linear trial ($t = -2.7$, $p = 0.021$). Furthermore, time at high speed was lower ($t = -5.8$, $p < 0.001$) and time at high power was higher ($t = 2.2$, $p = 0.046$) during the multi-directional trial in comparison to the linear trial. The ratio LoA demonstrated time at high power was 41% higher (range: 4 – 92%) than time at high speed during the multi-directional trial. During the linear trial time at high power was 5% lower (range: -17% – 9%) than time at high speed.

A difference between time at very high speed and high power ($F = 368$, $p < 0.001$) and a difference between trials ($F = 51.7$, $p < 0.001$) was also observed (Table 4.3). Specifically, time at high power was 149% (range: 44 – 331%) higher during the multi-directional trial ($t = 27.7$, $p < 0.001$) and 4% (range: -9 – 19%) higher during the linear trial ($t = 2.27$, $p = 0.045$), compared with time at very high speed. Furthermore, time at very high speed was lower ($t = -13.3$, $p < 0.001$) during the multi-directional trial in comparison to the linear trial.

Table 4.2 Agreement between time at high power and high speed during the multi-directional and linear trials

Trial	Time at high power (s)	Time at high speed (s)	Mean difference ± SD difference (s)	*r*	95% CI	Ratio LoA
Multi-directional	118.4 ± 11.7	85.5 ± 18.7	32.9 ± 11.1	0.86*	0.55 to 0.97	1.41 x/÷ 1.36
Linear	111.5 ± 10.4	117.4 ± 5.9	-5.9 ± 7.6	0.71*	0.40 to 0.90	0.95 x/÷ 1.15

** Denotes a significant correlation (p < 0.01)*

Table 4.3 Agreement between time at high power and very high speed during the multi-directional and linear trials

Trial	Time at high power (s)	Time at very high speed (s)	Mean difference ± SD difference (s)	*r*	95% CI	Ratio LoA
Multi-directional	118.4 ± 11.7	49.8 ± 15.7	68.6 ± 8.6	0.84*	0.61 to 0.94	2.49 x/÷ 1.73
Linear	111.5 ± 10.4	106.6 ± 8.0	4.9 ± 7.5	0.71*	0.35 to 0.95	1.04 x/÷ 1.14

** Denotes a significant correlation (p < 0.01)*

4.3.3 Reliability

The between-trial CV, ICC and ratio LoA for EE_{VO2} during the multi-directional trial was 7.6%, 0.95 (0.81-0.99) and 0.95 x/÷ 1.30, respectively. EE_{GPS} (2.2%), time at high power (4.2%) and time at high speed (6.1%) all demonstrated a lower CV in comparison to EE_{VO2}, whereas time at very high speed was higher (11.7%). The ICC varied for EE_{GPS} (>0.99; 95% CI: 0.98 – >0.99), time at high speed (0.96; 0.83 – 0.99), time at very high speed (0.92; 0.69 – 0.98) and time at high power (0.90; 0.61 – 0.98). The ratio limits of agreement for EE_{GPS} (1.02 x/÷ 1.06; range: -4 – 8%), time at high speed (0.99 x/÷ 1.21; range: -18 – 20%), time at very high speed (1.01 x/÷ 1.47; range: -31 – 48%) and time at high power (0.99 x/÷ 1.14; range: -13 – 13%) demonstrated small changes in the mean difference (< 3%), and less repeatability for time at very high speed compared with EE_{GPS} during multi-directional running.

4.4 Discussion

This study has demonstrated that regardless of movement type, energy expenditure derived using microtechnology systematically underestimates energy expenditure measured using indirect calorimetry, despite a strong association between the two measures. Measurements of high power, high speed and very high speed also differed during linear and multi-directional running, suggesting the two measures reflect different external loads. Furthermore, metabolic power derived measures of EE_{GPS} and time at high power demonstrated a good level of reliability during the multi-directional trial.

Whilst measurements of EE_{GPS} and EE_{VO2} were strongly related (*r* > 0.89), EE_{GPS} during the multi-directional and linear trials was underestimated by 52% (range: 20 –

93%) and 34% (range: 12% - 59%), respectively. This data reaffirms reports that energy expenditure derived from microtechnology underestimates measured energy expenditure (Brown et al., 2016; Buchheit et al., 2015; Highton et al., 2017; Steven et al., 2015; Walker et al., 2016), albeit the magnitude of this disagreement varies between studies. For example, underestimations in energy expenditure as large as ~44 – 51% have been reported during intermittent team sport circuits when compared with energy expenditure derived from $\dot{V}O_2$ (Brown et al., 2016; Buchheit et al., 2015). Conversely, Walker et al. (2016) reported differences of only ~9.4% in estimated energy expenditure between methods during Australian football match-play. These differences are possibly explained by the use of regression equations based on oxygen uptake and accelerometer data during a maximal test to estimate energy expenditure (Walker et al., 2016), which do not account for elevations in energy expenditure associated with excess post-exercise oxygen consumption during intermittent activity (Lyons et al., 2006). Accordingly, the use of varied criterion measures of energy expenditure, and the measurement of energy expenditure during static rest periods appears to affect the agreement with estimated energy expenditure derived from microtechnology. Furthermore, energy expenditure derived from microtechnology should not be used to determine the energy requirement of intermittent exercise.

The underestimation of energy expenditure was expectedly higher during the multi-directional trial compared with the linear trial, which might be because of the increase in aerobic (Hatamoto et al., 2013) and anaerobic (Ashton & Twist, 2015; Dellal et al., 2010) metabolism when performing an increased number of directional changes (160 *cf.* 32). As the metabolic power approach is based on linear running (di Prampero et al., 2015), the additional energy requirement associated with directional changes might not be accounted for, despite the inclusion of acceleration and deceleration actions within the energy expenditure calculation. Indeed, Stevens et al. (2015) reported metabolic power derived energy expenditure was overestimated (6 – 11%) during constant running, whereas underestimations of 13 – 16% were observed during shuttle running with directional change. A greater $\dot{V}O_2$ during backwards (Paes & Fernandez, 2016; Williford, Olson, Gauger, Duey & Blessing, 1998) and lateral (Williford et al., 1998) running, compared to forward running at the same speed has been observed indicating such activities are associated with a greater energy expenditure. Yet, the metabolic power approach is based on forward running (Osgnach et al., 2010) and potentially cannot account for the additional energy requirement of lateral and backwards movement, which reduces the agreement between the two measures. Collectively, these data suggest the agreement between EE_{VO2} and EE_{GPS} is reduced during running with an increased number of directional changes as well as backwards and lateral movement.

Time at high power was 41% greater (range: 4 – 92%) than time at high speed during the multi-directional trial, which is consistent with previous reports (37 – 84%; Gaudino et al., 2013; Kempton et al., 2015), despite a strong agreement between the two measures (r = 0.85). This disagreement was greater (149%) when time at high power was compared with time at very high speed. Conversely, during the linear trial, time at high power was 5% lower (range: -17 – 9%) and 4% higher (range: -9 – 19%) than time at high speed and very high speed, respectively. An improved agreement between time at high speed, very high speed and high power during linear running where participants performed fewer accelerations and decelerations, might be anticipated given that the metabolic cost of running at 16 km·h^{-1} has previously been shown to be approximately 20 W·kg^{-1} (Osgnach et al., 2010). During multi-directional activity, a greater number of accelerations over short distances would limit a participant's ability to attain the high-speed threshold (Gaudino et al., 2013; Kempton et al., 2015). Interestingly, time at high power and EE_{VO2} both demonstrated that the multi-directional trial imposed a greater load than the linear trial. Time at high speed and very high speed did not follow this pattern, suggesting time at high power better reflects changes in internal load during multi-directional activity, when participants are unable to attain the threshold of high-speed running. Accordingly, the use of high-speed running categories might underestimate the metabolic demands of team sport activity (di Prampero et al. 2005). Moreover, the agreement between time at high speed, very high speed and high power is dependent on the number of acceleration efforts performed, suggesting these two measures represent different external loads.

Finally, this study examined the reliability of measures of $EE_{VO2,}$ EE_{GPS} and time at high power, high speed and very high speed during multi-directional running. EE_{VO2} demonstrated a similar level of reliability to previous measures of $\dot{V}O_2$ and CO_2 during high-intensity running (Duffield, Dawson, Pinnington & Wong, 2004). In addition, the CV for EE_{VO2} was lower than the minimal detectable change in $\dot{V}O_2$ during exercise (>10%; Darter, Rodriguez & Wilken, 2013), indicating an acceptable level of reliability for EE_{VO2}. Time at high speed (CV: 6.1%) presented a similar reliability to the distance covered at high speed reported by Castellano et al. (2011). However, reliability for high power was much better than that reported previously during soccer specific exercise (CV: 74%, ICC: 0.09; Buchheit et al., 2015), which might partly be explained by the higher sampling frequency (10 Hz) of the GPS device used here. Buchheit et al. (2015)

used GPS devices sampling at only 4 Hz, which have demonstrated greater measurement error for measuring high speed running and accelerations when compared to 10 Hz devices (Varley et al., 2012). Furthermore, Buchheit and colleagues had participants dribble a ball for much of the distance covered during a circuit. This might have influenced the consistency of acceleration and deceleration actions, thus altering the distance covered at high power between trials (Buchheit et al., 2015). The CV for EE_{GPS} and time at high power was lower than the observed between-match variations in EE_{GPS} (4.0%), time at high power (8.2%) during team sport activity (Kempton et al., 2015), and time at very high speed in the present study (11.7%). Combined with the very high ICCs (>0.90), low CVs (< 7%) and low percentage mean difference (< 3%, range: -13 – 13%), these data suggest that metabolic power derived measures can be used to detect small changes in multi-directional running load.

This study is not without limitations. The comparison of indirect calorimetry inclusive of static rest periods with microtechnology, which cannot quantify energy expenditure when an athlete is stationary (Highton et al., 2017) is a potential limitation. However, it was deemed essential to measure energy expenditure during rest periods to quantify the anaerobic contribution to total energy expenditure using EPOC. Whilst this does not account for energy expenditure from rapid anaerobic glycolytic ATP turnover (Scott, 2005), the lack of a reasonable estimate of anaerobic energy expenditure, such as EPOC, would increase the error in quantifying total energy expenditure (Scott, 2006). Indeed, previous studies have utilised exercise protocols that were predominately aerobic (Buchheit et al., 2015; Stevens et al., 2015), hence it seemed necessary to implement a protocol that simulated the high intensity running demands typically observed in team sports. The use of one microtechnology device also potentially limits the generalizability of the present findings, despite the use of the same energy expenditure calculation amongst different microtechnology devices (Buchheit et al., 2015; Gaudino et al., 2013; Vescovi, 2016). Finally, the sample size was small, particularly for the reliability analysis of metabolic power, however the reported confidence intervals for the ICCs and LoA indicates the precision of our reliability measurements (Hopkins, 2000).

4.5 Conclusion

Whilst demonstrating a good level of reliability between trials, energy expenditure derived using microtechnology underestimates the energy expenditure of linear and multi-directional running when compared with indirect calorimetry. Accordingly, EE_{GPS} should not be used to determine the energy cost of intermittent exercise, but it can be used to detect small changes in load during multi-directional running. The agreement between time at high power and high speed appears to be dependent on the number of directional changes performed. This suggests that time at high speed and very high speed is likely to underestimate the high intensity demands of running incorporating multiple directional changes. Accordingly, metabolic power parameters can be used to quantify load during running with multiple directional changes.

Key messages

- *Energy expenditure derived from microtechnology underestimates the energy cost of exercise.*
- *Running with more changes of direction reduced the agreement between time at high speed and high power.*
- *Time at high power reflected changes in internal load during running more so than time at high speed.*

Next steps

- *Future research should further explore the utility of time at high power to reflect an individual's psychophysiological response to exercise.*

Chapter 5

Can player tracking devices monitor changes in internal load during multi-directional running? A comparison of high speed and high metabolic power

Rationale summary

Running with more directional changes can induce a greater internal response. However, it is unclear if measures of external load derived from player tracking devices (i.e. high speed and high power) reflect changes in internal load during running with more directional changes. This study therefore examined the internal and external demands of linear and multi-directional running to determine whether high speed or power better reflect changes in internal load.

5.1 Introduction

Intermittent team sports are characterised by numerous (20 - 60) high speed efforts over 10 – 30 m (Gabbett, 2012; Russell et al., 2016; Spencer, Bishop, Dawson, & Goodman, 2005), which can occur at pivotal moments during a match (Faude et al., 2012). Measures of high speed are therefore used to describe the external demands of team sport activity (Austin & Kelly, 2013; Cunningham et al., 2018; Springham et al., 2020; see Chapter 2.2.1). More recently, studies have also shown that team sport athletes perform numerous accelerations (~650) and decelerations (~600) during match-play (Russell et al., 2016), that evoke greater psychophysiological responses than running with fewer accelerations and decelerations, such as a higher blood lactate concentration (Ashton & Twist, 2015; Buchheit et al., 2010), rating of perceived exertion (Tang et al., 2018), oxygen consumption (Hatamoto et al., 2014) and heart rate (Akenhead et al., 2014; Tang et al., 2018). Greater decrements in peak knee flexor torque (Ashton & Twist, 2015) and muscular activity of the vastus lateralis and semitendinosus (Hader et al., 2014) also occur after running with an increased number of directional changes. Running with directional changes can therefore induce a greater internal response and neuromuscular fatigue when compared to linear running at a similar speed. However, few studies have reported the magnitude of force loss when directional changes are systematically manipulated and measured the external movement patterns of the change of direction protocols used. This would provide a more comprehensive understanding of neuromuscular adjustments from high-intensity exercise protocols including directional changes.

It is unclear if measures of external load derived from player tracking devices reflect changes in internal load during running with more directional changes, with varying associations reported between measures of high-speed distance and internal load during team sport activity (r = 0.13 *cf.* r = 0.71; Casamichana & Castellano, 2015; Delaney et al., 2018). Furthermore, correlating absolute markers of external load with internal load does not account for the between-participant variation in fitness, which largely dictates the internal response to a given external load (Weaving, Scantlebury, Roe & Jones, 2017). When expressed as a ratio, the external to internal load (quantified using measures of high-speed distance covered [external] and iTRIMP [internal]), has a moderate to strong relationship (r = 0.58 – 0.69) with measures of aerobic power during football (Akubat et al., 2018; Akubat et al., 2014). The external to internal load ratio has therefore been recommended to assess an individual player's readiness to perform (Akubat et al., 2014). However, high-speed running distance does not account for the numerous accelerations and decelerations performed during team sport match-play, that evoke greater physiological responses contributing to greater fatigue (Akenhead et al., 2014; Ashton & Twist, 2015; Buchheit et al., 2010).

Metabolic power, which accounts for both speed and acceleration has recently emerged as an alternative metric to quantify high intensity activity (Osgnach et al., 2010) that better reflects an individual's internal response (Polglaze et al., 2018a; see Chapter 4). However, further work is required to better understand how the systematic manipulation of the number of directional changes influences the demands of exercise and the utility of metabolic power using integrated ratios. Therefore, the aims of this study were twofold: a) to examine the internal and external demands of linear and multi-directional running and subsequent neuromuscular fatigue, b) to determine whether measures of high speed or power better reflect changes in internal load associated with linear and multi-directional running.

5.2 Method

5.2.1 Participants

With institutional ethics approval (see Appendix 4.1), seven male and five female participants (age: 20.8 ± 2.7 y; stature: 176.0 ± 12.0 cm; mass: 73.3 ± 12.8 kg; $\dot{V}O_2$: 45.2 ± 2.9 $ml \cdot kg^{-1} \cdot min^{-1}$) were recruited from University-level team sports (rugby, football, hockey and netball). The sample size exceeds an *a priori* sample size calculation using estimated power (Faul et al., 2009) and an effect size of 1.1 for differences in HR during running with an increased number of directional changes (Tang et al., 2018; see Appendix 5.1). All participants took part in team sport training sessions at least twice per week and competed in a minimum of one match per month. Participants were briefed on all procedures, provided written informed consent to take part in the study and completed pre-test health screening to ensure there were no contraindications to exercise.

5.2.2 Design

In a repeated measures design, participants completed three visits to the laboratory on separate days. On the first visit, participants performed a multi-stage fitness test to ensure they met the inclusion criteria of having an estimated maximal aerobic power >40 $ml \cdot kg^{-1} \cdot min^{-1}$ for females (Vescovi et al., 2006) or >45 $ml \cdot kg^{-1} \cdot min^{-1}$ for males (Ostojic, 2004) based on physiological characteristics of amateur team sport athletes. Thereafter, participants were habituated to the multi-directional and linear trials and the assessment of isometric muscle function of the knee extensors and flexors. In the subsequent two visits, participants completed the linear and multi-directional trials, separated by 3 – 7 days, in a randomized, cross-over design. During each of these trials movement was recorded using microtechnology and measurements of oxygen consumption ($\dot{V}O_2$), blood lactate concentration (B[La]), heart rate (HR) and rating of perceived exertion (RPE) were taken. Isometric muscle function was assessed immediately before and after each trial. Participants were required to abstain from performing any strenuous activity and consuming nutritional supplements 48 h before completing each trial.

5.2.3 Procedures

5.2.3.1 Multi-stage fitness test

During the test participants also wore a pre-calibrated portable gas analyser (Cosmed K4b2, Cosmrd S.r.I, Rome, Italy), with $\dot{V}O_{2peak}$ calculated as the highest value recorded over a 30 s epoch (Edgett et al., 2013). Please refer to General Methods section 3.2 for procedures.

5.2.3.2 Multi-directional and linear trials

The multi-directional and linear trials comprised eight bouts of ~60 s of intermittent activity (jogging and sprinting) followed by 120 s of passive rest. Please refer to General Methods section 3.3 and 3.4 for procedures.

All trials were conducted on an outdoor running track at a similar time of day (± 2 hours) to reduce the effects of diurnal variation. Mean temperature (p = 0.70) and humidity (p = 0.65) during the multi-directional (19.0 ± 4.2° and 32.5 ± 6.2%) and linear (19.6 ± 4.2° and 31.6 ± 3.7%) trials were similar. The coefficient of variation (CV) for total distance covered and time at high speed and high power during the multi-directional trial was 1.4%, 6.1% and 4.3%, respectively (see Chapter 4). Protocols similar to the linear trial have demonstrated good reliability (CV: 2.0-3.5%) for speed measures (De Andrade, Santiago, Kalva Filho, Campos, & Papoti, 2016).

5.2.3.3 Global positioning system and heart rate

Movement patterns were recorded using an OptimEye S5 global positioning system (GPS) unit sampling at 10 Hz with a 100 Hz tri-axial accelerometer (Team 2.5, Catapult Innovations, Melbourne, Australia). Total distance, relative distance ($m \cdot min^{-1}$), distance and time at high speed (>14.4 $km \cdot h^{-1}$) and very high speed (>16 $km \cdot h^{-1}$) during the whole trial, as well as mean speed during active bouts only (negating passive rest periods), were recorded. Two definitions of high speed were used to compare a common high-speed definition used in the literature (> 14.4 $km \cdot h^{-1}$; Kempton et al., 2015) and the speed equivalent of high metabolic power, during constant-speed running (>16 $km \cdot h^{-1}$; Osgnach et al., 2010). Kalman filtering techniques to combine accelerometer and gyroscope information to create a non-gravity vector were used to quantify the total number of accelerations and decelerations ($>1.5\ m{\cdot}s^{-2}$) performed during each trial. Accumulated PlayerLoad^{TM}, based on tri-axial accelerometer data, time at high metabolic power ($> 20\ W{\cdot}kg^{-1}$), and estimated energy expenditure (EE_{GPS}) were also calculated using the manufacturer's software (Sprint, Version 5.1, Catapult Sports, VIC, Australia). The same microtechnology device was used throughout the study for all participants to eliminate inter-device variability (Akenhead, French, Thompson & Hayes, 2013). The number of satellites detected by the player tracking device and the horizontal dilution of precision was 13.7 ± 0.8 and 0.7 ± 0.1, respectively. HR was measured at 5 s epochs throughout each trial using a HR monitor (Polar Electro, Oy, Finland) and recorded by the microtechnology unit using short-range telemetry to calculate mean and peak HR. Summated HR was also calculated based on the method devised by Edwards (1993):

(duration in zone 1 x 1) + (duration in zone 2 x 2) + (duration in zone 3 x 3) +
(duration in zone 4 x 4) + (duration in zone 5 x 5)

where zone 1 = 50-60% $HR_{peak,}$ zone 2 = 60-70% HR_{peak}, zone 3 = 70-80% $HR_{peak,}$ zone 4 = 80-90% HR_{peak} and zone 5 = 90-100% HR_{peak}

5.2.3.4 Physiological and perceptual responses

During each trial, expired air was measured using a portable, breath-by-breath gas analyser (Cosmed K4b2, Cosmed S.r.I, Rome, Italy) to calculate $\dot{V}O_2$. Before testing, the gas analyser was calibrated in accordance with manufacturer guidelines. $\dot{V}O_2$ data was subsequently averaged over the whole protocol (including rest periods). Mean $\dot{V}O_2$ in $L{\cdot}min^{-1}$ was multiplied by the duration of each trial to calculate total $\dot{V}O_{2.}$ B[La] was determined immediately after bouts 4 and 8 of the multi-directional and linear trials and analysed using a portable lactate analyser (Lactate Pro, Arkray, Japen). Blood samples were obtained from a single fingertip using a spring-loaded disposable lancet. At the end of each exercise bout, rating of perceived exertion was recorded using the Borg 6-20 scale (Borg, 1998).

5.2.3.5 External to internal ratio

The external to internal load ratio was calculated during each trial, to determine the extent to which measures of high speed and high power reflect changes in internal load. External load was quantified using time at high speed, very high speed and high power (s). Internal load was quantified using summated HR (AU) and total $\dot{V}O_2$ (L). External load measures were divided by each measurement of internal load to calculate the external to internal load ratio during each trial (Akubat et al., 2014). These ratios were used to determine the extent to which high speed, very high speed and high power reflect changes in internal load that might be induced by performing more multi-directional running. For example, a higher summated HR with multi-directional compared to linear running might also be accompanied by a greater time at high speed, and therefore the ratio between these two measurements should not be different between each running trial.

5.2.3.6 Neuromuscular function

A dynamometer (Biodex Medical, System 3, New York, USA) was used to measure isometric knee extensor and flexor peak torque at 80° knee flexion. For baseline measurements, participants performed a warm-up consisting of 5-min cycling at 90 W (model E834, Monark, Varup, Sweden). The dominant leg was fixed into the input arm of the dynamometer, and the limb mass was measured to allow for gravitational correction of peak torques. After two submaximal repetitions, participants performed three maximum efforts of knee extension and flexion for 4 s with 15 s passive recovery between each. Peak torque for each movement was taken for analysis. Participants were verbally encouraged to achieve maximum efforts and exceed target values achieved during habituation.

5.2.4 Statistical analysis

Descriptive data are reported as mean ± standard deviation. Comparisons between multi-directional and linear trials were analysed using paired sample *t*-tests and effect sizes with accompanying 95% confidence intervals (ES; ±95%CI). Furthermore, the magnitude of change in peak torque measurements (Pre-Post) across trials was directly compared using a two-way analysis of variance (ANOVA). Where differences were identified, *post hoc* analysis was performed (*t*-tests). The effect size was calculated as the difference in means divided by the pooled standard deviation. An effect size of 0.2, 0.6 and 1.2 were considered small, moderate and large, respectively. *P* values were reported for all analysis. All statistical analyses were performed using the Statistical Package for Social Sciences (SPSS, version 22; SPSS, Inc., IL, USA) and Microsoft Excel. The reader should refer to General Method section 3.8 for further information regarding the statistical approach adopted.

5.3 Results

The external demands of the linear and multi-directional trials are displayed in Table 5.1. A large increase in total distance, relative distance, distance covered at high speed and mean speed during active bouts was observed during the linear compared to the multi-directional trial. Conversely, a large decrease in total accelerations and decelerations performed was observed during the linear compared to the multi-directional trial. Time at high power demonstrated a moderate decrease during the linear trial, whereas EE_{GPS} demonstrated a small increase. A moderate decrease in exercise duration was observed during the linear compared to the multi-directional trial. PlayerLoad^{TM} remained the same between trials.

Table 5.1 The external demands of the multi-directional and linear trials

	Multi-directional	**Linear**	**Mean difference ± SD difference**	**ES; ±95% CI**	**P value**
Total distance (m)	1513.4 ± 59.6	1592.2 ± 90.4	78.8 ± 64.6	1.2; ±0.8	0.001
Duration (s)	1428.3 ± 40.3	1381.7 ± 45.6	-46.7 ± 39.0	-1.0; ±0.7	0.002
Relative distance ($m \cdot min^{-1}$)	68.2 ± 3.0	74.7 ± 5.0	6.4 ± 2.7	1.9; ±1.0	< 0.001
High speed distance (m)	416.5 ± 97.4	677.2 ± 57.5	260.7 ± 71.3	2.4; ±1.2	< 0.001
Time at high speed (s)	85.5 ± 18.7	117.4 ± 5.9	31.9 ± 19.2	1.5; ±0.9	< 0.001
Time at very high speed (s)	49.8 ± 15.0	106.6 ± 7.7	56.8 ± 14.7	3.4; ±1.6	< 0.001
Total accelerations (n)	48.3 ± 21.5	7.2 ± 3.8	-41.1 ± 20.3	-1.7; ±0.9	< 0.001
Total decelerations (n)	38.8 ± 19.5	3.8 ± 6.3	-33.8 ± 16.9	-1.5; ±0.8	< 0.001
Mean speed ($km \cdot h^{-1}$)	9.7 ± 0.5	11.3 ± 0.9	1.6 ± 0.7	2.9; ±1.5	< 0.001
PlayerLoad^{TM} (AU)	175.8 ± 17.4	173.8 ± 18.4	-2.0 ± 17.1	-0.1; ±0.6	0.7
Time at high power (s)	118.4 ± 11.7	111.5 ± 10.2	-6.9 ± 10.7	-0.5; ±0.6	0.046
EE_{GPS} ($kcal \cdot min^{-1}$)	5.9 ± 1.4	6.5 ± 1.5	0.5 ± 0.3	0.4 ±0.2	< 0.001

The internal demands of the multi-directional and linear trials are presented in Table 5.2. A moderate lower mean RPE, summated HR and bout 8 B[La] was observed during the linear compared with the multi-directional trial. Total $\dot{V}O_2$ and mean HR demonstrated a small decrease during the linear compared with the multi-directional trial. Mean $\dot{V}O_2$, Bout 4 B[La] and peak HR were similar between trials.

Table 5.2 The internal demands of the multi-directional and linear trials

	Multi-directional	**Linear**	**Mean difference ± SD difference**	**ES; ±95%CI**	***P* value**
Mean RPE	15.7 ± 1.1	14.9 ± 1.1	-0.83 ± 1.1	-0.7; ±0.6	0.024
Bout 4 B[La] (mmol·L^{-1})	8.7 ± 1.9	7.8 ± 2.9	-0.89 ± 2.9	-0.4; ±0.9	0.314
Bout 8 B[La] (mmol·L^{-1})	10.2 ± 2.0	8.2 ± 2.6	-2.1 ± 1.8	-0.9; ±0.6	0.002
Mean $\dot{V}O_2$ (ml·kg^{-1}·min^{-1})	27.0 ± 2.6	26.0 ± 1.9	-1.0 ± 2.8	-0.4; ±0.6	0.237
Total $\dot{V}O_2$ (L)	46.9 ± 9.0	44.2 ± 10.1	-2.7 ± 5.0	-0.3; ±0.3	0.087
Summated HR (AU)	78.1 ± 10.5	69.1 ± 10.1	-8.9 ± 8.1	-0.8; ±0.5	0.003
Mean HR (b·min^{-1})	161.6 ± 10.8	158.3 ± 12.6	-3.3 ± 6.2	-0.3; ±0.3	0.099
Peak HR (b·min^{-1})	199.9 ± 14.5	201.8 ± 14.7	1.9 ± 18.5	0.1; ±0.7	0.727

Measurements of external to internal load during the linear and multi-directional trials are displayed in Figure 5.1. Measures of very high speed:summated HR, high speed:summated HR, very high speed:total $\dot{V}O_2$ and high speed:total $\dot{V}O_2$ demonstrated large differences between the multi-directional and linear trials (Figure 5.1). Conversely, high power: summated HR and high power:total $\dot{V}O_2$ were the same between trials.

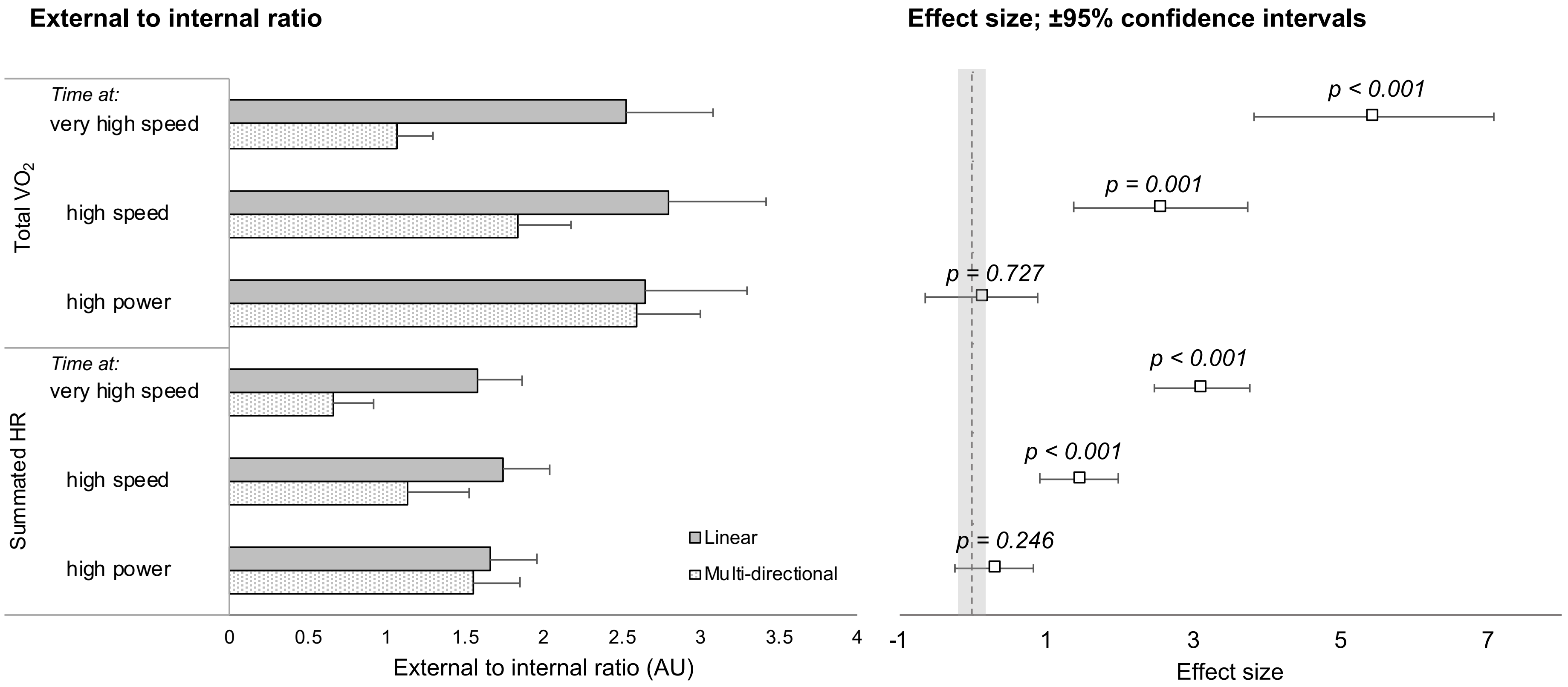


Figure 5.1 The external to internal ratio during the linear and multi-directional trials and the effect size; ±95% confidence intervals for differences in the external to internal ratio between trials using measures of time at very high speed, high speed and high power. Trivial changes (-0.2 < effect size < 0.2) are shaded in grey. Interpretation: A higher summated HR with multi-directional compared to linear running was also accompanied by a greater time at high power, and therefore the ratio between these two measurements was not different between each running trial.

There was a difference between pre and post peak extensor torque (F = 13.07, *p* = 0.004), but not between trials (*F* = 1.42, *p* = 0.26). Small reductions in peak knee extensor torque were observed after both trials (Figure 5.2). Differences in pre and post peak flexor torque were also evident (F = 14.08, *p* = 0.003), but not between trials (*F* = 0.06, *p* = 0.811). Specifically, a small reduction in knee flexor torque was evident after the multi-directional trial, and a tendency for a small reduction in knee flexor after the linear trial was noted (*p* = 0.077). Baseline extensor torque (*p* = 0.495) and flexor torque (*p* = 0.419) was similar between the multi-directional and linear trials. Comparison of sex specific changes in knee extensor and flexor torque after multi-directional running are provided in Appendix 5.2.

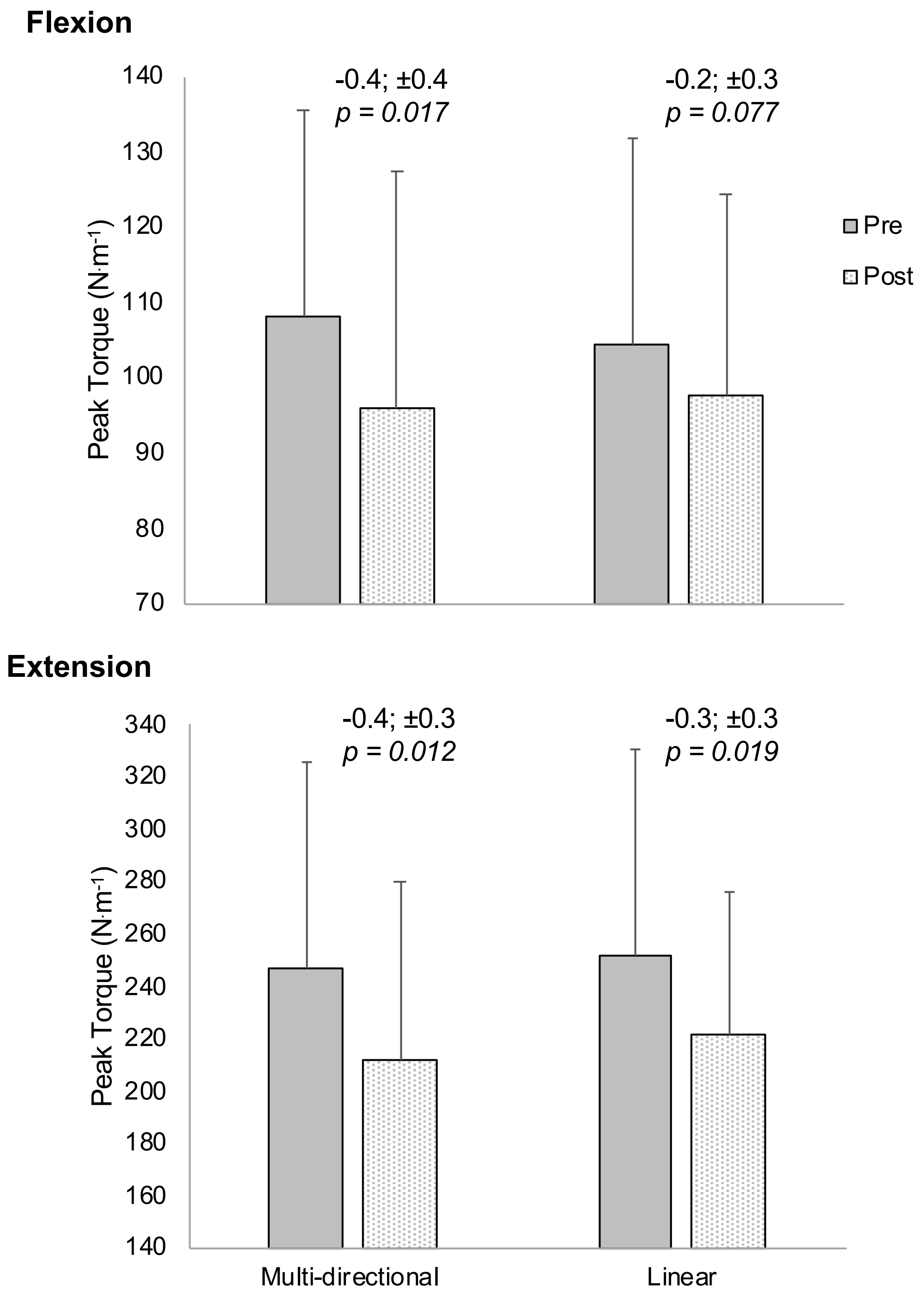


Figure 5.2 Peak knee torque for flexion and extension before (pre) and after (post) after the multi-directional and linear trials. Values are the effect size; ±95% confidence interval and accompanying *p* value.

5.4 Discussion

The purpose of the current study was to examine differences in internal and external load in response to linear and multi-directional running. Whilst trials were matched for total distance, participants covered more distance during the linear compared with the multi-directional trial. This difference is possibly explained by the use of GPS, which can underestimate distance measurements during rapid directional changes by ~3 ± 2.5% (Rawstorn, Maddison, Ali, Foskett, & Gant, 2014). Distance covered at high speed was also higher during the linear trial, which was expected in team sport athletes where peak acceleration does not occur until ~9-10 m (Vescovi, 2012; Brechue, Mayhew & Piper, 2010). During the multi-directional trial, participants performed multiple directional changes over short distances that meant they were unable to achieve velocities comparable with those achieved during the linear trial. Concomitantly, the duration of the multi-directional trial was ~47 s higher because sprint times increase when directional changes are included (Buchheit et al., 2012). Whilst others have accounted for the longer duration of directional changes when comparing linear and multi-directional running (Buchheit et al., 2012), such adjustments do not replicate real world practice.

More accelerations and decelerations suggest directional changes are the primary cause of increased internal load observed (as measured by RPE, HR, $\dot{V}O_2$ and B[La]), during multi-directional running. This coincides with the greater time at high power during the multi-directional trial, given that a high metabolic power (di Prampero et al., 2005) and a greater estimated energy cost (Stevens et al., 2015) occurs at lower running speeds when performing an increased number of directional changes. Indeed, Fox et al. (2017) reported high metabolic power distances were greater than high-speed distances covered during a soccer match, which reflects the inability of traditional speed-based thresholds to account for discrete, short duration acceleration movements. Conversely, EE_{GPS} was higher during the linear trial, which might be due to the underestimation of EE_{GPS} for changes of direction and backwards/lateral movement incorporated in the multi-directional trial (Chapter 4; Stevens et al., 2015). The measurement of metabolic power above 20 $W \cdot kg^{-1}$ might provide a more suitable measure of the high intensity demands of team sport activity when compared with high speed running, particularly when directional changes are performed.

The similarity in $PlayerLoad^{TM}$ between trials is probably explained by a higher total and high-speed distance covered during the linear trial, offsetting the higher accelerations and decelerations performed during the multi-directional trial. Indeed, both accelerations and decelerations (12 – 16%; Dalen et al., 2016) and total distance covered (56%; Casamichana et al., 2013) share considerably variability with $PlayerLoad^{TM}$, suggesting some ambiguity when making comparisons of $PlayerLoad^{TM}$ between different movement patterns. From the present study, it remains unclear if $PlayerLoad^{TM}$ reflects changes in the external demands of linear and multi-directional running.

The small increase in total $\dot{V}O_2$ during the multi-directional trial is consistent with previous literature demonstrating an increase in $\dot{V}O_2$ when more directional changes are performed (Buchheit et al., 2010; Buglione & Prampero, 2013; Hatamoto et al., 2014). The increased accelerations associated with more directional changes (Akenhead et al., 2014) and the inclusion of backwards movement (Williford, Olson, Gauger, Duey, & Blessing, 1998) during the multi-directional trial likely caused a higher

$\dot{V}O_2$ compared with forward running at the same speed. The multi-directional trial also elicited a higher mean HR and summated HR, again reaffirming an increased cardio-vascular strain during running with more directional changes (Akenhead et al., 2014; Dellal et al., 2010). Whilst others have reported a lower mean heart rate during running with more directional changes (e.g. Ashton & Twist, 2015), direct comparisons between protocols are difficult, given different recoveries (active vs. passive; Miladi, Temfemo, Mandengué, & Ahmaidi, 2011) and movement patterns (forward vs. backwards; Williford et al., 1998).

A higher B[La] after the multi-directional trial is also consistent with previous reports, reaffirming a greater reliance on anaerobic metabolism when an increased number of directional changes are performed (Akenhead et al., 2014; Ashton & Twist, 2015; Buchheit et al., 2010; Dellal et al., 2010). Whilst the specific mechanism for this change is unclear, di Prampero et al. (2005) suggest overcoming the body's inertia when changing direction requires an increased recruitment of larger motor units, composed of type II muscle fibres with a high glycolytic capacity (Mero, 1988). The findings here contrast with others who have reported a higher B[La] after linear running (Buchheit et al., 2012; Hader et al., 2014), which might be accounted for by the reduced running speed and running distance during directional changes (Buchheit et al., 2012; Hader et al., 2014). The moderate increase in RPE in response to the multi-directional trial reaffirms reports of an increased sense of exertion during exercise that includes more changes of direction (Ashton & Twist, 2015; Dellal et al., 2009; Tang et al., 2018), despite a reduction in high speed distance covered. In agreement, increases in RPE have been reported during intermittent compared with continuous running (Bartlett, Close, Drust, & Morton, 2010; Drust, Reilly, & Cable, 2000) and running with an increased number of accelerations (Gaudino et al., 2015). Future studies should explore the implications of an increased perceived exertion on exercise tolerance during high-intensity multi-directional exercise (Marcora & Staiano, 2010). Overall, these data indicate running with more directional changes causes a small to moderate increase in the metabolic and perceptual demands of exercise.

The external to internal ratio using time at high-speed and very high-speed were different (large effect) between trials, whereas external to internal ratio using time at high-power were similar between trials. This suggests increases in summated HR and total $\dot{V}O_2$ (the ‘response’) induced by altering running patterns (the ‘dose’) are accurately reflected by time at high power but not time at high speed and very high speed. These findings support studies reporting strong associations between measures of high metabolic power with measures of internal load (r = 0.77 – 0.92; Delaney et al., 2018) and determinants of aerobic fitness during team sport activity (r = 0.54 – 0.67; Akubat et al., 2018). In addition, Polglaze and colleagues (2018) reported measures of high metabolic power displayed a stronger association with time spent above 85% HR compared with measures of high-speed. The observation that high-speed does not reflect changes in internal responses contrasts the strong association between critical speed and time spent above 85% HR (r = 0.719; Polglaze et al., 2018b) and the ratio of high-speed distance to iTRIMP with markers of aerobic power (r = 0.58 – 0.65; Akubat et al., 2014). It can be speculated the multi-directional protocol incorporated more directional changes and short distance efforts compared to other protocols (Akubat et al., 2014; Polglaze et al., 2018b), which likely account for the differences observed. Taken together, the present study proposes integrated ratios using measures of time at high power provide a sensitive interpretation of the individual’s response during different forms of running (i.e. linear and multi-directional). This is pertinent given the practical and methodological issues of HR and $\dot{V}O_2$ measurements in applied contexts (Osgnach et al., 2010).

The similar small decrease in knee extensor torque after both trials is expected given that both the linear and multi-directional trials incorporated high intensity movement patterns (sprinting and accelerating). Specifically, muscle activity of the quadriceps increases during running at increasing velocities (Tsuji, Ishida, Oba, Ueki & Fujihashi, 2015) and running with an increased number of directional changes (Beisier et al., 2003), which might accelerate the accumulation of fatiguing metabolites (Mohr et al., 2004; Westerblad, Allen & Lannergren, 2002) and/or inhibit motor neurons, leading to neuromuscular fatigue (Hader et al., 2014). The higher speeds achieved during the linear trial could have been offset by the increased number of directional changes performed during the multi-directional trial. Accordingly, the magnitude of force loss after both linear and multi-directional running is similar but can be attributed to different causes. Decrements in knee flexor torque were similar after the multi-directional and linear trial, albeit the probability of obtaining the sample result if the null hypothesis were true was greater for the linear trial ($p = 0.077$ *cf.* $p = 0.017$). Previous reports have suggested a greater number of directional changes during intermittent running incur more likely activation and fatigue of the knee flexors (Ashton & Twist, 2015; Hader et al., 2014). The greater number of decelerations performed during the multi-directional trial requires the hamstrings and gastrocnemius to eccentrically contract to stabilize the knee joint as it experiences larger valgus and rotation moments (Besier et al., 2003). This, in turn, can lead to an inhibition of motor units (Hader et al., 2014), causing reductions in knee flexor torque, despite the reduction in high speed running.

Such decrements in knee flexor strength could have implications for injury risk, as hamstring fatigue has been associated with a mechanical loss of knee stability that can contribute towards increased risk of ACL injury (Melnyk & Gollhofer, 2007). Collectively, these data suggest decrements in neuromuscular function of the knee flexors are similar after multi-directional and linear running, despite an overall slower movement speed in the multi-directional trial. Future studies might seek to examine the effect of multi-directional running on lower limb injury risk.

It is important to acknowledge the limitations of the present study. Although the running courses used for both trials were matched for distance, differences in running style and technique both within and between participants were not controlled. Whilst the reliability of the microtechnology device for measuring distance, low and high-speed distance and high metabolic power was deemed favourable (<10%) during the multi-directional trial, repeatability of acceleration/deceleration metrics are known to be more variable (CV%: 3.1-11.3%; Varley et al., 2012). The direct compatibility of an absolute marker of internal load with an intensity marker of external load to calculate the external to internal load might be considered a limitation. However, gross $\dot{V}O_2$ has demonstrated very strong associations with intensity markers of external load (Hatamoto et al., 2014) and such markers of external to internal load are commonplace amongst the literature (McLaren et al., 2018). Finally, measures of muscle function relied on voluntary contraction of the muscle to assess fatigue. Future studies might wish to consider changes in voluntary activation to assess the contribution of peripheral and central mechanisms to reductions in force after linear and multi-directional running.

5.5 Conclusion

In conclusion, this study reaffirms that running incorporating multiple directional changes induces a greater physiological and perceptual response when compared to linear running, despite the reduced mean speed and work rate ($m \cdot min^{-1}$). Time at high power reflected changes in internal load between trials, whilst measures of high speed and very high speed did not. Decrements in knee flexor torque were similar after both trials, despite the reduction in high speed running. Practitioners should be wary of using measures of high speed alone to quantify the high intensity demands of running incorporating multiple directional changes. Here, the use of time at high metabolic power is proposed as an alternative measure of external load, which can also reflect an individual's internal response to multi-directional running.

Key messages

- *Running with more changes of direction increases the psychophysiological response to exercise.*
- *Time at high power can reflect changes in internal load between linear and multi-directional running, whilst time at high speed can not.*
- *Small reductions in knee extensor and flexor torque were observed after multi-directional running and could have implications for injury risk.*

Next steps

- *Future research should explore if injury risk is altered after multi-directional running.*

Chapter 6

Effect of multi-directional running on the biomechanics of side cuts in males and females

Rationale summary

Multi-directional running elicits a greater psychophysiological response compared with linear running and small decrements in knee flexor torque (Chapter 5) and could have implications for ACL injury risk. However, inconsistencies in fatigue-induced modifications in side cut biomechanics are apparent and likely reflect the non-uniformity of fatigue protocols, which arguably do not mimic the numerous changes of directions performed during team sports. Sex specific differences in side cut mechanics also make comparisons difficult. Accordingly, this study assessed the effect of fatigue induced by multi-directional running on side cut biomechanics in males and females.

6.1 Introduction

The incidence of ACL injury continues to rise in a collegiate athletic population (Agel et al., 2016), with most occurrences being non-contact in nature (Walden et al., 2015). Team sports, in particular, have a high incidence of ACL injuries (0.3 – 3.2 per 10,000 athlete exposures; Agel et al., 2016; Stanley, Kerr, Dompier, & Padua, 2016) as athletes perform numerous pressing, landing, deceleration and side cutting manoeuvres that increase the risk for this injury (Grassi et al., 2017; Krosshaug et al., 2007). Most ACL injuries during team sports occur during a 30-90° side cut in both male (Walden et al., 2015) and female (Koga et al., 2010) athletes. While some have quantified side cut kinematic mechanisms associated with ACL injury during competition (e.g. Grassi et al., 2017; Walden et al., 2015), 2D video footage from match-play are subject to errors due to low-quality video and limited camera angles (Grassi et al., 2017). The poor agreement reported between 2D and 3D frontal motion

(Sorenson, Kernozek, Willson, Ragan, & Hove, 2015) also question the accuracy of 2D motion capture, given that 3D motion capture is considered the gold standard to assess movement strategies that might predispose an athlete to ACL injury (Fox, Bonacci, McLean, & Saunders, 2017). Studies have examined biomechanical factors during a 45° side cut which are associated with ACL injury risk using 3D motion capture (McGovern et al., 2015; McLean et al., 2004; Savage et al., 2018) to help develop more specific preventative programmes. A 45° cutting angle is acute enough to require a substantial deceleration, but shallow enough for a change of direction to be achieved during a single foot contact (Alenezi et al., 2016), whilst maintaining speeds required to substantially load the knee joint (Dos'Santos, Thomas, Comfort, & Jones, 2018).

Side cutting or landing with decreased trunk (Blackburn & Padua, 2009), hip (Kipp, McLean & Palmieri-Smith, 2011) and knee (Walden et al., 2015) flexion angles, increased hip adduction (Grassi et al., 2017), knee valgus/abduction angles (Kobayashi et al., 2010; Walden et al., 2015) and increased knee abduction moments (Myer et al., 2015) are some of the reported mechanisms associated with increased risk of ACL injury. Whilst some debate still exists over the relative contribution of sagittal plane mechanics to ACL injury risk (Bakker et al., 2016; McLean et al., 2004), knee abduction angle, knee abduction moment and internal tibial rotation moment appear the most detrimental factors contributing to ACL injury (Kiapour et al., 2014; Myer et al., 2015; Shin, Chaudhari, & Andriacchi, 2011), particularly when combined (Navacchia et al., 2019; Shin et al., 2011). Specifically, larger knee abduction moments are associated with an increased risk of subsequent ACL injury (Myer et al., 2015) and both knee abduction moments (Navacchia et al., 2019) and angles (Kiapour et al., 2016) have demonstrated strong associations with peak ACL force during impacts (*r* = 0.67 - 0.82; Kiapour et al., 2016; Navacchia et al., 2019). Comparisons of individual mechanisms reveal knee abduction angle has a ~ 2-fold greater effect on the magnitude of peak ACL strain when compared with internal tibial rotation (Kiapour et al., 2016). Yet, internal tibial rotation moment plays a primary role in increasing ACL strain (Oh et al., 2012) and a combination of knee abduction and internal tibial rotation moments can increase ACL strain more so than either alone (Shin et al., 2011). Whilst these findings highlight the importance of knee frontal and transverse plane mechanics in the assessment of ACL injury risk, the mechanism of ACL injury is multifaceted. Indeed, hip adduction (Imwalle et al., 2009), knee abduction, hip rotation moment (Myer et al., 2014), hip internal rotation angle (McLean et al., 2004), lateral trunk position (Jamison et al., 2012) and braking ground reaction force (GRF) (Jones, Herrington, & Graham-Smith, 2015) are associated with knee abduction moment and might indirectly contribute towards ACL injury. The assessment of multi-planar motions, moments and GRF is therefore essential to understand factors which contribute to ACL injury risk.

Notable differences in cutting mechanics between the sexes have been identified. Females have been reported to cut in a more extended position, with less knee flexion (McGovern et al., 2015), less hip flexion and a smaller hip flexor moment (Landry et al., 2007), more knee abduction (Weinhandl, Irmischer, Sievert & Fontenot, 2017) and hip internal rotation (Landry et al., 2007; McGovern et al., 2015), higher vertical GRF (Sigward, Cesar & Haven, 2015) and a greater tendency towards lateral trunk flexion (Pollard et al., 2007), compared to males. Such movement patterns can increase strain on the ACL and concur with the ~2 – 6-fold higher ACL injury incidence rate sustained in females compared with males (Gray et al., 2019; Hewett et al., 2005; Stanley et al., 2016). However, sex comparisons in side cut mechanics have focused on hip and knee mechanics, typically in the sagittal and frontal plane (Iguchi et al., 2014; McGovern et al., 2015; McLean et al., 2007; Weinhandl et al., 2017). Further research examining potential differences in side cut mechanics between sexes with fatigue should include analysis of all three planes and the assessment of proximal segments, such as the trunk.

Altered side cut biomechanics have also been documented after fatiguing exercise. Fatigue is characterised by an objective decline in performance (e.g. peak torque, CMJ/sprint performance) over a discrete period of time, whether or not the task can be continued (Bishop, 2012; Enoka & Duchateau, 2016). Decrements in lower limb maximal voluntary force are evident after team sport activity (Chapter 5; Ashton & Twist, 2015; Goodall et al., 2017; Silva, Ascensão, Marques, Seabra, Rebelo & Magalhães, 2013) and have been associated with a mechanical loss of knee stability (Melnyk & Gollhofer, 2007). In vivo data has also demonstrated the ACL is susceptible to fatigue failure (Wojtys, Beaulieu & Ashton-Miller, 2016). Specifically, Wojtys et al. (2016) found when the knee joint was loaded multiple times (30-60 times) the simulated landing force required to cause an ACL injury was lower. Previous research has therefore explored the influence of fatigue on the mechanics of side cuts; however, results appear contradictory. For example, some studies have reported decreased hip and knee flexion (Lucci et al., 2011; McGovern et al., 2015) and knee internal rotation (Lucci et al., 2011), increased knee abduction (Collins et al., 2016; Tsai et al., 2008) and knee extensor moments (Savage et al., 2018) during a side cut with fatigue. Conversely, others have reported no such differences in knee flexion angle (Inguchi et al., 2014) or knee moments (Collins et al., 2016) and increases knee internal rotation (Sanna et al., 2008) and knee adduction (McGovern et al., 2015). Discrepancies amongst the literature are potentially due to the use of male (e.g. Savage et al., 2018) compared with female (e.g. Collins et al., 2016) participants, as an interaction effect between sex and fatigue has previously been reported (Inguchi et al., 2014). Fatigue is also specific to the nature, intensity and duration of the task performed (Impellizzeri et al., 2019), so the use of protocols ranging from repetitive explosive movements such as vertical jumps combined with sprints (Lucci et al., 2011; Tsai et al., 2008) to 60 minutes of intermittent shuttle running over 20 m (Collins et al., 2016; Sanna et al., 2008), might account for differences in side cut biomechanics after fatiguing exercise. These data highlight the need for careful consideration of the fatigue protocol used when assessing side cut biomechanics under fatigue. Inconsistencies in fatigue induced alterations in GRF (Iguchi et al., 2014; Khalid et al., 2015) and movement variability (Cortes, Onate & Morrison, 2014) during a side cut are also apparent, and warrant further research.

Whilst recent studies have used intermittent running protocols that better reflect the mechanical demands of team sport activity (Collins et al., 2016; Savage et al., 2018), they do not account for the numerous changes of direction team sport athletes perform during match-play (~700; Bloomfield et al., 2007). This is important given that running with an increased number of directional changes can induce greater decrements in knee flexor torque when compared with linear shuttle running (see Chapter 5), which are associated with a mechanical loss of knee stability and a higher risk of ACL injury (Melnyk & Gollhofer, 2007). However, few studies have investigated fatigue induced modifications in trunk and lower limb mechanics after intermittent running with numerous directional changes in both men and women. Thus, the purpose of this study was to assess the effect of fatigue induced by multi-directional running on trunk, hip and knee kinematics and kinetics and GRF during 45° side cuts in male and female team sport athletes.

6.2 Method

6.2.1 Participants

After institutional ethics approval (see Appendix 6.1), 16 team sport players, made up of 8 males (stature: 175.5 ± 8.0 cm; mass: 74.6 ± 8.5 kg; age: 21.6 ± 2.2 years; $\dot{V}O_{2\ peak}$: 46.0 ± 4.1 $ml{\cdot}kg^{-1}min^{-1}$) and 8 females (stature: 165.8 ± 8.5 cm; mass: 63.1 ± 13.5 kg; age: 21.3 ± 3.2 years; $\dot{V}O_{2\ peak}$: 39.4 ± 5.3 $ml{\cdot}kg^{-1}min^{-1}$) were recruited from University-level team sports (rugby, football, hockey and netball). This sample size was based on the number of participants used in previous research examining the effect of fatigue and sex on lower limb mechanics during a side cut (Iguchi et al., 2014; Khalid et al., 2015). This value also exceeds an *a priori* sample size calculation, based on estimated power (Faul et al., 2009) and an effect size of 1.08 for fatigue induced modifications in lower limb kinematics after intermittent running (McGovern et al., 2015; see Appendix 6.2). All participants took part in team sport training sessions at least twice per week. Participants completed pre-test health screening to ensure they had no previous history of knee surgery and/or no lower limb injuries in the past 6 months (Thomas, McLean & Palmieri-Smith, 2010). Participants were also required to refrain from exercise 48 h before each visit.

6.2.2 Design

Participants completed two sessions on separate days. In the first visit, participants completed a multi-stage fitness test to provide an estimate of peak aerobic capacity. Three to seven days later, participants completed baseline measurements of 20 m sprints and side cuts followed by the multi-directional trial. Repeated measurements of the 20 m sprints and side cuts were taken within 30 minutes after the multi-directional trial.

6.2.3 Procedures

6.2.3.1 Multi-stage fitness test

The multi-stage fitness test was used to estimate each participant's $\dot{V}O_{2\ peak}$. Please refer to General Methods section 3.2 for procedures.

6.2.3.2 Multi-directional trial

The multi-directional trial comprised twelve bouts of ~60 s of work followed by 120 s of passive rest, procedures for which can be found in the General Methods section 3.3. The multi-directional trial has previously demonstrated a good level of reliability (see Chapter 5).

6.2.3.3 Sprint performance

Participants performed three single maximal 20 m sprints immediately before and after the multi-directional trial. Please refer to General Methods section 3.5 for procedures.

6.2.3.4 Three-dimensional motion capture of 45° side cuts

Please refer to General Methods section 3.6 for procedures. Participants required between 5 - 27 and 6 – 14 attempts to perform the 5 successful side cuts before and after multi-directional running, respectively. Please refer to General Method section 3.6 for procedures.

6.2.3.5 Data Analysis of 45° side cuts

Please refer to General Methods section 3.7 for procedures.

6.2.4 Statistical analysis

Descriptive data are reported as mean ± standard deviation. Data were analysed using two-way mixed ANOVAs with time (pre vs. post multi-directional running) as a within-subject factor and sex (males vs. females) as a between-subject factor. The effect of time and the interaction of sex x time are reported. *P* values were reported for all analyses. Further *post hoc* analyses consisting of effect sizes with accompanying 95% confidence intervals (ES; ±95%CI) were performed for each sex. The effect size was calculated as the difference in means divided by the pooled standard deviation. An effect size of 0.2, 0.6 and 1.2 were considered small, moderate and large, respectively. The co-efficient of variation (CV%) was used to assess within-subject variability in sagittal plane variables and GRF. All statistical analyses were performed using the Statistical Package for Social Sciences (SPSS, version 22; SPSS, Inc., IL, USA) and Microsoft Excel (version 16.41, Microsoft). Please refer to the General Methods section 3.8 for further information regarding the adopted statistical approach.

6.3 Results

Peak 20 m sprint time was different before compared with after multi-directional running (*F* = 30.655, *p* < 0.001), however no interaction between time (pre vs. post) and sex (males vs. females) was noted (*F* = 1.754, *p* = 0.207). Specifically, peak 20 m sprint time was higher in females (3.48 ± 0.2 *cf.* 3.76 ± 0.2 s; ES; ±95% CI: 1.17; ±0.67) and males (3.09 ± 0.2 *cf.* 3.26 ± 0.3 s; 0.65; ±0.41) after multi-directional running. Data on task achievement during the side cuts are presented in Table 6.1. Centre of mass velocity at initial contact (*F* = 1.669, *p* = 0.219) and toe off (*F* = 1.603, *p* = 0.228) was similar before and after multi-directional running and no interaction between time and sex was noted at initial contact (*F* = 0.199, *p* = 0.663) or toe off (*F* = 0.07, *p* = 0.795). No differences in cut angle (*F* = 0.138, *p* = 0.716) and stance time (*F* = 0.720, *p* = 0.410) were observed before compared with after multi-directional running, and no interaction of time and sex was noted (*p* = 0.682 and *p* = 0.717, respectively). Time (pre vs. post) had an effect on percentage of stance time in weight acceptance (*F* = 4.849, *p* = 0.045), however no interaction between time and sex was noted (*F* = 1.477, *p* = 0.244). Specifically, percentage of stance time in weight acceptance was higher in females (0.73; ±0.97) and males (0.37; ±0.48) after multi-directional running.

Table 6.1 Task achievement during 45° side cuts in all participants.

	Females (n = 8)		*Males (n = 8)*	
	Pre	Post	Pre	Post
Centre of mass velocity at IC ($m{\cdot}s^{-1}$)	4.2 ± 0.3	4.1 ± 0.3	4.2 ± 0.2	4.1 ± 0.2
Centre of mass velocity at TO ($m{\cdot}s^{-1}$)	3.8 ± 0.3	3.7 ± 0.4	3.8 ± 0.3	3.7 ± 0.3
Change in centre of mass angle from IC to TO (°)	21.7 ± 2.0	21.7 ± 4.4	25.9 ± 4.6	25.4 ± 4.2
Stance time (s)	0.20 ± 0.03	0.21 ± 0.03	0.25 ± 0.04	0.25 ± 0.03
Weight acceptance percentage of stance (%)	53.9 ± 7.3	59.9 ± 7.6	47.7 ± 4.2	49.5 ± 5.1

IC = initial contact. TO = toe off

6.3.1 Kinematics

Discrete trunk kinematic data are presented in Table 6.2 and hip and knee angular data over stance for females and males are presented in Figures 6.1 and 6.2, respectively. Peak trunk flexion angle during the weight acceptance phase demonstrated a trivial to small increase after multi-directional running (Table 6.2). Peak hip internal rotation angle demonstrated a small decrease after multi-directional running (F = 3.313, p = 0.090) in females (-0.54; ±0.54) and males (-0.46; ±1.43), whereas peak knee extension angle demonstrated a trivial to small increase (F = 4.397, p = 0.055) in females (0.41; ±0.51) and males (0.17; ±0.38). Angular data at initial contact are included in Appendix 6.4. At initial contact, hip internal rotation angle (F = 3.323, p = 0.090) and knee abduction angle (F = 3.778, p = 0.072) demonstrated trivial to large decreases in females (-0.84; ±0.57 and -0.07; ±0.46, respectively) and males (-0.09; ±1.38 and -1.28; ±1.45, respectively) after multi-directional running. No other differences before and after multi-directional running in peak angular data (see Appendix 6.3) and angular data at initial contact (Appendix 6.4) were noted. In addition, no interactions between sex and time were observed (see Appendix 6.3 and 6.4). Peak knee abduction angular velocity ($F = 4.835$, $p = 0.045$) in females (212.8 ± 81.9 *cf.* 249.7 ± 116.4 $^{\circ} \cdot \mathrm{s}^{-1}$; 0.40; ±0.54) and males (118.5 ± 49.1 *cf.* 146.4 ± 57.0 $^{\circ} \cdot \mathrm{s}^{-1}$; 0.51; ±0.88) and knee internal rotation angular velocity ($F = 5.226$, $p = 0.038$) in females (476.6 ± 84.9 *cf.* 533.1 ± 155.2$^{\circ} \cdot \mathrm{s}^{-1}$; 0.59; ±1.18) and males (384.2 ± 124.8 *cf.* 498.3 ± 149.5 $^{\circ} \cdot \mathrm{s}^{-1}$; 0.81; ±0.97) was higher after multi-directional running. No other differences or interactions in peak angular velocities at the trunk, hip and knee were found (Table 6.2 and Appendix 6.5). Medio-lateral foot placement during the weight acceptance phase was similar before compared with after multi-directional running, and no interaction of time and sex was observed (see Appendix 6.6).

Table 6.2 Peak torso kinematic data during the weight acceptance phase in males and females, before and after multi-directional running

	Females (n = 8)			*Males (n = 8)*			*P value from two-way ANOVA*	
	Before	After	ES; ±95% CI	Before	After	ES; ±95% CI	Time	Sex x Time
Torso angle:								
Flexion (°)	7.4 ± 9.4	9.0 ± 9.3	0.16; ±0.38	14.1 ± 8.0	16.6 ± 6.9	0.28; ±0.37	0.082	0.701
Lateral lean over stance leg (°)	4.0 ± 5.4	3.6 ± 7.5	-0.06; ±0.38	2.7 ± 6.3	3.5 ± 6.3	0.11; ±0.39	0.790	0.455
Rotation over stance (°)	6.6 ± 11.2	5.5 ± 10.0	-0.08; ±0.36	9.1 ± 7.7	6.4 ± 7.0	-0.31; ±0.47	0.172	0.541
Torso angular velocity:								
Flexion (°·s^{-1})	135.7 ± 73.2	156.9 ± 61.5	0.26; ±0.46	169.2 ± 42.8	213.5 ± 122.5	0.92; ±1.93	0.145	0.596
Lateral lean over stance leg (°·s^{-1})	44.2 ± 23.1	46.3 ± 25.9	0.08; ±0.76	88.2 ± 44.7	100.0 ± 40.0	0.23; ±0.33	0.225	0.391
Rotation to new direction of travel (°·s^{-1})	230.3 ± 79.2	225.0 ± 73.5	-0.06; ±0.37	170.5 ± 59.5	174.8 ± 49.0	0.06; ±0.41	0.958	0.605

ES = effect size, CI = confidence interval

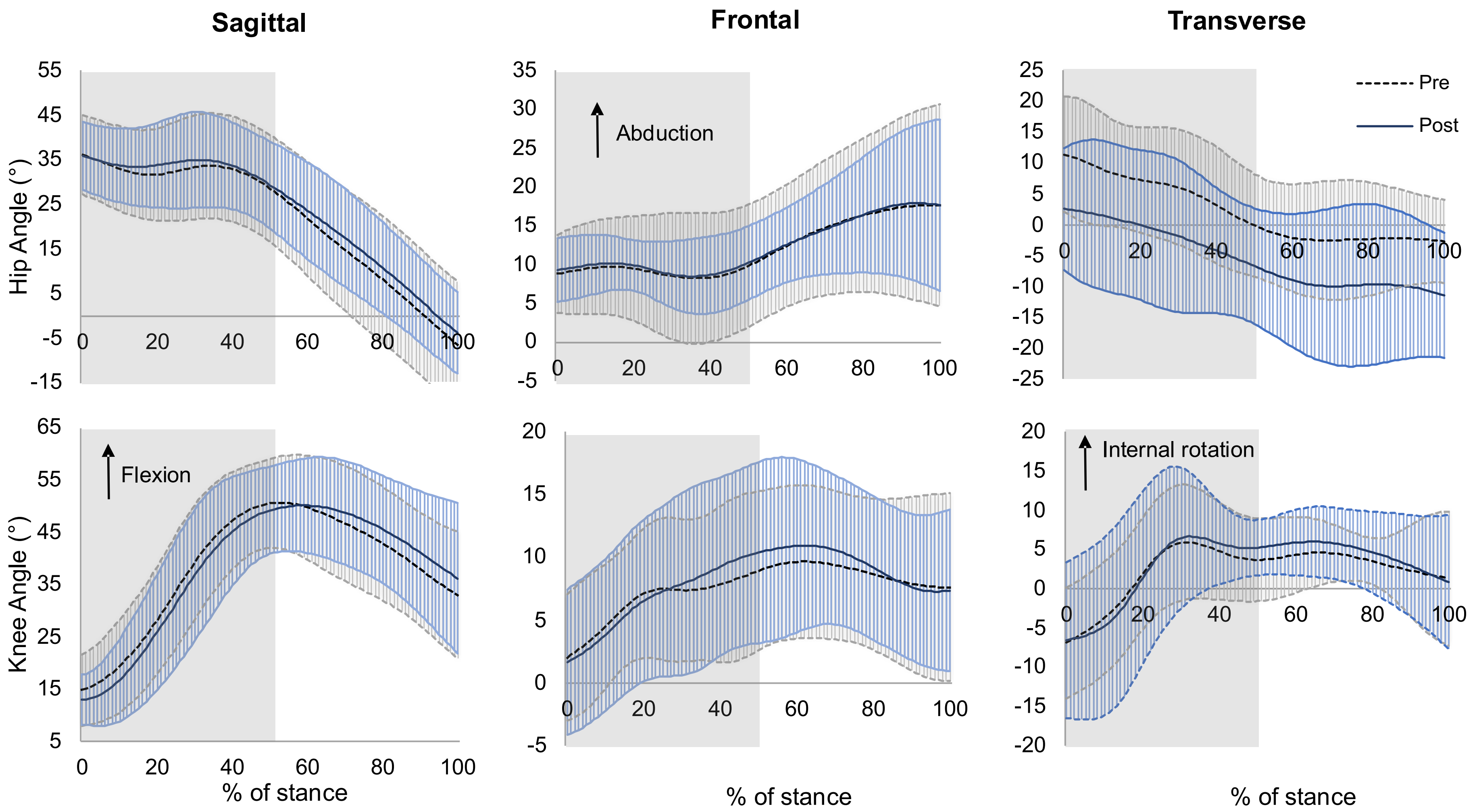


Figure 6.1. Mean female hip and knee angular data in the stance leg during a 45° side cut. The grey shaded area indicates the weight acceptance phase. The between group standard deviation for pre (grey) and post (blue) multi-directional running are also displayed.

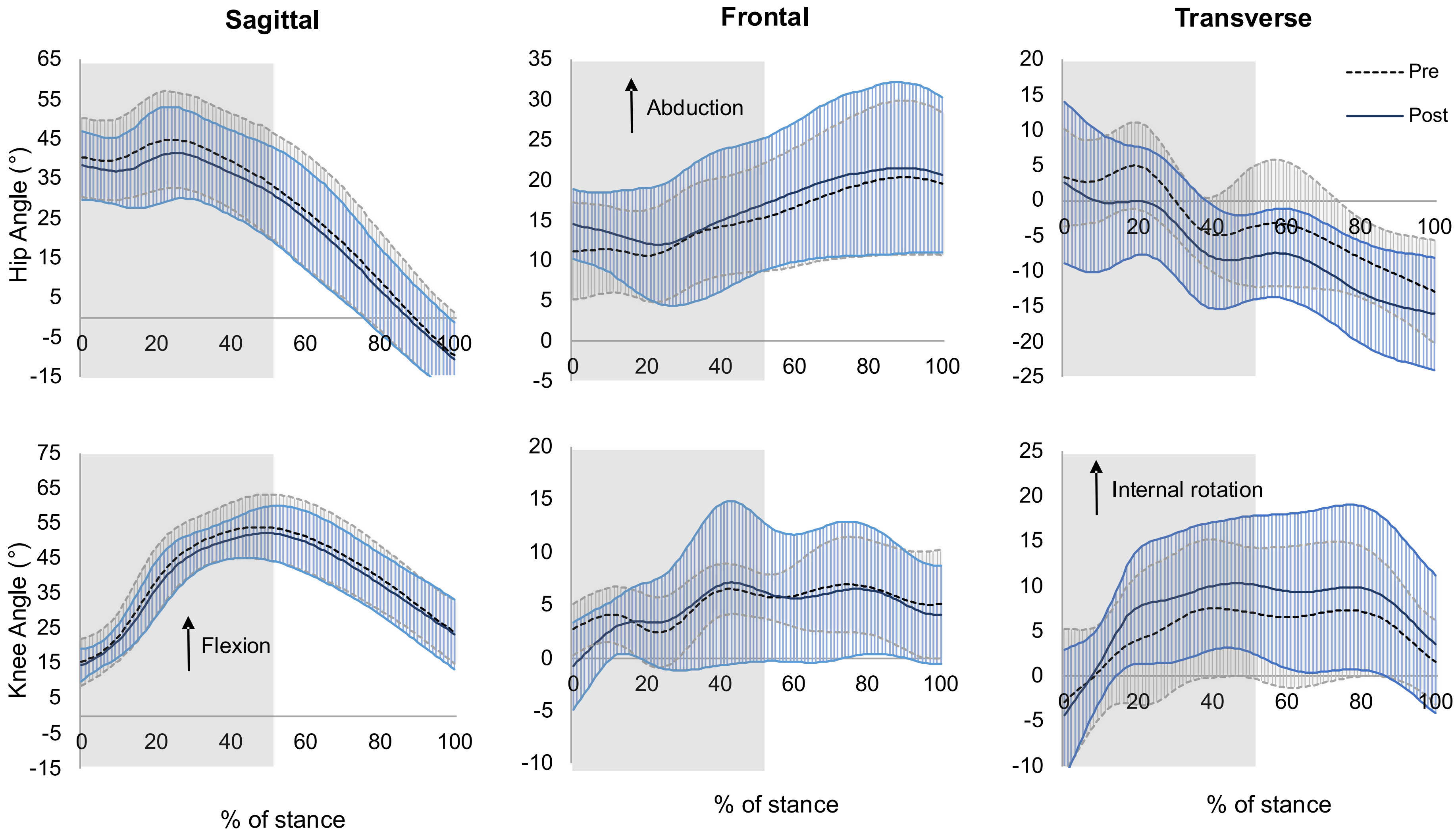


Figure 6.2. Mean male hip and knee angular data in the stance leg during a 45° side cut. The grey shaded area indicates the weight acceptance phase. The between group standard deviation for pre (grey) and post (blue) multi-directional running are also displayed.

6.3.2 Kinetics

Peak GRF data are presented in Appendix 6.7. Peak lateral GRF during the weight acceptance phase was lower after multi-directional running (*F* = 15.159, *p* = 0.002) and a sex x time interaction was observed (*F* = 4.447, *p* = 0.053). Specifically, peak lateral GRF was moderately lower in females after multi-directional running (1.23 ± 0.2 *cf.* 1.04 ± 0.17 N·BW^{-1}; -0.85; ±0.55) but only demonstrated a small decrease in males (1.13 ± 0.18 *cf.* 1.07 ± 0.22 N·BW^{-1}; -0.29; ±0.42). No other changes or interactions in peak GRF were observed. IGRF demonstrated a trivial to moderate increase after multi-directional running (*F* = 3.975, *p* = 0.066) in females (0.79; ±0.77) and males (0.04; ±0.35) during the weight acceptance phase of side cuts (Figure 6.3).

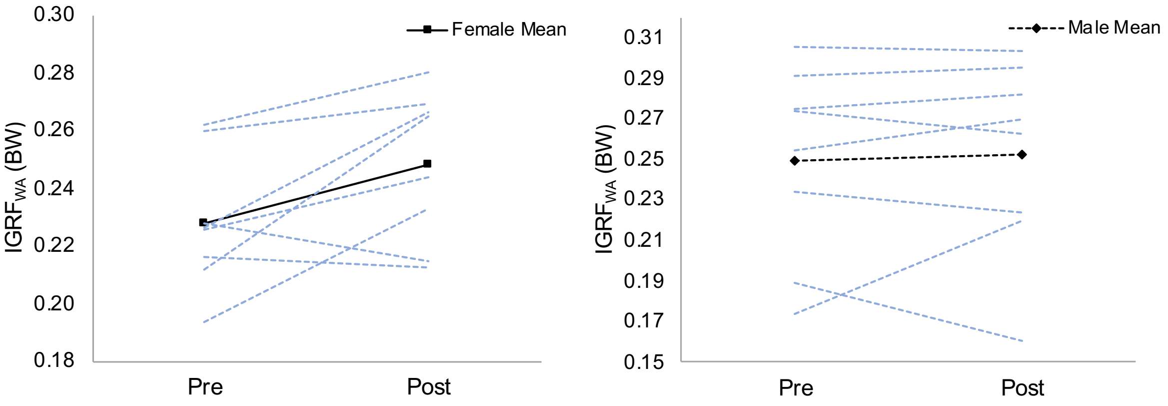


Figure 6.3 Mean IGRF in females (black line) and males (black dashed line) during the weight acceptance phase before and after multi-directional running. Individual participant changes are shown in blue.

Hip and knee moment data over stance in females and males are presented in Figures 6.4 and 6.5, respectively. After multi-directional running, peak hip extensor moment (*F* = 0.4372, *p* = 0.055) displayed a trivial to small increase in females (ES; ±95% CI: 0.19; ±0.27) and males (0.29; ±0.51) and peak hip external rotation moment was lower

(*F* = 8.683, *p* = 0.011) in females (-0.44; ±0.44) and males (-0.57; ±0.70) during the weight acceptance phase of side cuts. Peak knee extensor moment was lower (*F* = 13.336, *p* = 0.003) in females (-0.33; ±0.23) and males (-0.45; ±0.59) after multi-directional running, whereas peak knee external rotation moment displayed a small increase (*F* = 4.495, *p* = 0.052) in females (0.34; ±0.35) and males (0.22; ±0.51). The knee to hip peak extensor ratio was lower after multi-directional running (*F* = 11.409, *p* = 0.005) in females (0.88 ± 0.56 *cf.* 0.79 ± 0.54; -0.15; ±0.12) and males (0.93 ± 0.23 *cf.* 0.82 ± 0.18; -0.45; ±0.49). No other changes in peak moments during the weight acceptance phase of stance (see Appendix 6.8) and no interaction between time and sex for peak moments were observed.

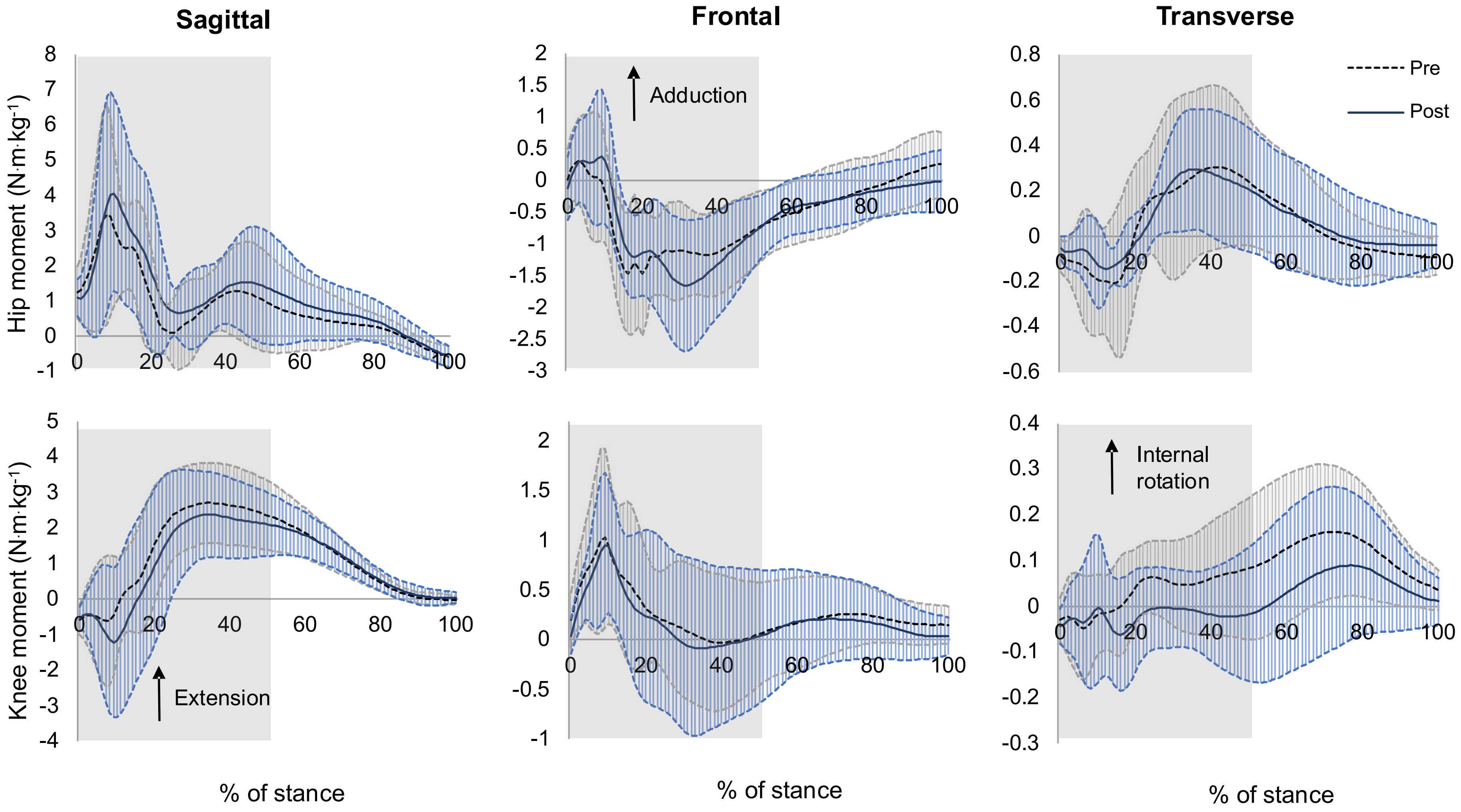


Figure 6.4. Mean female hip and knee moment data in the stance leg during a 45° side cut. The grey shaded area indicates the weight acceptance phase. The between group standard deviation for pre (grey) and post (blue) multi-directional running are also displayed.

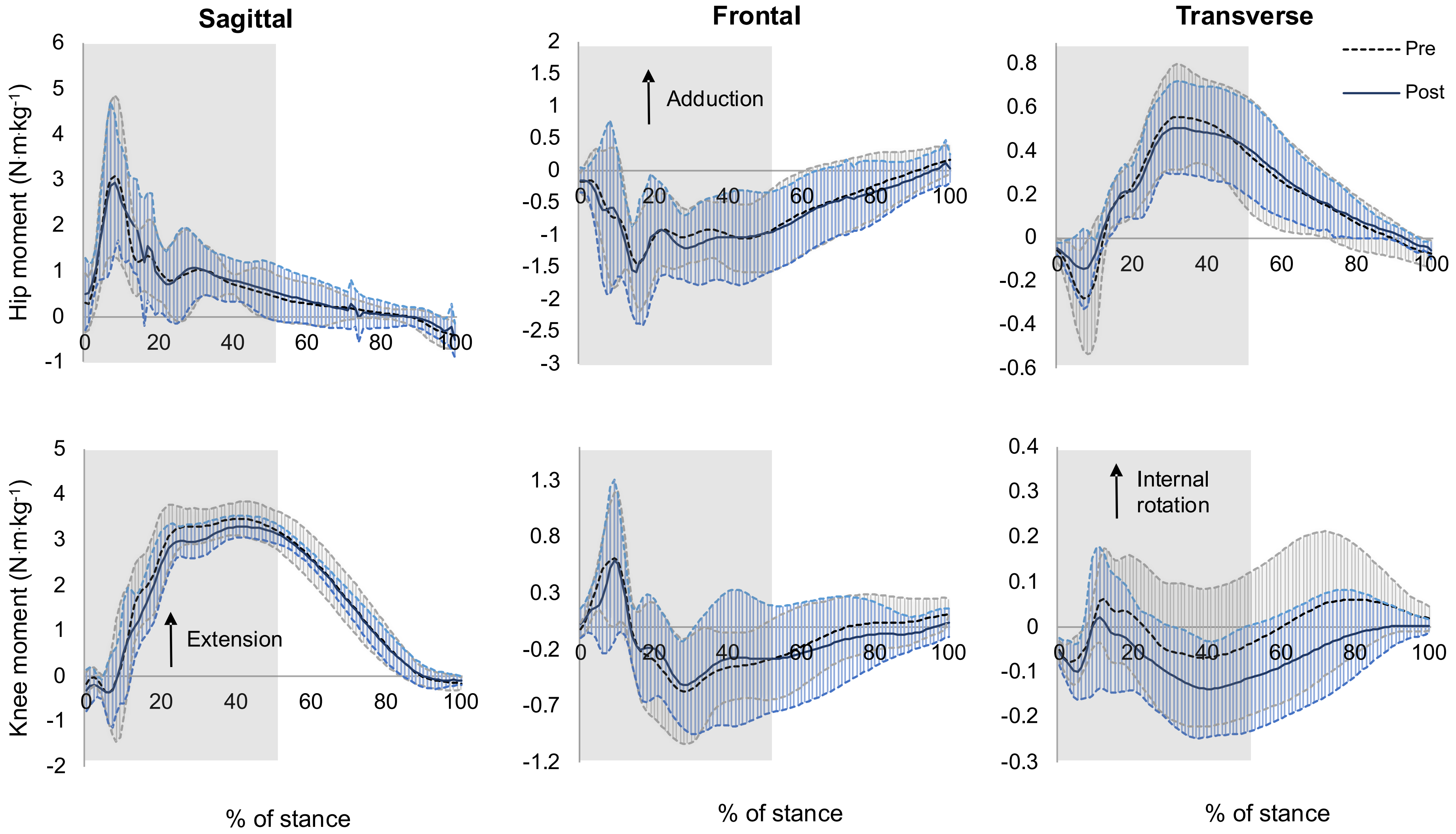


Figure 6.5. Mean male hip and knee moment data in the stance leg during a 45° side cut. The grey shaded area indicates the weight acceptance phase. The between group standard deviation for pre (grey) and post (blue) multi-directional running are also displayed.

6.3.3 Movement variability

Most variables displayed no change in movement variability after multi-directional running (see Appendix 6.9). However, peak hip extension angle displayed a moderate to large increase (F = 3.837, p = 0.072) in females (CV: 10.5 ± 4.9 *cf.* 34.5 ± 36.3%; 3.69; ±6.03) and males (12.1 ± 7.3 *cf.* 17.2 ± 11.0%; 0.62; ±0.75) after multi-directional running.

6.4 Discussion

The purpose of the study was to assess the effect of fatigue from a multi-directional running protocol on side cut mechanics in male and female team sport players. The moderate to large increase in 20 m sprint times (~7% in females and ~5% males) after running indicates that the multi-directional caused fatigue in both sexes. This reaffirms the decrease in knee extensor and flexor strength observed after the same multi-directional protocol in Chapter 5 and similar team sport protocols reported elsewhere (Goodall et al., 2015; Greig, 2019). While the precise mechanisms are beyond the scope of this study, a combination of central (e.g. reduced central motor drive; Girard, Mendez-Villanueva & Bishop, 2011; Rampinini et al., 2011) and peripheral factors (e.g. accumulation of metabolites; Brownstein et al., 2017; Goodall et al. 2015) are likely causes of fatigue that explain a decline in sprint performance observed here.

Data regarding task achievement demonstrates a disparity between the prescribed cut angle (45°) and the actual cut angle performed (~22 – 26°), i.e., the directional change in centre of mass. This likely reflects the trade-off between approach speed and cut angle (Vanrenterghem et al., 2012) and is consistent with previous literature indicating the executed angle is lower than the intended angle (David, Komnik, Peters, Funken

& Potthast, 2017; Vanrenterghem et al., 2012). It is noteworthy that side cutting technique is angle and velocity dependant (Dos'Santos et al., 2019) and task execution did not differ after multi-directional running. Taken together, task execution can be disregarded as a confounding variable.

The effect of multi-directional running on side cut kinematics was similar in males and females as no interaction between time and sex was noted. Peak trunk flexion displayed a trivial and small increase after multi-directional running, in females and males, respectively. Increasing trunk flexion during landing has been reported to decrease knee abduction angle and moment (Davis, Hinshaw, Critchley & Dai, 2019) and is therefore associated with a reduction in peak ACL strain (Kiapour et al., 2016; Navacchia et al., 2019). However, the trivial difference in trunk flexion (~1.6°) noted in females is unlikely to lead to meaningful reduction in ACL injury risk, given the ~2° measurement error in sagittal plane kinematics during a side cut (Alenezi et al., 2016).

A small reduction in peak hip internal rotation (a trivial to large reduction in hip internal rotation at initial contact) and a trivial to small increase in knee extension angle was noted in males and females, respectively, after multi-directional running. Landing in a more extended position is a common mechanism reported during an ACL injury (Koga et al., 2010; Walden et al., 2015) and peak knee flexion angles have shown a moderate negative correlation with peak ACL strain (*r* = -0.4; Bakker et al., 2015) using a combined in vivo/computational/in vitro approach. These data highlight cutting with less knee flexion can increase ACL strain. However, it is noteworthy that alterations in sagittal plane mechanics alone might be insufficient to cause an ACL rupture (McLean et al., 2004), compared with knee abduction and internal rotation, which places the greatest strain on the ACL in vitro (Bates et al., 2017). The trivial increase in knee extension in males (~ 1.2°) is also unlikely to have meaningful effect on ACL injury risk. The reduction in peak hip internal rotation angle observed after multi-directional running can increase ACL injury risk, given the association between decreased internal femoral rotation and ACL strain in silico (Bedi et al., 2016; Beaulieu, Oh, Bedi, Ashton-Miller & Wojtys, 2014). Data from the present study are consistent with reports of increased knee extension angles (Khalid et al., 2015; McGovern et al., 2015; Raja Azidin et al., 2015; Zago, Sforza, Ferrario, Esposito & Galli, 2018), and no change in peak frontal knee angles (McGovern et al., 2015), and a shift towards external hip rotation (Sanna & O'Connor, 2008), during a side cutting task after intermittent running. Whilst others have reported an increase in knee flexion (Savage et al., 2018) and knee abduction angle (Collins et al., 2016) after intermittent running, differences in the mechanical loading of fatigue protocols (e.g. with or without change of direction; Savage et al., 2018), which can alter the neuromuscular load of exercise (Hader et al., 2014), might partly explain contrasting findings. A reduced knee abduction angle at initial contact was also observed, and whilst no interaction between time and sex was noted, the size of the effect was deemed large in males and trivial in females. Whilst a reduction in knee abduction angle has been associated with reduced ACL injury risk in a prospective study (Hewett et al., 2005), peak ACL strain occurs simultaneously with peak knee abduction angle during a simulated landing task using a validated physiological cadaveric model (Kiapour et al., 2014). ACL injury risk is therefore unlikely to be reduced as peak knee abduction angle remained the same after multi-directional running. Taken together, fatigue that manifests as reduced sprint performance after multi-directional running appears to trigger similar and small adaptations in joint angles in males and females. Notably, the increased peak knee extension angle reaffirms previous studies, whilst the small decrease in peak hip internal rotation angle offers further insight into side cut alterations with fatigue as transverse hip kinematics have been investigated to a limited extend after multi-directional running (Chapter 2).

To the authors knowledge, this is the first study to evaluate the effects of fatigue on tri-planar angular velocities during a side cut. A moderate increase in knee abduction angular velocity and a moderate to large increase in peak knee internal rotation angular velocity, was observed after multi-directional running in females and males, respectively. Typically, increases in sagittal plane angular velocities have been reported under fatigue and are indicative of a reduced ability of the body to attenuate impact (Moran & Marshall, 2006; Tamura et al., 2017). Whilst few studies have examined frontal and transverse angular velocities after fatiguing exercise, the increase in abduction and internal rotation angular velocity observed in the present study indicates a reduced ability to control angular velocities after multi-directional running (Jenkins, Williams, Williams, Herner & Welch, 2017). A reduced activation of the biceps femoris could be responsible for the increase in knee internal rotation angular velocity (Fuji, Sato & Takahira, 2012; Olson, 2020), however this was not assessed in the present study. With regards to ACL injury risk, dynamic valgus collapse (defined as hip adduction, knee abduction and tibial internal rotation) has been reported as a key mechanism during injury to the ACL in females (Krosshaug et al., 2007; Stuelcken, Mellifont, Gorman & Sayers, 2016), but less so in males (Walden et al., 2015). An increase in knee abduction and internal rotation angular velocity after multi-directional running could therefore increase ACL injury risk, particularly in females. Further understanding of joint angular velocities during a side cut is warranted to comprehensively evaluate how this metric can inform injury risk.

Peak lateral GRF demonstrated a small and moderate reduction after multi-directional running, in males and females, respectively, and a propensity for a sex x time interaction was noted. This decrease in lateral GRF might serve as a strategy to maintain balance and avoid excessive lateral forces, which can increase disposition to ankle injuries (McClay et al., 1994). Whilst some have reported an association between lateral GRF and knee abduction moment (Sigward et al., 2015), knee adduction moment remained unaltered after multi-directional running, so it is unclear whether a reduction in peak lateral GRF would reduce ACL injury risk. Whilst peak vertical GRF remained unchanged, IGRF displayed a trivial increase in males and a moderate increase in females, albeit no interaction of sex x fatigue was noted. These findings are consistent with Iguchi and colleagues (2014) who reported females demonstrated larger IGRF during the first 50 ms of a side cut, after fatiguing exercise. The trivial and small increase in knee extension angle observed in males and females in the present study, respectively, partially explains the trivial to moderate changes in IGRF, given that landing with less knee flexion is associated with a higher GRF (Yu, Lin & Garrett, 2006). The moderately higher IGRF in females suggests an increased effort to decelerate the downward movement of the centre of mass during the weight acceptance phase (Harry, Freedman Silvernail, Mercer & Dufek, 2017) that can increase tibiofemoral compression (Iguchi et al., 2014) and might be a factor related to non-contact ACL injuries (Iguchi et al., 2014). Collectively, whilst a higher IGRF could increase joint loading, body position might play a greater role in knee abduction loading, compared with the magnitude of forces (Kristainslund, Faul, Bahr, Myklebust

& Krosshaug, 2014), and the trivial effect in males is unlikely to have a meaningful effect on ACL injury risk.

Peak hip extensor moment displayed a trivial to small increase, whereas peak knee extensor moment was lower, after multi-directional running in both males and females. Previous studies have reported both increases (Khalid et al., 2015) and decreases (Schmitz et al., 2014) in knee extensor moments under fatigue, which appear to be dependent on the fatigue protocol used (Zhang et al., 2018). With regards to ACL strain, Bakker et al. (2016) demonstrated peak knee moments were not associated with ACL strain, suggesting that maximum quadricep force was not associated with ACL strain, but peak knee extensor moment was correlated with time to peak ACL strain. Accordingly, the small reduction in peak knee extensor moment observed in the present study might not reduce ACL strain, but could increase the time to peak ACL strain. A lower knee to hip peak extensor ratio was also observed after multi-directional running, albeit the effect size was trivial in females and small in males. This is suggestive of increased use of the hip extensors compared to knee extensor as a means to control the deceleration phase of the side cut (Pollard, Sigward & Powers, 2017), and concurs with the decrease in knee extensor toque after multi-directional running (see Chapter 5). A greater distribution of hip moment can reduce knee abduction moment during a single leg landing (Nguyen, Taylor, Wimbish, Keith & Ford, 2018), but this was not observed in the present study. The trivial and small reduction in knee to hip peak extensor ratio, noted in females and males respectively, might have been insufficient to reduce frontal plane knee loading.

The small reduction in peak hip external rotation moments observed in males and females after multi-directional running could increase ACL injury risk as a prospective study found participants landing with less hip external rotation moment were over 8 times more likely to sustain a second ACL injury, compared to those with greater hip external rotation moment (Paterno et al., 2010). The increase in knee external rotation moment would likely increase risk of an ACL injury given that internal tibial moment (expressed as an external moment) plays a primary role in increasing ACL strain (Oh et al., 2012), particularly when combined with a knee abduction moment (Shin et al., 2011). Whilst knee adduction moment did not change after multi-directional running in the present study, the peak knee adduction values for females are considered high (Hewett et al., 2005), and therefore small alterations to joint loading which increase ACL risk further are important considerations. Taken together, fatigue induced from multi-directional running caused small alterations in lower limb joint moments which can increase ACL strain in males and females.

Fatigue caused by multi-directional running also caused moderate to large increases in movement variability of peak hip extension angles. In agreement, greater variability in kinematic data during a side cut has been reported after fatiguing exercise caused by intermittent running (Cortes et al., 2014). In the present study, peak hip extension occurs later during the weight acceptance of stance, and this is when the signal can become more irregular (Cortes et al., 2014). An increase in variability might reflect increased neuromuscular noise under fatigue (Cowley & Gates, 2017) and can redistribute the load placed on the tissues by spreading the load across different areas (Mathiassen, 2006). However, this could result in a loss of movement co-ordination (Cortes et al., 2014) and increase the possibility of extreme movements (i.e. landing in a more extended position) and injury. Indeed, in a recent case study higher movement variability during a fatigue protocol were reported in a participant who sustained an ACL injury compared with a control group (Hamdan & Raja Azidin, 2020). An increase in movement variability after multi-directional running might therefore increase ACL injury risk, however future research examining more trials are required to collaborate these data.

This study is not without limitations. There was a ~30-minutes delay between the end of the multi-directional running protocol and the first measurement of side cuts performed afterwards. Participants are therefore likely to have been afforded some recovery in that period of time that meant fatigue had subsided and subsequent kinematic and kinetic modifications in side cuts would be less pronounced had measures been performed more proximal to the running protocol. However, Tsai, Sigward, Pollard, Fletcher and Powers (2009) reported kinematic and kinetic alterations were generally similar when measured immediately after fatiguing exercise compared with 20 and 40 minutes afterwards. Furthermore, having a delay between fatiguing exercise and side cut measurements might be more representative of a team sport athletes typical training schedule, involving multiple training sessions a day interspersed with rest periods, and therefore help improve the generalizability of the findings of the present study. With regard to data processing, some have suggested that force and movement data should be processed with the same filter cut-off frequency (Bisseling & Hof, 2006; Kristianslund, Krosshaug & van den Bogert, 2011). However, Roewer and colleagues (2014) recommend force to be filtered at a higher frequency to ensure valuable GRF data is not removed that could lead to erroneous prediction of injury risk. In the present study residual analysis was used to determine the appropriate cut off frequencies for force and movement data (Winter, 1990). Researchers should be cautious when comparing these data to other literature which has used different processing techniques. Finally, whilst some of the changes in side cut mechanics are small, these are larger than the within day standard error of measurement for sagittal (~2°) and frontal (~2°) and transverse (~3°) angles during a side cut (Alenezi et al., 2016). Changes of 2° in joint angles can reduce injury threshold by 1 body weight (Chaudhari & Andriacchi, 2006), and therefore have meaningful implications for injury risk. Changes in sagittal kinetics in the present study (0.29 $N{\cdot}m{\cdot}kg^{-1}$ for males and females combined) are also greater than the inter-trial variability reported for sagittal kinetic variables (32 $N{\cdot}m$ [~0.27 $N{\cdot}m{\cdot}kg^{-1}$ for a 70 kg person]) using the same data collection procedures (Sankey et al., 2015). However, the percentage increase in knee external rotation moment in males and females (~16 - 28%) was lower than previous reports of the percentage variability in this variable (34%; Sankey et al., 2015). Whilst it is unclear if the small increase in knee external rotation moment is due to variability of the measurement or multi-directional running, small changes in knee rotation moment can still affect ACL strain (Shin et al., 2011). The changes in kinematic and kinetic variables are therefore deemed meaningful for ACL injury, but researchers should take into consideration the standard error of measurement for the variables, when interpreting the changes reported in the present study.

6.5 Conclusion

In conclusion, multi-directional running did not impair side cut task achievement but did cause small modifications in the biomechanics of side cuts which were similar between sexes. In particular, both males and females performed side cuts with less peak hip internal rotation angle and peak knee extensor moment and more peak knee abduction and internal rotation angular velocity and more peak knee external rotation moment. Such changes in side cut biomechanics (with the exception of knee extensor moment) have previously been reported to contribute to ACL injury risk. Peak lateral GRF was the only variable to display an interaction between sex and time, which suggests fatigue induced from multi-directional running has a similar effect on side cut biomechanics between sexes. In the present study some additional trivial effects were noted (e.g. trunk flexion in females, knee extension in males), which are unlikely to have a meaningful effect on ACL injury risk. Accordingly, future research should assess the size of the effect to help determine which changes in kinematic and kinetic data are meaningful.

Key messages

- *Multi-directional running caused fatigue and small modifications in side cut biomechanics which were similar in males and females.*
- *Specifically, increases in frontal and transverse angular velocities and transverse joint moments at the knee were observed after multi-directional running, despite a lower peak lateral GRF and knee extensor moment.*
- *Fatigue from multi-directional running might therefore indirectly contribute to ACL injury risk.*

Next steps

- *Future research should explore if side cut alterations after multi-directional running persist in the days after exercise.*

Chapter 7

The effect of exercise-induced muscle damage on the biomechanics of side cuts in males and females

Rationale summary

The biomechanical mechanisms of ACL injuries during side cuts (see Chapter 2) and the effect of fatigue on side cut mechanics (see Chapter 6) has been explored. Yet, the effect of exercise-induced muscle damage (EIMD) on the biomechanics of side cuts in males and females is poorly understood. Accordingly, this study assessed the effect of multi-directional running on indirect markers of EIMD and the biomechanics of side cuts in males and females.

7.1 Introduction

Symptoms of EIMD are common in team sport athletes, typically lasting for several days after exercise (Gastin et al., 2019; Howatson & Milak; 2009; Oxendale et al., 2016; Nedelec et al., 2014; Twist & Sykes, 2011). These symptoms include large increases in creatine kinase activity (CK; ~170 – 390% increase; Howatson & Milak, 2009; Malone et al., 2018; Oxendale et al., 2016), perceived muscle soreness (17 – 80% increase; Nedelec et al., 2014; Oxendale et al., 2016), and reductions in knee flexor and extensor strength (~ 6 – 15% decrease; Nedelec et al., 2014; Snyder et al., 2019), counter-movement jump (~ 5 – 15% decrease; Keane et al., 2015; Malone et al., 2018; Nedelec et al., 2014; Roe et al., 2017; Oxendale et al., 2016) and sprint performance (~5 – 6% decrease; Keane et al., 2015; Nedelec et al., 2014) 24 – 48 h after team sport activity. These markers of muscle damage are strongly correlated with the number of sprints (*r* = 0.39 – 0.76; Nedelec et al., 2014; Oxendale et al., 2016), accelerations and decelerations (*r* = 0.44 – 0.48; Oxendale et al., 2016) and changes of direction performed (*r* = -0.55; Nedelec et al., 2014), suggesting movement patterns typical of team sports place a high mechanical demand on the active musculature. During congested fixture and training schedules, athletes have to perform whilst experiencing symptoms of EIMD. This could have implications for injury risk as injury incidence in team sport players can be higher when they perform two compared with one match per week (25.6 *cf.* 4.1 injuries per 1000 hours of exposure; Dupont et al., 2010).

A reduction in knee proprioception (Naderi, Rezvani & Degens, 2020; Torres, Vasques, Duarte & Cabri, 2010), reflex sensitivity (Avela & Komi, 1998) and impaired balance performance (Twist, Gleeson & Eston, 2008) have been reported after muscle damaging exercise. Such impairments might be related to pain that might impair proprioception (Naderi et al., 2020; Paschalis et al., 2007b) and/or impairment in the intrafusal fibres of the muscle spindles (Naderi et al., 2020; Torres et al., 2010). EIMD can also affect walking and running biomechanics, as decreases in stride length (Burt et al., 2014; Chen et al., 2009; Tsatalas et al., 2013b) and reductions in lower limb range of motion during walking (Paquette et al., 2017; Paschalis et al., 2007a; Tsatalas et al., 2010) and running (Chen et al., 2009; Paschalis et al., 2007a; Tsatalas et al., 2013a) have been reported with symptoms of EIMD. Some have suggested this is due to an increased knee flexion angle at initial contact during walking and running (~1.4 – 3.7º; Tsatalas et al., 2013a; Tsatalas et al., 2013b) and might serve as a mechanism to prevent further musculoskeletal injury of the impaired muscles (Tsatalas et al., 2013b). However, others have reported a decrease in peak knee flexion angles (~ 4º; Paquette et al., 2017) and knee flexion angles at initial contact (~2º; Paschalis et al., 2007a) during running. A reduction in knee flexion has been identified as a common mechanism during an ACL injury in males and females (Koga et al., 2010; Walden et al., 2015), which suggests EIMD could have implications for knee injury risk. Indeed, ACL injuries account for a high injury incidence (0.3 – 3.2 per 10,000 athlete exposures; Agel et al., 2016; Stanley et al., 2016) and the longest time to return to play (~236 days; Awwad, Coleman, Dunkley & Dewar, 2019). However, most ACL injuries occur during a 30-90° side cut in both male (Walden et al., 2015) and female (Koga et al., 2010) team sport athletes, and side cuts place a greater emphasis on transverse and frontal mechanics compared with straight running (Besier et al., 2001). Taken together, these data highlight EIMD has the capacity to modify movement, however assessment of how EIMD affects side cut biomechanics is required to comprehensively evaluate the effect of EIMD on ACL injury risk.

Decreases in hip and knee flexion (Lucci et al., 2011; McGovern et al., 2015) and knee internal rotation angles (Lucci et al., 2011), increased knee abduction angles and moments (Collins et al., 2016; Tsai et al., 2008), knee extensor moments (Savage et al., 2018) and knee abduction and internal rotation angular velocities (Chapter 6) have been reported during a side cut with fatigue. These data highlight fatigue can increase ACL injury risk as reductions in knee flexion angles (Walden et al., 2015), and increases in knee abduction angles (Kobayashi et al., 2010; Walden et al., 2015) and moments (Myer et al., 2015) are some of the mechanisms reported during an ACL injury. However, these data do not indicate the effect on EIMD on side cut biomechanics, as the mechanisms of fatigue and muscle damage differ. Briefly, fatigue is associated with reduced central motor drive and limited ability to recruit available motor units, to the accumulation of metabolites within the muscle, reducing the muscle's ability to perform work (Girard et al., 2011); this fatigue often recovers quickly (within hours) after team sport activity (Carroll, Taylor & Gandevia, 2017).

Conversely, EIMD is accompanied by myofibrillar structural damage, E-C coupling failure, low frequency fatigue and significant muscle soreness, where recovery often takes longer (up to several days; Finsterer, 2012) and should therefore be considered separately.

To the author’s knowledge, only one study has assessed the biomechanics of side cuts during EIMD. Specifically, Snyder et al. (2019) reported that reductions in isometric knee extensor strength 12 h after match-play were accompanied by concurrent increases in posterior GRF and anterior tibial shear force during a side cut in females. These findings are particularly interesting given the ACL plays a key role in resisting anterior tibial shear force (Butler, Grood & Noyes, 1980) and suggests EIMD caused by a congested match fixture could increase ACL injury risk. This might also partly account for the ~2 – 6-fold higher ACL injury incidence rate sustained in females compared with males (Gray et al., 2019; Hewett et al., 2005; Stanley et al., 2016;). However, Snyder et al. (2019) only assessed females so it is not clear how EIMD might affect the biomechanics of side cuts in males, given that side cut knee kinetics have been reported to differ between sexes with fatigue (Sigward & Powers, 2006). Assessing EIMD 12 h after match-play is also unlikely to represent the peak magnitude of EIMD (see Chapter 2.3.2). In addition, Snyder et al. (2019) failed to assess knee abduction and internal rotation angles and moments, and trunk position, which are considered key mechanisms of ACL strain and injury (Hewett et al., 2009; Kiapour et al., 2016; Myer et al., 2015; Navacchia et al., 2019; Shin et al., 2011). Where team sport athletes are exposed to congested periods of training/competition they are likely to perform whilst exhibiting symptoms of EIMD. Accordingly, it seems prudent to explore the effect of EIMD on side cut biomechanics, in both male and female team sport athletes to understand how EIMD effects ACL injury risk. Thus, the purpose of the study was to assess the effect of EIMD induced from multi-directional running on trunk, hip and knee kinematics and kinetics and GRF during 45° side cuts in male and female team sport athletes.

7.2 Method

7.2.1 Participants

With institutional ethics approval (see Appendix 6.1), 8 males (stature: 175.5 ± 8.0 cm; mass: 74.6 ± 8.5 kg; age: 21.6 ± 2.2 years; $\dot{V}O_{2\ peak}$: 46.0 ± 4.1 ml·kg^{-1}min^{-1}) and 8 females (stature: 166.0 ± 8.4 cm; mass: 60.6 ± 9.2 kg; age: 21.8 ± 3.1 years; estimated $\dot{V}O_{2\ peak}$: 39.8 ± 4.5 ml·kg^{-1}min^{-1}) were recruited from University-level team sports (football, netball, hockey and rugby). This sample size was based on the number of participants used in previous research examining the effect of EIMD from congested match fixtures on lower limb mechanics during a side cut (Snyder et al., 2019). This value also exceeds *a priori* sample size calculation (see Appendix 7.1), based on estimated power (Faul et al., 2009) and an effect size of 1.49, for EIMD modifications in GRF (Snyder et al., 2019). All participants took part in team sport training sessions at least twice per week. Participants completed pre-test health screening to ensure they had no previous history of knee surgery and/or no lower limb injuries in the past 6 months (Thomas et al., 2010). Participants were also required to refrain from exercise 48 h before each visit.

7.2.2 Design

Participants completed three sessions on separate days. In the first visit, participants completed a 20 m multi-stage fitness test to provide an estimate of maximal aerobic capacity. Three to seven days later, baseline measurements of creatine kinase (CK) concentration, perceived muscle soreness, 20 m sprint time and side cut mechanics were measured. Thereafter, participants completed the multi-directional trial and repeated measurements of CK concentration, perceived muscle soreness, 20 m sprint time and side cut mechanics at 48 (± 2) hours after the multi-directional trial, when indirect markers of EIMD typically peak (see section 2.3.2.3).

7.2.3 Procedures

7.2.3.1 Multi-stage fitness test

The multi-stage fitness test was used to estimate each participant's $\dot{V}O_{2\ \text{peak}}$. Please refer to General Methods section 3.2 for procedures.

7.2.3.2 Multi-directional trial

The multi-directional trial comprised twelve bouts of ~60 s of work followed by 120 s of passive rest, procedures for which can be found in the General Methods section 3.3. The multi-directional trial has previously demonstrated a good level of reliability (see Chapter 5).

7.2.3.3 CK concentration

CK concentration was determined from a fingertip capillary sample whilst participants adopted a seated position. After cleaning the participant's middle finger with an alcohol wipe and waiting 1 minute for it to dry, a 30 µL sample of whole blood was taken using a spring-loaded disposable lancet. The whole blood sample was immediately analysed using a colorimetric assay procedure (Reflotron, Type 4, Boehringer, Germany).

7.2.3.4 Perceived muscle soreness

Participants provided a rating of their perceived muscle soreness for the lower limbs using a visual analogue scale. The sliding scale was numbered on the reserve side, where 0 indicated "no soreness on movement", 5 indicated "muscles sore on movement" and 10 indicated "muscles too sore to move". All participants performed a squat to an approximate knee angle of 90° with their hands-on hips, and then provided an overall rating of their perceived muscle soreness using the sliding scale.

7.2.3.5 Sprint performance

Participants performed three single maximal 20 m sprints immediately before and 48 ± 2 h after the multi-directional trial. Please refer to General Methods section 3.5 for procedures.

7.2.3.6 Three-dimensional motion capture of 45° side cuts

Please refer to General Methods section 3.6 for procedures.

7.2.3.7 Data Analysis of 45° side cuts

Please refer to General Methods section 3.7 for procedures.

7.2.4 Statistical analysis

Descriptive data are reported as mean ± standard deviation. Data were analysed using separate two-way mixed ANOVAs with time (before vs. 48 h after multi-directional running) as a within-subject factor, and sex (males vs. females) as a between-subject factor. *P* values were reported for all analyses. Further *post hoc* analyses consisting of effect sizes with accompanying 95% confidence intervals (ES; ±95%CI) were performed for each sex. The effect size was calculated as the difference in means divided by the pooled standard deviation. An effect size of 0.2, 0.6 and 1.2 were considered small, moderate and large, respectively. The coefficient of variation (CV%) was used to assess within-subject variability in sagittal plane variables and GRF. All statistical analyses were performed using the Statistical Package for Social Sciences (SPSS, version 22; SPSS, Inc., IL, USA) and Microsoft Excel. The reader should refer to General Method section 3.8, for further information regarding the statistical approach adopted.

7.3 Results

Indirect markers of EIMD before and 48 h after the multi-directional trial are displayed in Table 7.1. There was an increase in CK concentration 48 h after multi-directional running ($F = 9.261$, $p = 0.009$) which was large in males (ES; ±95% CI; 2.4; ±2.3) and females (4.94; ±5.39). Perceived muscle soreness ($F = 82.283$, $p < 0.001$) demonstrated a large increase in females (4.8; ±1.4) and males (4.2; ±1.9) and 20 m sprint time ($F = 30.655$, $p < 0.001$) demonstrated a moderate increase in females (0.9; ±0.7) and males (0.6; ±0.3) 48 h after the multi-directional trial. No interactions between time and sex were noted for any indirect markers of EIMD.

Table 7.1. In-direct markers of EIMD before and 48 h after the multi-directional trial

	Females		*Males*	
	Baseline	48 h	Baseline	48 h
CK concentration ($U{\cdot}L^{-1}$)	93.3 ± 38.9	308.9 ± 295.7	155.1 ± 47.8	282.3 ± 155.4
Perceived soreness (AU)	0.5 ± 0.8	4.6 ± 1.2	0.7 ± 0.7	4.1 ± 2.0
20 m sprint time (s)	3.4 ± 0.2	3.7 ± 0.3	3.1 ± 0.2	3.3 ± 0.2

Data on task achievement during the side cuts are presented in Table 7.2. Centre of mass velocity was similar at baseline and 48 h after multi-directional running at initial contact (F = 0.036, p = 0.853) in females (ES; ±95% CI: 0.16; ±0.44) and males (0.14; ±0.87) and at toe off (F = 0.238, p = 0.663) in females (0.17; ±0.54) and males (0.02; ±0.70). Centre of mass cut angle (F = 0.041, p = 0.842) and stance time (F = 0.669, p = 0.427) also remained similar 48 h after multi-directional running in females (0.14; ±0.82 and 0.37; ±0.65, respectively) and males (-0.17; ±0.46 and 0.00; ±0.51, respectively). Percentage of stance time in weight acceptance differed at 48 h (F = 3.786, p = 0.072) and an interaction between time (baseline vs. 48 hours) and sex (males vs. females) was noted (F = 8.335, p = 0.012). Specifically, females demonstrated a moderate increase in percentage of stance time in weight acceptance (0.87; ±0.75) whereas males displayed a small decrease (-0.29; ±0.66) 48 h after multi-directional running.

Table 7.2 Task achievement during 45° side cuts in all participants before and at 48 h after the multi-directional trial

	Females		*Males*	
	Baseline	48 h	Baseline	48 h
Centre of mass velocity at IC ($m \cdot s^{-1}$)	4.2 ± 0.3	4.3 ± 0.2	4.2 ± 0.2	4.2 ± 0.2
Centre of mass velocity at TO ($m \cdot s^{-1}$)	3.8 ± 0.3	3.7 ± 0.2	3.8 ± 0.3	3.8 ± 0.2
Change in centre of mass angle from IC to TO (°)	21.0 ± 3.4	21.3 ± 2.0	25.9 ± 4.6	25.1 ± 4.0
Stance time (s)	0.2 ± 0.03	0.21 ± 0.03	0.25 ± 0.04	0.25 ± 0.04
Weight acceptance percentage of stance (%)	56.0 ± 7.2	63.1 ± 10.5	47.7 ± 4.2	46.4 ± 4.6

IC = initial contact. TO = toe off

7.3.1 Kinematics

Discrete trunk kinematic data are presented in Table 7.3 and hip and knee angular data over stance for females and males are presented in Figures 7.1 and 7.2, respectively. Peak trunk flexion angle during the weight acceptance phase displayed a trivial to small decrease 48 h after multi-directional running (see Table 7.3), whereas peak knee internal rotation angle was higher ($F = 9.167$, $p = 0.009$) in females (0.5; ±0.39) and males (0.31; ±0.47). No other changes in peak angle data 48 h after multi-directional running or interactions between sex and time were noted. At initial contact, knee abduction angle was lower at 48 h ($F = 7.141$, $p = 0.018$) in females (-0.4; ±0.64) and males (-0.91; ±0.76) and an interaction between sex and time was noted for knee internal rotation angle ($F = 3.954$, $p = 0.067$). Specifically, females displayed more knee internal rotation at initial contact (0.51; ±0.41) whereas males displayed less knee internal rotation (-0.29; ±0.81) 48 h after the multi-directional trial. Peak angular data and angular data at initial contact are included in Appendix 7.2 and 7.3, respectively.

Peak angular velocity data for the trunk, hip and knee are presented in Table 7.3 and Appendix 7.4. Peak hip internal rotation angular velocity demonstrated a small decrease 48 h after multi-directional running (*F* = 3.749, *p* = 0.073) in females (200.7 ± 79.2 *cf.* 143.5 ± 95.3 °· s^{-1}; -0.64; ±0.59) and males (187.1 ± 128.2 *cf.* 124.8 ± 112.0 °· s^{-1}; -0.43; ±0.94). An interaction between sex and time was noted for peak knee flexion angular velocity (*F* = 3.925, *p* = 0.068), as males displayed an increase in peak knee flexion angular velocity (727.9 ± 86.3 *cf.* 655.6 ± 101.6 °· s^{-1}; 0.74 ±0.7) at 48 h, whereas the size of the effect in females was trivial (-0.04; ±0.29). Peak knee internal rotation angular velocity changed 48 h after multi-directional running (*F* = 3.369, *p* = 0.088) and an interaction between sex and time was noted (*F* = 4.309, *p* = 0.057). Specifically, peak knee internal rotation angular velocity was higher in males at 48 h (384.2 ± 124.8 *cf.* 484.6 *cf.* 130.1 °· s^{-1}; 0.72 ±0.8) but the size of the effect was trivial in females (-0.06; ±0.46). No other differences in peak angular velocity at the trunk, hip and knee were found. The minimum/maximum medio-lateral foot placement during the weight acceptance phase did not differ between baseline and 48 h in males and females (see Appendix 7.5).

Table 7.3. Peak trunk kinematic data during the weight acceptance phase in males and females, before and 48 h after the multi-directional trial.

	Female (n = 8)			*Male (n = 8)*			*P value from two-way ANOVA*	
	Baseline	48 h	ES; ±95% CI	Baseline	48 h	ES; ±95% CI	Time	Sex x Time
Torso angle:								
Flexion (°)	9.7 ± 10.0	5.8 ± 9.3	-0.35; ±0.2	14.1 ± 8.0	12.9 ± 8.0	-0.13; ±0.56	0.055	0.285
Lateral lean over stance leg (°)	3.9 ± 5.5	3.9 ± 7.2	0.00; ±0.51	2.7 ± 6.3	5.4 ± 9.7	0.39; ±0.89	0.354	0.355
Rotation over stance (°)	5.5 ± 11.8	5.5 ± 9.8	0.00; ±0.35	9.1 ± 7.7	5.5 ± 8.3	-0.42; ±0.78	0.321	0.307
Torso angular velocity:								
Flexion ($°·s^{-1}$)	144.0 ± 87.0	136.9 ± 45.5	-0.07; ±0.54	169.3 ±42.9	163.6 ± 47.6	-0.12; ±0.59	0.623	0.957
Lateral lean over stance leg ($°·s^{-1}$)	69.6 ± 82.1	42.0 ± 15.0	-0.3; ±0.68	88.2 ± 44.7	91.2 ± 28.7	0.06; ±0.43	0.397	0.295
Rotation to new direction of travel ($°·s^{-1}$)	235.9 ± 84.0	199.3 ± 81.8	-0.39; ±0.53	170.5 ±59.5	157.5 ± 47.3	-0.19; ±0.72	0.115	0.437

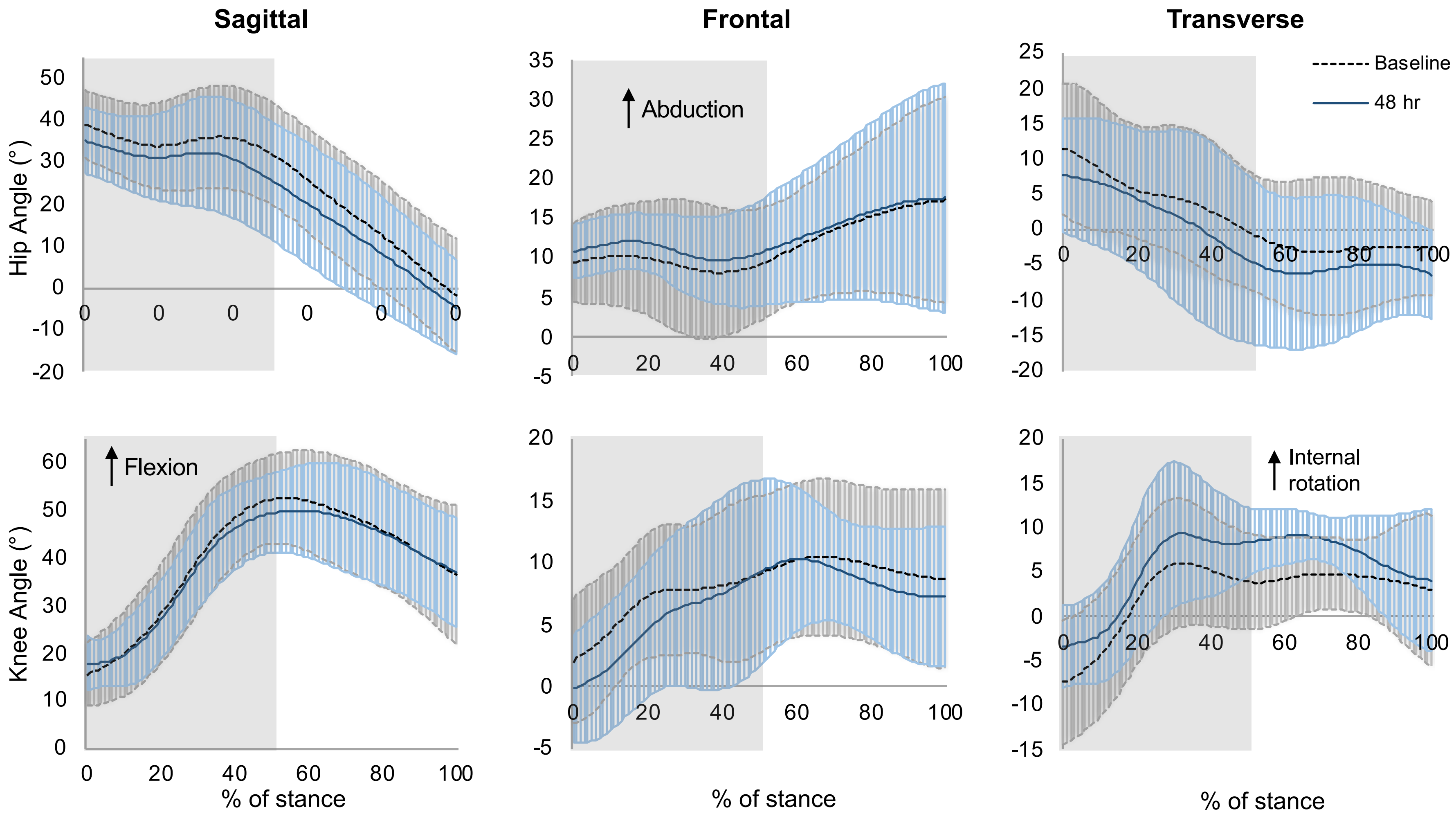


Figure 7.1. Mean female hip and knee angular data in the stance leg during a 45° side cut. The grey shaded area indicates the weight acceptance phase. The between group standard deviation for baseline (grey) and 48 h (blue) are also displayed.

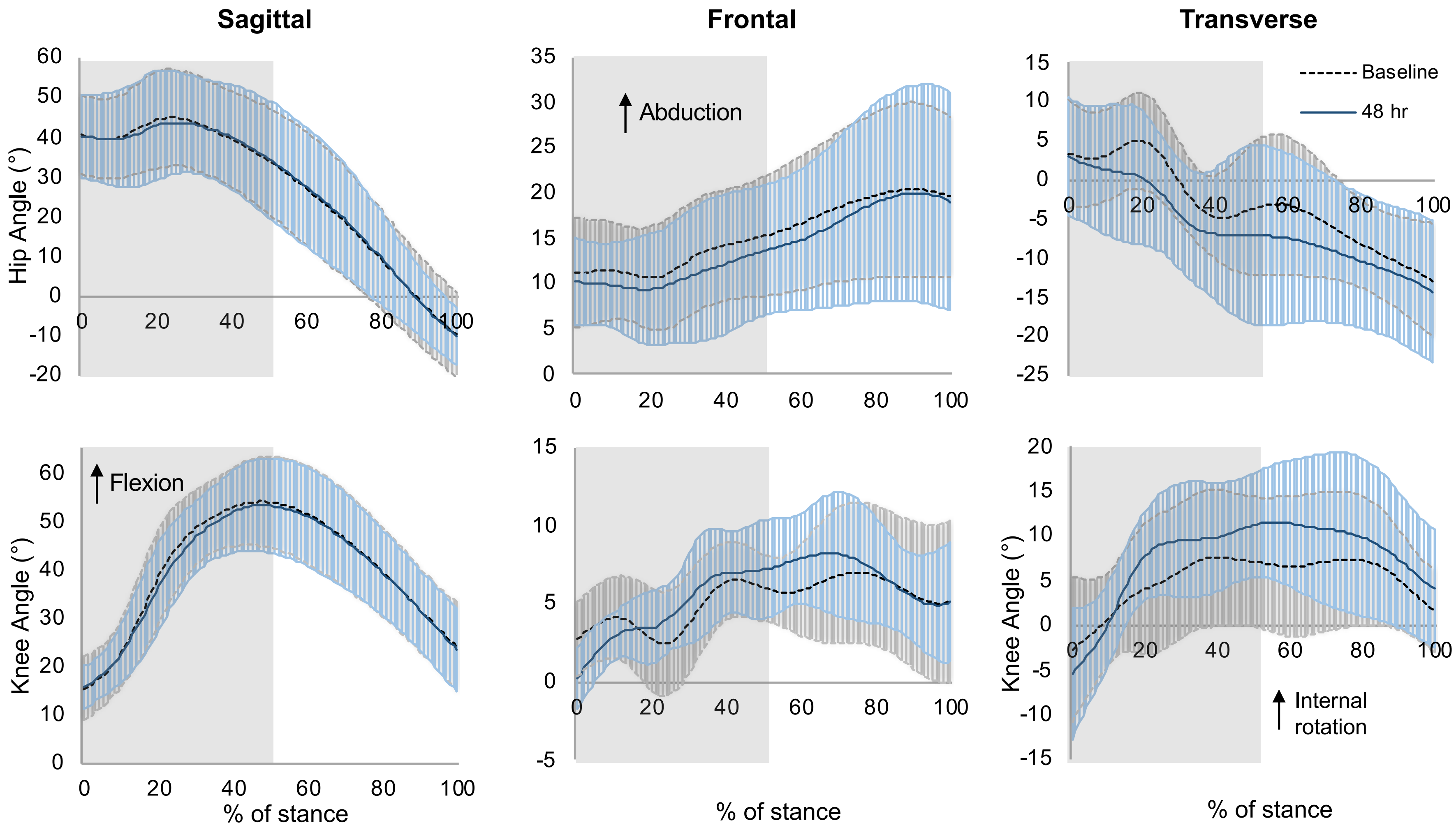


Figure 7.2 Mean male hip and knee angular data in the stance leg during a 45° side cut. The grey shaded area indicates the weight acceptance phase. The between group standard deviation for baseline (grey) and 48 h (blue) are also displayed.

7.3.2 Kinetics

Peak GRF data are presented in Appendix 7.6. Peak lateral GRF during the weight acceptance phase displayed a trivial to small decrease at 48 h ($F = 3.578$, $p = 0.079$) in females (1.23 ± 0.20 *cf.* 1.20 ± 0.26 $\text{N} \cdot \text{BW}^{-1}$; -0.14; ±0.52) and males (1.13 ± 0.2 *cf.* 1.04 ± 0.2 $\text{N} \cdot \text{BW}^{-1}$; -0.46; ±0.45), compared with baseline. An interaction between sex and time was noted for IGRF ($F = 5.329$, $p = 0.037$). Specifically, IGRF was higher in females at 48 h compared with baseline (1.4; ±1.4) but demonstrated a trivial change in males (-0.08; ±0.33; see Figure 7.3). No other changes in GRF were found.

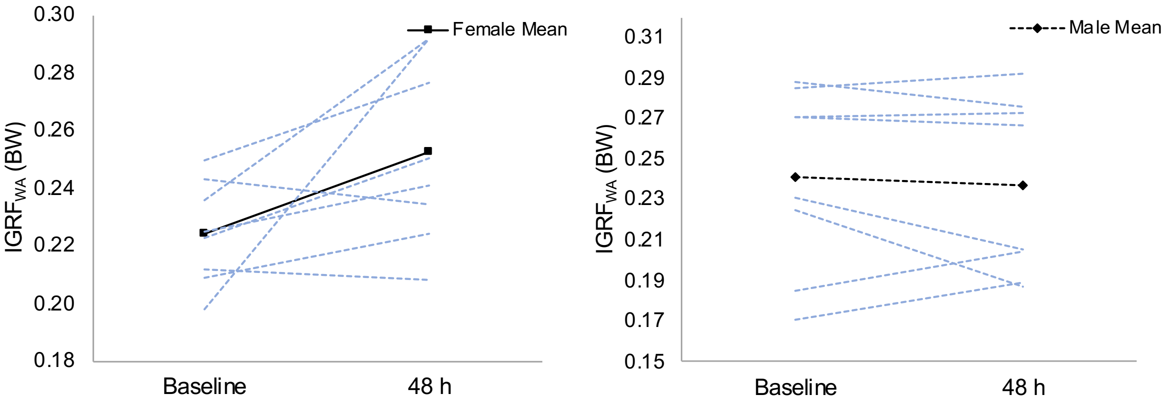


Figure 7.3. Mean IGRF during the weight acceptance phase in females (black line) and males (black dashed line) at baseline and 48 h. Individual changes are shown in blue.

Hip and knee moment data before and 48 h after the multi-directional trial in females and males are presented in Figures 7.4 and 7.5, respectively. At 48 h, peak hip extensor moment demonstrated a small increase ($F = 3.988$, $p = 0.066$) in females (0.21; ±0.41) and males (0.46; ±0.56) and peak knee extensor moment was lower ($F = 23.176$, $p < 0.001$) in females (-0.43; ±0.25) and males (-0.56; ±0.51) during the weight acceptance phase of the side cuts. In addition, peak knee external rotation moment displayed a small to moderate increase ($F = 4.122$, $p = 0.062$) in females

(0.78; ±0.9) and males (0.34; ±0.91) 48 h after multi-directional running. No other changes in peak hip and knee moments during the weight acceptance phase of stance were observed (see Appendix 7.7).

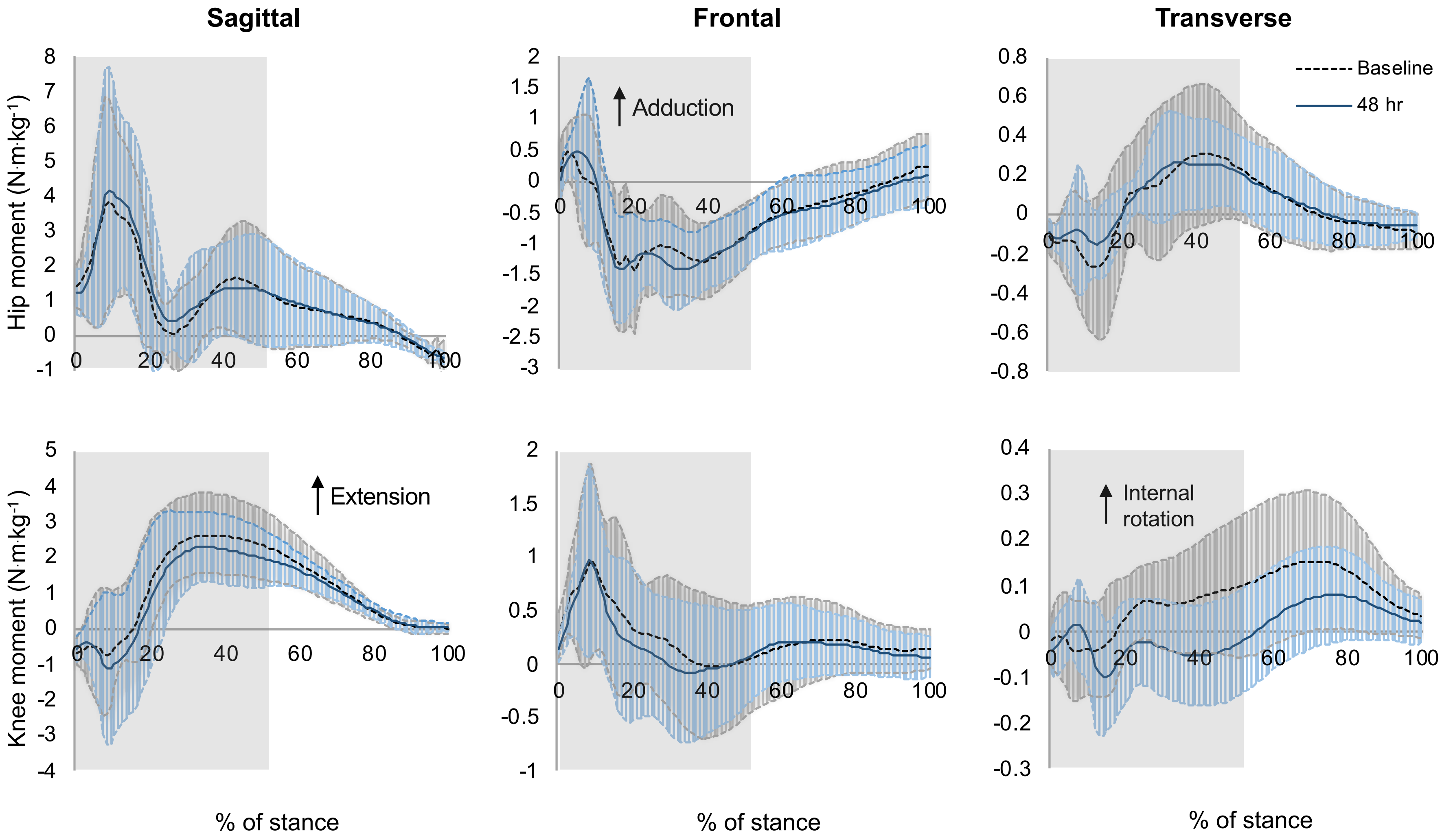


Figure 7.4. Mean female hip and knee moment data in the stance leg during a 45° side cut. The grey shaded area indicates the weight acceptance phase. The between group standard deviation for baseline (grey) and 48 h (blue) are also displayed.

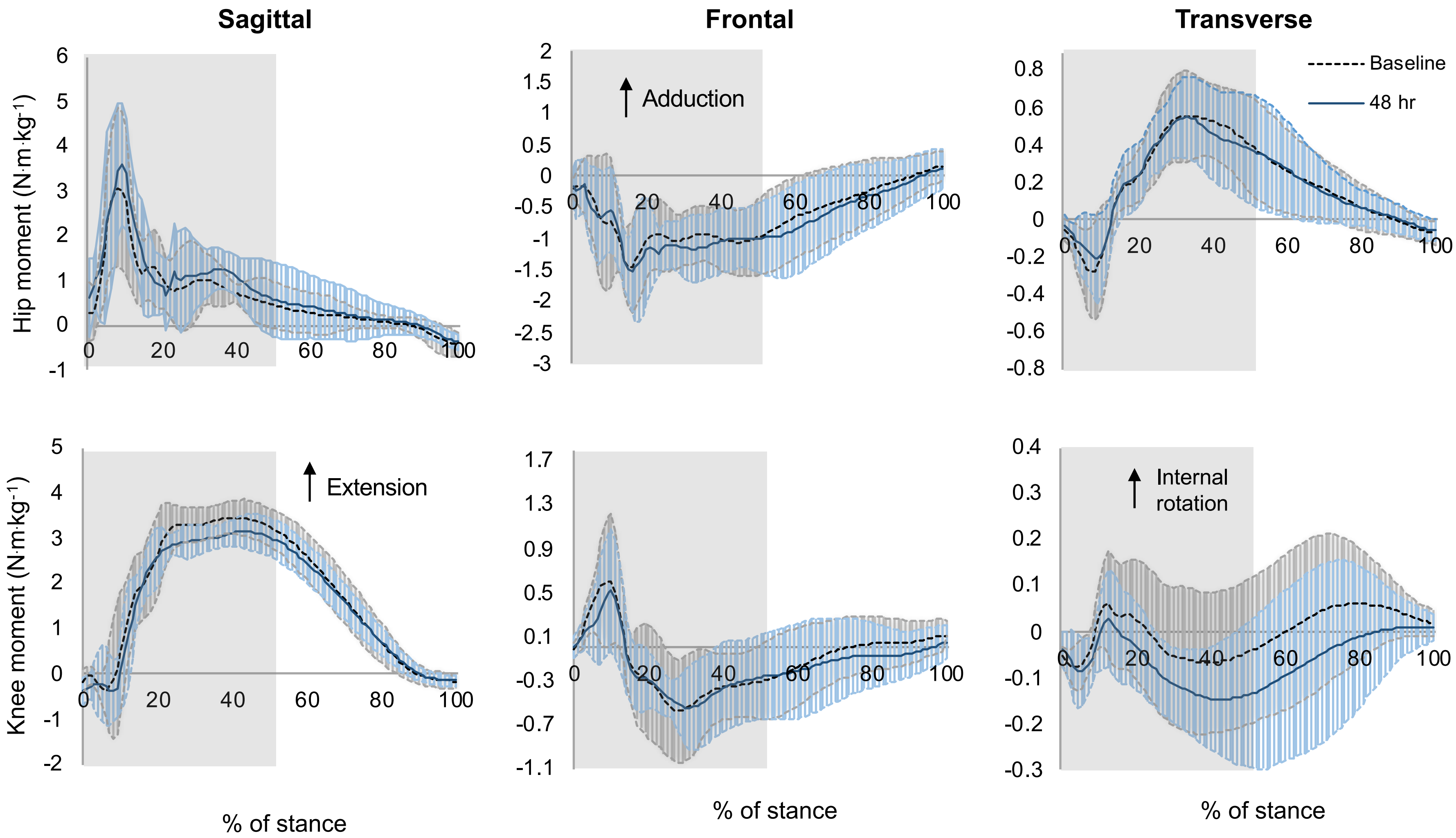


Figure 7.5. Mean male hip and knee moment data in the stance leg during a 45° side cut. The grey shaded area indicates the weight acceptance phase. The between group standard deviation for baseline (grey) and 48 h (blue) are also displayed.

7.3.3 Movement variability

Peak knee extensor moment displayed a moderate increase in variability (*F* = 4.174, *p* = 0.060) in females (0.55; ±0.68) and males (0.47; ±1.49) at 48 h (see Appendix 7.8). No other changes in movement variability were observed.

7.4 Discussion

The purpose of the study was to assess the effect of EIMD on the biomechanics of side cuts in males and females. The observed increases in CK concentration (~180 – 330%), perceived muscle soreness (~580 – 900%) and sprint times (~ 6 – 8%) were similar between males and females and provide indirect evidence that muscle damage was present 48 h after the multi-directional trial (Byrne et al., 2004). The similarity in magnitude of EIMD markers between males and females also reaffirm sex does not influence post-exercise muscle damage (Hicks et al., 2017; Rinard, Clarkson, Smith & Grossman, 2000). The percentage increase in CK and sprint times are similar to those reported after team sport activity (Keane et al., 2015; Malone et al., 2018; Nedelec et al., 2014; Oxendale et al., 2016), suggesting muscle damage in the present study is comparable. The increase in perceived muscle soreness in the present study is higher than previous reports (e.g. Nedelec et al., 2014), but this likely reflects differences in the training status of the participants, as well-trained athletes incur less delayed onset muscle soreness (Smith, 1992).

The numerous changes of direction in the multi-directional trial, which require high breaking forces and eccentric contractions to rapidly decelerate, is likely to have caused the muscle damage response (Howatson & Milak, 2009). Specifically, microdamage to the muscle fibre induced by the stretch of high force eccentric actions causes disproportionate lengthening of the sarcomeres within the muscle myofibril, leading to disrupted or “popped” sarcomeres (Morgan, 1990). This disruption has been associated with the appearance of sarcoplasmic proteins in the blood (e.g. CK; Hody, Croiser, Bury, Rogister & Leprince, 2019). The initial mechanical damage then triggers a cascade of events leading to secondary muscle damage, which has been discussed elsewhere (Hody et al., 2019; see Chapter 2.3.2).

As highlighted in Chapter 6, the difference in prescribed cut angle (45°) and the actual cut angle performed (~22 – 26°), is expected (David et al., 2017; Vanrenterghem et al., 2012) and reflects the trade-off between approach speed and cut angle (Vanrenterghem et al., 2012). The similarity in angle, COM velocity and stance time before compared with after muscle damaging exercise suggests task execution was the same at baseline and 48 h. However, an interaction between sex and time was noted for percentage of stance time in weight acceptance. Specifically, females had a moderate increase in weight acceptance percentage phase of side cuts after muscle damaging exercise. Whilst few studies have assessed changes in side cut weight acceptance after muscle damaging exercise, increases in walking and running stance time with EIMD have been reported (Tsatalas et al., 2013b; Tsatalas et al., 2010). This could serve as a protective mechanism to reduce mechanical strain (by increasing the time to absorb force) (Regueme, Nicol, Barthelemy & Grelot, 2005) and/or reflects impaired eccentric contractions and a loss of tolerance to imposed stretch loads which limit the ability of the body to attenuate shock, resulting in a progressive increase in contact time during braking (Komi, 2000; Tamura et al., 2016). In agreement, impaired mechanical efficiency of elastic elements in the muscle (Cheung et al., 2003; Vaczi, Racz, Hortobagyi & Tihanyi, 2013) and a reduced stretch reflex response (Nicol, Avela

& Komi, 2006) have been reported with EIMD. In the present study, the increase in percentage of stance time in weight acceptance also coincides with the large increase in IGRF during the weight acceptance phase of stance in females.

The trivial to small decrease in peak trunk flexion angle might be a strategy to reduce hamstring pain as the muscle stretches (Cleak & Eston, 1992) during trunk flexion, given that pain has the capacity to modify movement patterns (Henriksen et al., 2007). An increase in muscle spindle discharge rates with EIMD has also been proposed as a mechanism to alter perceived joint position, leading participants to concentrically contract their muscles and land in a more extended position (Proske & Gandevia, 2012; Paschalis et al., 2007b). Landing with reduced flexion has been reported with impaired hamstring force production (Weinhandl et al., 2014). A more extended trunk (Hewett et al., 2009; Sheehan et al., 2012) is also associated with an increased ACL injury risk, due to the increase in ACL strain (Bakker et al., 2016) and the increase in quadricep force requirement and subsequent load placed on the ACL (Blackburn & Padua, 2009). However, the trivial difference in trunk flexion (~1.2°) noted in males is unlikely to lead to meaningful reduction in ACL injury risk, given the ~2° measurement error in sagittal plane kinematics during a side cut (Alenezi et al., 2016).

Small changes in transverse kinematics with EIMD were also evident. Males and females had a small increase in peak knee internal rotation angle and females also displayed a small increase in knee internal rotation angle at initial contact. An increase in knee internal rotation is a common mechanism reported during ACL injuries (Grassi et al., 2017; Koga et al., 2010; Walden et al., 2015). Muscle damage could impair control of the lower limb during weight acceptance (Paquette et al., 2017;

Satkunskiene, Stasiulis, Enkoviene, Sakalauskaite & Rauktys, 2015), which Paquette and colleagues speculate could be due to delayed neural deficits and/or attenuated fibre excitability (Paquette et al., 2017). A reduction in knee proprioception has also been reported with EIMD (Torres et al., 2010), and can alter single leg landing biomechanics (Nagai, Sell, House, Abt & Lephart, 2013). Whilst few studies have assessed transverse side cut mechanics with EIMD, an increase in knee internal rotation angle (Cortes, Quammen, Lucci, Greska & Onate, 2012; Tsai et al., 2009; Sanna & O'Connor, 2008) and knee internal rotation angular velocity (see Chapter 6) have been observed during a side cut under fatigue. Fatigue induced alterations in side-cut mechanics might therefore have a prolonged effect if muscle damage is evident in the days after.

Hip internal rotation angular velocity displayed a small decrease in males and females 48 h after multi-directional running, which indicates a greater emphasis on control at the hip joint (Olson, 2020) and an increase in hip external rotators (e.g. gluteus maximus) contribution during the weight acceptance phase of the side cut. A moderate increase in knee flexion and internal rotation angular velocity was also observed in males but not females. An increase in knee flexion angular velocity after muscle damage suggests a decreased ability to attenuate impact (Tamura et al., 2017). This might be because the quadriceps had difficulty eccentrically controlling the weight acceptance phase of the side cut and concurs with a decrease in quadricep torque reported after the multi-directional trial (see Chapter 5). Whilst others have suggested increased knee flexion angular velocity can reduce vertical GRF given the strong negative correlation between the two variables (*r* = -0.6; Yu, Lin & Garrett, 2006), vertical GRF did not change in males. The increase in knee internal rotation angular velocity indicates a reduced ability to control transverse plane rotation velocities (Jenkins et al., 2017), and increases in internal tibial rotation has been associated with an increase in ACL strain (Beaulieu et al., 2014). Interestingly, in-direct markers of muscle damage did not differ between males and females in the present study, and the mechanisms of EIMD are not affected by sex (Lee et al., 2017; Nikolaidis, 2017). The reason for the change in angular velocity in males but not females is therefore not fully clear but might reflect differences in muscle activation strategies between sexes. Specifically, females activate their quadriceps to a greater extent during a side cut task whilst males have greater hamstring activation (Landry et al., 2007; Sigward & Powers, 2006). It could be speculated that muscle damage induced from multi-directional running affected the males muscle activation strategy more so than the females, however future research is required to substantiate this claim. Taken together, muscle damage induced some small to moderate changes in kinematics, which were similar in males and females for joint angles, but some sex differences were noted for angular velocity data.

A decrease in lateral GRF was observed 48 h after multi-directional running, and whilst no sex interaction was noted, the size of the effect was small in males and trivial in females. A small decrease in lateral GRF might serve as a strategy to maintain balance and to avoid excessive lateral forces, which can increase disposition to ankle injuries (McClay et al., 1994) and increase frontal plane knee loading (Sigward, Cesar & Havens, 2015). Indeed, it has been proposed that the body is equipped with a protective mechanism which lowers GRF when muscle function is impaired to reduce loading of painful tissues (Tsatalas et al., 2013a) and protect the body from possible injuries (Zadpoor & Nikoovan, 2012). A large increase in IGRF was observed in females 48 h after the multi-directional trial. This suggests an increased effort to decelerate the downward movement of the centre of mass during the weight acceptance phase (Harry et al., 2017), by increasing force and/or the time the force is applied during weight acceptance. In agreement, a reduced tolerance to impact and a loss of elastic energy potential has been reported after muscle damaging exercise (Komi, 2000). Taken together, GRF data suggest females required more effort to decelerate the body during a side cut after muscle damaging exercise. Males on the other hand adapted a protective strategy to maintain or reduce GRF.

Peak hip extensor moment displayed a small increase whereas peak knee extensor moments demonstrated a small decrease in males and females at 48 h. This is consistent with an increase in hip extensor moment during a side cut with fatigue (Whyte, Richter, O'Connor & Moran, 2018) and whilst not directly comparable, is also consistent with a decrease in knee extensor torque during running with muscle damage (Paquette et al., 2017). Quadricep strength has been associated with knee extensor moment (Asaeda et al., 2019), so impaired quadricep function caused by the multi-directional trial might explain the reduction in knee extensor moment observed and might serve as a protective mechanism to reduce loading of painful tissues (Tsatalas et al., 2013a). Impaired utilization of elastic energy (associated with decreased muscle stiffness and reduced muscle pre-activation) has also been reported after stretch-shortening cycle exercise (Avela & Komi, 1998) and is related to knee joint moment during the eccentric phase of a drop jump ($r = 0.7$; Horita, Komi, Nicol & Kyröläinen, 2002). Therefore, it could be speculated muscle damage induced from multi-directional running reduced the stiffness and pre activation of the quadriceps during the weight acceptance phase of the side cuts, reducing the peak knee extensor moment. Whilst a reduction in knee extensor might seem favourable, changes in knee extensor moment alone are considered a minor contributing factor to ACL loading (Bakker et al., 2016) and injury (Hewett, Ford, Hoogenboom & Myer, 2010). The observed changes in hip and knee extensor moment suggest increased use of the hip extensors compared to the knee extensors to control the deceleration phase of the side cut (Pollard, Sigward & Powers, 2017), however it is noteworthy that the knee to hip extensor ratio did not differ 48 h after multi-directional running.

Knee external rotation moment displayed a small and moderate increase in males and females respectively, 48 h after multi-directional running. Internal tibial rotation moments (expressed as an external moment), when combined with knee abduction moments, probably constitutes the greatest risk of a non-contact ACL injury (Dempsey et al., 2007) as internal tibial rotation moments are strongly correlated to ACL force ($r = 0.78$; Navacchia et al., 2019) in *vivo* cadaver models. Knee internal/external rotation moments are considered a key biomechanical variable associated with ACL loading (Markolf et al., 1995). Whilst few studies have assessed transverse moments after muscle impairment, results from the present study are consistent with Savage et al. (2018) who reported an increase in internal tibial rotation moment during side cutting with fatigue. Collectively, these data highlight shifts in sagittal joint loading and increased transverse joint loading are present 48 h after multi-directional running in males and females, some of which have previously been associated with ACL injury.

Finally, this study assessed the movement variability of sagittal plane variables and GRF. Frontal and transverse plane variables were not assessed as the coefficient of variation is overly sensitive for mean values close to zero (Brown, Bowser & Simpson, 2012). Only one variable, peak knee extensor moment, displayed a small increase in variability in males and females at 48 h, which is consistent with an increase in movement variability during a side cut with fatigue (Chapter 6; Cortes, Onate & Morrison, 2014). Pain, which is a common symptom of muscle damage and was observed in this study at 48 h, can impair proprioception and orientation (Malmström, Westergren, Fransson, Karlberg, & Magnusson, 2013). Accordingly, the nervous system might take advantage of the variability of multiple options available during a complex multi-joint task (Bergin, Tucket, Vicenzino, van den Hoorn & Hodges, 2014), such as a side cut, to alleviate the load and pain placed on the tissues by spreading the load across different areas (Mathiassen, 2006). The increase in knee extensor moment movement variability could also be due to impairment of muscle function, resulting in reduced control of the joints, as fewer muscles are functioning to achieve the desired movement pattern (Ferber, & Pohl, 2011). Whilst an increase in movement variability during landing can reduce the likelihood of overuse injuries (Nordin & Dufek, 2019), it could increase the possibility of extreme movements and injury.

This study is not without limitations. Limitations regarding data processing and consideration of a meaningful change in kinematic and kinetic variables have been highlighted in Chapter 6 and are therefore not repeated. Regarding movement variability, analysing a small number of trials can limit the ability to draw conclusions about variability (Nordin & Dufek, 2019). Accordingly, future research should incorporate 10-20 trials to assess the effect of muscle damage on movement variability. Whilst the presence of muscle damage was confirmed, the mechanisms of muscle damage symptoms, and the effect on flexor and extensor joint torque, was not assessed. Finally, the potential effect of the menstrual cycle when assessing female responses to muscle damaging exercise, should be considered in future research. Whilst these limitations are noteworthy, the findings of the present study offer useful insight for those working in team sports and highlight the need for future research assessing the mechanics of side cuts after muscle damaging exercise.

7.5 Conclusion

In conclusion, the multi-directional trial elicited a similar magnitude of EIMD between sexes. Whilst the task achievement of the side cut was not affected by EIMD, alterations in sagittal and transverse kinematics and kinetics of a side cut in males and females were observed. Sex specific differences were noted for angular velocity and IGRF, although the specific mechanism for the difference observed remain unclear, females showed an increased effort to decelerate. The increase in two factors in particular: peak knee internal rotation angle and knee external rotation moment, have been previously identified as ACL injury risk factors, suggesting EIMD might indirectly contribute to ACL injuries in males and females.

Key messages

- *Multi-directional running elicited symptoms of EIMD in the days after, which was accompanied by small changes in side cut biomechanics.*
- *In particular, peak knee internal rotation angle and knee external rotation moment was higher 2 days after multi-directional running.*
- *EIMD from multi-directional running might therefore indirectly contribute to ACL injury risk in males and females.*

Next steps

- *Future research should explore if symptoms of EIMD are present when athletes sustain ACL injuries in team sports to identify if EIMD is a factor for ACL injury incidence.*

Chapter 8

General Discussion

This thesis has explored the internal and external demands of multi-directional running and the subsequent effect on side cut biomechanics in males and females. More specifically, the extent to which metabolic power derived variables compare with traditional speed-based thresholds from player tracking devices when quantifying the external demands of linear and multi-directional running (Chapter 4), and how the systematic manipulation of the number of directional changes performed during running influences the internal demands of exercise, metabolic power using integrated ratios, and subsequent neuromuscular function (Chapter 5) was examined. With a deeper understanding of the physiological and neuromuscular demands of multi-directional running, the subsequent two chapters then focussed on the acute biomechanical adaptations in side cut biomechanics as a result of fatigue (Chapter 6) and EIMD (Chapter 7) from multi-directional running. A summary of the collective main findings from the four empirical studies, and how they inform the present understanding of load associated with multi-directional running, are presented in Figure 8.1. These findings are discussed below, along with the potential limitations, practical applications and areas for future research.

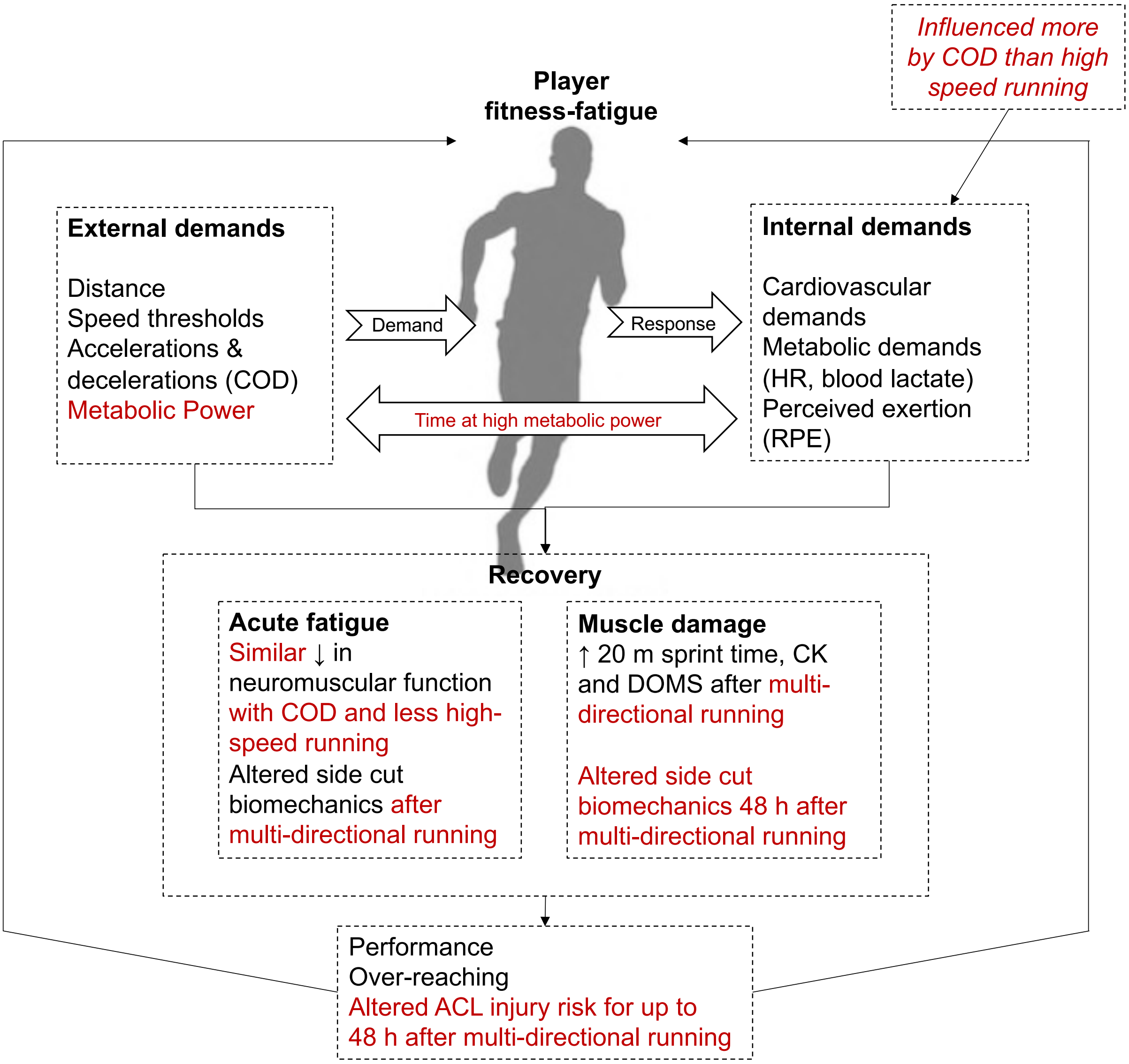


Figure 8.1 An appraisal of the internal and external demands of team sports, and the subsequent acute physiological and biomechanical responses in the days after multi-directional running, with reference to ACL injury risk. This figure has been adapted from Figure 1.1 based on the collective findings of Chapter 4-7 (denoted in red text). COD = change of direction, DOMS = delayed on-set of muscle soreness, CK = creatine kinase, HR = heart rate, ACL = anterior cruciate ligament, ↓ = decrease, ↑ = increase

8.1 Load monitoring during multi-directional running

Data from this thesis (Chapter 4 and 5) reaffirms that running with more directional changes increases the physiological and perceptual response to exercise (Akenhead et al., 2014; Ashton & Twist, 2015; Buchheit et al., 2010; Dellal et al., 2010; Hatamoto et al., 2014; Tang et al., 2018), which has implications for the monitoring of physical performance and implementation of team sport specific training drills. Practitioners can therefore manipulate the number of directional changes to alter the dose and therefore the response of athletes. Specifically, to increase the psychophysiological stimulus practitioners can increase the number of directional changes performed by athletes, and whilst this can cause symptoms of EIMD in the days after the initial insult (Chapter 7), repeated exposure to such stimuli might later provide some protection, due to the repeated bout effect (Lima & Denadai, 2015). Similarly, practitioners can reduce the number of directional changes performed to reduce the psychophysiological stimulus and promote recovery.

For the first time this thesis demonstrated the increase in internal load during running with more directional changes coincided with a reduction in distance covered in arbitrarily defined speed thresholds (Chapters 4 and 5), which contrasts with the strong associations reported previously between arbitrarily defined speed thresholds and markers of internal load (Gaudino et al., 2015; Polglaze et al., 2018b; Scott et al., 2013; Weaving et al., 2014). These data question the use of a single measure of distance covered at an arbitrary defined speed threshold (i.e. distance covered at high speed) to quantify an individual’s external load, particularly when numerous changes of direction are performed. A more holistic approach, encompassing more measures of the external demands of team sports (see Figure 8.1), is required when quantifying load during multi-directional activity.

8.1.1 The use of metabolic power to monitor changes in load

Data from Chapters 4 and 5 collectively demonstrate time at high power (> 20 $W \cdot kg^{-1}$) and estimated energy cost using microtechnology can reflect changes in internal load induced by altering running patterns (see Figure 8.1), but estimated energy cost cannot accurately quantify energy expenditure. Specifically, Chapter 4 reaffirms the underestimations in energy expenditure derived from the metabolic power approach compared with indirect calorimetry (13 – 51%; Brown et al., 2016; Buchheit et al., 2015; Stevens et al., 2015), but also highlights that the underestimation of energy cost derived from the metabolic power approach is influenced by the number of directional changes performed during running. That is, the underestimation of energy cost is higher when more changes of direction are performed. As team sports involve numerous changes of direction, accelerations and decelerations (Russell et al., 2016; Springham et al., 2020; Varley et al., 2014), energy expenditure derived using the metabolic power approach should not be used to determine the metabolic energy cost of intermittent team sport activity. However, the strong correlation between estimated and measured energy expenditure (r = 0.89; Chapter 4) suggests estimated energy expenditure can be used to detect relative changes in load during multi-directional running.

Time at high power better reflected changes in energy expenditure (derived from indirect calorimetry) during linear and multi-directional running, compared with time at high speed and very high speed (Chapter 4). Specifically, increases in internal load (summated HR and total VO_2 - the ‘response’) induced by altering running patterns (the ‘dose’) were also accompanied by a greater time at high power but not time at high speed and very high speed (Chapter 5), and further evidence the lack of agreement between measures of high speed and high power during running with more directional changes (Chapter 4). Time at high power also possessed sufficient reliability (CV: 4.2%) during multi-directional running (Chapter 4) which contrasts previous reports (e.g. Buchheit et al., 2015) using inferior player tracking devices (Chapter 2.2.2). Collectively, these data suggest time at high metabolic power can be used to detect small changes in external load and reflect changes in internal load during multi-directional running, whilst measures of high speed and very high speed cannot.

8.2 Fatigue and EIMD after multi-directional running

Small decrements in knee extensor and flexor torque (11 – 14%; Chapter 5) and moderate to large decrements in 20 m sprint performance (5 – 7%; Chapter 6) immediately after multi-directional running, confirm short-term running protocols incorporating numerous changes of direction can elicit fatigue. Despite an overall slower movement speed in the multi-directional trial (see Figure 8.1), the similar decrements in knee flexor torque after linear and multi-directional running reaffirm more directional changes during running can induce fatigue (Ashton & Twist, 2015; Hader et al., 2014) and further highlight the need to consider the contributions of accelerations and decelerations to player fatigue (Tang et al., 2018). That multi-directional running also elicited symptoms of EIMD at 48 h (Chapter 7) was also expected, given the association between accelerations, decelerations and changes of directions during team sports with markers of EIMD (de Hoyo et al., 2016; Nedelec et al., 2014; Oxendale et al., 2016; Varley et al., 2017). These data further highlight the importance of incorporating accelerations and decelerations when mimicking the specific movement demands of team sport activity, particularly when assessing the implications of fatigue and EIMD in team sports.

8.3 Alterations in side cut biomechanics after multi-directional running

Inconsistencies in fatigue-induced alterations in side cut biomechanics after exercise still exist in the literature (Collins et al., 2016; Inguchi et al., 2014; Lucci et al., 2011; McGovern et al., 2015), and likely reflect the non-uniformity of fatigue protocols utilised, which often do not mimic the acceleration and deceleration demands of team sport activity. Similarly, few studies have assessed side cut biomechanics in the days after exercise when symptoms of EIMD can persist. Chapters 6 and 7 resolve these issues, by determining alterations in side cut biomechanics immediately and 48 h after multi-directional running, which are summarised in Table 8.1. Data from Chapters 6 and 7 indicate there are meaningful changes in side cut biomechanics, and some of these alterations differed depending on the time of the measurement. Both males and females tended to land in a more extended position and displayed increased peak angular velocities, particularly in males, immediately and 48 h after multi-directional running (see Table 8.1). Changes in transverse joints angle differed depending on the time of measurement. For example, knee internal rotation angle was increased at 48 h but displayed no change immediately after multi-directional running, suggesting alterations in side cut biomechanics might only be evident in the days after activity.

Interestingly, changes in joint moments were generally consistent both immediately and 48 h after multi-directional running (see Table 8.1). For the first time, these data indicate short-term intermittent running that elicits fatigue and EIMD causes changes in side cut kinetics which persist for at least 48 h in both males and females. The changes in transverse kinematics and kinetics observed immediately and 48 h after multi-directional running are common mechanisms associated with ACL strain (Bakker et al., 2016; Navacchia et al., 2019; Oh et al., 2012) and have been reported during ACL injuries (Koga et al., 2010; Olsen et al., 2004; Waldén et al., 2015). These data confirm that fatigue induced from multi-directional running can cause ‘risky’ modifications in side cut biomechanics (Collins et al., 2016; McGovern et al., 2015; Sanna & O’Connor, 2008). Furthermore, multi-directional running causes alterations in side cut biomechanics in males and females which can persist for up to 48 h, suggesting fatigue and EIMD might indirectly contribute to ACL injuries in males and females (see Figure 8.1).

Table 8.1. Changes in peak kinematics and kinetics of side cuts immediately and 48 h after multi-directional running.

Variable	**Change in variables compared with baseline**	
	Post	**48 h**
Kinematics		
Torso flexion	↑	↓
Hip internal rotation	↓	-
Knee extension	↑	-
Knee internal rotation	-	↑
Hip internal rotation angular velocity	-	↓
Knee flexion angular velocity	-	SI ↑ in M
Knee abduction angular velocity	↑	-
Knee internal rotation angular velocity	↑	SI ↑ in M
Kinetics		
Hip extensor moment	↑	↑
Hip external rotation moment	↓	-
Knee extensor moment	↓	↓
Knee external rotation moment	↑	↑
GRF impulse	↑	SI ↑ in F
Lateral GRF	SI ↓ in M and F	↓

SI = sex interaction, M = males, F = females

Whilst alterations in side cut biomechanics were similar between males and females, some sex specific changes in GRF and angular velocities were noted in Chapters 6 and 7. Sex can influence side cut biomechanics with females possessing a ~2-6 fold increased incidence of ACL injury compared with males (Gray et al., 2019; Iguchi et al., 2014; McGovern et al., 2015; McLean et al., 2007; Stanley et al., 2016; Weinhandl et al., 2017). Whilst the specific mechanism for the differences between sexes is beyond the scope of this thesis, these data highlight the need to consider the effect of sex on side cut biomechanics and examine how differences between sexes might contribute to ACL incidence rates.

8.4 Potential Limitations

8.4.1 Assessment of fatigue and EIMD

The assessment of fatigue relied on voluntary contraction of the muscle and 20 m sprint performance in Chapters 5 and 6. Accordingly, these studies can confirm the presence of fatigue (Enoka & Duchateau, 2016), but the specific mechanisms contributing to fatigue cannot be determined. This information could help provide a mechanistic insight into why performance decrements were observed in relation to the demands of the task (Hunter, 2018) and provide further insight into the cause of the altered side cut biomechanics reported in Chapter 6. The presence of muscle damage was confirmed in Chapter 7, using appropriate in-direct markers of EIMD (Damas et al., 2016). However, the extent to which EIMD induced from multi-directional running affected knee flexor and extensor torque was not determined, which might provide insight into the observed changed in side cut biomechanics in Chapter 7.

8.4.2 Biomechanical measurement error

Whilst all of the reported kinematic and kinetic changes in side cut biomechanics were generally considered small to moderate (Chapter 6 and 7), these generally exceeded the standard error of measurement and were deemed to be of a meaningful magnitude (see Chapter 6). Mean changes in knee external rotation moment in this thesis ranged from ~16 – 62%, and in some cases was below previous reports of the trial to trial variability in this variable (34%; Sankey et al., 2015). Changes in knee external rotation moment reported in this thesis could have implications for ACL injury risk (Shin et al., 2011), but researchers should interpret this change with caution. Finally, whilst this thesis demonstrates alterations in side cut mechanics after exercise can persist for up to 48 h in the presence of EIMD, it is important to note the reliability of between day biomechanics during a side cut is less favourable than within day (Alenezi et al., 2016). For example, the standard error of measurement for knee internal rotation angle during a run task is 2.8° and 3.5° for within and between day, and the mean change in knee internal rotation angle observed in Chapter 7 was 2.4° for males and 3.5° for females. Future research should incorporate a control group, where possible, to corroborate the biomechanical alterations reported. Finally, the use of different cut off filter values for force and movement data continues to be an area of debate (Kristianslund et al., 2011; Roewer et al., 2014). Whilst this is beyond the scope of the thesis, researchers should consider differences in processing techniques when comparing data from this thesis to other literature.

8.4.3 Training status of participants

Amateur standard team sport athletes have been used in the present thesis, and the average participant estimated aerobic capacity in Chapters 4 – 7 (39.4 – 46.0 ml·kg^{-}

^{1}min^{-1}), are similar to previous reports of amateur standard team sport athletes (40 – 45 ml·kg·$^{-1}$min^{-1}; Ostojic, 2004; Vescovi et al., 2006). Whilst direct comparisons to elite athletes should be carefully considered, as these players are likely to possess superior fitness (e.g. ~55 ml·kg·$^{-1}$min^{-1}; Gabbett, Jenkins & Abernethy, 2011), the percentage decrease in knee flexor and extensor torque (Chapter 5), and increase in CK concentration (Chapter 7) and sprint times (Chapters 6 and 7) are similar to those reported in elite athletes after team sport activity (Magalhães et al., 2010; Nedelec et al., 2014; Oxendale et al., 2016; Rampinini et al., 2011). The magnitude of fatigue and EIMD markers in this thesis are therefore comparable with previous literature but highlight elite athletes with superior fitness might have an attenuated response to multi-directional running (Johnston, Gabbett & Jenkins, 2015). Finally, the use of amateur athletes in this thesis reflects a large population who typically participate in team sports for health and well-being benefits (Griffin et al., 2021b). Injury in amateur athletes can have long term consequences for an individual’s health (Hind et al., 2020), so understanding factors which are associated with an increased risk of injury in this population, has wider implications for risk minimisation and health effect maximisation (Griffin et al., 2021a).

8.5 Practical implications

8.5.1 Use of time at high metabolic power to quantify the demands of team sports

Practitioners should be wary of using measures of high speed alone to quantify the high intensity demands of running incorporating multiple directional changes. Here, the use of time at high metabolic power is proposed as an alternative measure of external load, which can be used to detect small changes in external load and reflects an individual’s internal response to multi-directional running. Furthermore, the use of integrated ratios using measures of time at high metabolic power might provide a more sensitive interpretation of an individual's response during different forms of running compared with traditional speed-based thresholds.

8.5.2 Multi-directional running for sport specific training/simulations and ACL screening

Manipulating the number of directional changes during running can alter the internal demands of running, and whilst this can reduce the quantity of high-speed running performed, it does not reduce decrements in knee extensor / flexor torque and therefore fatigue. Performing multi-directional running can also induce symptoms of EIMD which should be considered in athlete recovery programmes, particularly given that EIMD can alter side cut biomechanics which have previously been reported to increase ACL injury risk. This means practitioners can manipulate the number of changes of direction for the desired response, e.g. increase the number of directional changes to increase internal load and training response or reduce the number of directional changes performed to attenuate symptoms of EIMD and altered side cut biomechanics after training. This is particularly important for team sport simulations, as the use of treadmill-based match simulations (e.g. Savage et al., 2018) are unlikely to mimic the change of direction demands of the sport, and therefore the athlete's internal response.

Screening of ACL injury risk often involves the assessment of bilateral landing mechanics (Fox et al., 2016; Padua et al., 2015), however key determinants of ACL injury, such as knee abduction moments, differ during a drop landing compared to a side cut (Kristianslund & Krosshaug, 2013). This thesis highlights ACL injuries often occur during side cuts in males and females (Chapter 2) and multi-directional running can alter side cut mechanics immediately, and for at least 2 days after (Chapters 6 and 7). Accordingly, practitioners should use side cuts as an injury screening tool and incorporate fatigue and EIMD induced from multi-directional running as part of a multifaceted screening approach, in accordance with the procedures adopted in this thesis. This can provide an insight into an athlete's risk of ACL injury during a sport specific action, when experiencing symptoms of fatigue and EIMD, to provide a more comprehensive assessment of ACL injury risk in team sports. This proposed screening method could also be implemented as part of return to sport testing (Capin, Synder-Mackler, Risberg & Grindem, 2019a) given the need to consider sport exposure (Capin, Synder-Mackler, Risberg & Grindem, 2019b).

8.5.3. Interventions to offset 'risky' biomechanical alterations in side cuts after multi-directional running

Multi-directional running induced some negative changes in side cut biomechanics, such as increases in knee internal rotation angle and knee external rotation moment in males and females. Injury-prevention intervention programmes might help off-set these biomechanical changes after multi-directional running and should therefore be implemented in training. Whilst the effect of specific warm-up interventions (e.g. F-Marc 11+) on side cut biomechanics are equivocal (Dos'Santos, Thomas, Comfort & Jones, 2019; Thompson et al., 2017), the use of augmented feedback (Neilson, Ward, Hume, Lewis & McDaid, 2019) and body weight plyometric, resistance and balance exercises over a 6 – 16 week training period (see review by Dos'Santos et al., 2019) have been shown to reduce transverse joint moments and GRF, promoting safer side cut biomechanics. Balance exercise interventions have been advocated as an effective means to improve side cut biomechanics (Cochrane et al., 2010; Donnelly et al., 2012; Oliveira et al., 2017), however transverse kinematics (Cochrane et al., 2010; Donnelly et al., 2012) and the prolonged effect of prevention interventions are often not assessed. Questions therefore remain regarding the use of such interventions and whether reductions in transverse kinetics are affected by fatigue and EIMD. Future research should therefore assess prolonged modifications in side cut mechanics after prevention interventions, and where possible incorporate the assessment of side cut mechanics under fatigue and EIMD (see section 8.6.1).

8.6 Future research

8.6.1 Chronic adaptation from change of direction training

Given the changes in internal and external response with multi-directional running, future research should assess the chronic adaptations from change of direction training on performance and injury risk. An editorial by Chaabene (2017) highlighted the need for longitudinal studies examining the effect of eccentric training on change of direction outcomes and eccentric strength training has been associated with improved change of direction performance in athletes (Chaabene, Prieske, Negra & Granacher, 2018). As changes of direction involve a rapid deceleration (Spiteri, Cochrane, Hart, Haff & Nimphius, 2013) and eccentric muscle actions, it is speculated that change of direction training itself could promote change of direction performance. Assessment of side cut biomechanics after several weeks of multi-directional running could also have implications for injury risk, given that changes of direction require high core activation (Staynor, Alderson, Cresswell & Donnelly, 2018) and several weeks of balance training can promote safer side cut mechanics (Cochrane et al., 2010). In accordance with procedures adapted in this thesis, future research could compare the longitudinal effect of linear compared with multi-directional running on side cut performance and injury risk.

8.6.2 Comparison of continuous versus discrete biomechanical data

This thesis assessed discrete peak biomechanical variables during a side cut, as discrete peak values have been directly related to ACL injury risk (Hewett et al., 2005). Specifically, Hewett et al. (2005) reported peak knee abduction moment predicted ACL injury status with 73% specificity and 78% sensitivity, and therefore the assessment of peak values has clinical relevance. However, the assessment of the whole kinematic and kinetic waveform could provide further insight into biomechanical alterations in technique that exist over a specific phase of a movement and negate the need to preselect discrete measures to be analysed (Pataky, Robinson & Vanrenterghem, 2013; Richter, O'Connor, Marshall & Moran, 2014). For example, Whyte et al. (2018) reported knee extension moment was smaller at 70-98% of the weight acceptance phase of a side cut when athletes were fatigued using statistical parametric mapping. These data are consistent with Chapter 6, and the reduction in peak knee extension moment observed in the thesis likely occurred during the same phase of stance reported by Whyte et al. (2018). Accordingly, the assessment of discrete peak measures in the present thesis can adequately identify differences in side cut technique with fatigue but comparing the whole wave form can provide additional information on when, and for how long, biomechanical alterations were observed. Future research should therefore include more comprehensive statistical approaches, such as statistical parametric mapping (Pataky et al., 2013) to provide more information on biomechanical alterations in technique relative to the specific phase of a movement, immediately, and the in the days after team sport activity.

8.6.3 Consideration of fatigue and EIMD when reporting ACL incidence rates

Whilst data from this thesis demonstrates fatigue and EIMD can alter side cut biomechanics, it is still unclear if fatigue and EIMD contribute to ACL incidence rates or not. Accordingly, future epidemiology research assessing ACL injury rates in team sports should, where possible, consider the fatigue/EIMD status of athletes when an injury has occurred. Indeed, the use of player tracking devices, physical performance tests and athlete self-report measures to monitor training load and the fatigue status of athletes are now routine in both research and practice (Thorpe, Atkinson, Drust & Gregson, 2017). Whilst issues remain regarding the validity of single measure athlete self-reports for monitoring training responses (Jeffries et al., 2020), combining objective measures of training load and fatigue status described in this thesis with injury incidences rates can further clarify the role of fatigue and EIMD in ACL injuries.

8.6.4 Mechanisms of fatigue after multi-directional running

Further investigation into the potential causes of altered side cut biomechanics after multi-directional running via the assessment of muscle activity and/or changes in voluntary and involuntary joint torque are warranted. Indeed, previous literature has investigated the mechanisms of fatigue after repeated sprint exercise (Goodall et al., 2015) and simulated soccer match-play (Thomas et al., 2017). Greater understanding of the mechanisms of fatigue after multi-directional running can help inform performance decrements observed and help explain alterations in side cut biomechanics under fatigue.

8.7 Overall conclusion

This thesis highlights running with more directional changes induces an increased psychophysiological response to exercise as well as small alterations in side cut biomechanics after exercise, which has implications for training prescription, recovery and injury risk. Specifically, time at high metabolic power was able to reflect changes in internal load induced by altering running patterns and can therefore be used as a surrogate marker of internal load. Practitioners should carefully consider the number of directional changes performed during running to optimise the training stimulus of a session or promote recovery. Symptoms of fatigue and EIMD observed immediately, and in the days after multi-directional running, were accompanied by small alterations in side cut biomechanics, which have previously been associated with an increased risk of ACL injury. Fatigue and EIMD induced from multi-directional running might therefore indirectly contribute to ACL injury in males and females and should be considered in future research examining ACL incidence rates.

References

Achten, J. & Jeukendrup, A. E. (2003). Heart rate monitoring: Applications and limitations. *Sports Medicine, 33*(7), 517-538.

Agel, J., Rockwood, T., & Klossner, D. (2016). Collegiate ACL injury rates across 15 sports: National collegiate athletic association injury surveillance system data update (2004-2005 through 2012-2013). *Clinical Journal of Sport Medicine, 26*(6), 518-523. Doi:10.1097/JSM.0000000000000290

Akenhead, R. & Nassis, G. P. (2016). Training load and player monitoring in high-level football: Current practice and perceptions. *International Journal of Sports Physiology and Performance, 11*(5), 587-593.

Akenhead, R., French, D., Thompson, K. G., & Hayes, P. R. (2013). The acceleration dependant validity and reliability of 10 Hz GPS. *Journal of Science and Medicine in Sport, 17*(5), 562-566.

Akenhead, R., French, D., Thompson, K. G., & Hayes, P. R. (2014). The physiological consequences of acceleration during shuttle running. *International Journal of Sports Medicine, 36*(4), 302-307.

Akenhead, R., Hayes, P. R., Thompson, K. G., & French, D. (2013). Diminutions of acceleration and deceleration output during professional football match play. *Journal of Science and Medicine in Sport, 16(*6), 556-561. doi:10.1016/j.jsams.2012.12.005

Akubat, I., Barrett, S., & Abt, G. (2014). Integrating the internal and external training loads in soccer. *International Journal of Sports Physiology and Performance, 9*(3), 457-462.

Akubat, I., Barrett, S., Sagarra, M. L., & Abt, G. (2018). The validity of external:internal training load ratios in resting and fatigued soccer players. *Sports, 6*(2), 44. doi:10.3390/sports6020044.

Alenezi, F., Herrington, L., Jones, P., & Jones, R. (2016). How reliable are lower limb biomechanical variables during running and cutting tasks. *Journal of Electromyography and Kinesiology, 30,* 137-142. doi:10.1016/j.jelekin.2016.07.001.

Alentorn-Geli, E., Myer, G., Silvers, H., Samitier, G., Romero, D., Lazaro-Haro, C., & Cugat, R. (2009). Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanism of injury and underlying risk factors. *Knee Surgery, Sports Traumatology, Arthroscopy, 17*(7), 705-729.

Alexandre, D., da Silva, C. D., Hill-Haas, S., Wong, D. P., Natali, A. J., De Lima, Jorge, R. P., … Karim, C. (2012). Heart rate monitoring in soccer: Interest and limits during competitive match play and training, practical application. *Journal of Strength and Conditioning Research, 26*(10), 2890-2906. doi:10.1519/JSC.0b013e3182429ac7.

Ali, N., Robertson, D., & Rouhi, G. (2014). Sagittal plane body kinematics and kinetics during single-leg landing from increasing vertical height and horizontal distances: Implications for risk of non-contact ACL injury. *Knee, 21*(1), 38-46.

Allen, D. G., & Westerblad, H. (2001). Role of phosphate and calcium stores in muscle fatigue, *The Journal of Physiology, 536*(3), 657-665.

Allen, D. G., Lamb, G. D., & Westerblad, H. (2008a). Impaired calcium release during fatigue. *Journal of Applied Physiology, 104*(1), 296-305.

Allen, D. G., Lamb, G. D., & Westerblad, H. (2008b). Skeletal muscle fatigue: Cellular mechanisms. *Physiological Reviews, 88*(1), 287-332. doi:10.1152/physrev.00015.2007

Almosnino, S., Stevenson, J., Bardana, D., Diaconescu, E., & Dvir, Z. (2012). Reproducibility of isokinetic knee eccentric and concentric strength indices in asymptomatic young adults. *Physical Therapy in Sport, 13*(3), 156-162.

Altmann, S., Spielmann, M., Engel, F. A., Neumann, R., Ringhof, S., Oriwol, D., & Haertel, S. (2017). Validity of single-beam timing lights at different heights. *Journal of Strength and Conditioning Research, 31(7*), 1994-1999. doi:10.1519/JSC.0000000000001889

Andersson, H., Raastad, T., Nilsson, J., Paulsen, G., Garthe, I., & Kadi, F. (2008). Neuromuscular fatigue and recovery in elite female soccer: Effects of active recovery. *Medicine and Science in Sports and Exercise, 40*(2), 372-380. doi:10.1249/mss.0b013e31815b8497

Ansdell, P., Thomas, K., Hicks, K. M., Hunter, S. K., Howatson, G., & Goodall, S. (2020). Physiological sex differences affect the integrative response to exercise: Acute and chronic implications. *Experimental Physiology, 105*(12), 2007-2021. doi:10.1113/EP088548

Asaeda, M., Deie, M., Kono, Y., Mikami, Y., Kimura, H., & Adachi, N. (2019). The relationship between knee muscle strength and knee biomechanics during running at 6 and 12 months after anterior cruciate ligament reconstruction. *Asia-Pacific Journal of Sports Medicine, Arthroscopy, Rehabilitation and Technology, 16*, 14-18. doi:10.1016/j.asmart.2018.11.004

Ascensão, A., Rebelo, A., Oliveira, E., Marques, F., Pereira, L., & Magalhães, J. (2008). Biochemical impact of a soccer match — analysis of oxidative stress and muscle damage markers throughout recovery. *Clinical Biochemistry, 41*(10), 841-851. doi:10.1016/j.clinbiochem.2008.04.008Link

Ashton, R. & Twist, C. (2015). Number of directional changes alters the physiological, perceptual and neuromuscular responses of netball players during intermittent shuttle running. *Journal of Strength and Conditioning, 29*(10), 2731-2737. doi:10.1519/JSC.0000000000000933

Aslan, A., Acikada, C., Guvenc, A., Goren, H., Hazir, T., & Ozkara, A. (2012). Metabolic demands of match performance in young soccer players. *Journal of Sports Science and Medicine, 11*(1), 170-179.

Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine, 26*(4), 217-238.

Aughey, R. (2010). Australian football player work rate: Evidence of fatigue and pacing?. *International Journal of Sports Physiology and Performance, 5*(3), 394-405

Austin, D. J. & Kelly, S. J. (2013). Positional differences in professional rugby league match play through the use of global positioning systems. *Journal of Strength and Conditioning Research, 27*(1), 14-19.

Avela, J., & Komi, P. V. (1998). Reduced stretch reflex sensitivity and muscle stiffness after long-lasting stretch-shortening exercise in humans. *European Journal of Applied Physiology, 78,* 403-410.

Avela, J., Kyrolainen, H., Komi, P. V., & Rama, D. (1999). Reduced reflex sensitivity persists several days after long-lasting stretch-shortening cycle exercise. *Journal of Applied Physiology, 86*, 1292–300.

Awwad, G. E. H., Coleman, J. H., Dunkley, C. J., & Dewar, D. C. (2019). An analysis of knee injuries in rugby league: The experience at the newcastle knights professional rugby league team. *Sports Medicine, 5*(1), 1-7. doi:10.1186/s40798-019-0206-z

Bailey, D. M., Erith, S. J., Griffin, P. J., Dowson, A., Brewer, D. S., Gant, N., & Williams, C. (2007). Influence of cold-water immersion on indices of muscle damage following prolonged intermittent shuttle running. *Journal of Sport Sciences, 25*(11), 1163-1170.

Baird, M. F., Graham, S. M., Baker, J. S., & Bickerstaff, G. F. (2012). Creatine-kinase- and exercise-related muscle damage implications for muscle performance and recovery. *Journal of Nutrition and Metabolism, 2012*, 1-13. doi:10.1155/2012/960363

Bakker, R., Tomescu, S., Brenneman, E., Hangalur, G., Laing, A., & Chandrashekar, N. (2016). Effect of sagittal plane mechanics on ACL strain during jump landing. *Journal of Orthopaedic Research, 34*(9), 1636-1644. doi:10.1002/jor.23164

Bangsbo, J., Mohr, M., & Krustrup, P. (2006). Physical and metabolic demands of training and match-play in the elite football player. *Journal of Sports Science, 24*(7), 665-674. doi:10.1080/02640410500482529.

Barber-Westin, S. D., & Noyes, F. R. (2017). Effect of fatigue protocols on lower limb neuromuscular function and implications for anterior cruciate ligament injury prevention training: A systematic review. *The American Journal of Sports Medicine, 45*(14), 3388-3396. doi:10.1177/0363546517693846

Barlett, R., Wheat, J., & Robins, M. (2007). Is movement variability important for sports biomechanists? *Sports Biomechanics, 6*(2), 224-243. doi:10.1080/14763140701322994

Bartlett, J. D., Close, G. L., Drust, B., & Morton, J. P. (2010). Development of laboratory-based intermittent running protocols that are matched for various physiological parameters. *British Journal of Sports Medicine, 44*(14), i9, doi:10.1136/bjsm.2010.078972.26

Bartlett, J., O’Connor, F., Pitchford, N., Torres-Ronda, L., & Robertson, S. (2017). Relationships between internal and external training load in team-sport athletes: Evidence for an individualized approach. *International Journal of Sports Physiology and Performance, 12*(2), 230-234. doi:10.1123/ijspp.2015-0791.

Bartlett, R., Wheat, J., & Robins, M. (2007). Is movement variability important for sports biomechanists? *Sports Biomechanics, 6*(2), 224-243. doi:10.1080/14763140701322994

Bates, N. A., Ford, K. R., Myer, G. D., & Hewett, T. E. (2013). Timing differences in the generation of ground reaction forces between the initial and secondary landing phases of the drop vertical jump. *Clinical Biomechanics, 28*(7), 796-799. doi:10.1016/j.clinbiomech.2013.07.004

Bates, N. A., Nesbitt, R. J., Shearn, J. T., Myer, G. D., & Hewett, T. E. (2017). Knee abduction affects greater magnitude of change in ACL and MCL strains than matched internal tibial rotation in vitro. *Clinical Orthopaedics and Related Research, 475*(10), 2385-2396. doi:10.1007/s11999-017-5367-9

Bates, N. A., Nesbitt, R. J., Shearn, J. T., Myer, G. D., & Hewett, T. E. (2018). The influence of internal and external tibial rotation offsets on knee joint and ligament biomechanics during simulated athletic tasks. *Clinical Biomechanics, 52*, 109-116. doi:10.1016/j.clinbiomech.2018.01.019

Batterham, A., & Hopkins, W. (2006). Making meaningful inferences about magnitudes. *International Journal of Sports Physiology and Performance, 1*(1), 50-57.

Beato, M., Bartolini, D., Ghia, G., & Zamparo, P. (2016). Accuracy of a 10 hz GPS unit in measuring shuttle velocity performed at different speeds and distances (5 – 20 M). *Journal of Human Kinetics, 54*(1), 15-22. doi:10.1515/hukin-2016-0031.

Beaulieu, M. L., Oh, Y. K., Bedi, A., Ashton-Miller, J. A., & Wojtys, E. M. (2014). Does limited internal femoral rotation increase peak anterior cruciate ligament strain during a simulated pivot landing? *The American Journal of Sports Medicine, 42(*12), 2955-2963. doi:10.1177/0363546514549446

Beaulieu, M., Lamontagne, M., & Xu, L. (2009). Lower limb muscle activity and kinematics of an unanticipated cutting manoeuvre: A gender comparison. *Knee Surgery, Sports Traumatology, Arthroscopy, 17*(8), 968-976.

Bedi, A., Warren, R. F., Wojtys, E. M., Oh, Y. K., Ashton-Miller, J. A., Oltean, H., & Kelly, B. T. (2016). Restriction in hip rotation is associated with an increased risk of ACL injury. *Knee Surgery, Sports Traumatology, Arthroscopy, 24*(6), 2024-2031. doi:10.1007/s00167-014-3299-4

Behan, F. P., Willis, S., Pain, M. T. G., & Folland, J. P. (2018). Effects of football simulated fatigue on neuromuscular function and whole-body response to disturbances in balance. *Scandinavian Journal of Medicine and Science in Sport, 28*(12), 2547-2557.

Bencke, J., Curtis, D., Krogshede, C., Jensen, L. K., Bandholm, T., & Zebis, M. K. (2013). Biomechanical evaluation of the side-cutting manoeuvre associated with ACL injury in young female handball players. *Knee Surgery, Sports Traumatology, Arthroscopy, 21*(8), 1876-1881. doi:10.1007/s00167-012-2199-8

Benjaminse, A., Benjaminse, A., Habu, A., Habu, A., Sell, T. C., Sell, T. C., . . . Lephart, S. M. (2008). Fatigue alters lower extremity kinematics during a single-leg stop-jump task. *Knee Surgery, Sports Traumatology, Arthroscopy, 16*(4), 400-407. doi:10.1007/s00167-007-0432-7Link

Benjaminse, A., Webster, K. E., Kimp, A., Meijer, M., & Gokeler, A. (2019). Revised approach to the role of fatigue in anterior cruciate ligament injury prevention: A systematic review with meta-analyses. *Sports Medicine, 49*(4), 565-586. doi:10.1007/s40279-019-01052-6

Benoit, D. L., Ramsey, D. K., Lamontagne, M., Xu, L., Wretenberg, P., & Renström, P. (2006). Effect of skin movement artefact on knee kinematics during gait and cutting motions measures in vivo. *Gait & Posture, 24*(2), 152-164.

Benoit, D., Damsgaard, M., & Anderson, M. (2015). Surface marker cluster translation, rotation, scaling and deformation: Their contribution to soft tissue artefact and impact on knee joint kinematics. *Journal of Biomechanics, 48*(10), 2124-2129.

Besier, T. F., Lloyd, D. G., Ackland, T. R. (2003). Muscle activation strategies at the knee during running and cutting maneuvers. *Medicine and Science in Sports and Exercise, 35*(1), 119-127.

Besier, T. F., Sturnieks, D. L., Alderson, J. A., & Lloyd, D. G. (2003). Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. *Journal of Biomechanics, 36*(8), 1159-1168.

Besier, T., Lloyd, D., Cochrane, J., & Ackland, T. (2001). External loading of the knee joint during running and cutting maneuvers. *Medicine and Science in Sports and Exercise, 33*(7), 1168-1175. doi:10.1097/00005768-200107000-00014

Bishop, D. J. (2012). Fatigue during intermittent-sprint exercise. *Clinical and Experimental Pharmacology and Physiology, 39*(9), 836-841. doi:10.1111/j.1440-1681,2012.05735.x

Bisseling, R. W., & Hof, A. L. (2006). Handling of impact forces in inverse dynamics. *Journal of Biomechanics, 39*(13), 2438-2444. doi:10.1016/j.jbiomech.2005.07.021

Black, G. M., Gabbett, T. J., Naughton, G. A., & McLean, B. D. (2016). The effect of intense exercise periods on physical and technical performance during elite australian football match-play: A comparison of experienced and less experienced players. *Journal of Science and Medicine in Sport, 19*(7), 596-602. doi:10.1016/j.jsams.2015.07.007

Blackburn, J. T., & Padua, D. A. (2008). Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Clinical Biomechanics, 23*(3), 313-319.

Blackburn, J. T., & Padua, D. A. (2009). Sagittal-plane trunk position, landing forces, and quadriceps electromyographic activity. *Journal of Athletic Training, 44*(2), 174-179. doi:10.4085/1062-6050-44.2.174

Bloomfield, J., Polman, R., & Donoghue, P. (2007). Physical demands of different positions in FA Premier League soccer. *Journal of Sports Science and Medicine, 63*(6), 63-70.

Boden, B., Dean, G., Feagin, J., & Garrett, W. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics, 23*(6), 573-578.

Boden, B., Torg, J., Knowles, S., & Hewett, T. (2009). Video analysis of anterior cruciate ligament injury abnormalities in hip and ankle kinematics. *American Journal of Sports Medicine, 37*(2), 252-259.

Borg, G. (1998). *Borg's perceived exertion and pain scales*. Champaign, IL: Human Kinetics.

Borotikar, B. S., Newcomer, R., Koppes, R., & McLean, S. G. (2008). Combined effects of fatigue and decision making on female lower limb landing postures: Central and peripheral contributions to ACL injury risk. *Clinical Biomechanics, 23*(1), 81-92.

Borsa, P. A., Sauers, E. L. (2000). The importance of gender on myokinetic deficits before and after microinjury. *Medicine and Science in Sport & Exercise, 32,* 891-896.

Bowen, L., Gross, A. S., Gimpel, M., & Li, F. (2017). Accumulated workloads and the acute:chronic workload ratio relate to injury risk in elite youth football players. *British Journal of Sports Medicine, 51*(5), 452-459. doi:10.1136/bjsports-2015-095820

Bowers, E., Morgan, D., & Proske, U. (2004). Damage to the human quadriceps muscle from eccentric exercise and the training effect. *Journal of Sports Sciences, 22*(11-12), 1005-1014.

Boyd, L. J., Ball, K., & Aughey, R. J. (2011). The reliability of MinimaxX accelerometers for measuring physical activity in australian football. *International Journal of Sports Physiology and Performance, 6*(3), 311-321. doi:10.1123/ijspp.6.3.311

Brancaccio, P., Maffulli, N., & Limongelli, F. M. (2007). Creatine kinase monitoring in sport medicine. *British Medical Bulletin, 81-82*(1), 209-230. doi:10.1093/bmb/ldm014

Brechue, W. F., Mayhew, J. L., & Piper, F. C. (2010). Characteristics of sprint performance in college football players. *Journal of Strength and Conditioning Research, 24*(5), 1169-1178.

Bresler, E., & Frankel, J. P. (1950). The forces and moment in the leg during level walking. *Journal of Applied Mechanics,* 27-36

Brown, C. N., Bowser, B., & Simpson, K. J. (2012). Movement variability during single leg jump landing in individuals with and without chronic ankle instability. *Clinical Biomechanics, 27*(1), 52-63. doi:10.1016/j.clinbiomech.2011.07.012

Brown, D. M., Dwyer, D. B., Robertson, S. J., & Gaston, P. B. (2016). Metabolic power method underestimates energy expenditure in field sport movements using a GPS tracking system. *International Journal of Sports Physiology and Performance, 11*(8), 1067-1073. doi:10.1123/ijspp.2016-0021.

Brown, J. & Glaister, M. (2014). The interactive effects of recovery mode and duration on subsequent repeated sprint performance. *Journal of Strength and Conditioning Research, 28*(3), 651-660.

Brownstein, C. G., Dent, J. P., Parker, P., Hicks, K. M., Howatson, G., Goodall, S., & Thomas, K. (2017). Etiology and recovery of neuromuscular fatigue following competitive soccer match-play. *Frontiers in Physiology, 8*, 831. doi:10.3389/fphys.2017.00831

Brueckner, J. C., Atchou, G., Capelli, C., Duvallet, A., Barrault, D., Jousselin, E., . . . di Prampero, P. E. (1991). The energy cost of running increases with the distance covered. *European Journal of Applied Physiology and Occupational Physiology, 62(*6), 385

Brughelli, M., Cronin, J., Levin, G., & Chaouachi, A. (2008). Understanding change of direction ability in sport: a review of resistance training studies. *Sports Medicine, 38,* 1045-1063.

Buchheit, M., Bishop, D., Haydar, B., Nakamura, F. Y., & Ahmaidi, S. (2010). Physiological responses to shuttle repeated-sprint running. *International Journal of Sports Medicine, 31*(6), 402-409.

Buchheit, M., Manouvrier, C., Cassirame, J., & Morin, J. (2015). Monitoring locomotor load in soccer: Is metabolic power, powerful? *International Journal of Sports Medicine, 36*(14), 1149-1155. doi:10.1055/s-0035-1555927.

Buchhiet, M., Hayder, B., & Ahmaidi, S. (2012). Repeated sprints with directional changes: Do angles matter? *Journal of Sports Sciences, 30*(6), 555-562.

Burt, D. G., Lamb, K., Nicholas, C., & Twist, C. (2014). Effects of exercise-induced muscle damage on resting metabolic rate, sub-maximal running and post-exercise oxygen consumption. *European Journal of Sport Science, 14*(4), 337- 344.

Butler, D., Grood, E. S., & Noyes, F. (1980). Ligamentous restraints to anterior drawer in the human knee: A biomechanical study. *The Journal of Bone and Joint Surgery*, 62, 259–270. doi: 10.2106/00004623-198062020-00013.

Byrne, C., Twist, C. & Eston, R. (2004). Neuromuscular function after exercise-induced muscle damage: Theoretical and applied implications. *Sports Medicine, 34*(1), 49-69.

Cairns, S. P., & Lindinger, M. I. (2008). Do multiple ionic interactions contribute to skeletal muscle fatigue? *The Journal of Physiology, 586*(17), 4039-4054. doi:10.1113/jphysiol.2008.155424

Caldwell, G. E., Robertson, G. E., & Whittlesey, S. N. (2014). Forces and their movements. In Robertson, D. G. E. (Ed.), *Research Methods in Biomechanics* (pp. 79-108). Champaign, IL: Human Kinetics.

Capin, J. J., Snyder-Mackler, L., Risberg, M. A., & Grindem, H. (2019b). *Keep calm and carry on return to sport testing after an ACL injury: clinician-scientists weigh in on knee injury risk*. Retrieved from https://blogs.bmj.com/bjsm/2019/05/09/keep-calm-and-carry-on-return-to-sport-testing-after-an-acl-injury-clinician-scientists-weigh-in-on-knee-injury-risk/

Capin, J. J., Snyder-Mackler, L., Risberg, M. A., & Grindem, H. (2019a). Keep calm and carry on testing: A substantive reanalysis and critique of 'what is the evidence for and validity of return-to-sport testing after anterior cruciate ligament reconstruction surgery? A systematic review and meta-analysis'. *British Journal of Sports Medicine, 53*(23), 1444-1446. doi:10.1136/bjsports-2019-100906

Carling, C., Bradley, P., McCall, A., & Dupont, G. (2016). Match-to-match variability in high-speed running activity in a professional soccer team. *Journal of Sports Sciences: Science and Medicine in Football, 34*(24), 2215-2223. doi:10.1080/02640414.2016.1176228

Carr, C. M., McMahon, J. J. & Comfort, P. (2015). Relationships between jump and sprint performance in first-class county cricketers, *Journal of Trainology, 4*(1), 1-5.

Carroll, T. J., Taylor, J. L., & Gandevia, S. C. (2017). Recovery of central and peripheral neuromuscular fatigue after exercise. *Journal of Applied Physiology, 122*(5), 1068-1076. doi:10.1152/japplphysiol.00775.2016

Casamichana, D., & Castellano, J. (2015). The relationship between intensity indicators in small-sided soccer games. *Journal of Human Kinetics, 46*(1), 119-128. doi:10.1515/hukin-2015-0040.

Casamichana, D., Castellano, J., Calleja-Gonzalez, J., San Román, J., & Castagna, C. (2013). Relationship between indicators of training load in soccer players. *Journal of Strength and Conditioning Research, 27*(2), 369-374. doi:10.1519/JSC.0b013e3182548af1.

Castellano, J., Casamichana, D., Calleja-Gonzalez, J., San Roman, J., & Ostojic, S. (2011). Reliability and accuracy of 10 Hz GPS devices for short-distance exercise. *Journal of Sport Science and Medicine, 10*(1), 233-234.

Chaabene, H. (2017) Change of Direction Tasks: Does the Eccentric Muscle Contraction Really Matter? *The Scientific Pages of Sports Medicine, 1*(1), 1-2

Chaabene, H., Prieske, O., Negra, Y., & Granacher, U. (2018). Change of direction speed: Toward a strength training approach with accentuated eccentric muscle actions. *Sports Medicine, 48*(8), 1773-1779. doi:10.1007/s40279-018-0907-3

Chappell, J. D., Yu, B., Kirkendall, D. T., & Garrett, W. E. (2002) A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *American Journal of Sports Medicine, 30*, 261–267

Chappell, J., Creighton, R., Giuliani, C., Yu, B., & Garrett, W. (2007). Kinematics and electromyography of landing preparation in vertical stop-jump – risks for noncontact anterior cruciate ligament injury. *American Journal of Sports Medicine, 35*(2), 235-241.

Chappell, J., Herman, D., Knight, B., Kirkendall, D., Garrett, W., & Yu, B. (2005). Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. *American Journal of Sports Medicine, 33*(7), 1022-1029.

Chaudhari, A. M., & Andriacchi, T. P. (2006). The mechanical consequences of dynamic frontal plane limb alignment for non-contact ACL injury. *Journal of Biomechanics, 39*(2), 330-338. doi:10.1016/j.jbiomech.2004.11.013

Chazaud, B. (2016). Inflammation during skeletal muscle regeneration and tissue remodeling: Application to exercise-induced muscle damage management. *Immunology and Cell Biology, 94*(2), 140–145.

Chen, T. C., Nosaka, K., Lin, M., Chen, H., & Wu, C. (2009). Changes in running economy at different intensities following downhill running. *Journal of Sports Sciences, 27*(11), 1137-1144. doi:10.1080/02640410903062027

Cheung, K., Hume, P. A., & Maxwell, L. (2003). Delayed onset muscle soreness: Treatment strategies and performance factors. *Sports Medicine, 33*(2), 145-164. doi:10.2165/00007256-200333020-00005

Cleak, M. J., & Eston, R. G. (1992). Muscle soreness, swelling, stiffness and strength loss after intense eccentric exercise. *British Journal of Sports Medicine, 26,* 267–272.

Cochrane, J. L., Lloyd, D. G., Besier, T. F., Elliott, B.C., Doyle, T.L., & Ackland, T.R. (2010). Training affects knee kinematics and kinetics in cutting maneuvers in sport. *Medicine and Science in Sports and Exercise, 42*(8), 1535–1544.

Coelho, D. B., Coelho, L. G., Mortimer, L. A., Condessa, L. A., Ferreira-Junior, Borba, J., Borba, D. A., Oliveira, B., Bouzas-Marins, J., Soares, D. & Silami-Garcia, E. (2010). Energy expenditure estimation during official soccer matches. *Brazilian Journal of Biomotricity, 4*(4), 246-255.

Collins, B. W., Pearcey, G. E. P., Buckle, N. C. M., Power, K. E., & Button, D. C. (2018). Neuromuscular fatigue during repeated sprint exercise: Underlying physiology and methodological considerations. *Applied Physiology, Nutrition, and Metabolism, 43*(11), 1166-1175. doi:10.1139/apnm-2018-0080

Collins, J. D., Almonroeder, T. G., Ebersole, K. T., & O'Connor, K. M. (2016). The effects of fatigue and anticipation on the mechanics of the knee during cutting in female athletes. *Clinical Biomechanics, 35*, 62-67. doi:10.1016/j.clinbiomech.2016.04.004

Coppalle, S., Rave, G., Ben Abderrahman, A., Ali, A., Salhi, I., Zouita, S., . . . Zouhal, H. (2019). Relationship of pre-season training load with in-season biochemical markers, injuries and performance in professional soccer players. *Frontiers in Physiology, 10*, 409. doi:10.3389/fphys.2019.00409

Cormack, S., Smith, R., Mooney, M., Young, W., & O’Brien, B. (2014). Accelerometer load as a measure of activity profile in different standards of netball match-play. *International Journal of Sports Physiology and Performance, 9*(2), 283-291. doi:10.1123/IJSPP.2012-0216.

Cortes, N., Greska, E., Ambegaonkar, J. P., Kollock, R. O. Caswell, S. V., & Onate, J. A. (2014). Knee kinematics is altered post-fatigue while performing a crossover task. *Knee Surgery, Sports Traumatology, Arthroscopy, 22*(9), 2202-8

Cortes, N., Greska, E., Kollock, R., Ambegaonkar, J., & Onate, J. (2013). Changes in lower extremity biomechanics due to a short-term fatigue protocol. *Journal of Athletic Training, 48*(3), 306-313. doi:10.4085/1062-6050-48.2.03

Cortes, N., Onate, J., & Morrison, S. (2014). Differential effects of fatigue on movement variability. *Gait & Posture, 39*(3), 888-893. doi:10.1016/j.gaitpost.2013.11.020

Cortes, N., Quammen, D., Lucci, S., Greska, E., & Onate, J. (2012). A functional agility short-term fatigue protocol changes lower extremity mechanics. *Journal of Sports Sciences, 30*(8), 797-805. Doi:10.1080/02640414.2012.671528

Coutts, A. J., & Duffield, R. (2010). Validity and reliability of GPS devices for measuring movement demands of team sports. *Journal of Science and Medicine in Sport, 13*(1), 133-135.

Coutts, A. J., Rampinini, E., Marcora, S. M., Castagna, C., & Impellizzeri, F. M. (2009). Heart rate and blood lactate correlates of perceived exertion during small-sided soccer games. *Journal of Science and Medicine in Sport, 12*(1), 79-84.

Coutts, A., Kempton, T., Sullivan, C., Bilsborough, J., Cordy, J., & Rampinini, E. (2015). Metabolic power and energetics costs of professional australian football match-play. *Journal of Science and Medicine in Sport, 18*(2), 219-224.

Coutts, A., Reaburn, P. & Abt, G. (2003). Heart rate, blood lactate concentration and estimated energy expenditure in a semi-professional rugby league team during a match: case study. *Journal of Sports Sciences, 21*(2), 97-103.

Coventry, E., O’Connor, K. M., Hart, B. A., Earl, J. E., & Ebersole, K. T. (2006). The effect of lower extremity fatigue on shock attenuation during single-leg landing. *Clinical Biomechanics, 21*(10), 1090-1097. doi:10.1016/j.clinbiomech.2006.07.004

Cowley, J., Gates, D. (2017). Proximal and distal muscle fatigue differentially affect movement coordination. *Plos One, 12*(2), e0172835. doi:10.1371/journal.pone.0172835

Cummins, C., Orr, R., O’Connor, H., & West, C. (2013). Global positioning systems (GPS) and microtechnology sensors in team sports: A systematic review. *Sports Medicine, 43*(10), 1025-1042. doi:10.1007/s40279-013-0069-2.

Cunniffe, B., Proctor, W., Baker, J. S., & Davies, B. (2009). An evaluation of the physiological demands of elite rugby union using global positioning system tracking software. *Journal of Strength and Conditioning Research, 23*(4), 1195-1203.

Cunningham, D. J., Shearer, D. A., Carter, N., Drawer, S., Pollard, B., Bennett, M., . . . Kilduff, L. P. (2018). Assessing worst case scenarios in movement demands derived from global positioning systems during international rugby union matches: Rolling averages versus fixed length epochs. *PloS One, 13*(4), e0195197. doi:10.1371/journal.pone.0195197

Dai, B. Y., Garrett, W. E., Gross, M. T., Padua, D. A., Queen, R. M., & Yu, B. (2015). The effect of 2 landing techniques on knee kinematics, kinetics, and performance during stop-jump and side cutting tasks. *American Journal of Sports Medicine, 43*(2), 466-474. doi:10.1177/0363546514555322.

Dalen, T., Jørgen, I., Gertian, E., Geir Havard, H., & Ulrik, W. (2016). Player load, acceleration, and deceleration during forty-five competitive matches of elite soccer. *Journal of Strength and Conditioning Research, 30*(2), 351-359. doi:10.1519/JSC0000000000001063.

Damas, F., Nosaka, K., Libardi, C. A., Chen, T. C., & Ugrinowitsch, C. (2016). Susceptibility to exercise-induced muscle damage: A cluster analysis with a large sample. *International Journal of Sports Medicine, 37*(8), 633-640. doi:10.1055/s-0042-100281

Darter, B. J., Rodriguez, K. M., & Wilken, J. M. (2013). Test-retest reliability and minimum detectable change using K4b2: Oxygen consumption, gait efficiency and heart rate for healthy adults during submaximal walking. *Research Quarterly for Exercise and Sport, 84*(2), 223-231.

David, S., Komnik, I., Peters, M., Funken, J., & Potthast, W. (2017). Identification and risk estimation of movement strategies during cutting maneuvers. *Journal of Science and Medicine in Sport, 20*(12), 1075-1080. doi:10.1016/j.jsams.2017.05.011

Davis, D. J., Hinshaw, T. J., Critchley, M. L., & Dai, B. (2019). Mid-flight trunk flexion and extension altered segment and lower extremity joint movements and subsequent landing mechanics. *Journal of Science and Medicine in Sport, 22*(8), 955-961. doi:10.1016/j.jsams.2019.03.001

Davis, J. M., & Bailey, S. P. (1997). Possible mechanisms of central nervous system fatigue during exercise. *Medicine and Science in Sport & Exercise, 29*(1), 45-57.

De Andrade, V. L., Santiago, P. R. P., Kalva Filho, C. A., Campos, E. Z., & Papoti, M. (2016). Reproducibility of running anaerobic sprint test for soccer players. *The Journal of Sports Medicine and Physical Fitness, 56*, 34.

de Hoyo, M., Cohen, D. D., Sañudo, B., Carrasco, L., Álvarez-Mesa, A., del Ojo, J. J., … Otero-Esquina, C. (2016). Influence of football match time-motion parameters on recovery time course of muscle damage and jump ability. *Journal of Sports Sciences, 34*(14), 1363-1370. doi:10.1080/02640414.2016.1150603.

Decker, M. J., Torry, M. R., Wyland, D. J., Sterett, W. I., Richard Steadman, J. (2003). Gender difference in lower extremity kinematics, kinetics and energy absorption during landing. *Clinical Biomechanics, 18*(7), 662-669.

Delaney, J. A., Duthie, G. M., Thornton, H. R., & Pyne, D. B. (2018). Quantifying the relationship between internal and external work in team sports: Development of a novel training efficiency index. *Science and Medicine in Football, 2*(2), 149-156. doi:10.1080/24733938.2018.1432885

Dellal, A., Keller, D., Carling, C., Chaouachi, A., Wong, D. P. & Chamari, K. (2010). Physiologic effects of directional changes in intermittent exercise in soccer players. *Journal of Strength and Conditioning Research, 24*(12), 3219-3226.

Deluzio, K., Harrison, A., Coffey, N., & Caldwell, G. (2014). Analysis of Biomechanical waveform data. In G. Robertson, G. Caldwell, J. Hamill & G. Kamen (Ed.). *Research methods in biomechanics* (pp. 317-336). Champaign, IL: Human Kinetics.

DeMorat, G., Weinhold, P., Blackburn, T., Chudik, S., & Garrett, W. (2004). Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. *American Journal of Sports Medicine, 32*(2), 477-483.

Dempsey, A. R., Lloyd, D. G., Elliott, B. C., Steele, J. R., Munro, B. J., & Russo, K. A. (2007). The effect of technique change on knee loads during sidestep cutting. *Medicine and Science in Sports and Exercise, 39*(10), 1765-1773. Doi:10.1249/mss.0b013e31812f56d1

Dempster, W. T. (1955). *Space requirements of the seated operator: geometrical, kinematic, and mechanical aspects of the body, with special reference to the limbs.* Wright-Patterson Air Force Base, Springfield, Ohio: Carpenter Litho & Printing Co.

Derrick, T. (2014). Signal processing. In G. Robertson, G. Caldwell, J. Hamill & G. Kamen (Ed.). *Research methods in biomechanics* (pp. 279-290). Champaign, IL: Human Kinetics.

Deutsch, M. U., Maw, G. J., Jenkins, D., & Reaburn, P. (1998). Heart rate, blood lactate and kinematic data of elite colts (under-19) rugby union players during competition. *Journal of Sports Sciences, 16*(6), 561-570. doi:10.1080/026404198366524.

di Prampero, P. E., Botter, A. & Osgnach, C. (2015). The energy cost of sprint running and the role of metabolic power in setting top performances. *European Journal of Applied Physiology, 115*(3), 451-469.

di Prampero, P. E., Fusi, S., Sepulcri, L., Morin, J. B., Belli, A., & Antonutto, G. (2005). Sprint running: a new energetic approach. *Journal of Experimental Biology, 208,* 2809-2816.

di Prampero, P., & Osgnach, C. (2018). Metabolic power in team sports – part 1: An update. *International Journal of Sports Medicine, 39*(8), 581-587. doi:10.1055/a-0592-7660.

Dittrich, N., de Lucas, R., Maioral, M., Diefenthaeler, F., & Guglielmo, L. (2013). Continuous and intermittent running to exhaustion at maximal lactate steady state: Neuromuscular, biochemical and endocrinal responses. *Journal of Science and Medicine in Sport, 16*(6), 545-549.

Dobbin, N., Hunwicks, R., Highton, J., & Twist, C. (2017). Validity of a Jump Mat for assessing Countermovement Jump Performance in Elite Rugby Players. *International Journal of Sports Medicine. 38*(02), 99-104.

Doeven, S. H., Brink, M. S., Kosse, S. J., & Lemmink, K. (2018). Postmatch recovery of physical performance and biochemical markers in team ball sports: A systematic review. *BMJ Open Sport & Exercise Medicine, 4*(1), e000264-e000264. doi:10.1136/bmjsem-2017-000264

Donelon, T. A., Dos'Santos, T., Pitchers, G., Brown, M., & Jones, P. A. (2020). Biomechanical Determinants of Knee Joint Loads Associated with Increased Anterior Cruciate Ligament Loading During Cutting: A Systematic Review and Technical Framework. *Sports Medicine, 6*, 53 doi.10.1186/s40798-020-00276-5

Donnelly, C. J., Elliott, B. C., Doyle, T. L. A., Finch, C. F., Dempsey, A. R., & Lloyd D. G. (2012). Changes in knee joint biomechanics following balance and technique training and a season of Australian football. *British Journal of Sports Medicine, 46*(13), 917–922.

Donnelly, C. J., Lloyd, D. G., Elliott, B. C., & Reinbolt, J. A. (2012). Optimizing whole-body kinematics to minimize valgus knee loading during sidestepping: Implications for ACL injury risk. *Journal of Biomechanics, 45*(8), 1491-1497. doi:10.1016/j.jbiomech.2012.02.010

Dos'Santos, T., Bishop, C., Thomas, C., Comfort, P., & Jones, P. A. (2019). The effect of limb dominance on change of direction biomechanics: A systematic review of its important for injury risk. *Physical Therapy in Sport, 37*, 179-189. doi:10.1016/j.ptsp.2019.04.005.

Dos'Santos, T., Thomas, C., Comfort, P., & Jones, P. A. (2018). The effect of angle and velocity on change of direction biomechanics: An angle-velocity trade-off. *Sports Medicine, 48*(10), 2235-2253. doi:10.1007/s40279-018-0968-3

Dos'Santos, T., Thomas, C., Comfort, P., & Jones, P. A. (2019). The effect of training interventions on change of direction biomechanics associated with increased anterior cruciate ligament loading: A scoping review. *Sports Medicine, 49*(12), 1837-1859. doi:10.1007/s40279-019-01171-0

Draganidis, D., Chatzinikolaou, A., Avloniti, A., Barbero-Álvarez, J. C., Mohr, M., Malliou, P., . . . Fatouros, I. G. (2015). Recovery kinetics of knee flexor and extensor strength after a football match. *PloS One, 10*(6), e0128072. doi:10.1371/journal.pone.0128072

Drust, B., Reilly, T., & Cable, N. T. (2000). Physiological responses to laboratory-based soccer-specific intermittent and continuous exercise. *Journal of Sports Sciences, 18*(11), 885-892. doi:10.1080/026404100750017814

Dubois, R., Paillard, T., Lyons, M., McGrath, D., Maurelli, O., & Prioux, J. (2017). Running and metabolic demands of elite rugby union using traditional, metabolic power, and heart rate monitoring methods. *Journal of Sports Science and Medicine, 16*(1), 84-92.

Duffield, R., Dawson, B., Pinnington, H., & Wong, P. (2004). Accuracy and reliability of a cosmed k4b2 portable gas analysis system. *Journal of Science and Medicine in Sport, 7*(1), 11-22.

Duffield, R., Nakamura, F. Y., Bezerra, E. d. S., Sakugawa, R. L., Bobinski, F., Guglielmo, L. G. A., . . . Martins, D. F. (2019). Recovery following rugby union matches: Effects of cold water immersion on markers of fatigue and damage. *Applied Physiology Nutrition and Metabolism, 44*(3). doi:10.1139/apnm-2018-

Dupont, G., Nedelec, M., McCall, A., McCormack, D., Berthoin, S., & Wisløff, U. (2010). Effect of 2 soccer matches in a week on physical performance and injury rate. *The American Journal of Sports Medicine, 38*(9), 1752-1758. doi:10.1177/0363546510361236

Dutto, D., & Braun, W. (2004). DOMS-associated changes in ankle and knee joint dynamics during running. *Medicine and Science in Sports and Exercise, 36*(4), 560-566.

Edgett, B. A., Ross, J. E. D., Green, A. E., Macmillan, N. J., Milne, K. J., & Gurd, B. J. (2013). The effects of recreational sport on VO2 peak, VO2 kinetics and submaximal exercise performance in males and females. *European Journal of Applied Physiology, 113*(1), 259-266.

Edwards, S. (1993). *The heart rate monitor book*. Sacramento, CA: Fleet Feet Press.

Edwards, S., Brooke, H., & Cook, J. (2017). Distinct cut task strategy in australian football players with a history of groin pain. *Journal of Science and Medicine in Sport, 20*, e27-e28. doi:10.1016/j.jsams.2016.12.066

Ehrig, R. M., Taylor, W. R., Duda, G. N., & Heller, M. O. (2007). A survey of formal methods for determining functional joint axes. *Journal of Biomechanics, 40*(10), 2150-2157. doi:10.1016/j.jbiomech.2006.10.026

Ekstrand, J., Walden, M., & Hagglund, M. (2004). A congested football calendar and the wellbeing of players: correlation between match exposure of European footballers before the World Cup 2002 and their injuries and performances during that World Cup. *British Journal of Sports Medicine, 38*(4), 493–497.

Eniseler, N. (2005). Heart rate and blood lactate concentrations as predictors of physiological load on elite soccer players during various soccer training activities. *Journal of Strength and Conditioning Research, 19*(4), 799-804.

Enns, D. L., & Tiidus, P. M. (2010). The influence of estrogen on skeletal muscle: Sex matters. *Sports Medicine, 40*(1), 41-58.

Enoka, R. M., & Duchateau, J. (2008). Muscle fatigue: What, why and how it influences muscle function. *The Journal of Physiology, 586*(1), 11-23. doi:10.1113/jphysiol.2007.139477

Enoka, R. M., & Duchateau, J. (2016). Translating fatigue to human performance. *Medicine and Science in Sports and Exercise, 48*(11), 2228.

Evans, R., Knight, K., Draper, D., & Parcell, A. (2002). Effects of warm-up before eccentric exercise on indirect markers of muscle damage. *Medicine and Science in Sports and Exercise, 34*(12), 1892-1899.

Farley, C. T., & Gonzalez, O. (1996). Leg stiffness and stride frequency in human running. *Journal of Biomechanics, 29,* 181-186.

Faude, O., Koch, T., & Meyer, T. (2012). Straight sprinting is the most frequent action in goal situations in professional football. *Journal of Sports Sciences, 30*(7), 625-631.

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. (2009). Statistical power analyses using GPower 3.2: Tests for correlation and regression analyses. *Behavior Research Methods, 41*(4), 1149-1160. doi:10.3758/BRM.41.4.1149

Ferber, R., & Pohl, M. B. (2011). Changes in joint coupling and variability during walking following tibialis posterior muscle fatigue. *Journal of Foot and Ankle Research, 4*(1), 6-6. Doi:10.1186/1757-1146-4-6

Ferri-Morales, A., Alegre, L., Basco, A., & Aguado, X. (2014). Test-retest relative and absolute reliability of knee extensor strength measures and minimal detectable change. *Isokinetics and Exercise Science, 22*(1), 17-26.

Finsterer, J. (2012). Biomarkers of peripheral muscle fatigue during exercise. *BMC Musculoskeletal Disorders, 13(*1), 218. doi:10.1186/1471-2474-13-218

Fitts, R. H. (1994). Cellular mechanisms of muscle fatigue. *Physiological Reviews, 74*, 49-94.

Fleming, B., Renstom, P., Beynnon, B., Engstrom, B., Peura, G. D., Badger, G. J., & Johnston, R. J. (2001). The effect of weight-bearing and external loading on anterior cruciate ligament strain. *Journal of Biomechanics, 34*(2), 163-170.

Ford, K. R., Myer, G. D., Toms, H. E., & Hewett, T. E. (2005). Gender differences in the kinematics of unanticipated cutting in young athletes. *Medicine and Science in Sports and Exercise, 37*(1), 124-129.

Foster, C., Hector, L. L., Welsh, R., Schrager, M., Green, M. A., & Snyder, A. C. (1995). Effects of specific versus cross-training on running performance. *European Journal of Applied Physiology, 70,* 367-372.

Fowles, J. R., Green, H. J., Tupling, R., O'Brain, S. & Roy, B. D. (2002). Human neuromuscular fatigue is associated with altered Na^+-K^+-ATPase activity following isometric exercise. *Journal of Applied Physiology, 92,* 1585-1593.

Fox, A. S., Bonacci, J., McLean, S. G., & Saunders, N. (2017). Efficacy of ACL injury risk screening methods in identifying high-risk landing patterns during a sport-specific task. *Scandinavian Journal of Medicine & Science in Sports, 27*(5), 525-534. doi:10.1111/sms.12715

Fox, A. S., Fox, A. S., Bonacci, J., Bonacci, J., McLean, S. G., McLean, S. G., . . . Saunders, N. (2016). A systematic evaluation of field-based screening methods for the assessment of anterior cruciate ligament (ACL) injury risk. *Sports Medicine, 46*(5), 715-735. doi:10.1007/s40279-015-0443-3

Fox, R., Patterson, S., & Waldron, M. (2017) The relationship between heart rate recovery and temporary fatigue of kinematic and energetic indices among soccer players, *Science and Medicine in Football, 1*(2), 132-138, doi:10.1080/24733938.2017.1329590

Frank, B., Bell, D., Norcross, M., Blackburn, J., Goerger, B., & Padua, D. (2013). Trunk and hip biomechanics influence anterior cruciate loading mechanisms in physically active participants. *American Journal of Sports Medicine, 41*(11), 2676-2683. doi:10.1177/0363546513496625

Fridén, J., Sjöström, M., & Ekblom, B. (1983). Myofibrillar damage following intense eccentric exercise in man. *International Journal of Sports Medicine, 4*(3), 170.

Fujiya, H., Kousa, P., Fleming, B., Churchill, D., & Beynnon, B. (2011). Effect of muscle loads and torque applied to the tibia on the strain behaviour of the anterior cruciate ligament: An in vitro investigation. *Clinical Biomechanics, 26*(10), 1005-1011.

Gabbett, T. J. (2012). Sprinting patterns of national rugby league competition. *Journal of Strength and Conditioning Research, 26*(1), 121-130.

Gabbett, T. J. (2013). Influence of the opposing team on the physical demands of elite rugby league match play. *Journal of Strength and Conditioning Research, 27*(6), 1629-1635.

Gabbett, T. J. (2015). Relationships between accelerometer load, collisions, and repeated high-intensity effort activity in rugby league players. *Journal of Strength and Conditioning Research, 29*(12), 3424-3431. doi:10.1519/JSC.0000000000001017.

Gabbett, T. J., Jenkins, D., & Abernethy, B. (2011). Relationships between physiological, arthrometric, and skill qualities and playing performance in professional rugby league players, *Journal of Sports Sciences, 29*(15), 1655-1664.

Gabbett, T., Jenkins, D. & Abernethy, B. (2012). Physical demands of professional rugby league training and competition using microtechnology. *Journal of Science and Medicine in Sport,* 15(1), 80-86.

Gabbett, T., Polley, C., Dwyer, D., Kearney, S., & Corvo, A. (2014). Influence of field position and phase of play on the physical demands of match-play in professional rugby league forwards*. Journal of Science and Medicine in Sport, 17*(5), 556-561.

Gabbett, T.J. & Ullah, S. (2012). Relationship between running loads and soft tissue injury in elite team sport athletes. *Journal of Strength and Conditioning Research, 26*(4), 953-960.

Gandevia, S. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews, 81*, 4, 1725-1789

Garrett, J., Gunn, R., Eston, R. G., Burgess, D., Jakeman, J. R., & Norton, K. (2019). The effects of fatigue on the running profile of elite team sport athletes. A systematic review and meta-analysis. *The Journal of Sports Medicine and Physical Fitness, 59*(8), doi:10.23736/S0022-4707.19.09356-3

Gastin, P. B., Hunkin, S. L., Fahrner, B., & Robertson, S. (2019). Deceleration, acceleration, and impacts are strong contributors to muscle damage in professional australian football. *Journal of Strength and Conditioning Research*, 33(12), 3374-3383. doi:10.1519/JSC.0000000000003023

Gathercole, R. J., Sporer, B. C., Stellingwerff, T., & Sleivert, G. G. (2015). Comparison of the capacity of different jump and sprint field tests to detect neuromuscular fatigue. *Journal of Strength and Conditioning Research, 29*(9), 2522-2531. doi:10.1519/JSC.0000000000000912.

Gaudino, P., Iaia, F. M., Strudwick, A. J., Hawkins, R. D., Alberti, G., Atkinson, G., & Gregson, W. (2015). Factors influencing perception of effort (session rating of perceived exertion) during elite soccer training. *International Journal of Sports Physiology and Performance, 10*(7), 860. doi:10.1123/ijspp.2014-0518.

Gaudino, P., Iaia, F., Alberti, G., Strudwick, A., Atkinson, G., & Gregson, W. (2013). Monitoring training in elite soccer players: Systematic bias between running speed and metabolic power data. *International Journal of Sports Medicine, 34*(11), 963-968. doi:10.1055/s-0033-1337943.

Gianotti, S. M., Marshall, S. W., Hume, P. A., & Bunt, L. (2009). Incidence of anterior cruciate ligament injury and other knee ligament injuries: A national population-based study. *Journal of Science and Medicine in Sport, 12*(6), 622-627.

Gibala, M., Iterisano, S., Tarnopolsky, M., Roy, B., MacDonald, J., Yarasheski, K., & MacDougall, J. (2000). Myofibrillar disruption following acute concentric and eccentric resistance exercise in strength-trained men. *Canadian Journal of Physiology and Pharmacology, 78*(8), 656-661.

Girard, O., Lattier, G., Maffiuletti, N. A., Micallef, J., & Millet, G. P. (2008). Neuromuscular fatigue during a prolonged intermittent exercise: Application to tennis. *Journal of Electromyography and Kinesiology, 18*(6), 1038-1046. doi:10.1016/j.jelekin.2007.05.005

Girard, O., Mendez-Villanueva, A., & Bishop, D. (2011). Repeated-sprint ability – part I: Factors contributing to fatigue. *Sports Medicine, 41*(8), 673-694.

Glaister, M. (2005). Multiple Sprint Work: Physiological responses, mechanisms of fatigue and the influence of Aerobic Fitness. *Sports Medicine, 35*, 757-777.

Goodall, S., Charlton, K., Howatson, G., & Thomas, K. (2015). Neuromuscular fatigability during repeated-sprint exercise in male athletes. *Medicine & Science in Sports & Exercise, 47(*3), 528-536. doi:10.1249/MSS.0000000000000443

Goodall, S., Thomas, K., Harper, L. D., Hunter, R., Parker, P., Stevenson, E., … Howatson, G. (2017). The assessment of neuromuscular fatigue during 120 min of simulated soccer exercise. *European Journal of Applied Physiology, 117*(4), 687-697. doi:10.1007/s00421-017-3561-9

Grassi, A., Smiley, S. P., Roberti di Sarsina, T., Signorelli, C., Marcheggiani Muccioli, G. M., Bondi, A., … Zaffagnini, S. (2017). Mechanisms and situations of anterior cruciate ligament injuries in professional male soccer players: A YouTube-based video analysis. *European Journal of Orthopaedic Surgery & Traumatology, 27*(7), 967-981. doi:10.1007/s00590-017-1905-0

Gray, A. D., Miller, S. M., Galloway, S., Sherman, S., Leary, E., & Willis, B. W. (2019). anterior cruciate ligament injuries in high school female and male soccer athletes: Are match acl rates being underestimated? *Orthopaedic Journal of Sports Medicine, 7*(3).doi:10.1177/2325967119S00009

Grazioli, R., Lopez, P., Machado, C. L. F., Farinha, J. B., Fagundes, A., O., Voser, R., … Cadore, E. L. (2019). Mederate volume of sprint bouts does not induce muscle damage in well-trained athletes. *Journal of Bodywork and Movement Therapies,* doi:10.1016/j.jbmt.2019.05.019.

Greenland, S., Senn, S. J., Rothman, K. J., Carlin, J. B., Poole, C., Goodman, S. N., & Altman, D. G. (2016). Statistical tests, P values, confidence intervals, and power: A guide to misinterpretations. *European Journal of Epidemiology, 31*(4), 337-350. doi:10.1007/s10654-016-0149-3

Gregson, W., Drust, B., Atkinson, G., Salvo, V. (2010). Match-to-match variability of high-speed activities in premier league soccer. *International Journal of Sports Medicine, 31*(4), 237-242.

Greig, M. (2019). Concurrent changes in eccentric hamstring strength and knee joint kinematics induced by soccer-specific fatigue. *Physical Therapy in Sport, 37*, 21-26. doi:10.1016/j.ptsp.2019.02.003

Griffin, S. A., Mendham, A., Krustrup, P., Murray, A., Peirce, N., Larkin, J., Jaques, R., Cowie, C. M., Stokes, K. A., & Kemp, S. P. (2021a). Team sport in a COVID-19 world. A catastrophe in waiting, or an opportunity for community sport to evolve and further enhance population health? *British Journal of Sports Medicine*, 55(3), 130-131. doi:10.1136/bjsports-2020-102963

Griffin, S. A., Perera, N., K., P., Murray, A., Hartley, A., Fawkner, S. G., … Kelly, P. (2021b). The relationships between rugby union, and health and well-being: A scoping review. *British Journal of Sports Medicine*, 55, 319-326. doi:10.1136/bjsports-2020-102085

Hader, K., Mendez-Villanueva, A., Ahmaidi, S., Williams, B. K. & Buchheit, M. (2014). Changes of direction during high-intensity intermittent runs: Neuromuscular and metabolic. *BMC Sports Science, Medicine and Rehabilitation, 6*(1), 2-12. doi:10.1186/2052-1847-6-2

Hader, K., Mendez-Villanueva, A., Palazzi, D., Ahmaidi, S., & Buchheit, M. (2016). Metabolic power requirement of change of direction speed in young soccer players: Not all is what it seems. *PloS One, 11*(3), e0149839. doi:10.1371/journal.pone.0149839

Hagstrom, A. D., & Shorter, K. A. (2018). Creatine kinase, neuromuscular fatigue, and the contact codes of football: A systematic review and meta-analysis of pre and post-match differences. *European Journal of Sport Science, 18*(9), 1234-1244. doi:10.1080/17461391.2018.1480661

Halson, S. L. (2014). Monitoring training load to understand fatigue in athletes. *Sports Medicine, 44*, 139–47.

Hamdan, M., & Raja Azidin, R. M. F. (2020). Reflecting on side cutting variability on ACL injury risk: a case study. *Malaysian Journal of Movement, Health & Exercise, 9*(1), 77-88.

Hamill, J., van Emmerik, R. E. A., Heiderscheit, B. C., & Li, L. (1999). A dynamical systems approach to lower extremity running injuries. *Clinical Biomechanics, 14*(5), 297-308. doi:10.1016/S0268-0033(98)90092-4

Hanson, A., Padua, D., Blackburn, J., Prentice, W., & Hirth, C. (2008), Muscle activation during side-step cutting maneuvers in male and female soccer athletes. *Journal of Athletic Training, 43*(2), 133-143. doi:10.4085/1062-6050-43.2.133

Harmer, A. R., Ruell, P. A., Hunter, S. K., McKenna, M. J., Thom, J. M., Chisholm, D. J., & Flack, J. R. (2014). Effects of type 1 diabetes, sprint training and sex on skeletal muscle sarcoplasmic reticulum Ca2+ uptake and Ca2+-ATPase activity. *The Journal of Physiology, 592(*3), 523-535. doi:10.1113/jphysiol.2013.261172

Harper, D. J., Carling, C., & Kiely, J. (2019). High-intensity acceleration and deceleration demands in elite team sports competitive match play: A systematic review and meta-analysis of observational studies. *Sports Medicine, 49*(12), 1923-1947. doi:10.1007/s40279-019-01170-1

Harry, J. R., Freedman Silvernail, J., Mercer, J. A., & Dufek, J. S. (2017). Comparison of pre-contact joint kinematics and vertical impulse between vertical jump landings and step-off landings from equal heights. *Human Movement Science, 56,* 88-97. doi:10.1016/j.humov.2017.10.022

Hartmann, A., Knols, R., Murer, K., & de Bruin, E. D. (2009). Reproducibility of an isokinetic strength-testing protocol of the knee and ankle in older adults. *Gerontology, 55*(3), 259-268.

Hatamoto, Y., Yamade, Y., Fujii, T., Higaki, Y., Kiyonaga, A., & Tanaka, H. (2013). A novel method for calculating the energy cost of turning during running. *Open Access Journal of Sports Medicine, 4,* 117-122*.*

Hausler, J., Halaki, M., & Orr, R. (2016). Application of global positioning system and microsensor technology in competitive rugby league match-play: A systematic review and meta-analysis. *Sports Medicine, 46*(4), 559-588. doi:10.1007/s40279-015-0440-6.

Havens, K. L., & Sigward, S. M. (2015). Joint and segmental mechanics differ between cutting maneuvers in skilled athletes. *Gait and Posture, 41*(1), 33-38. doi:10.1016/j.gaitpost.2014.08.005.

Hawkins, R., Hulse, M., Wilkinson, C., Hodson, A., & Gibson, M. (2001). The association football medical research programme: An audit of injuries in professional football. *British Journal of Sports Medicine, 35*(1), 43-47. doi:10.1136/bjsm.35.1.43

Heidari, J., Beckmann, J., Bertollo, M., Brink, M., Kallus, K. W., Robazza, C., & Kellmann, M. (2019). Multidimensional monitoring of recovery status and implications for performance. *International Journal of Sports Physiology and Performance, 14*(1), 2-8. doi:10.1123/ijspp.2017-0669

Heled, Y., Bloom, M. S., Wu, T. J., Stephen, Q., & Deuster, P. A. (2007). CK-MM and ACE genotypes and physiological prediction of the creatine kinase response to exercise. *Journal of Applied Physiology, 103*(4), 504.

Henriksen, M., Alkjaer, T., Lund, H., Simonsen, E. B., Graven-Nielsen, T., Danneskiold-Samsoe, B., & Bliddal, H. (2007) Experimental quadriceps muscle pain impairs knee joint control during walking. *Journal of Applied Physiology, 103*, 132–139

Hewett, T. E. (2000). Neuromuscular and hormonal factors associated with knee injuries in female athletes. Strategies for intervention. *Sports Medicine, 29,* 313-327.

Hewett, T. E., Ford, K. R., Hoogenboom, B. J., & Myer, G. D. (2010). Understanding and preventing ACL injuries: Current biomechanical and epidemiologic considerations – updates 2010. *North American Journal of Sports Physical Therapy, 5*(4), 234-251.

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., McLean, S. G., . . . Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *The American Journal of Sports Medicine, 33*(4), 492-501. doi:10.1177/0363546504269591

Hewett, T. E., Torg, J. S., & Boden, B. P. (2009). Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: Lateral trunk and knee abduction motion are combined components of the injury mechanism. *British Journal of Sports Medicine, 43(*6), 417-422. doi:10.1136/bjsm.2009.059162

Hewit, J., Cronin, J., Button, C. & Hume, P. (2011). Understanding deceleration in sport. *Strength and Conditioning Journal, 33*(1), 47-52.

Hicks, K., Onambele-Pearson, G., Winwood, K., & Morse, C. (2017). Oral contraceptive pill use and the susceptibility to markers of exercise-induced muscle damage. *European Journal of Applied Physiology, 117*(7), 1393-1402. doi:10.1007/s00421-017-3629-6

Highton, J. M., Twist, C., & Eston, R. G. (2009). The effects of exercise-induced muscle damage on agility and sprint running performance. *Journal of Exercise Science & Fitness, 7*(1), 24-30. doi:10.1016/S1728-869X(09)60004-6Link

Highton, J., Mullen, T., Norris, J., Oxendale, C., & Twist, C. (2017). The unsuitability of energy expenditure derived from microtechnology for assessing internal load in collision-based activities. *International Journal of Sports Physiology and Performance, 12*(2), 264-267. doi:10.1123/ijspp.2016-0069.

Hind, K., Konerth, N., Entwistle, I., Theadom, A., Lewis, G., King, D., Chazot, P., & Hume, P. (2020). Cumulative sport-related injuries and longer term impact in retired male elite- and amateur-level rugby code athletes and non-contact athletes: A retrospective study. *Sports Medicine (Auckland),* 50(11), 2051-2061. https://doi.org/10.1007/s40279-020-01310-y

Hody, S., Croisier, J., Bury, T., Rogister, B., & Leprince, P. (2019). Eccentric muscle contractions: Risks and benefits. *Frontiers in Physiology, 10*, 536. Doi:10.3389/fphys.2019.00536

Hof, A. L. (2008). The ‘extrapolated center of mass’ concept suggests a simple control of balance in walking. *Human Movement Science, 27*(1), 112-125. doi:10.1016/j.humov.2007.08.003

Hogarth, L. W., Burkett, B. J., & McKean, M. R. (2015) Understanding the fatigue-recovery cycle in team sport athletes. *Journal of Sports Medicine and Doping Studies, 5*(1), 1000e143. doi:10.4172/2161-0673.1000e143.

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine, 30*(1), 1-15.

Hoppe, M. W., Baumgart, C., Slomka, M., Polglaze, T., & Freiwald, J. (2017). Variability of metabolic power data in elite soccer players during pre-season matches. *Journal of Human Kinetics, 58*(1), 233-245. doi:10.1515/hukin-2017-0083

Horita, T., Komi, P., Nicol, C., & Kyröläinen, H. (2002). Interaction between pre-landing activities and stiffness regulation of the knee joint musculoskeletal system in the drop jump: Implications to performance. *European Journal of Applied Physiology, 88*(1), 76-84. doi:10.1007/s00421-002-0673-6

Houck, J. R., Duncan, A., & De Haven, K. E. (2005). Knee and hip angle and moment adaptations during cutting tasks in subjects with anterior cruciate ligament deficiency classified as noncopers. *The Journal of Orthopaedic and Sports Physical Therapy, 35(*8), 531

Howatson, G., & Milak, A. (2009). Exercise-induced muscle damage following a bout of sport specific repeated sprints. *Journal of Strength and Conditioning Research, 23*(8), 2419-2424. doi:10.1519/JSC.0b013e3181bac52e

Hubal, M., & Clarkson, P. (2009). counterpoint: Estrogen and sex do not significantly influence post-exercise indexes of muscle damage, inflammation, and repair. *Journal of Applied Physiology, 106*(3), 1012-1014. doi:10.1152/japplphysiol.90848.2008a

Hughes, J. D., Denton, K., S. Lloyd, R., Oliver, J. L., & De Ste Croix, M. (2018). The impact of soccer match play on the muscle damage response in youth female athletes. *International Journal of Sports Medicine, 39*(5), 343-348. doi:10.1055/s-0044-101147

Hulin, B., Gabbett, T., Kearney, S., & Corvo, A. (2015). Physical demands of match play in successful and less-successful elite rugby league teams. *International Journal of Sports Physiology and Performance, 10*(6), 703-710. doi:10.1123/ijspp.2014-0080.

Hunter, F., Bray, J., Towlson, C., Smith, M., Barrett, S., Madden, J., … & Lovell, R. (2015). Individualisation of time-motion analysis: a method comparison and case report series. *International Journal of Sports Medicine, 36*(1), 41–48.

Hunter, S. K. (2009). Sex differences and mechanisms of task-specific muscle fatigue. *Exercise and Sport Sciences Reviews, 37*(3), 113-122. doi:10.1097/jes.0b013e3181aa63e2

Hunter, S. K. (2014). Sex differences in human fatigability: Mechanisms and insight to physiological responses. *Acta Physiologica, 210*(4), 768-789. doi:10.1111/apha.12234

Hunter, S. K. (2016). Sex differences in fatigability of dynamic contractions. *Experimental Physiology, 101*(2), 250-255. doi:10.1113/ep085370

Hunter, S. K. (2018). Performance fatigability: Mechanisms and task specificity. *Cold Spring Harbor Perspectives in Medicine, 8(*7), a029728. doi:10.1101/cshperspect.a029728

Hyldahl, R. D., & Hubal, M. J. (2014). Lengthening our perspective: Morphological, cellular, and molecular responses to eccentric exercise. *Muscle & Nerve, 49*(2), 155-170. doi:10.1002/mus.24077

Iacono, A. D., Martone, D., Cular, D., Milic, M., & Padulo, J. (2017). Game-profile-based training in soccer: A new field approach. *Journal of Strength and Conditioning Research, 31*(12), 3333-3342. doi:10.1519/JSC.0000000000001768.

Iguchi, J., Tateuchi, H., Taniguchi, M., & Ichihashi, N. (2014). The effect of sex and fatigue on lower limb kinematics, kinetics and muscle activity during unanticipated side-step cutting. *Knee Surgery, Sports Traumatology, Arthroscopy, 22*(1), 41-48. doi:10.1007/s00167-013-2526-8

Impellizzeri, F. M., Marcora, S. M., & Coutts, A. J. (2019). Internal and external training load: 15 years on. *International Journal of Sports Physiology and Performance, 14*(2), 270-273. doi:10.1123/ijspp.2018-0935

Impellizzeri, F. M., Rampinini, E., & Marcora, S. M. (2005). Physiological assessment of aerobic training in soccer. *Journal of Sports Sciences, 23*(6), 583-592. doi:10.1080/02640410400021278

Impellizzeri, F. M., Rampinini, E., & Marcora, S. M. (2007). Physiological assessment of aerobic training in soccer. *Journal of Sports Sciences, 23*(6), 583-592. doi:10.1080/02640410400021278

Impellizzeri, F., Rampinini, E., Coutts, A., Sassi, A., & Marcora, S. (2004). Use of RPE-based training load in soccer. *Medicine and Science in Sports and Exercise, 36*(6), 1042-1047.

Imwalle, L. E., Myer, G. D., Ford, K. R., & Hewett, T. E. (2009). Relationship between hip and knee kinematics in athletic women during cutting maneuvers: A possible link to noncontact anterior cruciate ligament injury and prevention. *Journal of Strength and Conditioning Research, 23*(8), 2223-2230. doi:10.1519/JSC.0b013e3181bc1a02

Ishii, H., Nagano, Y., Ida, H., Fukubayashi, T., & Maruyama, T. (2011). Knee kinematics and kinetics during shuttle run cutting: Comparison of the assessments performed with and without the point cluster technique. *Journal of Biomechanics, 44*(10), 1999-2003.

James, C. R. (2004). Considerations of movement variability in biomechanics research. In N. Stergiou (Ed.), *Innovative analyses of human movement* (pp. 29–62). Champaign, IL: Human Kinetics.

James, C. R., Dufek, J. S., & Bates, B. T. (2000). Effects of injury proneness and task difficulty on joint kinetic variability. *Medicine and Science in Sports and Exercise, 32(*11), 1833–1844

Jamison, S. T., Pan, X., & Chaudhari, A. M. W. (2012). Knee moments during run-to-cut maneuvers are associated with lateral trunk positioning. *Journal of Biomechanics, 45*(11), 1881-1885. doi:10.1016/j.jbiomech.2012.05.031

Jamkrajang, P., Robinson, M. A., Limroongreungrat, W., & Vanrenterghem, J. (2017). Can segmental model reductions quantify whole-body balance accurately during dynamic activities? *Gait & Posture, 56*, 37-41. doi:10.1016/j.gaitpost.2017.04.036

Jaspers, A., De Beeck, T., Brink, M., Frencken, W., Staes, F., Davis, J., & Helsen, W. (2018). Relationships between the external and internal training load in professional soccer: What can we learn from machine learning? *International Journal of Sports Physiology and Performance, 13*(5), 625-630. doi:10.1123/ijspp.2017-0299.

Jenkins, W. L., Williams, D. S. B., Williams, K., Hefner, J., & Welch, H. (2017). Sex differences in total frontal plane knee movement and velocity during a functional single-leg landing. *Physical Therapy in Sport, 24,* 1-6. doi:10.1016/j.ptsp.2016.09.005

Jennings, D., Cormack, S., Coutts, A. J., Boyd, L., & Aughey, R. J. (2010). The validity and reliability of GPS units for measuring distance in team sport specific running patterns. *International Journal of Sports Physiology and Performance, 5*(3), 328-341. doi:10.1123/ijspp.5.3.328.

Jennings, D., Cormack, S., Coutts, A., & Aughey, R. (2012). GPS analysis of an international field hockey tournament. *International Journal of Sports Physiology and Performance, 7*(3), 224-231. doi:10.1123/ijspp.7.3.224.

Johnston, R. D., Gabbett, T. J. & Jenkins, D. G. (2013). Influence of an intensified competition on fatigue and match performance in junior rugby league players. *Journal of Science and Medicine in Sport,16*(5), 460–5. doi:10.1016/j.jsams.2012.10.009.

Johnston, R. D., Gabbett, T. J., & Jenkins, D. G. (2015). Influence of playing standard and physical fitness on activity profiles and post-match fatigue during intensified junior rugby league competition. *Sports medicine, 1*(1), 18.

Johnston, R. D., Gibson, N.V., Twist, C., Gabbett, T. J., Macnay, S. A., & Macfarlane, N. G. (2013). Physiological responses to an intensified period of rugby league competition. *Journal of Strength and Conditioning Research, 27*(3), 643–54. 10.1519/JSC.0b013e31825bb469.

Johnston, R. J., Watsford, M. L., Kelly, S. J., Pine, M. J., & Spurrs, R. W. (2014). Validity and interunit reliability of 10 Hz and 15 Hz GPS units for assessing athlete movement demands. *Journal of Strength and Conditioning Research*, *28*(6), 1649-1655.

Johnston, R., Gabbett, T., Jenkins, D., & Hulin, B. (2015). Influence of physical qualities on post-match fatigue in rugby league players. *Journal of Science and Medicine in Sport, 18*(2), 209-213.

Johnston, R., Gabbett, T., Seibold, A., & Jenkins, D. (2014). Influence of physical contact on neuromuscular fatigue and markers of muscle damage following small-sided games. *Journal of Science and Medicine in Sport, 17*(5), 535-540.

Jones, C. M., Griffiths, P. C., & Mellalieu, S. D. (2017). Training load and fatigue marker associations with injury and illness: A systematic review of longitudinal studies. *Sports Medicine, 47*(5), 943-974. doi:10.1007/s40279-016-0619-5

Jones, M. R., West, D. J., Crewther, B. T., Cook, C. J., & Kilduff, L. P. (2015). Quantifying positional and temporal movement patterns in professional rugby union using global positioning system. *European Journal of Sport Science, 15*(6), 488-496. doi:10.1080/17461391.2015.1010106.

Jones, M. R., West, D. J., Harrington, B. J., Cook, C. J., Bracken, R. M., Shearer, D. A., & Kilduff, L. P. (2014). Match play performance characteristics that predict post-match creatine kinase responses in professional rugby union players. *BMC Sports Science, Medicine & Rehabilitation, 6*(1), 38-38. doi:10.1186/2052-1847-6-38

Jones, P. A., Herrington, L. C., & Graham-Smith, P. (2015). Technique determinants of knee joint loads during cutting in female soccer players. *Human Movement Science, 42,* 203-211. doi:10.1016/j.humov.2015.05.004

Joseph, A. M., Collins, C. L., Henke, N. M., Yard, E. E., Fields, S. K., & Comstock, R. D. (2013). A multisport epidemiologic comparison of anterior cruciate ligament injuries in high school athletics. *Journal of Athletic Training, 48*(6), 810-817. doi:10.4085/1062-6050-48.6.03

Juel, C., Pilegaard, H., Nielsen, J. J., Bangsbo, J. (2000). Interstitial K+ in human skeletal muscle during and after dynamic graded exercise determined by microdialysis. *American Journal of Physiology – Regulatory, Integrative and Comparative, 278*(2), 400-406.

Kanda, K., Sugama, K., Hayashida, H., Sakuma, J., Kawakami, Y., Miura, S., … Suzuki, K. (2013). Eccentric exercise-induced delayed-onset muscle soreness and changes in markers of muscle damage and inflammation. *Exercise Immunology Review, 19,* 72-85.

Kawamura, T., Suzuki, K., Takahashi, M., Tomari, M., Hara, R., Gando, Y., & Muraoka, I. (2018). Involvement of neutrophil dynamics and function in exercise-induced muscle damage and delayed-onset muscle soreness: Effect of hydrogen bath. *Antioxidants, 7*(10), 127. doi:10.3390/antiox7100127.

Keane, K. M., Salicki, R., Goodall, S., Thomas, K., & Howatson, G. (2015). Muscle damage response in female collegiate athletes after repeated sprint activity. *Journal of Strength and Conditioning Research, 29*(10), 2802-2807. doi:10.1519/JSC.0000000000000961

Kellis, E., & Kouvelioti, V. (2009). Agonist versus antagonist muscle fatigue effects on thigh muscle activity and vertical ground reaction during drop landing. *Journal of Electromyography and Kinesiology, 19*(1), 55-64.

Kelly, S. Murphy, A., Watsford, M., Austin, D. & Rennie, M. (2015). Reliability and validity of sports accelerometers during static and dynamic testing. *International Journal of Sports Physiology and Performance, 10*(1), 106-111. doi:10.1123/ijspp.2013-0408.

Kempton, T., Sirotic, A., & Coutts, A. (2014). Between match variation in professional rugby league competition. *Journal of Science and Medicine in Sport, 17*(4), 404-407

Kempton, T., Sirotic, A., Rampinini, E., & Coutts, A. (2015). Metabolic power demands of rugby league match play. *International Journal of Sports Physiology and Performance, 10*(1), 23-28. doi:10.1123/ijspp.2013-0540.

Kernozek, T., Torry, M., & Iwasaki, M. (2008). Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue. *American Journal of Sports Medicine, 36*(3), 554-565. doi:10.1177/0363546507308934

Khalid, A. J., Ian Harris, S., Michael, L., Joseph, H., & Qu, X. (2015). Effects of neuromuscular fatigue on perceptual-cognitive skills between genders in the contribution to the knee joint loading during side-stepping tasks. *Journal of Sports Sciences, 33*(13), 1322-1331. doi:10.1080/02640414.2014.990485

Khan, M. A., Moiz, J. A., Raza, S., Verma, S., Shareef, M. Y., Anwer, S., . . . Alghadir, A. (2016). Physical and balance performance following exercise induced muscle damage in male soccer players. *Journal of Physical Therapy Science, 28*(10), 2942-2949. doi:10.1589/jpts.28.2942

Kiapour, A. M., Kiapour, A., Goel, V. K., Quatman, C. E., Wordeman, S. C., Hewett, T. E., & Demetropoulos, C. K. (2015). Uni-directional coupling between tibiofemoral frontal and axial plane rotation supports valgus collapse mechanism of ACL injury. *Journal of Biomechanics, 48*(10), 1745-1751.

Kiapour, A., Quatman, C., Goel, V., Wordeman, S., Hewett, T., & Demetropoulos, C. (2014). Timing sequence of multi-planar knee mechanics revealed by physiologic cadaveric simulation of landing: Implications for ACL injury mechanism. *Clinical Biomechanics, 29*(1), 75-82. doi:10.1016/j.clinbiomech.2013.10.017

Kipp, K., McLean, S. G., & Palmieri-Smith, R. M. (2011). Patterns of hip flexion motion predict frontal and transverse plane knee torques during a single-leg land-and-cut maneuver. *Clinical Biomechanics, 26*(5), 504-508. doi:10.1016/j.clinbiomech.2011.01.004

Kirkendall, D. T., & Garrett, W. E. (2000). The anterior cruciate ligament enigma. Injury mechanisms and prevention. *Clinical Orthopaedics and Related Research, 372,* 64-68.

Kluger, B. M., Krupp, L. B., & Enoka, R. M. (2013). Fatigue and fatigability in neurologic illnesses: proposal for a unified taxonomy. *Neurology, 80*(4), 409–16.

Kobayashi, H., Kanamura, T., Koshida, S., Miyashita, K., Okado, T., Shimizu, T., & Yokoe, K. (2010). Mechanisms of the anterior cruciate ligament injury in sports activities: A twenty-year clinical research of 1,700 athletes. *Journal of Sports Science and Medicine, 9*(4), 669-675.

Kobayashi, H., Kanamura, T., Koshida, S., Miyashita, K., Okado, T., Shimizu, T., & Yokoe, K. (2010). Mechanisms of anterior cruciate ligament injury in sports activities: A twenty-year clinical research of 1,700 athletes. *Journal of Sports Science and Medicine, 9*(4), 669-675.

Koga, H., Nakamae, A., Shima, Y., Iwasa, J., Myklebust, G., Engebretsen, L., … Krosshaug, T. (2010). Mechanisms for noncontact anterior cruciate ligament injuries knee joint kinematics in 10 injury situations from female team handball and basketball. *American Journal of Sports Medicine, 38*(11), 2218-2225. doi:10.1177/0363546510373570

Komi, P. V. (2000). Stretch-shortening cycle: A powerful model to study normal and fatigued muscle. *Journal of Biomechanics, 33*(10), 1197–1206. doi: 10.1016/S0021-9290(00)00064-6

Kristianslund, E., & Krosshaug, T. (2013). Comparison of drop jumps and sport-specific sidestep cutting: Implications for anterior cruciate ligament injury risk screening. *The American Journal of Sports Medicine, 41*(3), 684-688. doi:10.1177/0363546512472043

Kristianslund, E., Faul, O., Bahr, R., Myklebust, G., & Krosshaug, T. (2014). Sidestep cutting technique and knee abduction loading: Implications for ACL prevention exercises. *British Journal of Sports Medicine, 48*(9), 779-783. doi:10.1136/bjsports-2012-091370

Kristianslund, E., Krosshaug, T., & van den Bogert, Antonie J. (2011). Effect of low pass filtering on joint moments from inverse dynamics: Implications for injury prevention. *Journal of Biomechanics, 45*(4), 666-671. doi:10.1016/j.jbiomech.2011.12.011

Kristianslund, E., Krosshaug, T., Mok, K., McLean, S., & van den Bogert, A. J. (2014). Expressing the joint moments of drop jumps and sidestep cutting in different reference frames – does it matter? *Journal of Biomechanics, 47*(1), 193-199. doi:10.1016/j.jbiomech.2013.09.016

Krosshaug, T., Nakamae, A., Boden, B., Engebretsen, L., Smith, G., Slauterbeck, J., … Bahr, R. (2007). Mechanisms of anterior cruciate ligament injury in basketball – video analysis of 39 cases. *American Journal of Sports Medicine, 35*(3), 359-367. doi:10.1177/0363546506293899

Kruschke, J.K. (2010). What to believe: Bayesian methods for data analysis. *Trends in Cognitive Science, 14(*7),293–300.

Krustrup, P., Mohr, M., Steensberg, A., Bencke, J., Kjaer, M., & Bangsbo, J. (2006). Muscle and blood metabolites during a soccer game: Implications for sprint performance. *Medicine and Science in Sports and Exercise, 38*(6), 1165-1174.

Krustrup, P., Zebis, M., Jensen, J. M., & Mohr, M. (2010). Game-induced fatigue patterns in elite female soccer. *Journal of Strength and Conditioning Research, 24*(2), 437-441.

Kulas, A., Zalewski, P., Hortobagyi, T., & De Vita, P. (2008). Effects of added trunk load and corresponding trunk position adaptations on lower extremity biomechanics during drop-landing. *Journal of Biomechanics, 41*(1), 180-185.

Kyröläinen, H., Avela, J. & Komi, P. V. (2005). Changes in muscle activity with increasing running speed. *Journal of Sports Sciences, 23*(10), 1101-1109. doi:10.1080/02640410400021575

Lamb, K. L., & Rogers, L. (2007). A re-appraisal of the reliability of the 20 m multi-stage shuttle run test. *European Journal of Applied Physiology, 100*(3), 287-292. doi:10.1007/s00421-007-0432-9

Landry, S., McKean, K., Hubley-Kozey, C., Stanish, W., & Deluzio, K. (2007). Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated run and crosscut maneuver. *American Journal of Sports Medicine, 35*(11), 1901-1991. doi:10.1177/0363546507307400

Laurent, C. M., Green, J. M., Bishop, P. A., Sjökvist, J., Schumacker, R. E., Richardson, M. T., & Curtner-Smith, M. (2010). Effect of gender on fatigue and recovery following maximal intensity repeated sprint performance. *Journal of Sports Medicine and Physical Fitness, 50*, 243-253.

Lavender, A. P., & Nosaka, K. (2006). Changes in fluctuation of isometric force following eccentric and concentric exercise of the elbow flexors. *European Journal of Applied Physiology, 96*, 235–240. doi:10.1007/s00421-005-0069-5.

Lee, A., Baxter, J., Eischer, C., Gage, M., Hunter, S., & Yoon, T. (2017). Sex differences in neuromuscular function after repeated eccentric contractions of the knee extensor muscles. *European Journal of Applied Physiology, 117*(6), 1119-1130. doi:10.1007/s00421-017-3599-8

Lephart, S. M., Pincivero, D. M., & Rozzi, S. L. (1998). Proprioception of the ankle and knee, *Sports Medicine, 25*(3), 149-155.

Leppänen, M., Pasanen, K., Krosshaug, T., Kannus, P., Vasankari, T., Kujala, U. M., . . . Parkkari, J. (2017). Sagittal plane hip, knee, and ankle biomechanics and the risk of anterior cruciate ligament injury: A prospective study. *Orthopaedic Journal of Sports Medicine, 5*(12), 2325967117745487. doi:10.1177/2325967117745487

Lima, L. C. R., & Denadai, B. S. (2015). Attenuation of eccentric exercise-induced muscle damage conferred by maximal isometric contractions: A mini review. *Frontiers in Physiology, 6*, 300-300. doi:10.3389/fphys.2015.00300

Little, T. & Williams, A. G. (2007). Effects of sprint duration and exercise: Rest ratio on repeated sprint performance and physiological responses in professional soccer players. *Journal of Strength and Conditioning Research, 21*(2), 646-648.

López-Valenciano, A., Ruiz-Pérez, I., Garcia-Gómez, A., Vera-Garcia, F. J., De Ste Croix, M., Myer, G. D., & Ayala, F. (2020). Epidemiology of injuries in professional football: A systematic review and meta-analysis. *British Journal of Sports Medicine, 54*(12), 711-718. doi:10.1136/bjsports-2018-099577

Lovell, R., Midgley, A., Barrett, S., Carter, D., & Small, K. (2011). Effects of different half-time strategies on second half soccer-specific speed, power and dynamic strength. *Scandinavian Journal of Medicine & Science in Sport, 23*(1), 105-113.

Lucci, S., Cortes, N., Van Lunen, B., Ringleb, S., & Onate, J. (2011). Knee and hip sagittal and transverse plane changes after two fatigue protocols. *Journal of Science and Medicine in Sport, 14*(5), 453-459. doi:10.1016/j.jsams.2011.05.001

Lund, H., Sondergaard, K., Zachariassen, T., Christensen, R., Bulow, P., Henriksen, M., Bliddal, H. (2005). Learning effect of isokinetic measurements in healthy subjects, and reliability and comparability of biodex and lido dynamometers. *Clinical Physiology and Functional Imaging, 25*(2), 75-82.

Lyons, S., Richardson, M., Bishop, P., Smith, J., Heath, H., & Giesen, J. (2006). Excess post-exercise oxygen consumption in untrained males: Effects of intermittent durations of arm ergometry. *Applied Physiology, Nutrition and Metabolism, 31*(3), 196-201.

Lythe, J., & Kilding, A. E. (2011). Physical demands and physiological responses during elite field hockey. *International Journal of Sports Medicine, 32*(7), 523-528.

Mador, M. J., Kufel, T. J. Pineda, L. A., & Sharma, G. K. (2000). Diaphragmatic fatigue and high-intensity exercise in patients with chronic obstructive pulmonary disease. *American Journal of Respiratory and Critical Care Medicine, 161*(1), 118-123.

Magal. M., Dumke, C. L., Urbiztondo, Z. G., Cavill, M. J., Triplett, N. T., Quindry, J. C… Epstein, Y. (2010). Relationship between serum creatine kinase activity following exercise-induced muscle damage and muscle fibre composition. *Journal of Sports Sciences, 28*(3), 257-266.

Magalhães, J., Rebelo, A., Oliveira, E., Silva, J. R., Marques, F., & Ascensão, A. (2010). Impact of Loughborough intermittent shuttle test versus soccer match on physiological, biochemical and neuromuscular parameters. *European Journal of Applied Physiology, 108*(1), 39-48.

Maiolo, C., Melchiorri, G., Iacopino, L., Masala, S., & De Lorenzo, A. (2003). Physical activity energy expenditure measured using a portable telemetric device in comparison with a mass spectrometer. *British Journal of Sports Medicine, 37*(5), 445-447.

Majewski, M., Susanne, H., & Klaus, S. (2006). Epidemiology of athletic knee injuries: A 10-year study. *The Knee, 13*(3), 184-188. doi:10.1016/j.knee.2006.01.005

Malmström, E. M., Westergren, H., Fransson, P. A., Karlberg, M., & Magnusson, M. (2013) Experimentally induced deep cervical muscle pain distorts head on trunk orientation. *European Journal of Applied Physiology, 113*, 2487–2499

Malone, S., Mendes, B., Hughes, B., Roe, M., Devenney, S., Collins, K., & Owen, A. (2018). Decrements in neuromuscular performance and increases in creatine kinase impact training outputs in elite soccer players. *Journal of Strength and Conditioning Research, 32*(5), 1342-1351. doi:10.1519/JSC.0000000000001997

Manal, K., McClay, I., Stanhope, S., Richards, J., & Galinat, B. (2000). Comparison of surface mounted markers and attachment methods in estimating tibial rotations during walking: an in vivo study. *Gait & Posture, 11,* 38-45.

Manzi, V., Impellizzeri, F., & Castagna, C. (2014). Aerobic fitness ecological validity in elite soccer players: A metabolic power approach. *Journal of Strength and Conditioning Research, 28*(4), 914-919.

Marcora, S. M., & Staiano, W. (2010). The limit to exercise tolerance in humans: Mind over muscle? *European Journal of Applied Physiology, 109*(4), 763-770.

Markolf, K. L., Burchfield, D. M., Shapiro, M. M., Shepard, M. F., Finerman, G. A., & Slauterbeck, J. L. (1995). Combined knee loading states that generate high anterior cruciate ligament forces. *Journal of Orthopaedic Research, 13*(6), 930

Martin, D. T. & Anderson, M. B. (2000). Heart rate perceived exertion relationship during training and taper. *Journal of Sports Medicine and Physical Fitness, 40,* 201-208.

Mathiassen, S. E. (2006). Diversity and variation in biomechanical exposure: what is it, and why would we like to know? *Applied Ergonomics, 37*(4), 419-427. doi:10.1016/j.apergo.2006.04.006

McClay, I. S., Robinson, J. R., Andriacchi, T. P., Frederick, E. C., Gross, T., Martin, P., … Cavanagh, P. R. (1994). A profile of ground reaction forces in professional basketball. *Journal of Applied Biomechanics, 10,* 222-236.

McGawley, K., & Bishop, D.J. (2015). Oxygen uptake during repeated-sprint exercise. *Journal of Science and Medicine in Sport, 18*(2), 214-218.

McGovern, A., Dude, C., Munkley, D., Martin, T., Wallace, D., Feinn, R., … Garbalosa, J. (2015). Lower limb kinematics of male and female soccer players during a self-selected cutting maneuver: Effect of prolonged activity. *Knee, 22*(6), 510-516. doi:10.1016/j.knee.2015.05.005

McLaren, S. J., Macpherson, T. W., Coutts, A. J., Hurst, C., Spears, I. R., & Weston, M. (2018). The relationships between internal and external measures of training load and intensity in team sports: A meta-analysis. *Sports Medicine, 48(*3), 641-658. doi:10.1007/s40279-017-0830-z

McLaren, S. J., Weston, M., Smith, A., Cramb, R., & Portas, M. D. (2016). Variability of physical performance and player match load in professional rugby union. *Journal of Science and Medicine in Sport, 19*(6), 493-497. doi:10.1016/j.jsams.2015.05.010.

McLean, S. G., Huang, X., & van den Bogert A. J. (2005). Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: Implications for ACL injury. *Clinical Biomechanics, 20*(8), 863-870. doi:10.1016/j.clinbiomech.2005.05.007

McLean, S. G., Huang, X., Su, A., & van den Bogert, A. J. (2004). Sagittal plane biomechanics cannot injure the ACL during sidestep cutting. *Clinical Biomechanics, 19*(8), 828-838.

McLean, S. G., Lipfert, S. W., & Van den Bogert, A. J. (2004). Effect of gender and defensive opponent on the biomechanics of sidestep cutting. *Medicine and Science in Sports and Exercise, 36*(6), 1008-1016. doi:10.1249/01.mss.0000128180.51443.83

McLean, S., & Samorezov, J. (2009). Fatigue-induced ACL injury risk stems from a degradation in central control. *Medicine and Science in Sports and Exercise, 41*(8), 1661-1672.

McLean, S., Felin, R., Suedekum, N., Calabrese, G., Passerallo, A., & Joy, S. (2007). Impact of fatigue on gender-based high-risk landing strategies. *Medicine and Science in Sports and Exercise, 39*(3), 502-514.

McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011). Markers of postmatch fatigue in professional rugby league players. *Journal of Strength and Conditioning Research, 25*(4), 1030-1039. doi:10.1519/JSC.0b013e3181cc22ccLink

Melnyk, M., & Gollhofer, A. (2007). Submaximal fatigue of the hamstrings impairs specific reflex components and knee stability. *Knee Surgery, Sports Traumatology, Arthroscopy, 15*(5), 525-532. doi:10.1007/s00167-006-0226-3

Mendez-Villanueva, A., Edge, J., Suriano, R., Hamer, P., & Bishop, D. (2012). The recovery of repeated-sprint exercise is associated with PCr resynthesis, while muscle pH and EMG amplitude remain depressed. *PloS One, 7*(12), e51977. doi:10.1371/journal.pone.0051977

Mendez-Villanueva, A., Hamer, P., & Bishop, D. (2007). Fatigue responses during repeated sprints matched for initial mechanical output. *Medicine and Science in Sport & Exercise, 39,* 2219-2225.

Mendez-Villanueva, A., Hamer, P., & Bishop, D. (2008). Factors in repeated sprint exercise is related to muscle power factors and reduced neuromuscular activity. *European Journal or Applied Physiology, 103,* 411-419.

Mero, A. (1988). Blood lactate production and recovery from anaerobic exercise in trained and untrained boys. *European Journal of Applied Physiology and Occupational Physiology, 57*(6), 660.

Miladi, I., Temfemo, A., Mandengué, S. H., & Ahmaidi, S. (2011). Effect of recovery mode on exercise time to exhaustion, cardiorespiratory responses, and blood lactate after prior, intermittent supramaximal exercise. *Journal of Strength and Conditioning Research, 25*(1), 205-210. doi:10.1519/JSC.0b013e3181af5152

Miller, A. E., MacDougall, J. D., Tarnopolsky, M. A., & Sale, D. G. (1993). Gender differences in strength and muscle fibre characteristics. *European Journal of Applied Physiology and Occupational Physiology, 66*(3), 254.

Minett, G. M., & Duffield, R. (2014). Is recovery driven by central or peripheral factors? A role for the brain in recovery following intermittent-sprint exercise. *Frontiers in Physiology, 5*, 24. doi:10.3389/fphys.2014.00024

Minett, G. M., Diffield, R., Billaut, F., Cannon, J., Portus, M. R., & Marino, F. E. (2014). Cold-water immersion decreases cerebral oxygenation but improves recovery after intermittent-sprint exercise in the heat. *Scandinavian Journal of Medicine & Science in Sports, 24*(4), 656-666.

Minshull, C., Gleeson, N., Walters-Edwards, M., Eston, R., & Rees, D. (2007). Effects of acute fatigue on the volitional and magnetically-evoked electromechanical delay of the knee flexors in males and females. *European*

Journal of Applied Physiology, 100(4), 469-478. doi:10.1007/s00421-007-0448-1

Mizumura, K., & Taguchi, T. (2016). Delayed onset muscle soreness: Involvement of neurotrophic factors. *The Journal of Physiological Sciences, 66*(1), 43-52. doi:10.1007/s12576-015-0397-0

Mohr, M., Draganidis, D., Chatzinikolaou, A., Barbero-Álvarez, J. C., Castagna, C., … Douroudos, I. (2015). Muscle damage, inflammatory, immune and performance responses to three football games in 1 week in competitive male players. *European Journal of Applied Physiology*, 1-15

Mohr, M., Nordsborg, N., Nielsen, J. J., Pedersen, L. D., Fischer, C., Krustrup, P., & Bangsbo, J. (2004). Potassium kinetics in human muscle interstitium during repeated intense exercise in relation to fatigue. *European Journal of Physiology, 448*(4), 452-456.

Monks, M.R., Compton, C.T., Yetman, J.D., Power, K.E., and Button, D.C. 2017. Repeated sprint ability but not neuromuscular fatigue is dependent on short versus long duration recovery time between sprints in healthy males. *Journal of Science and Medicine in Sport, 20,* 600-605. doi:10.1016/j.jsams.2016.10.008. PMID:27825551.

Moran, K. A., & Marshall, B. M. (2006). Effect of fatigue on tibial impact acceleration and knee kinematics in drop jumps. *Journal of Medicine and Science in Sports & Exercise, 38,* 1836-1842

Morgan, D. L. (1990). New insights into the behaviour of muscle during active lengthening. *Biophysics Journal, 57*, 209-221.

Morgan, D. L., & Proske, U. (2006). Sarcomere popping requires stretch over a range where total tension decreases with length. *Journal of Physiology, 574*(2), 627- 8.

Mullen, T., Twist, C., & Highton, J. (2019). Stochastic ordering of simulated rugby match activity produces reliable movements and associated measures of subjective task load, cognitive and neuromuscular function. *Journal of Sports Sciences, 37*(21). doi:10.1080/02640414.2019.1646071

Myer, C. A., Torry, M. R., Peterson, D. S., Shelburne, K. B., Giphart, J. E., Krong, J. P., … Steadman, J. R. (2011). Measurements of tibiofemoral kinematics during soft and stiff drop landings using biplane fluoroscopy. *American Journal of Sports Medicine, 39*(8), 1714–1722.

Myer, G., Ford, K., Di Stasi, S., Foss, K., Micheli, L., & Hewett, T. (2015). High knee abduction moments are common risk factors for patellofemoral pain (PFP) and anterior cruciate ligament (ACL) injury in girls: Is PFP itself a predictor for subsequent ACL injury? *British Journal of Sports Medicine, 49*(2), 118-122. doi:10.1136/bjsports-2013-092536

Myer, G., Ford, K., Foss, K., Rauh, M., Paterno, M., & Hewett, T. (2014). A predictive model to estimate knee-abduction moment: Implications for development of clinically applicable patellofemoral pain screening tool in female athletes. *Journal of Athletic Training, 49*(3), 389-398. doi:10.4085/1062-6050-49.2.17

Naderi, A., Rezvani, M. H., & Degens, H. (2020). Foam rolling and muscle and joint proprioception after exercise-induced muscle damage. *Journal of Athletic Training, 55*(1), 58-64. doi:10.4085/1062-6050-459-18

Nagahara, R., Mizutani, M., Matsuo, A., Kanehisa, H., & Fukunaga, T. (2017). Association of step width with accelerated sprinting performance and ground reaction force. *International Journal of Sports Medicine, 38*(7), 534-540. doi:10.1055/s-0043-106191

Nagai, T., Sell, T. C., House, A. J., Abt, J. P., & Lephart, S. M. (2013). Knee proprioception and strength and landing kinematics during a single-leg stop-jump task. *Journal of Athletic Training, 48*(1), 31-38. doi:10.4085/1062-6050-48.1.14

Navacchia, A., Bates, N. A., Schilaty, N. D., Krych, A. J., & Hewett, T. E., (2019). Knee abduction and internal rotation moments increase ACL force during landing through the posterior slope of the tibia. *Journal of Orthopaedic Research, 37*(8). doi:10.1002/jor.24313

Nédélec, M., McCall, A., Carling, C., Legall, F., Berthoin, S., & Dupont, G. (2014). The influence of soccer playing actions on the recovery kinetics after a soccer match. *Journal of Strength and Conditioning Research, 28*(6), 1517-1523.

Nédélec, M., McCall, A., Carling, C., Legall, F., Berthoin, S., & Dupont, G. (2012). Recovery in soccer: Part I - post-match fatigue and time course of recovery. *Sports Medicine, 42*(12), 997-1015. doi:10.2165/11635270-000000000-00000

Nedergaard, N., Robinson, M., Eusterwiemann, E., Drust, B., Lisboa, P., & Vanrenterghem, J. (2017). The relationship between whole-body external loading and body-worn accelerometry during team-sport movements. *International Journal of Sports Physiology and Performance, 12*(1), 18-26. doi:10.1123/ijspp.2015-0712

Neilson, V., Ward, S., Hume, P., Lewis, G., & McDaid, A. (2019). Effects of augmented feedback on training jump landing tasks for ACL injury prevention: A systematic review and meta-analysis. *Physical Therapy in Sport, 39*, 126-135. doi:10.1016/j.ptsp.2019.07.004

Nevill, A., & Atkinson, G. (1997). Assessing agreement between measurements recorded on a ratio scale in sports medicine and sports science. *British Journal of Sports Medicine, 31*(4), 314-318.

Newham, D.J., McPhail, G., Mills, K. R., & Edwards, R. H. (1983). Ultrastructural changes after concentric and eccentric contractions of human muscle. *Journal of Neurological Science, 61*, 109-122.

Nguyen, A., Taylor, J. B., Wimbish, T. G., Keith, J. L., & Ford, K. R. (2018). Preferred hip strategy during landing reduces knee abduction moment in collegiate female soccer players. *Journal of Sport Rehabilitation, 27*(3), 213-217. doi:10.1123/jsr.2016-0026

Nguyen, H. X., & Tidball, J. G. (2003). Interactions between neutrophils and macrophages promote macrophage killing of rat muscle cells in vitro. *The Journal of Physiology, 547(*Pt 1), 125–132.

Nicol, C., Avela, J., & Komi, P. V. (2006). The stretch-shortening cycle: A model to study naturally occurring neuromuscular fatigue. *Sports Medicine, 36*(11), 977-999. doi:10.2165/00007256-200636110-00004

Nielsen, J., Krustrup, P., Nybo, L., Gunnarsson, T., Madsen, K., Daa Schroder, H., Bangsbo, J. & Ortenblad, N. (2012). Skeletal muscle glycogen content and particle size of distinct subcellular localizations in the recovery period after a high-level soccer match. *European Journal of Applied Physiology, 112*(10), 3559-3567.

Nielsen, O. B., & Clausen, T. (2000). The Na^+/K^+ pump protects muscle excitability and contractility during exercise. *Exercise and Sport Science Reviews, 28,* 159-164.

Nikolaidis, M. (2017). The effects of eccentric exercise on muscle damage and blood redox status in men and women. *Journal of Functional Morphology and Kinesiology, 2*(2), 20. doi:10.3390/jfmk2020020

Nikolaidis, P., Clemente, F., van der Linden, C., Rosemann, T., & Knechtle, B. (2018). Validity and reliability of 10-hz global positioning system to assess in-line movement and change of direction. *Frontiers in Physiology, 9,* 228. doi:10.3389/fphys.2018.00228.

Noakes, T. D., St Clair Gibson, A., Lambert, E. V. (2005). From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans: summary and conclusions. *British Journal of Sports Medicine, 39,* 120-124.

Nordin, A. D., & Dufek, J. S. (2019) Reviewing the Variability-Overuse Injury Hypothesis: Does Movement Variability Relate to Landing Injuries?, *Research Quarterly for Exercise and Sport, 90*(2), 190-205. doi:10.1080/02701367.2019.1576837

Nosaka, K., Newton, M., & Sacco, P. (2002). Delayed-onset muscle soreness does not reflect the magnitude of eccentric exercise-induced muscle damage. *Scandinavian Journal of Medicine & Science in Sports, 12*(6), 337-346.

O'Connor, D. (2002). Time-motion analysis of elite touch players. In T. Reilly, W. Spinks, & A. Murphy (Ed.), *Science and Football IV* (pp. 126-131). London: Routledge.

O'Connor, K., Johnson, C., & Benson, L. (2015). The effect of isolated hamstrings fatigue on landing and cutting mechanics. *Journal of Applied Biomechanics, 31*(4), 211-220.

Oh, Y., Lipps, D., Ashton-Miller, J., & Wojtys, E. (2012). What strains the anterior cruciate ligament during a pivot landing? *American Journal of Sports Medicine, 40*(3), 574-583. doi:10.1177/0363546511432544

Oliveira, A. S., Silva, P. B., Lund, M. E., Farina, D., & Kersting, U. G. (2017). Balance training enhances motor coordination during a perturbed sidestep cutting task. *The Journal of Orthopaedic and Sports Physical Therapy, 47*(11), 853-862. doi:10.2519/jospt.2017.6980

Olsen, O., Myklebust, G., Engebretsen, L., & Bahr, R. (2004). Injury mechanisms for anterior cruciate ligament injuries in team handball a systematic video analysis. *American Journal of Sports Medicine, 32*(4), 1002-1012.

Olson, M. W. (2020). Static loading of the knee joint results in modified single leg landing biomechanics. *PloS One, 15*(2), e0219648. doi:10.1371/journal.pone.0219648

Oosthuyse, T., & Bosch, A. (2017). The effect of gender and menstrual phase on serum creatine kinase activity and muscle soreness following downhill running. *Antioxidants, 6*(1), 16. doi:10.3390/antiox6010016

Ortiz, A., Olsen, S. L., Etnyre, B., Trudelle-Jackson, E. E., Bartlett, W., & Venegas-Rio, H. L. (2010). Fatigue effects on knee joint stability during two jump tasks in women. *Journal of Strength and Conditioning Research, 24*(4), 1019-1027.

Osgnach, C., Paolini, E., Roberti, V., Vettor, M., & di Prampero, P. E. (2016). Metabolic power and oxygen consumption in team sports: A brief response to buchheit et al. *International Journal of Sports Medicine, 37*(1), 77-81. doi:10.1055/s-0035-1569321

Osgnach, C., Paolini, E., Roberti, V., Vettor, M., & di Prampero, P. E. (2016). Metabolic power and oxygen consumption in team sports: A brief response to buchheit et al. *International Journal of Sports Medicine, 37*(1), 77-81.

Osgnach, C., Poser, S., Bernardini, R., Rinaldo, R. & di Prampero, P. E. (2010). Energy cost and metabolic power in elite soccer: a new match analysis approach. *Medicine and Science in Sports and Exercise, 42,* 170-178.

Ostojic, S. M. (2004). Elite and non-elite soccer players: Pre-seasonal physical and physiological characteristics. *Research in Sport Medicine, 12*(2), 143-150.

Owens, D. J., Twist, C., Cobley, J. N., Howatson, G., & Close, G. L. (2019). Exercise-induced muscle damage: What is it, what causes it and what are the nutritional solutions? *European Journal of Sport Science: Exercise Nutrition for Health, 19*(1), 71-85. doi:10.1080/17461391.2018.1505957

Oxendale, C. L., Twist, C., Daniels, M., & Highton, J. (2016). The relationship between match-play characteristics of elite rugby league and indirect markers of muscle damage. *International Journal of Sports Physiology and Performance, 11*(4), 515-521. doi:10.1123/ijspp.2015-0406

Padua, D. A., DiStefano, L. J., Beutler, A. I., de la Motte, Sarah J, DiStefano, M. J., & Marshall, S. W. (2015). The landing error scoring system as a screening tool for an anterior cruciate ligament injury-prevention program in elite-youth soccer athletes. *Journal of Athletic Training, 50*(6), 589-595. doi:10.4085/1062-6050-50.1.10

Paes, M., & Fernandez, R. (2016). Evaluation of energy expenditure in forward and backward movements performed by soccer referees. *Brazilian Journal of Medicine and Biological Research, 49*(5), e5061.

Paquette, M. R., Peel, S. A., Schilling, B. K., Melcher, D. A., & Bloomer, R. J. (2017). Soreness-related changes in three-dimensional running biomechanics following eccentric knee extensor exercise. *European Journal of Sport Science, 17*(5), 546-554. doi:10.1080/17461391.2017.1290140

Paradisis, G. P., Zacharogiannis, E., Mandila, D., Smirtiotou, A., Argeitaki, P., & Cooke, C. B. (2014). Multi-stage 20-m shuttle run fitness test, maximal oxygen uptake and velocity at maximal oxygen uptake. *Journal of Human Kinetics, 41*(1), 81-87. doi:10.2478/hukin-2014-0035

Paschalis, V., Giakas, G., Baltzopoulos, V., Jamurtas, A. Z., Theoharis, V., Kotzamanidis, C., & Koutedakis, Y. (2007a). The effects of muscle damage following eccentric exercise on gait biomechanics. *Gait & Posture, 25*(2), 236-242. doi:10.1016/j.gaitpost.2006.04.002

Paschalis, V., Nikolaidis, M. G., Giakas, G., Jamurtas, A. Z., Pappas, A., & Koutedakis, Y. (2007b). The effect of eccentric exercise on position sense and joint reaction angle of the lower limbs. *Muscle & Nerve, 35*(4), 496-503. doi:10.1002/mus.20723

Pataky, T. C., Robinson, M. A., & Vanrenterghem, J. (2013). Vector field statistical analysis of kinematic and force trajectories. *Journal of Biomechanics, 46*(14), 2394-2401. doi:10.1016/j.jbiomech.2013.07.031

Paterno, M. V., Schmitt, L. C., Ford, K. R., Rauh, M. J., & Myer, G. (2010). Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *American Journal of Sports Medicine, 38*(10), 1968-1978.

Patrek, M. F., Kernozek, T. W., Willson, J. D., Wright, G. A., & Doberstein, S. T. (2011). Hip-abductor fatigue and single-leg landing mechanics in women athletes. *Journal of Athletic Training, 46*(1), 31-42. doi:10.4085/1062-6050-46.1.31

Paulsen, G., Crameri, R., Benestad, H. B., Field, J. G., Morkrid, L., Hallen, J., & Raastad, T. (2010a). Time course of leukocyte accumulation in human muscle after eccentric exercise. *Medicine and Science in Sport & Exercise, 42*, 75-85.

Paulsen, G., Egner, I. M., Drange, M., Langberg, H., Benestad, H. B., Field, J. G. … Raastad, T. (2010b). A COX-2 inhibitor reduces muscle soreness, but does not influence recovery and adaptation after eccentric exercise. *Scandinavian Journal of Medicine and Science in Sport, 20,* e195-e207.

Paulsen, G., Mikkelsen, U. R., Raastad, T., & Peake, J. M. (2012). Leucocytes, cytokines and satellite cells: What role do they play in muscle damage and regeneration following eccentric exercise? *Exercise Immunology Review, 18,* 42-97

Peake, J. M., Neubauer, O., Della Gatta, P. A., & Nosaka, K. (2017). Muscle damage and inflammation during recovery from exercise. *Journal of Applied Physiology, 122*(3), 559-570. doi:10.1152/japplphysiol.00971.2016Link

Perrey, S., Racinais, S., Saimouaa, K., & Girard, O. (2010). Neural and muscular adjustments following repeated running sprints. *European Journal of Applied Physiology, 109*(6), 1027-1036. doi:10.1007/s00421-010-1445-3

Podraza, J. T., & White, S. C. (2010). Effect of knee flexion angle on ground reaction forces, knee moments and muscle co-contraction during an impact-like deceleration landing: Implications for the non-contact mechanism of ACL injury. *The Knee, 17*(4), 291-295.

Polglaze, T., & Hoppe, M. (2019). Metabolic power: A step in the right direction for team sports. *International Journal of Sports Physiology and Performance, 14*(3), 407-411. doi:10.1123/ijspp.2018-0661.

Polglaze, T., Dawson, B., Buttfield, A., & Peeling, P. (2018a). Metabolic power and energy expenditure in an international men's hockey tournament. *Journal of Sports Sciences, 36*(2), 140-148. doi:10.1080/02640414.2017.1287933.

Polglaze, T., Dawson, B., Hiscock, D., & Peeling, P. (2015). A comparative analysis of accelerometer and time-motion data in elite men's hockey training and competition. *International Journal of Sports Physiology and Performance, 10*(4), 446-451. doi:10.1123/ijspp.2014-0233.

Polglaze, T., Hogan, C., Dawson, B., Buttfield, A., Osgnach, C., Lester, L., & Peeling, P. (2018b). Classification of intensity in team sport activity. *Medicine and Science in Sports and Exercise, 50*(7), 1487-1494. doi:10.1249/MSS.0000000000001575.

Pollard, C. D., Sigward, S. M., & Powers, C. M. (2010). Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. *Clinical Biomechanics, 25*(2), 142-146. doi:10.1016/j.clinbiomech.2009.10.005

Pollard, C. D., Sigward, S. M., & Powers, C. M. (2017). ACL injury prevention training results in modification of hip and knee mechanics during a drop-landing task. *Orthopaedic Journal of Sports Medicine, 5*(9), 232596711772626. doi:10.1177/2325967117726267

Pollard, C., Sigward, S., & Powers, C. (2007). Gender differences in hip joint kinematics and kinetics during side-step cutting maneuver. *Clinical Journal of Sports Medicine, 17*(1), 38-42.

Portas, M., Harley, J., Barnes, C., & Rush, C. (2010). The validity and reliability of 1 Hz and 5- Hz global positioning systems for linear, multi-directional, and soccer-specific activities. *International Journal of Sports Physiology and Performance, 5*(4), 448-458. doi:10.1123/ijspp.5.4.448.

Proske, U., & Gandevia, S. C. (2012). The proprioceptive senses: Their roles in signalling body shape, body position and movement, and muscle force. *Physiological Reviews, 92*(4), 1651-1697. doi:10.1152/physrev.00048.2011

Rago, V., Brito, J., Figueiredo, P., Krustrup, P., & Rebelo, A. (2020). Application of individualized speed zones to quantify external training load in professional soccer. *Journal of Human Kinetics, 72*(1), 279-289. doi:10.2478/hukin-2019-0113

Raja Azidin, R. M. F., Sankey, S., Drust, B., Robinson, M. A., & Vanrenterghem, J. (2015). Effects of treadmill versus overground soccer match simulation on biomechanical markers of anterior cruciate ligament injury risk in side cutting. *Journal of Sports Sciences, 33*(13), 1332-1341. doi:10.1080/02640414.2014.990491

Rampinini, E., Alberti, G., Fiorenza, M., Riggio, M., Sassi, R., Borges, T., & Coutts, A. (2015). Accuracy of GPS devices for measuring high-intensity running in field-based team sports. *International Journal of Sports Medicine, 36*(1), 49-53. doi:10.1055/s-0034-1385866

Rampinini, E., Bosio, A., Farrarsi, I., Petruolo, A., Morelli, A., & Sassi, A. (2011). Match-related fatigue in soccer players. *Medicine and Science in Sports and Exercise, 43*(11), 2161-2170. doi:10.1249/MSS.0b013e31821e9c5c

Rampinini, E., Coutts, A. J., Castagna, C., Sassi, R., & Impellizzeri, F. M. (2007). Variation in top level soccer match performance. *International Journal of Sports Medicine, 28*(12), 1018-1024. doi:10.1055/s-2007-965158

Ramsbottom, R., Brewer, J., & Williams, C. (1988). A progressive shuttle run test to estimate maximal oxygen uptake. *British Journal of Sports Medicine, 22*(4), 141-144. doi:10.1136/bjsm.22.4.141

Rawstorn, J., Maddison, R., Ali, A., Foskett, A., & Gant, N. (2014). Rapid directional change degrades GPS distance measurement validity during intermittent intensity running. *Plos One, 9*(4), e93693.

Reardon, C., Tobin, D., & Delahunt, E. (2015). Application of individualized speed thresholds to interpret position specific running demands in elite professional rugby union: A GPS study. *Plos One, 10*(7), e0133410. doi:10.1371/journal.pone.0133410.

Regueme, S. C., Nicol, C., Barthelemy, J. I., & Gerlot, L. (2005). Acute and delayed neuromuscular adjustments of the triceps surae muscle group to exhaustive stretch-shortening cycle fatigue. *European Journal of Applied Physiology,*

Richter, C., O׳Connor, N. E., Marshall, B., & Moran, K. (2014). Comparison of discrete-point vs. dimensionality-reduction techniques for describing performance-related aspects of maximal vertical jumping. *Journal of Biomechanics, 47*(12), 3012-3017. doi:10.1016/j.jbiomech.2014.07.001

Rinard, J., Clarkson, P. M., Smith, L. L., & Grossman, M. (2000). Response of males and females to high-force eccentric exercise. *Journal of Sports Sciences, 18*(4), 229-236. doi:10.1080/026404100364965

Roberts, S. P., Stokes, K. A., Trewartha, G., Doyle, J., Hogben, P. & Thompson, D. (2010). Effects of carbohydrate and caffeine ingestion on performance during a rugby union simulation protocol. *Journal of Sports Sciences, 28*(8), 833-842.

Robinson, M., & Vanrenterghem, J. (2012). An evaluation of anatomical and functional knee axis definition in the context of side-cutting. *Journal of Biomechanics, 45*(11), 1941-1946.

Rodríguez, F. A., & Iglesias, X. (1998). The energy cost of soccer: telemetric oxygen uptake measurements versus heart rate-VO_2 estimations. *Journal of Sports Sciences, 16*, 484-485.

Roe, G., Darrall-Jones, J., Till, K., Phibbs, P., Read, D., Weakley, J., & Jones, B. (2016). Between-days reliability and sensitivity of common fatigue measures in rugby players. *International Journal of Sports Physiology and Performance, 11*(5), 581-586. doi:10.1123/ijspp.2015-0413

Roe, G., Darrall-Jones, J., Till, K., Phibbs, P., Read, D., Weakley, J., … Jones, B. (2017). The effect of physical contact on changes in fatigue markers following rugby union field-based training. *European Journal of Sport Science, 17*(6), 647-655. doi:10.1080/17461391.2017.1287960

Roewer, B., Ford, K., Myer, G., & Hewett, T. (2014). The ‘impact’ of force filtering cut-off frequency on peak knee abduction moment during landing: Artefact or ‘artifiction’? *British Journal of Sports Medicine, 48*(6), 464-468. doi:10.1136/bjsports-2012-091398

Rogan, S., Radlinger, L., Imhasly, C., Kneubuehler, A., & Hifiker, R. (2015). Validity study of a jump mat compared to the reference standard force plate. *Asain Journal of Sports Medicine, 6*(4), e25561.

Ronglan, L. T., Raastad, T., & Borgesen, A. (2006). Neuromuscular fatigue and recovery in elite female handball players. *Scandinavian Journal of Medicine & Science in Sport, 16*(4), 267-273.

Ross, A., Leveritt, M., & Riek, S. (2001). Neural influences on sprint running: Training adaptations and acute responses. *Sports Medicine, 31,* 409-425.

Russell, M., Northeast, J., Atkinson, G., Shearer, D. A., Sparkes, W., Cook, C. J., & Kilduff, L. P. (2015). Between-match variability of peak power output and creatine kinase responses to soccer match-play. *Journal of Strength and Conditioning Research, 29*(8), 2079-2085. doi:10.1519/JSC.0000000000000852

Russell, M., Rees, G., Benton, D., & Kingsley, M. (2011). An exercise protocol that replicates soccer match-play. *International Journal of Sports Medicine, 32*(7), 511-518. doi:10.1055/s-0031-1273742

Russell, M., Sparkes, W., Northeast, J., Cook, C. J., Love, T. D., Bracken, R. M., & Kilduff, L. P. (2016). Changes in acceleration and deceleration capacity throughout professional soccer match-play. *Journal of Strength and Conditioning Research, 30*(10), 2839-2844. doi:10.1519/JSC.0000000000000805

Sankey, S. P., Robinson, M. A., & Vanrenterghem, J. (2020). Whole-body dynamic stability in side cutting: Implications for markers of lower limb injury risk and change of direction performance. *Journal of Biomechanics, 104*, 109711. doi:10.1016/j.jbiomech.2020.109711

Sankey, S., Raja Azidin, R., Robinson, M., Malfait, B., Deschamps, K., Verschueren, S.,… Vanrenterghem, J. (2015). How reliable are knee kinematics and kinetics during side-cutting manoeuvres? *Gait and Posture, 41*(4), 905-911. doi:10.1016/j.gaitpost.2015.03.014

Sanna, G., & O’Connor, K. M. (2008). Fatigue-related changes in stance leg mechanics during sidestep cutting maneuvers. *Clinical Biomechanics, 23*(7), 946-954. doi:10.1016/j.clinbiomech.2008.03.065

Savage, R. J., Lay, B. S., Wills, J. A., Lloyd, D. G., & Doyle, T. L. A. (2018). Prolonged running increases knee moments in sidestepping and cutting manoeuvres in sport. *Journal of Science and Medicine in Sport, 21*(5), 508-512. doi:10.1016/j.jsams.2017.07.007

Savage, T., Fantini, C., & Brüggemann, G. (2011). A comparison of muscular activation patterns during running and landing. *British Journal of Sports Medicine, 45*(4), 328-328. doi:10.1136/bjsm.2011.084038.51

Scherr, J., Wolfarth, B., Christle, J., Pressler, A., Wagenpfeil, S., & Halle, M. (2013). Associations between borg's rating of perceived exertion and physiological measures of exercise intensity. *European Journal of Applied Physiology, 113*(1), 147-155.

Schmitz, R. J., Cone, J. C., Tritsch, A. J., Pye, M. L., Montgomery, M. M., Hensen, R. A., & Shultz, S. J. (2014). Changes in drop-jump landing biomechanics during prolonged intermittent exercise. *Sports Health: A Multidisciplinary Approach, 6*(2), 128-135.

Scholes, C., McDonald, M., & Parker, A. (2012). Single-subject analysis reveals variation in knee mechanics during step landing. *Journal of Biomechanics, 45*(12), 2074-2078. doi:10.1016/j.jbiomech.2012.05.046

Scott, C. (2005). Misconceptions about aerobic and anaerobic energy expenditure. *Journal of the International Society of Sports Nutrition, 2*(2), 32-37.

Scott, C. B. (2006). Estimating energy expenditure for brief bouts of exercise with acute recovery. *Applied Physiology, Nutrition and Metabolism, 31*(2), 144-149.

Scott, M. T. U., Scott, T. J., & Kelly, V. G. (2016). The validity and reliability of global positioning systems in team sport: A brief review. *Journal of Strength and Conditioning Research*, *30*(5), 1470-1490. doi:10.1519/JSC.0000000000001221

Scott, T. J., Black, C. R., Quinn, J., & Coutts, A. J. (2013). Validity and reliability of the session-RPE method for quantifying training in australian football: A comparison of the CR10 and CR100 scales. *Journal of Strength and Conditioning Research, 27*(1), 270-276. doi:10.1519/JSC.0b013e3182541d2e.

Senefeld, J., Yoon, T., Bement, M. H., & Hunter, S. K. (2013). Fatigue and recovery from dynamic contractions in men and women differ for arm and leg muscles. *Muscle & Nerve, 48(*3), 436-439. doi:10.1002/mus.23836

Sheehan, F., Sipprell, W., & Boden, B. (2012). Dynamic sagittal plane trunk control during anterior cruciate ligament injury. *American Journal of Sports Medicine, 40*(5), 1068-1074.

Shimokochi, Y., & Shultz, S. (2008). Mechanisms of noncontact anterior cruciate ligament injury. *Journal of Athletic Training, 43*(4), 396-408.

Shimokochi, Y., Ambegaonkar, J. P., Meyer, E. G., Lee, S. Y., & Shultz, S. J. (2013). Changing sagittal plane body position during single-leg landings influences the risk of non-contact anterior cruciate ligament injury. *Knee Surgery, Sports Traumotology, Arthroscopy, 21*(4), 888-897.

Shin, C. S., Chaudhari, A. M., & Andriacchi, T. P. (2007). The influence of deceleration forces on ACL strain during single-leg landing: A simulation study. *Journal of Biomechanics, 40*(5), 1145-1152.

Shin, C. S., Chaudhari, A. M., & Andriacchi, T. P. (2011). Valgus plus internal rotation moments increase anterior cruciate ligament strain more than either alone. *Medicine and Science in Sport and Exercise, 43*(8), 1484-1491

Shultz, S. J., Schmitz, R. J., Cone, J. R., Henson, R. A., Montgomery, M. M., Pye, M. L., & Tritsch, A. J. (2015). Changes in fatigue, multiplanar knee laxity, and landing biomechanics during intermittent exercise. *Journal of Athletic Training, 50*(5), 486-497. doi:10.4085/1062-6050-49.5.08

Sigward, S. M., & Powers, C. M. (2006). The influence of gender on knee kinematic, kinetics and muscle activation patterns during side-step cutting. *Clinical Biomechanics, 21*(1), 41-48.

Sigward, S. M., & Powers, C. M. (2006). The influence of gender on knee kinematics, kinetics and muscle activation patterns during side-step cutting. *Clinical Biomechanics, 21*(1), 41-48. doi:10.1016/j.clinbiomech.2005.08.001

Sigward, S., Cesar, G., & Havens, K. (2015). Predictors of frontal plane knee moments during side-step cutting to 45 and 110 degrees in men and women: Implications for anterior cruciate ligament injury. *Clinical Journal of Sport Medicine, 25*(6), 529-534. doi:10.1097/JSM.0000000000000015

Silva, J. R., Ascensão, A., Marques, F., Seabra, A., Rebelo, A., & Magalhães, J. (2013). Neuromuscular function, hormonal and redox status and muscle damage of professional soccer players after a high-level competitive match. *European Journal of Applied Physiology, 113*(9), 2193-2201. doi:10.1007/s00421-013-2633-8

Silva, J. R., Silva, J. R., Rumpf, M. C., Rumpf, M. C., Hertzog, M., Hertzog, M., . . . Hader, K. (2018). Acute and residual soccer match-related fatigue: A systematic review and meta-analysis. *Sports Medicine, 48*(3), 539-583. doi:10.1007/s40279-017-0798-8

Sinclair, J., Taylor, P. J., & Hobbs, S. J. (2013). Digital filtering of three-dimensional lower extremity kinematics: An assessment. *Journal of Human Kinetics, 39*(1), 25-36. doi:10.2478/hukin-2013-0065.

Small, K., McNaughton, L., Greig, M., & Lovell, R. (2010). The effects of multidirectional soccer-specific fatigue on markers of hamstring injury risk. *Journal of Science and Medicine in Sport, 13*(1), 120-125.

Smith, L. (1992). Causes of delayed onset muscle soreness and the impact on athletic performance: A review. *Journal of Applied Sport Science Research, 6*(3), 135-141.

Smith, M., Sizer, P., & James, C. (2009). Effects of fatigue on frontal plane knee motion, muscle activity, and ground reaction forces in men and women during landing. *Journal of Sports Science and Medicine, 8*(3), 419-427.

Snyder, B. J., Hutchison, R. E., Mills, C. J., & Parsons, S. J. (2019). Effects of two competitive soccer matches on landing biomechanics in female division I soccer players. *Sports (Basel), 7*(11), 237. doi:10.3390/sports7110237.

Sorenson, B., Kernozek, T., Willson, J., Ragan, R., & Hove, J. (2015). Two- and three-demensional relationships between knee and hip kinematic motion analysis: Single-leg drop-jump landings. *Journal of Sport rehabilitation, 24*(4), 363-372. doi:10.1123/jsr.2014-0206

Souglis, A., Bogdanis, G. C., Chryssanthopoulos, C., Apostolidis, N., & Geladas, N. D. (2018). Time course of oxidative stress, inflammation, and muscle damage markers for 5 days after a soccer match: Effects of sex and playing position. *Journal of Strength and Conditioning Research, 32*(7), 2045-2054. doi:10.1519/JSC.0000000000002436

Spencer, M., Bishop, D., Dawson, B., & Goodman, C. (2005). Physiological and metabolic responses of repeated-sprint activities: Specific to field-based team sports. *Sports Medicine, 35*(12), 1025-1044.

Spiteri, T., Cochrane, J. L., Hart, N. H., Haff, G. G., & Nimphius, S. (2013). Effect of strength on plant foot kinetics and kinematics during a change of direction task. *European Journal of Sport Science, 13*(6), 646-652. doi:10.1080/17461391.2013.774053

Springham, M., Williams, S., Waldron, M., Strudwick, A. J., Mclellan, C., & Newton, R. U. (2020). Prior workload has moderate effects on high-intensity match performance in elite-level professional football players when controlling for situational and contextual variables. *Journal of Sports Sciences*, 1-12. doi:10.1080/02640414.2020.1778355

Stackhouse, S. K., Reisman, D. S., & Binder-Macleod, S. A. (2001). Challenging the role of pH in skeletal muscle fatigue. *Physical Therapy, 81*(12), 1897-1903. doi:10.1093/ptj/81.12.1897

Stanley, L., Kerr, Z., Dompier, T., & Padua, D. (2016). Sex differences in the incidence of anterior cruciate ligament, medial collateral ligament, and meniscal injuries in colleagiate and high school sports: 2009-2010 through 2013-2014. *American Journal of Sports Medicine, 44*(6), 1565-1572. doi:10.1177/0363546516630927

Staynor, J., Alderson, J., Cresswell, A., & Donnelly, C. (2018). Trunk muscle activation during planned and unplanned sidestepping: Implications for frontal plane trunk positioning and ACL injury risk. *Conference of the International Society of Biomechanics in Sports, 36*(1), 10-14

Stergiou N., & Decker, L. M. (2011). Human movement variability, nonlinear dynamics, and pathology: is there a connection? *Human Movement Science, 30*(5), 869–88.

Stern, A., Kuenze, C., Herman, D., Sauer, L., & Hart, J. (2012). A gender comparison of central and peripheral neuromuscular function after exercise. *Journal of Sport Rehabilitation, 21*(3), 209-217.

Stevens, T. G. A., De Ruiter, C. J., Van Maurik, D., Van Lierop, C. J. W., Savelsbergh, G. J. P. & Beek, P. J. (2015). Measured and estimated energy cost or constant and shuttle running in soccer players. *Medicine and Science in Sport and Exercise, 47*(6), 1219-1224.

Stolen, T., Chamari, K., Castagna, C. & Wisloff, U. (2005). Physiology of soccer. *Sports Medicine, 35,* 501-536.

Stovitz, S. D., & Shrier, I. (2012). Injury rates in team sport events: Tackling challenges in assessing exposure time. *British Journal of Sports Medicine, 46*(14), 960-963. doi:10.1136/bjsports-2011-090693

Strauss, A., Sparks, M., & Pienaar, C. (2019). The use of GPS analysis to quantify the internal and external match demands of semi-elite level female soccer players during a tournament. *Journal of Sports Science & Medicine, 18*(1), 73-81

Stuelcken, M. C., Mellifont, D. B., Gorman, A. D., & Sayers, M. G. L. (2016). Mechanisms of anterior cruciate ligament injuries in elite women's netball: A systematic video analysis. *Journal of Sports Sciences, 34*(16), 1516-1522.

Suarez-Arrones, L., Portillo, L., Gonzalez-Rave, J., Munoz, V., & Sanchez, F. (2012). Match running performance in Spanish elite male rugby union using global positioning system*. Isokinetics and Exercise Science, 20*(2), 77-83.

Swenson, D. M., Collins, C. L., Best, T. M., Flanigan, D. C., Fields, S. K., & Comstock, R. D. (2013). Epidemiology of knee injuries among us high school athletes, 2005/06–2010/11. *Medicine and Science in Sports and Exercise, 45*(3), 462-469. doi:10.1249/MSS.0b013e318277acca

Sykes, D., Nicholas, C., Lamb, K., & Twist, C. (2013). An evaluation of the external validity and reliability of a rugby league match simulation protocol. *Journal of Sports Sciences, 31*(1), 48-57. doi:10.1080/02640414.2012.720702

Symons, T., Vandervoort, A., Rice, C., Overend, T., & Marsh, G. (2005). Reliability of a single-session isokinetic and isometric strength measurement protocol in older men. *Journals of Gerontology Series a Biological Science and Medical Sciences, 60*(1), 114-119.

Szent-Györgyi, A., G. (1975). Calcium regulation of muscle contraction. *Biophysical Journal, 15*(7), 707-723.

Szucs, D., & Ioannidis, J. P. A. (2017). When null hypothesis significance testing is unsuitable for research: A reassessment. *Frontiers in Human Neuroscience, 11*, 390. doi:10.3389/fnhum.2017.00390

Tabata, I., Irisawa, K., Kouzaki, M., Nishimura, K., Ogita, F. & Miyachi, M. (1997). Metabolic profile of high intensity intermittent exercises. *Medicine and Science in Sports and Exercise, 29,* 390-395.

Tamura, A., Akasaka, K., Otsudo, T., Sawada, Y., Okubo, Y., Shiozawa, J., . . . Yamada, K. (2016). Fatigue alters landing shock attenuation during a single-leg vertical drop jump. *Orthopaedic Journal of Sports Medicine, 4*(1), 2325967115626412. doi:10.1177/2325967115626412

Tamura, A., Akasaka, K., Otsudo, T., Shiozawa, J., Toda, Y., & Yamada, K. (2017). Fatigue influences lower extremity angular velocities during a single-leg drop vertical jump. *Journal of Physical Therapy Science, 29*(3), 498-504. doi:10.1589/jpts.29.498

Tang, R., Murtagh, C., Warrington, G., Cable, T., Morgan, O., O'Boyle, A., . . . Drust, B. (2018). Directional change mediates the physiological response to high-intensity shuttle running in professional soccer players. *Sports (Basel), 6*(2), 39. doi:10.3390/sports6020039

Taylor, R., Sanders, D., Myers, T., & Akubat, I. (2017). The reliability and validity of integrated external and internal load ratios as measures of fitness in academy rugby union players. *Journal of Strength and Conditioning Research, 32*(8), 2103-2399, doi:10.1519/JSC.0000000000002391.

Tee, J. C., Bosch, A. N., & Lambert, M. I. (2007). Metabolic consequences of exercise-induced muscle damage. *Sports Medicine, 37*(10), 827-836.

Tee, J. C., Lambert, M. I., & Coopoo, Y. (2016). GPS comparison of training activities and game demands of professional rugby union. *International Journal of Sports Science & Coaching, 11*(2), 200-211. doi:10.1177/1747954116637153.

Temesi, J., Arnal, P. J., Rupp, T., Feasson, L., Cartier, R., Gergele, L., … Millet, G. Y. (2015). Are females more resistant to extreme neuromuscular fatigue? *Medicine and Science in Sports and Exercise, 47*(7), 1372-1382. doi:10.1249/mss.0000000000000540.

Thatcher, R. & Batterham, A. M. (2004). Development and validation of a sport-specific exercise protocol for elite youth soccer players. *Journal of Sports Medicine and Physical Fitness*, *44*, 15-22.

Thomas, A., McLean, S., & Palmieri-Smith, R. (2010). Quadriceps and hamstrings fatigue alter hip and knee mechanics. *Journal of Applied Biomechanics, 26*(2), 159-170.

Thompson, J. A., Tran, A. A., Gatewood, C. T., Shultz, R., Silder, A., Delp, S. L., & Dragoo, J. L. (2017). Biomechanical effects of an injury prevention program in preadolescent female soccer athletes. *The American Journal of Sports Medicine, 45(*2), 294-301. doi:10.1177/036354651666932

Thompson, J., & Manore, M. M. (1996). Predicted and measured resting metabolic rate of male and female endurance athletes. *Journal of the American Dietetic Association, 96*(1), 30-34.

Thorlund, J. B., Michalsik, L. B., Madsen, K., & Aagaard, P. (2008). Acute fatigue induced changes in muscle mechanical properties and neuromuscular activity in elite handball players following a handball match. *Scandinavian Journal of Medicine & Science in Sport, 18*(4), 462-472.

Thorlund, J., Aagaard, P., & Madsen, K. (2009). Rapid muscle force capacity changes after soccer match play. *International Journal of Sports Medicine, 30*(4), 273- 278.

Thorpe, R. T., Atkinson, G., Drust, B., & Gregson, W. (2017). Monitoring fatigue status in elite team-sport athletes: Implications for practice. *International Journal of Sports Physiology and Performance, 12*(2), S2-27-S2-34. doi:10.1123/ijspp.2016-0434

Thorpe, R., & Sunderland, C. (2012). Muscle damage, endocrine, and immune marker response to a soccer match. *Journal of Strength and Conditioning Research, 26*(10), 2783-2790. doi:10.1519/JSC.0b013e318241e174

Tierney, P. J., Young, A., Clarke, N. D., & Duncan, M. J. (2016). Match play demands of 11 versus 11 professional football using global positioning system tracking: Variations across common playing formations. *Human Movement Science, 49,* 1-8. doi:10.1016/j.humov.2016.05.007.

Tiidus, P. M. (2005). Can oestrogen influence skeletal muscle damage, inflammation, and repair? *British Journal of Sports Medicine, 39*(5), 251-253. doi:10.1136/bjsm.2005.016881

Timmins, R. G., Opar, D. A., Williams, M. D., Schache, A. G., Dear, N. M., & Shield, A. J. (2014). Reduced biceps femoris myoelectrical activity influences eccentric knee flexor weakness after repeat sprint running. *Scandinavian Journal of Medicine & Science in Sports, 24*(4), e299-e305.

Tomazin, K., Morin, J., & Millet, G. Y. (2017). Etiology of neuromuscular fatigue after repeated sprints depends on exercise modality. *International Journal of Sports Physiology and Performance, 12*(7), 878-885. doi:10.1123/ijspp.2016-0200

Tomazin, K., Tomazin, K., Morin, J. B., Morin, J. B., Strojnik, V., Strojnik, V., . . . Millet, G. Y. (2012). Fatigue after short (100-m), medium (200-m) and long (400-m) treadmill sprints. *European Journal of Applied Physiology, 112*(3), 1027-1036. doi:10.1007/s00421-011-2058-1

Torreño, N., Munguía-Izguierdo, D., Coutts, A., de Villarreal, E. S., Asian-Clemente, J., & Suarez-Arrones, L. (2016). Relationship between external and internal load of professional soccer players during full matches in official games using global positioning systems and heart-rate technology. *International Journal of Sports Physiology and Performance, 11*(7), 940-946. doi:10.1123/ijspp.2015-0252.

Torres, R., Vasques, J., Duarte, J. A., & Cabri, J. M. H. (2010). Knee proprioception after exercise-induced muscle damage. *International Journal of Sports Medicine, 31*(6), 410-415. doi:10.1055/s-0030-1248285

Trewin, J., Meylan, C., Varley, M. C. & Cronin, J. (2018). The match-to-match variation of match-running in elite female soccer. *Journal of Science and Medicine in Sport, 21*(2), 196-201. doi:10.1016/j.jsams.2017.05.009.

Tsai, L. C., Sigward, S. M., Pollard, C. D., Fletcher, M. J., & Powers, C. M. (2008). The effect of fatigue and recovery on knee kinetics and kinematics during side-step cutting. *Journal of Athletic Training, 43*(5), 552.

Tsai, L., Sigward, S. M., Pollard, C. D., Fletcher, M. J., & Powers, C. M. (2009). Effects of fatigue and recovery on knee mechanics during side-step cutting. *Medicine and Science in Sports and Exercise, 41*(10), 1952-1957. doi:10.1249/MSS.0b013e3181a4b266

Tsatalas, T., Giakas, G., Spyropoulos, G., Paschalis, V., Nikolaidis, M. G., Tsaopoulos, D. E., . . . Koutedakis, Y. (2010). The effects of muscle damage on walking biomechanics are speed-dependent. *European Journal of Applied Physiology, 110*(5), 977-988. Doi:10.1007/s00421-010-1589-1

Tsatalas, T., Giakas, G., Spyropoulos, G., Sideris, V., Kotzamanidis, C., & Koutedakis, Y. (2013a). Walking kinematics and kinetics following eccentric exercise-induced muscle damage. *Journal of Electromyography and Kinesiology, 23*(5), 1229-1236. doi:10.1016/j.jelekin.2013.04.008

Tsatalas, T., Giakas, G., Spyropoulos, G., Sideris, V., Lazaridis, S., Kotzamanidis, C., & Koutedakis, Y. (2013b). The effects of eccentric exercise-induced muscle damage on running kinematics at different speeds. *Journal of Sports Sciences, 31*(3), 288-298. doi:10.1080/02640414.2012.729135

Tsuji, K., Ishida, H., Oba, K., Ueki, T., & Fujihashi, Y. (2015). Activity of lower limb muscles during treadmill running at different velocities. *Journal of Physical Therapy Science, 27*(2), 353-356.

Twist, C., & Eston, R. (2005). The effects of exercise-induced muscle damage on maximal intensity intermittent exercise performance. *European Journal of Applied Physiology, 94*(5), 652-658.

Twist, C., & Highton, J. (2013). Monitoring fatigue and recovery in rugby league players. *International Journal of Sports Physiology and Performance, 8,* 467-474.

Twist, C., & Sykes, D. (2011). Evidence of exercise-induced muscle damage following a simulated rugby league match. *European Journal of Sport Science, 11*(6), 401-409. Doi:10.1080/17461391.2010.536575

Twist, C., Gleeson, N., & Eston, R. (2008). The effects of plyometric exercise on unilateral balance performance. *Journal of sports sciences, 26*(10), 1073-1080.

Twist, C., Waldron, M., Highton, J., Burt, D., & Daniels, M. (2012). Neuromuscular, biochemical and perceptual post-match fatigue in professional rugby league forwards and backs. *Journal of Sports Sciences, 30(*4), 359-367. doi:10.1080/02640414.2011.640707

Vaczi, M., Racz, L., Hortobagyi, T., & Tihanyi, J. (2013). Dynamic contractility and efficiency impairments in stretch-shortening cycle are stretch-load-dependent after training-induced muscle damage. *Journal of Strength and Conditioning Research, 27*(8), 2171-2179. doi:10.1519/JSC.0b013e31827da32c

Vanrenterghem, J., Gormley, D., Robinson, M., & Lees, A. (2010). Solutions for representing the whole-body centre of mass in side cutting manoeuvres based on data that is typically available for lower limb kinematics. *Gait & Posture, 31*(4), 517-521. doi:10.1016/j.gaitpost.2010.02.014

Vanrenterghem, J., Nedergaard, N. J., Robinson, M. A., & Drust, B. (2017). Training load monitoring in team sports: A novel framework separating physiological and biomechanical load-adaptation pathways. *Sports Medicine, 47*(11), 2135-2142. doi:10.1007/s40279-017-0714-2.

Vanrenterghem, j., Venables, E., Pataky, T., & Robinson, M. A. (2012). The effect of running speed on knee mechanical loading in females during side cutting. *Journal of Biomechanics, 45*(14), 2444-2449. doi:10.1016/j.jbiomech.2012.06.029

Varley, I., Lewin, R., Needham, R., Thorpe, R. T., & Burbeary, R. (2017). Association between match activity variables, measures of fatigue and neuromuscular performance capacity following elite competitive soccer matches. *Journal of Human Kinetics, 60*(1), 93-99. doi:10.1515/hukin-2017-0093

Varley, M. C. & Aughey, R.J. (2013). Acceleration profiles in elite Australian soccer. *International Journal of Sports Medicine, 34*(1), 34-39.

Varley, M. C., Fairweather, I. H., & Aughey, R. J. (2012). Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. *Journal of Sports Sciences, 30*(2), 121-127.

Varley, M. C., Gabbett, T. & Aughey, R.J. (2014) Activity profiles of professional soccer, rugby league and Australian football match play. *Journal of Sports Sciences, 32*(20), 1858-1866.

Vescovi, J. (2012). Sprint speed characteristics of high level American female soccer players: Female athletes in motion (FAiM) study. *Journal of Science and Medicine in Sport, 15*(5), 4774-478.

Vescovi, J. D. (2016). Locomotor, heart-rate, and metabolic power characteristics of youth women's field hockey: Female athletes in motion (FAiM) study. *Research Quarterly for Exercise and Sport, 87(*1), 68-77. doi:10.1080/02701367.2015.1124972

Vescovi, J., Brown, T., & Murray, T. (2006). Positional characteristics of physical performance in division 1 college female soccer players. *Journal of Sports medicine and Physical Fitness, 46*(2), 221-226.

Vigne, G., Gaudino, C., Rogowski, I., Alloatti, G., & Hautier, C. (2010). Activity profile in elite italian soccer team. *International Journal of Sports Medicine, 31*(5), 304-310.

Walden, M., Krosshaug, T., Bjorneboe, J., Andersen, T., Faul, O., & Hagglund, M. (2015). Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: A systematic video analysis of 39 cases. *British Journal of Sports Medicine, 49*(22), 1452-1460. doi:10.1136/bjsports-2014-094573

Waldron, M., Twist, C., Highton, J., Worsfold, P. & Daniels, M. (2011). Movement and physiological match demands of elite rugby league using portable global positioning systems. *Journal of Sports Science, 29*(11), 1223-1230.

Waldron, M., Worsfold, P., Twist, C., & Lamb, K. (2011). Concurrent validity and test–retest reliability of a global positioning system (GPS) and timing gates to assess sprint performance variables. *Journal of Sports Sciences, 29*(15), 1613-1619. doi:10.1080/02640414.2011.608703

Walker, E. J., McAinch, A. J., Sweeting, A., & Aughey, R. J. (2016). Inertial sensors to estimate the energy expenditure of team-sport athletes. *Journal of Science and Medicine in Sport, 19*(2), 177-181.

Wallace, L. K., Slattery, K. M., & Coutts, A. J. (2014). A comparison of methods for quantifying training load: Relationships between modelled and actual training responses. *European Journal of Applied Physiology, 114*(1), 11-20. doi:10.1007/s00421-013-2745-1.

Wan, J., Qin, Z., Wang, P., Sun, Y., & Liu, X. (2017). Muscle fatigue: General understanding and treatment. *Experimental & Molecular Medicine, 49*(10), e384-e384. doi:10.1038/emm.2017.194

Warren, G. L., Ingalls, C. P., Lowe, D. A. & Armstrong, R. B. (2001). Excitation-contraction uncoupling: major role in contraction-induced muscle injury. *Exercise and Sport Sciences Reviews, 29,* 82-87.

Warren, G. L., Lowe, D. A. & Armstrong, R. B. (1999). Measurement tools used in the study of eccentric contraction-induced injury. *Sports Medicine, 27,* 43-59.

Wasserstein, R. L., & Lazar, N. A. (2016). The ASA's statement on p-values: context, process, and purpose. *American Statistical Association, 70*(2), 129–133.

Weaving, D., Marshall, P., Earle, K., Nevill, A., & Abt, G. (2014). Combining internal- and external-training-load measures in professional rugby league. *International Journal of Sports Physiology and Performance, 9*(6), 905-912. doi:10.1123/ijspp.2013-0444.

Wehbe, G. M., Hartwig, T. B., & Duncan, C. S. (2014). Movement analysis of Australian national league soccer players using global positioning system technology. *Journal of Strength and Conditioning Research, 28*(3), 834-842.

Weinhandl, J. T., Earl-Boehm, J. E., Ebersole, K. T., Huddleston, W. E., Armstrong, B. S. R., & O'Connor, K. M. (2014). Reduced hamstring strength increases anterior cruciate ligament loading during anticipated sidestep cutting. *Clinical Biomechanics, 29(7*), 752-759. doi:10.1016/j.clinbiomech.2014.05.013

Weinhandl, J. T., Weinhandl, J. T., Irmischer, B. S., Sievert, Z. A., & Fontenot, K. C. (2017). Influence of sex and limb dominance on lower extremity joint mechanics during unilateral land-and-cut manoeuvres. *Journal of Sports Sciences, 35*(2), 166-174. doi:10.1080/02640414.2016.1159716

Weir, J. B. (1949). New methods for calculating metabolic rate with special reference to protein metabolism. *Journal of Physiology, 109*, 1-9.

Weiss, K., & Whatmann, C. (2015). Biomechanics associated with patellofemoral pain and ACL injuries in sports. *Sports medicine, 45*(9), 1325-1337.

Weltin, E., Gollhofer, A., & Mornieux, G. (2016). Effect of gender on trunk and pelvis control during lateral movements with perturbed landing. *European Journal of Sport Science, 16*(2), 182-189.

Westerbald, H., Allen, D. G., & Lannergren, J. (2002). Muscle fatigue: lactic acid of inorganic phosphate the major cause? *News in Physiological Sciences, 17,* 17-21.

Whyte, E. F., Richter, C., O'Connor, S., & Moran, K. A. (2018). An investigation of the effects of high intensity, intermittent exercise and unanticipation on trunk and lower limb biomechanics during a side cutting maneuver using statistical parametric mapping. *Journal of Strength and Conditioning Research, 32*(6), 1583-1593. doi:10.1519/JSC.0000000000002567

Wiewelhove, T., Raeder, C., Meyer, T., Kellmann, M., Pfeiffer, M., & Ferrauti, A. (2015). Markers for routine assessment of fatigue and recovery in male and female team sport athletes during high-intensity interval training. *Plos One, 10*(10), e0139801-e0139801. doi:10.1371/journal.pone.0139801

Wiig, H., Raastad, T., Luteberget, L. S., Ims, I., & Spencer, M. (2019). External load variables affect recovery markers up to 72 h after semiprofessional football matches. *Frontiers in Physiology, 10*, 689. doi:10.3389/fphys.2019.00689

Williams, C., & Rollo, I. (2015). Carbohydrate nutrition and team sport performance. *Sports Medicine, 45*(S1), 13-22.

Williford, H. N., Olson, M. S., Gauger, S., Duey, W. J., & Blessing, D. L. (1998). Cardiovascular and metabolic costs of forward, backward, and lateral motion. *Medicine and Science in Sports and Exercise, 30*(9), 1419-1423. doi:10.1097/00005768-199809000-00011

Winter, D. A. (1990). *Biomechanics and motor control of human movement.* Wiley and Sons, Inc; New York.

Wojtys, E. M., Beaulieu, M. L., & Ashton-Miller, J. A. (2016). New perspectives on ACL injury: On the role of repetitive sub-maximal knee loading in causing ACL fatigue failure: New perspectives on ACL injury. *Journal of Orthopaedic Research, 34*(12), 2059-2068. doi:10.1002/jor.23441

Wollin, M., Thorborg, K., & Pizzari, T. (2017). The acute effect of match play on hamstring strength and lower limb flexibility in elite youth football players. *Scandinavian Journal of Medicine & Science in Sports, 27*(3), 282-288. doi:10.1111/sms.12655

Yanagawa, T., Shelburne, K., Serpas, F., & Pandy, M. (2002). Effect of hamstrings muscle action on stability of the ACL deficient knee in isokinetic extension exercise. *Clinical Biomechanics, 17,* 705-712.

Yeomans, C., Kenny, I. C., Cahalan, R., Warrington, G. D., Harrison, A. J., Hayes, K., . . . Comyns, T. M. (2018). The incidence of injury in amateur male rugby union: A systematic review and meta-analysis. *Sports Medicine, 48*(4), 837-848. doi:10.1007/s40279-017-0838-4

Yeow, C. H., Lee, P. V. S., & Goh, J. C. H. (2010). Sagittal knee joint kinematics and energetics in response to different landing heights and techniques. *The Knee, 17*(2), 127-131. doi:10.1016/j.knee.2009.07.015

Yin, L., Sun, D., Mei, Q. C., Gu, Y. D., Baker, J. S., & Feng, N. (2015). The kinematics and kinetics analysis of the lower extremity in the landing phase of a stop-jump task. *The Open Biomedical Engineering Journal, 9*(1), 103-107.

Yoon, T., Doyel, R., Widule, C., & Hunter, S. K. (2015). Sex differences with aging in the fatigability of dynamic contractions. *Experimental Gerontology, 70*, 1-10. doi:10.1016/j.exger.2015.07.001

Yquel, R. J., Arsac, L. M., Thiaudiere, E., Canioni, P., & Manier, G. (2002). Effects of creatine supplementation on phosphocreatine resynthesis, inorganic phosphate accumulation and pH during intermittent maximal exercise. *Journal of Sports Sciences, 20*(5), 427-437.

Yu, B., Garrett, W. E. (2007). Mechanisms of non-contact ACL injuries. *British Journal of Sports Medicine, 41*(1), i47–i51.

Yu, B., Lin, C., & Garrett, W. E. (2006). Lower extremity biomechanics during the landing of a stop-jump task. *Clinical Biomechanics, 21*(3), 297-305. doi:10.1016/j.clinbiomech.2005.11.003

Yu, J., Malm, C., Thornell, L. (2002). Eccentric contractions leading to DOMS do not cause loss of desmin nor fibre necrosis in human muscle. *Histochemisty and Cell Biology, 118*(1), 29-34.

Zadpoor, A. A., & Nikooyan, A. A. (2012). The effects of lower-extremity muscle fatigue on the vertical ground reaction force: A meta-analysis. *Journal of Engineering in Medicine, 226*(8), 579-588. Doi:10.1177/0954411912447021

Zago, M., Sforza, C., Ferrario, V. F., Esposito, F., & Galli, M. (2018). Fatigue alters the biomechanics of turns while running. *Conference of the International Society of Biomechanics in Sports, New Zealand.*

Zazulak, B., Hewett, T., Reeves, N., Goldberg, B., & Cholewicki, J. (2007). Deficits in neuromuscular control of the trunk predict knee injury risk – A prospective biomechanical-epidemiologic study. *American Journal of Sports Medicine, 35*(7), 1123-1130.

Zhang, B., Yeung, S. S., Allen, D. G., Qin, L., & Yeung, E. W. (2008). Role of the calcium-calpain pathway in cytoskeletal damage after eccentric contractions. *Journal of Applied Physiology, 105*(1), 352-357. doi:10.1152/japplphysiol.90320.2008

Zhang, X., Xia, R., Dai, B., Sun, X., & Fu, W. (2018). Effects of exercise-induced fatigue on lower extremity joint mechanics, stiffness, and energy absorption during landings. *Journal of Sports Science and Medicine, 17*(4), 640-649.

Zhou, J., Schilaty, N. D., Hewett, T. E., & Bates, N. A. (2020). Analysis of timing of secondary ACL injury in professional athletes does not support game timing or season timing as a contributor to injury risk. *International Journal of Sport and Physical Therapy, 15*(2), 254-262.

Appendices Contents

Appendix 1.1

Calculation of metabolic power

Metabolic power is based on the assumption that estimated energy cost can be calculated based on the equivalence of an accelerating frame of reference (i.e. a runner's centre of mass) with the Earth's gravitational field (di Prampero et al., 2005; Figure 1). During sprinting accelerated running can be considered equivalent to running at a constant speed up an "equivalent slope" (ES) where:

$$ES = \tan(90 - \alpha) = \frac{\text{forward acceleration}}{\text{acceleration of gravity}}$$

where 90 - α = the angle between T (terrain) and H (horizontal).

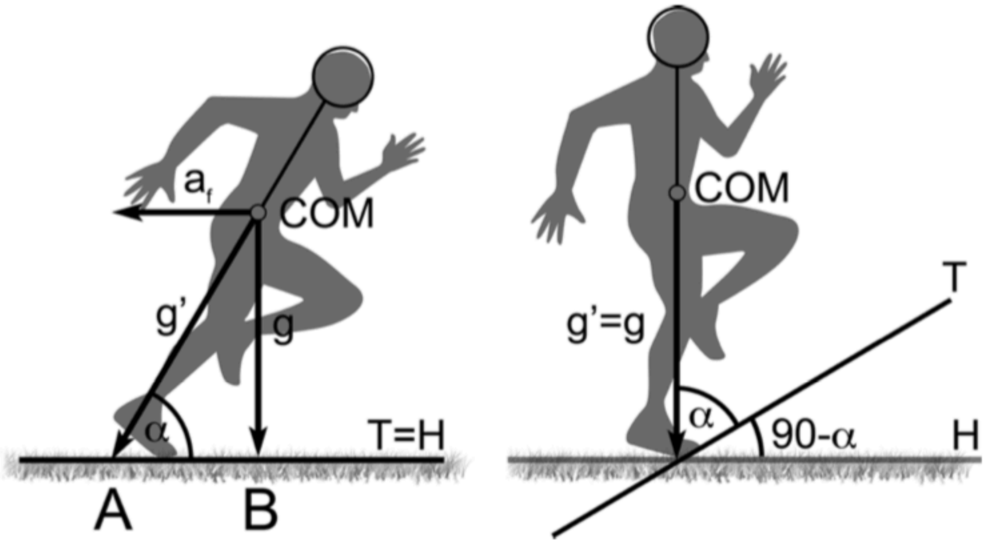


Figure 1.1.1 The subject is accelerating forward while running on a flat terrain (left) or running uphill at a constant speed (right). Taken from de Prampero, Bottter and Osgnach (2015). COM is the subjects centre of mass, a_f is forward acceleration and g' is the acceleration of gravity.

The average force exerted by the muscles during sprinting is greater than the subject's body weight by a ratio called "equivalent mass" (EM).

$$EM = \frac{M \times g'}{M \times g} = \frac{F_{acc}}{F_{const}}$$

Where F_{acc} is the force acting on the subject during accelerated running and F_{const} is the force acting during constant speed running

According to Minetti, Moia, Roi, Susta & Ferrett (2002) the energy cost (EC) of uphill running at a constant speed can be calculated as:

$EC = 155.4ES^5 – 30.4ES^4 – 43.3ES^3 + 46.3ES^2 + 19.5ES + 3.6$

where 3.6 ($J{\cdot}kg^{-1}{\cdot}m^{-1}$) is the EC of running at a constant velocity on a flat terrain.

Therefore, the EC of accelerated running can be determined as follows:

$EC = (155.4ES^5 – 30.4ES^4 – 43.3ES^3 + 46.3ES^2 + 19.5ES + 3.6)EM$

Finally, metabolic power (P) can be calculated by multiplying the EC by running velocity (v):

$P = ECv$

The model proposed by di Prampero et al. (2005) is based on several assumption, which have been detailed by di Prampero, Botter & Osgnach (2015) below.

i) energy expenditure during accelerated running is the same as uphill running at a constant speed.

ii) Stride frequency of accelerated running is equal to that of constant speed running over the corresponding incline.

iii) The efficiency of metabolic to mechanical energy transformation during accelerated running is the same to that of constant speed running over a corresponding incline.

iv) Energy cost and metabolic power do not take into consideration energy expenditure against air resistance.

Appendix 2.1

Differences in the calculation of Player Load^{TM}

Dalen et al. (2016):

Player load = $\{(X^2) + (Y^2) + (Z^2)\} \div 800$

McLaren et al. (2015); Polglaze et al. (2015); Gabbett (2015):

Player load = $\sqrt{(X_{t=i+1} - X_{t=i})^2 + (Y_{t=i+1} - Y_{t=i})^2 + (Z_{t=i+1} - Z_{t=i})^2}$

Were X, Y and Z are forward, sideways and upwards accelerometer values, respectively, and t is time.

Appendix 3.1

Residual analysis

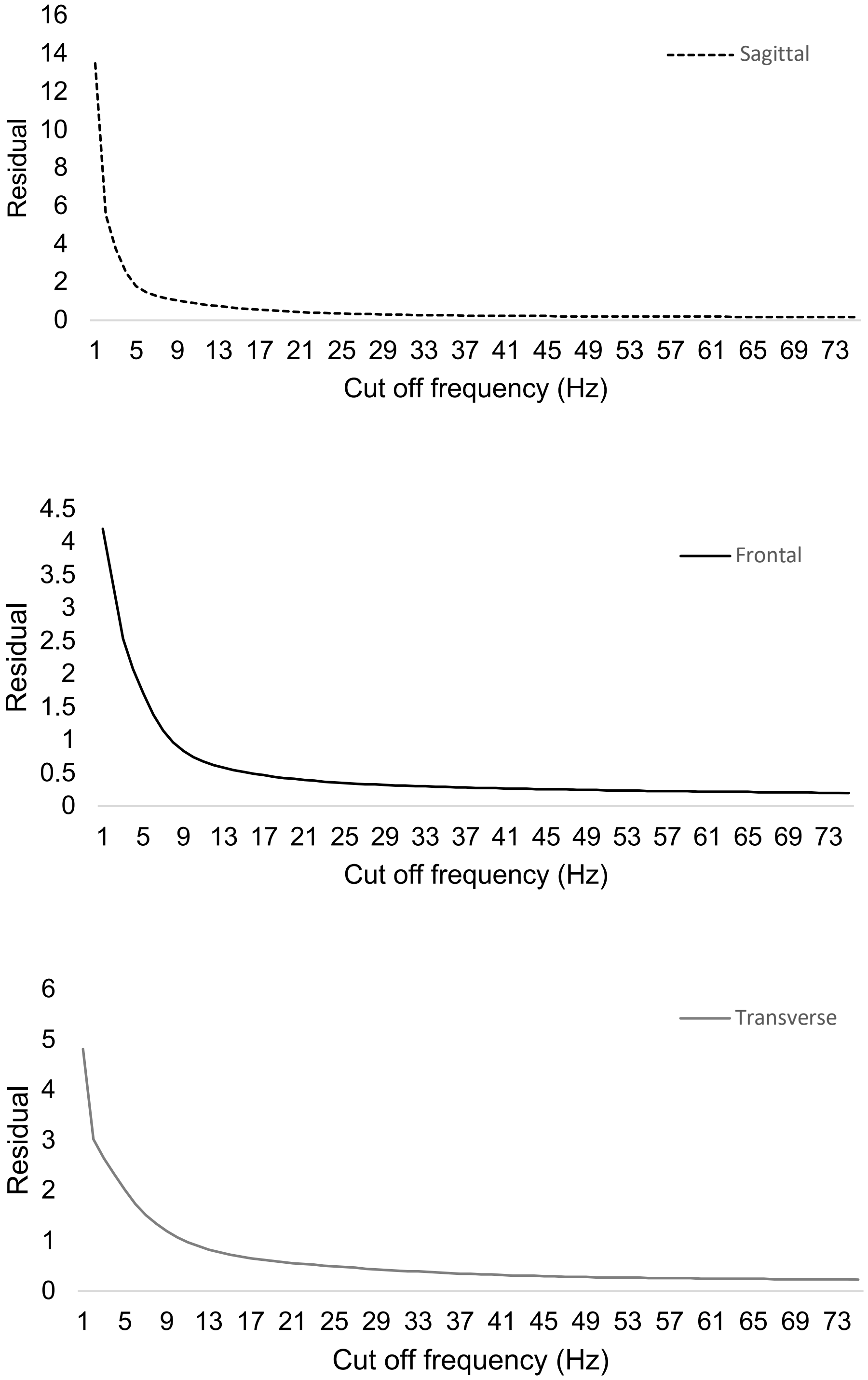


Figure A. Residual plot for knee joint angle in the sagittal, frontal and transverse plane.

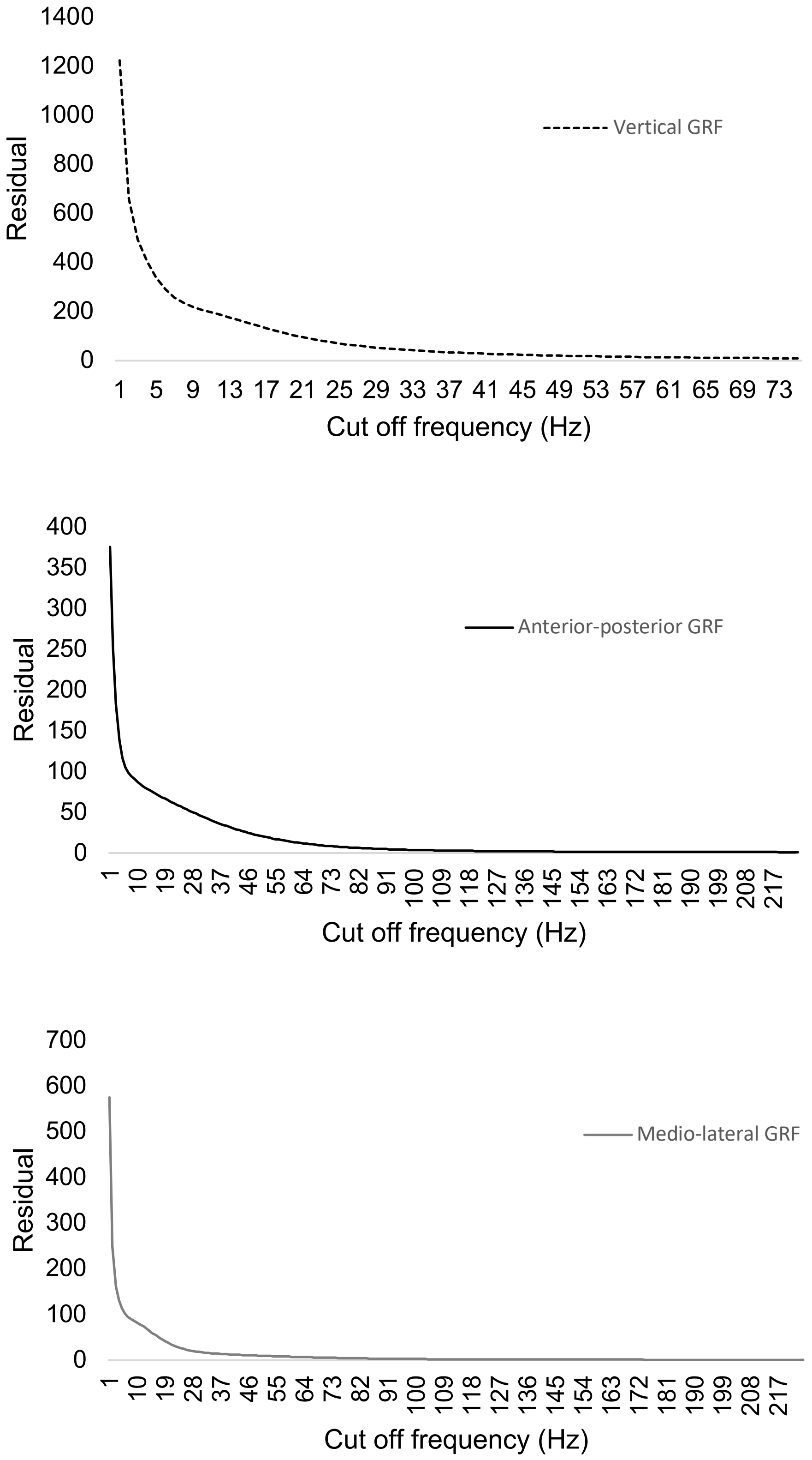


Figure B. Residual plot for GRF in the vertical, anterior-posterior and medio-lateral axis

Appendix 4.1

Ethics Approval for Chapters 4 and 5

Faculty of Life Sciences
Research Ethics Committee

frec@chester.ac.uk

Chelsea Oxendale
Rhuddlan Court,
Saltney,
Chester.

26/02/2015

Dear Chelsea

Study title: The external validity and reliability of a novel touch rugby simulation protocol.
FREC reference: 1001/15/CO/SES
Version number: 1

Thank you for the above application which was considered by the Faculty Research Ethics Committee at the meeting held on Wednesday, 18th February 2015

Provisional opinion

The Committee would be pleased to give ethical approval of the research, subject to receiving a complete response to the request for further information set out below.
Your response will be considered by Dr Clare Soulsby (Lead Reviewer) and
Dr Stephen Fallows (Chair of the Faculty Research Ethics Committee) on behalf of the Committee.

Further information or clarification

- Clarify whether validity is being assessed - i.e. both reliability and validity and revise title of the study accordingly.

- If validity is to be assessed provide an appropriate protocol.
- Expand Risk Assessment to include strains, sprains, slips, bangs etc.
- Replace PIS - download the current version of the Participant Information Sheet from the FREC web page which includes the recommended text.

Please send **three copies** of your response template and revised documentation to the Committee, underlining or otherwise highlighting the changes you have made, and giving revised version numbers and dates to all documents.

Responses should be submitted within **two months** of the date of this letter. You do not need to resubmit your full application. Please send your response to the FREC Secretary, Faculty of Life Sciences Administration Office, Molloy 106, University of Chester, Parkgate Road, Chester CH1 4BJ with an electronic copy to frec@chester.ac.uk

The Committee will confirm the final ethical opinion on the application within a maximum of 10 working days from receipt of an appropriate and acceptable response.

Yours sincerely,

Dr. Stephen Fallows
Chair, Faculty Research Ethics Committee

University of
Chester

Faculty of Life Sciences
Research Ethics Committee

frec@chester.ac.uk

31/03/2015

Chelsea Oxendale
Rhuddlan Court
Saltney
Chester

Dear Chelsea

Study title: The external validity and reliability of a novel touch rugby simulation protocol.
FREC reference: 1001/15/CO/SES
Version number: 2

Thank you for providing notice of variation to the above project.

The following variation has been approved by the Faculty Research Ethics Committee:-

- Addition of third simulation trial without changes of direction and cutting manoeuvers.
- Changes of title to "The reliability of a novel multidirectional team sport simulation protocol: A comparison to linear based running".
- Addition of additional markers of oxygen consumption and use of a RPE scale.

With the Committee's best wishes for the success of this project.

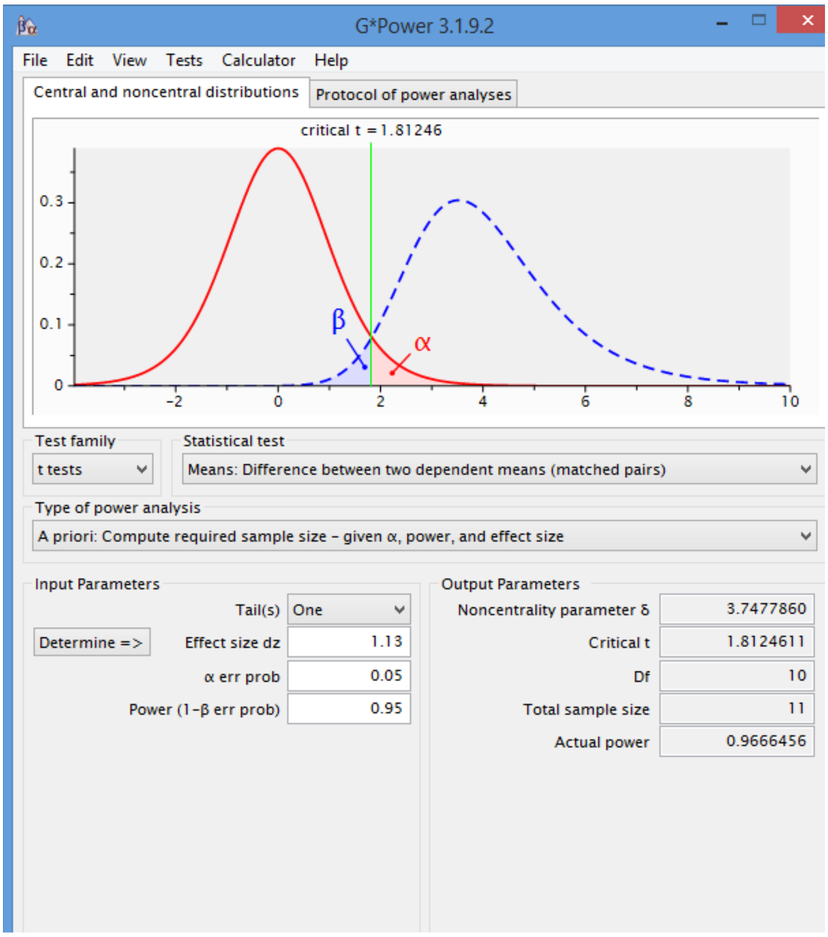
Yours sincerely,

SFallows

Dr. Stephen Fallows
Chair, Faculty Research Ethics Committee

Appendix 4.2

Sample size calculation for Chapter 4



Test family: t tests

Statistical test: Means: Difference between two dependent means (matched pairs)

Type of power analysis: A priori: Compute required sample size – given α, power, and effect size

Input Parameters

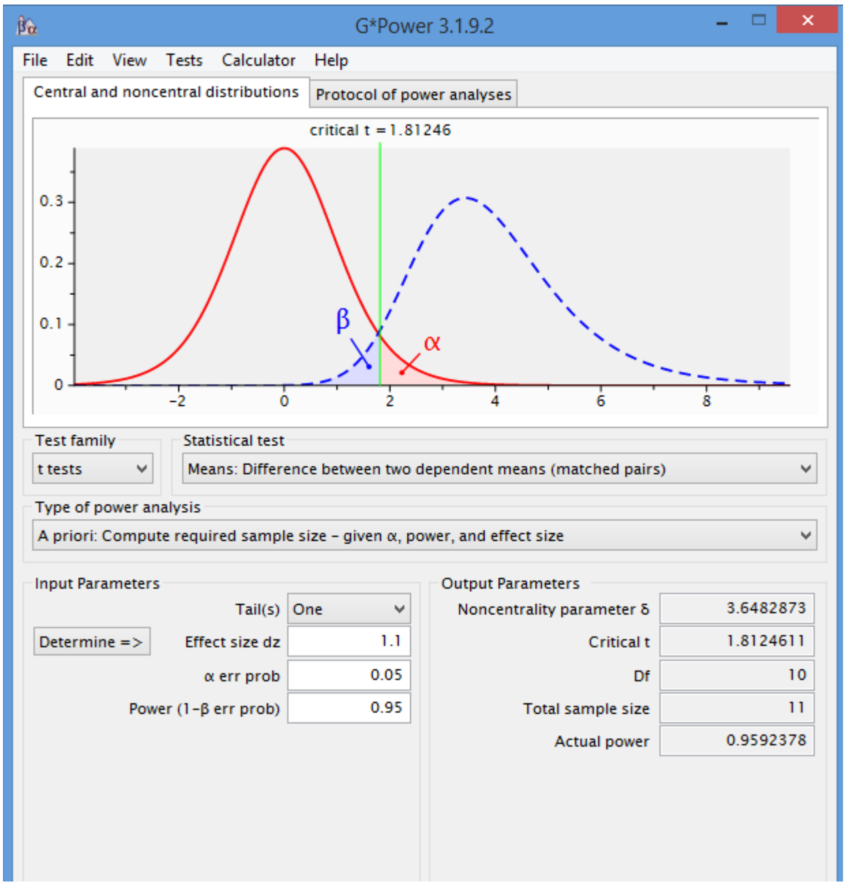
Tail(s): One
Effect size dz: 1.13
α err prob: 0.05
Power (1−β err prob): 0.95

Output Parameters

Noncentrality parameter δ: 3.7477860
Critical t: 1.8124611
Df: 10
Total sample size: 11
Actual power: 0.9666456

Appendix 5.1

Sample size calculation for Chapter 5



Test family
t tests

Statistical test
Means: Difference between two dependent means (matched pairs)

Type of power analysis
A priori: Compute required sample size – given α, power, and effect size

Input Parameters
Tail(s) One
Effect size dz 1.1
α err prob 0.05
Power (1-β err prob) 0.95

Output Parameters
Noncentrality parameter δ 3.6482873
Critical t 1.8124611
Df 10
Total sample size 11
Actual power 0.9592378

Appendix 5.2

Males vs. female comparison of muscle function changes before and after the multi-directional trial

No trial (multi-directional vs. linear), sex (male vs. females) and movement (flexor vs. extensor) interaction was apparent in the muscle function data ($F = 0.011$, $p = 0.917$). Similarly, no trial (multi-directional vs. linear), sex (male vs. females) and time (before vs after) interaction was apparent ($F = 0.038$, $p = 0.850$). However, there was a tendency for an interaction between time (before vs. after) and sex (male vs female) in the muscle function data ($F = 3.567$, $p = 0.088$). Specific changes in knee flexor and extensor torque for males and females only are provided below in Table 5.2.1

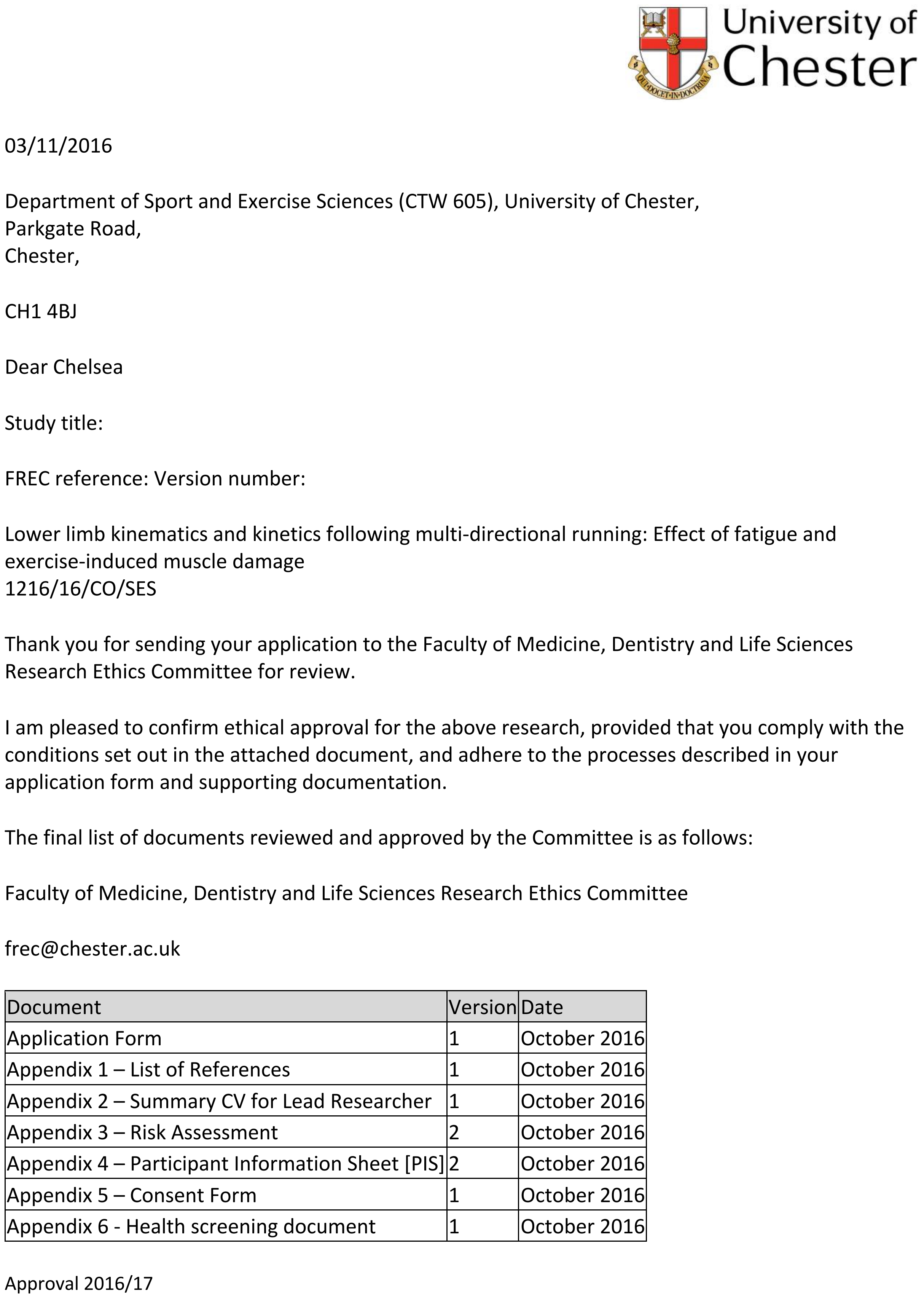
Table 5.2.1 Changes in knee extensor and flexor torque in males and females during the multi-directional and linear trial

Torque (Trial: MD or LIN)	Female		Male	
	ES; ±95% CI	**P value**	**ES; ±95% CI**	**P value**
Knee extensor (MD)	0.24; ±0.46	0.223	0.75; ±0.64	0.027
Knee Flexor (MD)	0.36; ±0.39	0.062	1.01; ±1.24	0.092
Knee extensor (LIN)	0.24; ±0.29	0.084	0.56; ±0.57	0.055
Knee flexor (LIN)	0.19; ±0.37	0.234	0.41; ±0.67	0.183

These data indicate females generally showed trivial to small reductions in knee extensor and flexor torque after multidirectional and linear running, whereas males demonstrated small to moderate reductions in knee flexor and extensor torque. These data are in agreement with previous literature demonstrating females are generally less fatigable than males (see section 2.3.1.2).

Appendix 6.1

Ethics approval for Chapters 6 and 7



03/11/2016

Department of Sport and Exercise Sciences (CTW 605), University of Chester,
Parkgate Road,
Chester,

CH1 4BJ

Dear Chelsea

Study title:

FREC reference: Version number:

Lower limb kinematics and kinetics following multi-directional running: Effect of fatigue and exercise-induced muscle damage
1216/16/CO/SES

Thank you for sending your application to the Faculty of Medicine, Dentistry and Life Sciences Research Ethics Committee for review.

I am pleased to confirm ethical approval for the above research, provided that you comply with the conditions set out in the attached document, and adhere to the processes described in your application form and supporting documentation.

The final list of documents reviewed and approved by the Committee is as follows:

Faculty of Medicine, Dentistry and Life Sciences Research Ethics Committee

frec@chester.ac.uk

Document	Version	Date
Application Form	1	October 2016
Appendix 1 – List of References	1	October 2016
Appendix 2 – Summary CV for Lead Researcher	1	October 2016
Appendix 3 – Risk Assessment	2	October 2016
Appendix 4 – Participant Information Sheet [PIS]	2	October 2016
Appendix 5 – Consent Form	1	October 2016
Appendix 6 - Health screening document	1	October 2016

Approval 2016/17

Appendix 7 – Definition of biomechanical terms	1	October 2016
Appendix 8 – Side cutting manoeuvre	1	October 2016
Appendix 9 – Marker placement	1	October 2016
Appendix 10 – Figure of the multi-directional condition	1	October 2016
Appendix 11 – Example email to recruit participants	2	October 2016
Response to FREC request for further information or clarification	1	

Please note that this approval is given in accordance with the requirements of English law only. For research taking place wholly or partly within other jurisdictions (including Wales, Scotland and Northern Ireland), you should seek further advice from the Committee Chair / Secretary or the Research and Knowledge Transfer Office and may need additional approval from the appropriate agencies in the country (or countries) in which the research will take place.

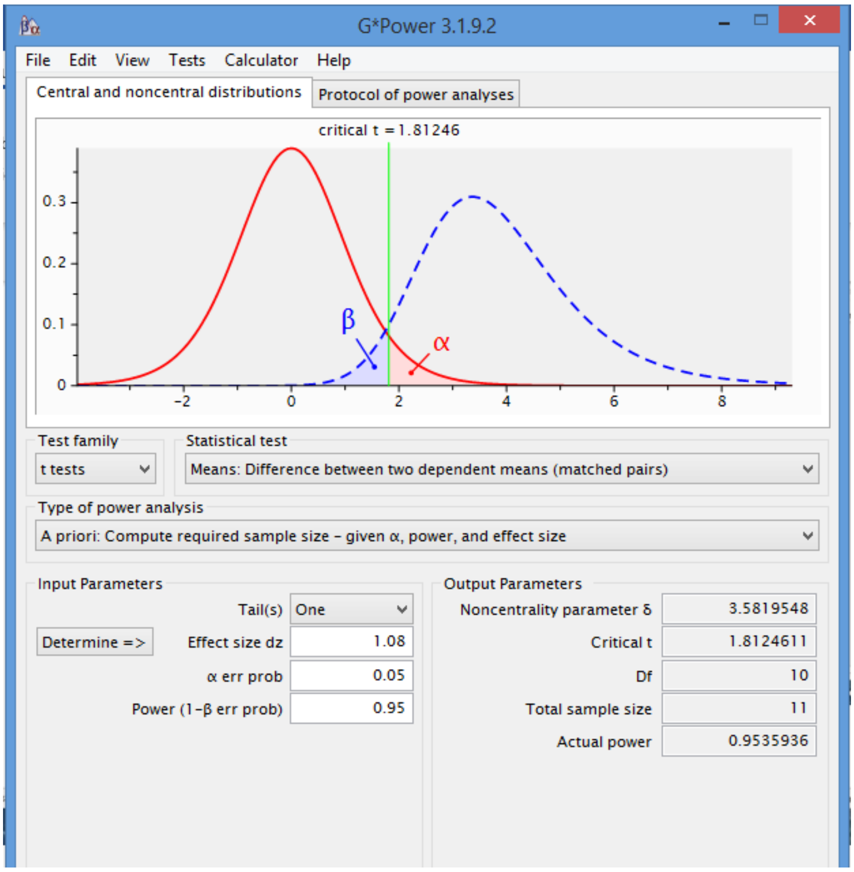
With the Committee's best wishes for the success of this project. Yours sincerely,

Professor Ben Green

Chair, Faculty Research Ethics Committee Enclosures: Standard conditions of approval. Cc. Supervisor

Appendix 6.2

Sample size calculation for Chapter 6



Test family: t tests

Statistical test: Means: Difference between two dependent means (matched pairs)

Type of power analysis: A priori: Compute required sample size – given α, power, and effect size

Input Parameters

Tail(s): One
Effect size dz: 1.08
α err prob: 0.05
Power (1-β err prob): 0.95

Output Parameters

Noncentrality parameter δ: 3.5819548
Critical t: 1.8124611
Df: 10
Total sample size: 11
Actual power: 0.9535936

Appendix 6.3

Peak angle data in males and females during a 45º side cut before and after the multi-directional trial

	Females (n = 8)			***Males (n = 8)***			***P value from two-way ANOVA***	
	Pre (°)	Post (°)	ES; ±95% CI	Pre (°)	Post (°)	ES; ±95% CI	Time	Sex x Time
Hip extension (0° = full extension)	26.0 ± 13.2	24.3 ± 12.4	0.11; ±0.40	35.1 ± 10.5	31.4 ± 9.5	0.31; ±0.46	0.140	0.565
Hip adduction (0° = full adduction)	4.7 ± 6.2	5.1 ± 2.7	0.06; ±0.49	8.4 ± 5.6	10.1 ± 5.8	0.27; ±088	0.457	0.638
Hip internal rotation	12.7 ± 8.6	7.5 ± 10.9	0.54; ±0.54	7.7 ± 5.9	4.6 ± 9.6	0.46; ±1.43	0.090	0.636
Knee extension (0° = full extension)	15.0 ± 4.9	12.7 ± 4.8	0.41; ±0.51	15.1 ± 6.5	13.9 ± 4.3	0.17; ±0.38	0.055	0.550
Knee abduction	11.1 ± 5.0	13.1 ± 6.8	0.36; ±0.58	7.6 ± 2.1	8.7 ± 5.7	0.45; ±1.85	0.203	0.688
Knee internal rotation	7.9 ± 6.2	10.4 ± 5.9	0.36; ±0.63	9.2 ± 7.0	11.23 ± 7.3	0.26; ±1.02	0.261	0.915

ES = effect size, CI = confidence interval

n.b. Peak torso data are presented in Table 6.3.

Appendix 6.4

Angular data at initial contact in males and females during a 45º side cut before and after the multi-directional trial

	Females (n = 8)			***Males (n = 8)***			***P value from two-way ANOVA***	
	Pre (°)	Post (°)	ES; ± 95% CI	Pre (°)	Post (°)	ES; ±95% CI	Time	Sex x Time
Trunk flexion	0.6 ± 7.2	0.9 ± 7.8	0.04; ±0.39	4.3 ± 7.5	6.1 ± 6.2	0.22; ±0.56	0.365	0.535
Trunk lateral flexion over stance	2.1 ± 5.8	1.7 ± 7.2	0.07; ±0.25	-2.4 ± 4.5	-1.4 ± 5.1	0.20; ±0.32	0.567	0.163
Trunk rotation over stance	7.8 ± 10.7	6.7 ± 9.7	0.09; ±0.39	9.5 ± 7.4	6.8 ± 6.7	0.33; ±0.47	0.165	0.521
Hip flexion	36.1 ± 8.9	35.9 ± 7.7	0.02; ±0.79	40.4 ± 9.9	38.4 ± 8.7	0.18; ±0.64	0.634	0.694
Hip abduction	8.8 ± 5.0	9.3 ± 4.1	0.09; ±0.79	11.2 ± 6.0	14.6 ± 4.3	0.50; ±0.80	0.216	0.349
Hip internal rotation	11.4 ± 9.4	2.6 ± 9.9	0.84; ±0.57	3.2 ± 6.9	2.6 ± 11.4	0.09; ±1.38	0.090	0.141
Knee flexion	14.8 ± 6.8	13.0 ± 4.8	0.24; ±0.67	15.3 ± 6.6	14.5 ± 4.7	0.12; ±0.40	0.307	0.711
Knee abduction	2.0 ± 5.0	1.6 ± 5.8	0.07; ±0.46	2.7 ± 2.4	0.8 ± 4.1	1.28; ±1.45	0.072	0.143
Knee internal rotation	6.9 ±7.1	6.6 ± 9.9	0.04; ±0.79	2.8 ± 8.0	4.4 ± 7.3	0.17; ±1.03	0.803	0.698

ES = effect size, CI = confidence interval

Appendix 6.5

Angular velocity data in males and females during a 45º side cut before and after the multi-directional trial

	Females (n = 8)			***Males (n = 8)***			***P value from two-way ANOVA***	
	Pre (°)	Post (°)	ES; ±95% CI	Pre (°)	Post (°)	ES; ±95% CI	Time	Sex x Time
Hip flexion	166.2 ± 97.5	124.6 ± 108.6	0.38; ±0.63	290.1 ± 147.3	324.9 ± 179.3	0.21; ±0.83	0.918	0.260
Hip abduction	244.8 ± 96.0	270.0 ± 76.8	0.23; ±0.79	210.3 ± 78.0	232.2 ± 93.4	0.25; ±1.30	0.448	0.958
Hip internal rotation	194.7 ± 83.2	199.3 ± 84.1	0.05; ±0.80	187.1 ± 128.2	183.0 ± 105.3	0.03; ±0.59	0.992	0.858
Knee flexion	671.9 ± 222.5	694.9 ± 194.0	0.09; ±0.31	727.9 ± 86.3	708.3 ± 79.8	0.20; ±0.35	0.927	0.260
Knee abduction	212.8 ± 81.9	249.7 ± 116.4	0.40; ±0.54	118.5 ± 49.1	146.4 ± 57.0	0.51; ±0.88	0.045	0.765
Knee internal rotation	476.6 ± 84.9	533.1 ± 155.2	0.59; ±1.18	384.2 ± 124.8	498.3 ± 149.5	0.81; ±0.97	0.038	0.453

ES = effect size, CI = confidence interval

n.b. Peak torso angular velocity data are presented in Table 6.3.

Appendix 6.6

Medio-lateral foot placement data in males and females during a 45º side cut before and after the multi-directional trial

BOS-XCOM (m)	***Females (n = 8)***			***Males (n = 8)***			***P value from two-way ANOVA***	
	Before	After	ES; ±95% CI	Before	After	ES; ±95% CI	Time	Sex x Time
Minimum	0.52 ± 0.04	0.49 ± 0.03	0.66; ±0.74	0.42 ± 0.06	0.42 ± 0.06	0.02; ±0.36	0.138	0.101
Maximum	0.83 ± 0.08	0.82 ± 0.05	0.10; ±0.56	0.75 ± 0.08	0.79 ± 0.11	0.35; ±0.58	0.390	0.177

ES = effect size, CI = confidence interval

Appendix 6.7

GRF data in males and females during a 45º side cut before and after the multi-directional trial

GRF ($N·BW^{-1}$)	***Females (n = 8)***			***Males (n = 8)***			***P value from two-way ANOVA***	
	Pre	Post	ES; ±95% CI	Pre	Post	ES; ±95% CI	Time	Sex x Time
Lateral	1.23 ± 0.2	1.04 ± 0.17	0.85; ±0.55	1.13 ± 0.18	1.07 ± 0.22	0.29; ±0.42	0.002	0.053
Posterior	1.43 ± 0.40	1.41 ± 0.25	0.05; ±0.58	1.44 ± 0.30	1.43 ± 0.27	0.02; ±0.62	0.839	0.921
Vertical	3.41 ± 0.40	3.30 ± 0.45	0.26; ±0.55	3.36 ± 0.52	3.39 ± 0.62	0.04; ±0.51	0.577	0.398

ES = effect size, CI = confidence interval

Appendix 6.8

Peak joint moment data in males and females during a 45º side cut before and after the multi-directional trial

	Females (n = 8)			***Males (n = 8)***			***P value from two-way ANOVA***	
	Pre ($N \cdot m \cdot kg^{-1}$)	Post ($N \cdot m \cdot kg^{-1}$)	ES; ±95% CI	Pre ($N \cdot m \cdot kg^{-1}$)	Post ($N \cdot m \cdot kg^{-1}$)	ES; ±95% CI	Time	Sex x Time
Hip extension	4.50 ± 2.2 0	4.96 ± 2.85	0.19; ±0.27	4.11 ± 0.92	4.41 ± 0.95	0.29; ±0.51	0.055	0.670
Hip Adduction	0.79 ± 0.56	0.83 ± 0.67	0.08; ±0.76	0.30 ± 0.42	0.45 ± 0.45	0.32; ±0.51	0.398	0.661
Hip external rotation	0.40 ± 0.22	0.29 ± 0.16	0.44; ±0.44	0.36 ± 0.20	0.23 ± 0.14	0.57; ±0.70	0.011	0.818
Knee extension	2.96 ± 1.01	2.59 ± 1.03	0.33; ±0.23	3.66 ± 0.43	3.45 ± 0.26	0.45; ±0.59	0.003	0.354
Knee Adduction	1.40 ± 0.59	1.32 ± 0.64	0.13; ±0.52	0.92 ± 0.42	0.81 ± 0.50	0.23; ±0.72	0.367	0.925
Knee external rotation	0.13 ± 0.09	0.16 ± 0.09	0.34; ±0.35	0.19 ± 0.09	0.22 ± 0.08	0.22; ±0.51	0.052	0.644
Knee to hip extensor ratio	0.88 ± 0.56	0.79 ± 0.54	0.15; ±0.12	0.93 ± 0.23	0.82 ± 0.18	0.45; ±0.49	0.005	0.747

ES = effect size, CI = confidence interval

Appendix 6.9

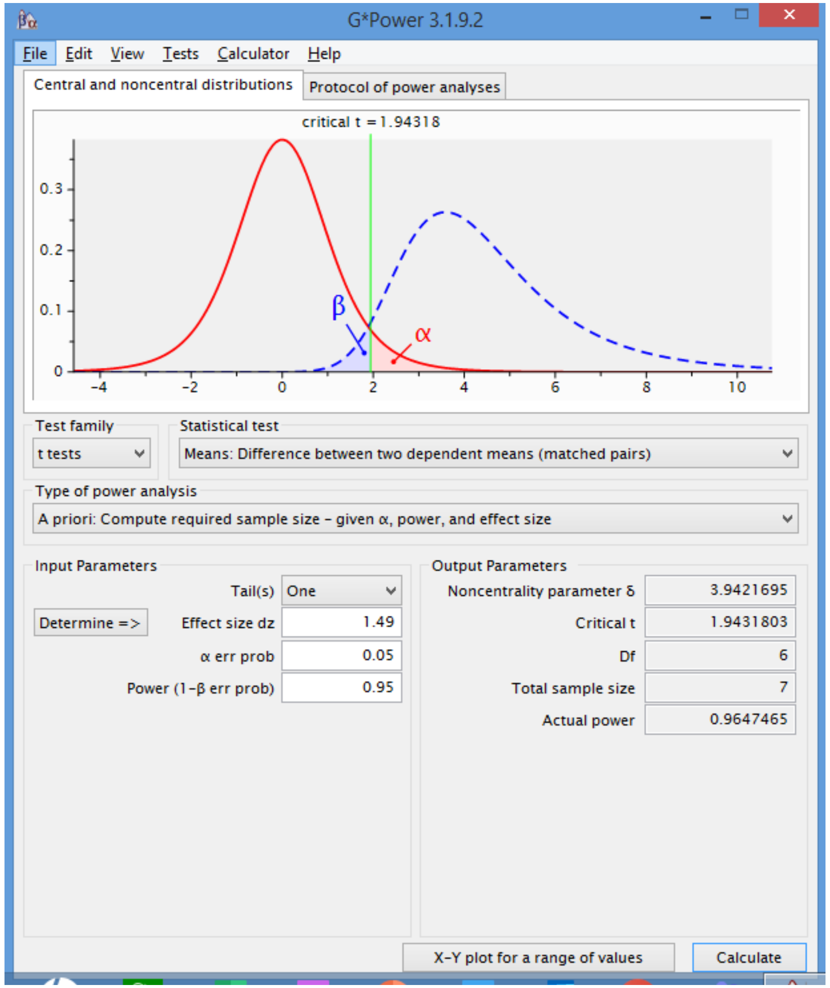
Movement variability data in males and females during a 45º side cut before and after the multi-directional trial

	Females (n = 8)			***Males (n = 8)***			***P value from two-way ANOVA***	
	Pre (CV%)	Post (CV%)	ES; ±95% CI	Pre (CV%)	Post (CV%)	ES; ±95% CI	Time	Sex x Time
Angle:								
Hip extension	10.5 ± 4.9	34.6 ± 36.3	3.69; ±6.03	12.1 ± 7.3	17.2 ± 11.0	0.62; ±0.75	0.072	0.258
Knee extension	26.4 ± 28.0	31.3 ± 28.7	0.16; ±0.84	17.1 ± 12.2	25.4 ± 13.0	0.61; ±1.22	0.332	0.803
Angular velocity:								
Hip flexion	93.4 ± 160.8	61.2 ± 202.9	0.18; ±0.70	33.4 ± 16.4	54.6 ± 26.0	1.15; ±1.37	0.843	0.345
Knee flexion	16.4 ± 8.0	23.0 ± 6.7	0.24; ±1.17	9.7 ± 1.7	12.7 ± 5.8	1.60; ±2.71	0.190	0.482
Moment:								
Hip extensor	23.0 ± 16.2	16.4 ± 7.0	0.36; ±0.83	13.7 ± 8.0	17.2 ± 5.1	0.39; ±0.73	0.665	0.172
Knee extensor	19.9 ± 16.9	18.2 ± 13.9	0.09; ±0.25	6.4 ± 2.6	7.8 ± 2.3	0.49; ±1.23	0.898	0.224
GRF:								
GRF X	14.0 ± 4.3	14.0 ± 6.2	0.00; ±0.67	19.6 ± 7.8	15.9 ± 5.0	0.42; ±0.91	0.330	0.333
GRF Y	17.7 ± 10.9	17.2 ± 10.7	0.04; ±0.56	20.3 ± 12.0	23.0 ±10.0	0.20; ±1.14	0.762	0.654
GRF Z	9.6 ± 3.8	6.3 ± 2.5	0.77; ±0.86	12.4 ± 6.0	10.6 ± 4.5	0.26; ±0.97	0.133	0.644

ES = effect size, CI = confidence interval

Appendix 7.1

G power prior sample size calculation for Chapter 7



Test family: t tests

Statistical test: Means: Difference between two dependent means (matched pairs)

Type of power analysis: A priori: Compute required sample size – given α, power, and effect size

Input Parameters

Tail(s): One
Effect size dz: 1.49
α err prob: 0.05
Power (1-β err prob): 0.95

Output Parameters

Noncentrality parameter δ: 3.9421695
Critical t: 1.9431803
Df: 6
Total sample size: 7
Actual power: 0.9647465

Appendix 7.2

Peak angle data in males and females at baseline and 48 h during a 45º side cut

	Females (n = 8)			*Males (n = 8)*			*P value from two-way ANOVA*	
	Baseline (°)	48 hr (°)	ES; ±95% CI	Baseline (°)	48 hr (°)	ES; ±95% CI	Time	Sex x Time
Hip extension (0° = full extension)	27.5 ± 13.0	21.3 ± 13.4	0.43; ±0.43	35.1 ± 10.5	35.3 ± 11.7	0.02; ±0.85	0.252	0.222
Hip adduction (0° = full adduction)	4.9 ± 6.4	5.7 ± 2.3	0.11; ±0.57	8.4 ± 5.6	7.8 ± 5.5	0.1; ±0.72	0.948	0.587
Hip internal rotation	12.7 ± 8.6	11.1 ± 8.0	0.16; ±0.34	7.7 ± 5.9	5.4 ± 7.0	0.35; ±0.9	0.199	0.800
Knee extension (0° = full extension)	16.2 ± 5.6	15.0 ± 6.0	0.19; ±0.56	15.1 ± 6.5	15.2 ± 4.2	0.01; ±0.43	0.578	0.545
Knee abduction	11.9 ± 4.9	11.7 ± 5.2	0.04; ±0.61	7.6 ± 2.1	8.4 ± 2.8	0.31; ±0.65	0.749	0.541
Knee internal rotation	8.7 ± 6.3	12.2 ± 4.4	0.5; ±0.39	9.2 ± 7.0	11.6 ± 5.9	0.31; ±0.65	0.009	0.583

ES = effect size, CI = confidence interval

n.b. Peak torso data are presented in Table 7.3.

Appendix 7.3

Angle data at initial contact in males and females at baseline and 48 h during a 45º side cut

	Females (n = 8)			*Males (n = 8)*			*P value from two-way ANOVA*	
	Baseline (°)	48 hr (°)	ES; ±95% CI	Baseline (°)	48 hr (°)	ES; ±95% CI	Time	Sex x Time
Trunk flexion (+)	3.2 ± 7.9	-0.9 ± 6.7	0.05; ±0.99	4.3 ± 7.5	2.8 ± 4.6	0.61; ±0.81	0.254	0.338
Trunk lateral flexion over stance (+)	2.6 ± 5.2	1.5 ± 6.6	0.4; ±1.27	-2.4 ± 4.5	0.2 ± 7.2	0.76; ±1.19	0.710	0.148
Trunk rotation over stance	6.7 ± 11.3	5.2 ± 9.6	0.11; ±0.88	9.5 ± 7.4	5.3 ± 7.6	0.52; ±1.12	0.370	0.635
Hip flexion	38.8 ± 8.1	35.0 ± 7.8	0.41; ±0.78	40.4 ± 9.9	40.3 ± 10.5	0.01; ±0.9	0.469	0.499
Hip abduction	9.4 ± 5.0	10.8 ± 3.4	0.25; ±0.62	11.2 ± 6.0	10.1 ± 4.8	0.15; ±0.76	0.890	0.370
Hip internal rotation	11.5 ± 9.3	7.6 ± 8.1	0.38; ±0.58	3.3 ± 6.9	2.8 ± 7.6	0.06; ±0.79	0.250	0.355
Knee flexion	15.7 ± 6.8	17.9 ± 5.7	0.28; ±0.82	15.3 ± 6.6	15.5 ± 4.5	0.02; ±0.45	0.466	0.518
Knee abduction (+)	2.1 ± 5.1	-0.2 ± 4.3	0.4; ±0.64	2.7 ± 2.4	-0.2 ± 2.0	0.91; ±0.76	0.018	0.913
Knee external rotation	7.4 ± 7.0	3.3 ± 4.7	0.51; ±0.41	2.8 ± 8.0	5.5 ± 7.4	0.29; ±0.81	0.677	0.067

ES = effect size, CI = confidence interval

Appendix 7.4

Angular velocity data in males and females during a 45º side cut at baseline and 48 h after the multi-directional trial

	Females (n = 8)			*Males (n = 8)*			*P value from two-way ANOVA*	
	Baseline (°)	48 hr (°)	ES; ±95% CI	Baseline (°)	48 hr (°)	ES; ±95% CI	Time	Sex x Time
Hip flexion	173.3 ± 98.2	153.4 ± 133.0	0.18; ±0.58	290.1 ± 147.3	341 ± 222.0	0.31; ±0.61	0.541	0.178
Hip abduction	260.6 ± 76.7	255.3 ± 74.7	0.06; ±0.6	210.3 ± 78.0	230.1 ± 118.5	0.23; ±1.34	0.793	0.651
Hip internal rotation	200.7 ± 79.2	143.5 ± 95.3	0.64; ±0.59	187.1 ± 128.2	124.8 ± 112.0	0.43; ±0.94	0.073	0.934
Knee flexion	692.8 ± 221.8	704.0 ± 223.1	0.04; ±0.29	727.9 ± 86.3	655.6 ± 101.6	0.75; ±0.7	0.169	0.068
Knee abduction	205.9 ± 85.8	209.5 ± 90.2	0.04; ±0.67	118.5 ± 49.1	141.6 ± 42.8	0.42; ±0.81	0.438	0.567
Knee internal rotation	473.4 ± 88.0	467.3 ± 77.9	0.06; ±0.46	384.2 ± 124.8	484 ± 130.1	0.72 ±0.8	0.088	0.057

ES = effect size, CI = confidence interval

n.b. Peak torso angular velocity data are presented in Table 7.3.

Appendix 7.5:

Medio-lateral foot placement data in males and females during a 45º side cut at baseline and 48 h

BOS-XCOM (m)	*Females (n = 8)*			*Males (n = 8)*			*P value from two-way ANOVA*	
	Baseline	48 hr	ES; ±95% CI	Baseline	48 h	ES; ±95% CI	Time	Sex x Time
Minimum	0.52 ± 0.04	0.51 ± 0.05	0.38; ±1.07	0.43 ± 0.06	0.45 ± 0.06	0.26; ±0.45	0.930	0.230
Maximum	0.82 ± 0.08	0.85 ± 0.08	0.4; ±0.59	0.75 ± 0.08	0.76 ± 0.07	0.1; ±0.6	0.185	0.418

ES = effect size, CI = confidence interval

Appendix 7.6

GRF data at maximum vertical GRF in males and females at baseline and 48 h during a 45º side cut

GRF	*Females (n = 8)*			*Males (n = 8)*			*P value from two-way ANOVA*	
(N·BW^{-1})	Baseline	48 hr	ES; ±95% CI	Baseline	48 hr	ES; ±95% CI	Time	Sex x Time
Lateral	1.23 ± 0.20	1.20 ± 0.26	0.14; ±0.52	1.13 ± 0.18	1.04 ± 0.23	0.46; ±0.45	0.079	0.387
Posterior	1.43 ± 0.4	1.56 ± 0.43	0.31; ±0.62	1.44 ± 0.30	1.32 ± 0.28	0.37; ±0.85	0.942	0.140
Vertical	3.41 ± 0.4	3.41 ± 0.56	0.04; ±0.53	3.36 ± 0.52	3.21 ± 0.38	0.26; ±0.42	0.388	0.258

ES = effect size, CI = confidence interval

Appendix 7.7

Peak joint moment data in males and females during a 45º side cut before and 48 h after the multi-directional trial

	Females (n = 8)			*Males (n = 8)*			*P value from two-way ANOVA*	
	Baseline (N·m·kg^{-1})	48hr (N·m·kg^{-1})	ES; ±95% CI	Baseline (N·m·kg^{-1})	48 hr (N·m·kg^{-1})	ES; ±95% CI	Time	Sex x Time
Hip extension	4.92 ± 2.19	5.43 ± 3.03	0.21; ±0.41	4.11 ± 0.92	4.59 ± 1.27	0.46; ±0.56	0.066	0.946
Hip Adduction	0.85 ± 0.48	0.95 ± 0.7	0.18; ±1.3	0.30 ± 0.42	0.35 ± 0.35	0.11; ±1.13	0.689	0.900
Hip external rotation	0.40 ± 0.22	0.31 ± 0.14	0.35; ±0.69	0.36 ± 0.20	0.29 ± 0.19	0.31; ±0.73	0.135	0.863
Knee extension	2.91 ± 1.03	2.41 ± 0.95	0.43; ±0.25	3.66 ± 0.43	3.39 ± 0.44	0.56; ±0.51	0.001	0.170
Knee Adduction	1.32 ± 0.64	1.25 ± 0.66	0.1; ±0.8	0.92 ± 0.42	0.81 ± 0.36	0.25; ±0.60	0.513	0.872
Knee external rotation	0.13 ± 0.09	0.21 ± 0.14	0.78; ±0.90	0.19 ± 0.09	0.23 ± 0.09	0.34; ±0.91	0.062	0.428
Knee to hip extensor ratio	0.81 ± 0.58	0.74 ± 0.64	0.12; ±0.46	0.93 ± 0.23	0.78 ± 0.19	0.57; ±0.61	0.148	0.626

ES = effect size, CI = confidence interval

Appendix 7.8

Movement variability in males and females at baseline and 48 h during a 45º side cut

	Females (n = 8)			*Males (n = 8)*			*P value from two-way ANOVA*	
	Baseline (CV%)	48 hr (CV%)	ES; ±95% CI	Baseline (CV%)	48 hr (CV%)	ES; ±95% CI	Time	Sex x Time
Angle:								
Hip extension	18.0 ± 11.9	25.7 ± 10.4	0.57; ±0.7	12.1 ± 7.3	15.6 ± 14.4	0.43; ±1.64	0.139	0.570
Knee extension	28.8 ± 27.7	23.1 ± 22.9	0.18; ±0.95	17.1 ± 12.2	27.9 ± 13.6	0.79; ±0.63	0.696	0.228
Angular velocity:								
Hip flexion	98.8 ± 159.5	29.4 ± 68.2	0.39; ±1.04	33.4 ± 16.4	50.0 ± 34.3	0.9; ±2.09	0.521	0.302
Knee flexion	12.3 ± 5.7	11.7 ± 6.4	0.09; ±1.0	9.7 ± 1.7	10.2 ± 3.3	0.26; ±1.46	0.980	0.722
Moment:								
Hip extensor	29.1 ± 18.0	26.6 ± 11.0	0.13; ±0.59	13.7 ± 8.0	17.2 ± 5.4	0.39; ±0.69	0.876	0.306
Knee extensor	21.7 ± 16.1	31.7 ± 25.4	0.55; ±0.68	6.4 ± 2.6	7.8 ± 3.2	0.47; ±1.49	0.060	0.141
GRF:								
GRF X	13.9 ± 4.6	13.1 ± 6.2	0.15; ±1.36	19.6 ± 7.8	18.4 ± 7.7	0.14; ±1.09	0.699	0.932
GRF Y	19.9 ± 11.4	13.9 ± 6.4	0.47; ±0.75	20.3 ± 12.0	25.0 ± 9.4	0.34; ±0.89	0.841	0.125
GRF Z	11.2 ± 4.7	10.0 ± 2.5	0.22; ±0.73	12.4 ± 6.0	11.5 ± 2.3	0.13; ±0.58	0.390	0.915

ES = effect size, CI = confidence interval