

What is the role of joint coupling variability and joint stiffness in lower limb injury?

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by

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ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

A handwritten signature in black ink, appearing to read 'P S Maulder', enclosed within a thin black rectangular border.

Peter Scott Maulder

February 2011

DEDICATION

I wish to dedicate this thesis to my best friend and companion for life, Antoinette my beautiful wife. The completion of this thesis would not have been possible without your patience, understanding, love and support throughout the duration of this thesis. Thank you so much, love you always.

Additionally, to my four gorgeous children: Kaleb (9), Izekiel (6), Aria (3) and Levi (10 months) thank you for being so much fun throughout the time of this thesis. Daddy loves you all very much.

CANDIDATE CONTRIBUTIONS TO CO-AUTHORED WORKS

The following is a list of conference presentations that have arisen from work reported in this thesis:

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Maulder, P. S., Bradshaw, E. J., & Hume, P. A. (2010). Dominant limb asymmetry greater than 10% during an unanticipated agility sprint with 180° turn is associated with prospective lower limb injury occurrence. In *Proceedings of the New Zealand Sports Medicine and Science Conference 2010*, Wellington, New Zealand, November, p. 38. (Author contribution percentages: Maulder 90%, Hume 5%, Bradshaw 5%). (see Appendix 5).

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Ethical approval

Ethical approval for this thesis research was granted by the Auckland University of Technology Ethics Committee (AUTEC). The AUTEC reference was 06/202, with approval granted on the 2nd of March 2007. (see Appendix 10).

ABSTRACT

Netball requires direction changes whilst sprinting, which predisposes netballers to risk of injury. The main question this thesis addressed was “What is the role of joint coupling variability and joint stiffness during change of direction sprints and the association with lower limb injury?”. Specifically, differences in joint coupling variability and joint stiffness between elite and non-elite netballers, between male and female netballers, between dominant and non-dominant lower limbs and between injured and non-injured netballers post six months of prospective monitoring were ascertained. Before these study aims could be addressed the reliability of joint coupling variability and joint stiffness measures during unanticipated straight run and unanticipated 180° turning tasks performed by netballers required examination.

Twelve elite female netballers, 12 male non-elite netballers and 12 non elite female netballers performed unanticipated straight sprints and sprints with a 180° turn on their dominant and non-dominant legs in a motion analysis laboratory from a 10 m approach. Measurement reliability and measurement variability of joint coupling and joint stiffness were measured within players across testing sessions. Joint coupling variability for rearfoot and knee motion were most reliable for most unanticipated tasks whereas ankle frontal plane stiffness was most reliable for all four unanticipated tasks. Consequently, these measures were used throughout the thesis research for comparisons between groups.

Female netballers, in particular at the elite level, that demonstrated low levels of lower extremity joint coupling variability (JCV) in their dominant leg during unanticipated straight sprint tasks were susceptible to injury ($r = 0.66$). Conversely, male netballers that demonstrated high joint coupling variability in their dominant leg during unanticipated sprint tasks were likely to sustain injury ($\text{Rearfoot}_{(\text{eversion/inversion})}\text{Knee}_{(\text{flexion/extension})}$ injury $r = -0.46$; $\text{Rearfoot}_{(\text{eversion/inversion})}\text{Knee}_{(\text{rotation})}$ injury $r = -0.35$; $\text{Tibial}_{(\text{rotation})}\text{Knee}_{(\text{flexion/extension})}$ injury $r = -0.54$). Associations with injury occurrence were not as prevalent or strong for joint stiffness (JS) as those found with joint coupling variability (JCV 7 out of 12, $r = -0.54$ to 0.66 ; JS 7 out of 12, $r = -0.55$ to 0.33). During ground contact for an unanticipated turn, injury was more likely for elite level female netballers if they had low levels of ankle joint stiffness ($r = 0.33$), and for non-elite female netballers if they had high knee joint stiffness ($r = -0.51$). In contrast male netballers with high levels of ankle joint stiffness during ground contact of an unanticipated straight sprint were likely to be injured ($r = -0.55$). Therefore, the role of joint coupling variability and joint stiffness during change of direction sprints and the association with lower limb injury was gender and movement specific.

The thesis findings support low joint coupling variability associations with injury and injury occurrence associations with both high and low joint stiffness theories proposed in the literature. Further investigations related to context specificity of joint coupling variability or joint stiffness between genders, limbs and other athletic populations is required. Additionally research involving training interventions to optimise joint coupling variability and joint stiffness may benefit the performance and welfare of netballers.

CHAPTER 1: INTRODUCTION AND RATIONALISATION

Background

In New Zealand and Australia netball is considered the primary team sport played both recreationally and competitively by females (McManus, Stevenson & Finch, 2006). Netball has grown in spectator interest and participation rate at both recreational and competitive levels for both females and males (Tagg, 2008). Netball is a high-strategy sport that requires the precise execution of technical motor skills with and without the ball, as well as the application of tactical knowledge when making decisions during many explosive sprints, abrupt stops, change of direction and landing movements (Bock-Jonathan, Venter & Bressan, 2007; McManus et al., 2006). Given the physical demands of netball there is a heightened risk of injury (Hume & Steele, 2000). During the years 2004 to 2008, injury claims received by the Accident Compensation Corporation (ACC) New Zealand for netball increased by ~30% (ACC, 2010). Epidemiological studies in netball have identified that the ankle and knee are the most frequent sites for injury, with ligament sprains the most common injury type (ACC, 2010; Hopper, Elliott & Lalor, 1995; Hume, 1993; Hume & Steele, 2000).

Injury prevention researchers have indicated a need for a better understanding of biomechanical mechanisms of injury (Finch, 2006). Research is required to identify mechanisms and strategies that may reduce the risk of injuries. Mechanistic measures of movement control such as joint coupling variability (JCV) and joint stiffness (JS) have been recently identified as possible markers of lower extremity injury risk (Hamill, Van Emmerik, Heiderscheit & Li, 1999; Heiderscheit, Hamill & Van Emmerik, 1999; Kurz, Stergiou, Buzzi & Georgoulis, 2005; Milner, Ferber, Pollard, Hamill & Davis, 2006; Williams, McClay Davis, Scholz, Hamill & Buchanan, 2004; Williams, McClay, Hamill & Buchanan, 2001). Joint coupling variability is an index of the inter-segment system fluctuations necessary to allow the movement system to adapt to changing constraints from one situation to the next (Bartlett, Wheat & Robins, 2007; Hamill et al., 1999). Joint stiffness in its simplest sense is the relationship between the deformation of a body such as the leg and the force attenuated (Butler, Crowell III & McClay Davis, 2003). A small body of knowledge surrounds these biomechanical paradigms and injury prevention, with most studies utilising retrospective study designs that provide limited insight into the causation of injury. It is therefore unclear whether or not knowledge of JCV or JS patterns can be beneficial for preventing injury, because currently there is a lack of any prospective studies designed to monitor individuals over a period of time.

Questions addressed in this thesis

The main question this thesis addresses is “What is the role of joint coupling variability and joint stiffness during change of direction sprints and the association with lower limb injury?”. Specifically, differences in joint coupling variability and joint stiffness between elite and non-elite netballers, between male and female netballers, between dominant and non-dominant lower limbs and between injured and non-injured netballers post 6 months of prospective monitoring were ascertained. Before these study aims could be addressed the reliability of joint coupling variability and joint stiffness measures during unanticipated straight run and unanticipated 180° turning tasks performed by netballers required examination.

Structure

The structure of the thesis relates to the two sub themes of JCV and JS. Each sub theme has a literature review and then a reliability study. Emphasis was then placed on the examination of the effects of player level (elite vs. non-elites), gender, limb dominance, and injury occurrence for JCV and JS via one descriptive experimental laboratory-based study, and a prospective injury surveillance study. The final chapter is an overall discussion of the key findings, implications and limitations of the preceding chapters and areas for further research (see Figure 1). Given the use of the same laboratory methods for various chapters, there is some overlap in chapters when reporting methodological details. To reduce duplication of reporting the same text in this thesis, the reader is referred back to previous chapters where appropriate.

Chapter 2 focused on reviewing the literature pertaining to JCV with a focus on the role JCV plays in lower extremity injury prevention during dynamic sporting tasks. Key findings were literature promoting males to exhibit higher joint coupling variability than females in explosive change of direction tasks which may verify the higher incidence of injury associated with females. Several studies demonstrated links between JCV and injury retrospectively however it is unknown whether or not the reduced variability identified in the injured individuals' system was observed as a result of pain, or possibly existed prior to the onset of pain placing them at greater risk of injury. This information formed the premise for Chapter 5.

Chapter 3 determined the reliability of various lower extremity JCV measures of the dominant and non-dominant stance leg during unanticipated straight run and unanticipated 180° turning tasks performed by netballers calculated using the vector coding method. Reliability was not previously reported for these movements, let alone for differences in dominance of legs, but was required to enable clinically beneficial changes to be determined in the planned prospective injury study reported in Chapter 5. A number of JCV measures involving rearfoot motion and knee motion were most

reliable. Measurement reliability outcomes presented in this chapter provide sufficient information for researchers to make an informed decision on whether or not to utilise some of the lower extremity coupling measures during unanticipated straight and turn sprints. Consequently, these JCV measures were used as measures of interest throughout later chapters in this thesis.

Chapter 6 focused on reviewing the literature pertaining to JS with a focus on the role joint stiffness plays in athletic performance and injury, and the discrepancies between genders. Findings indicated the importance of JS in functional performance, and the tendency of males to possess greater stiffness compared to females during athletic tasks. It also appeared that JS is associated with injury retrospectively. It is still unclear whether or not joint stiffness is directly related with injury prospectively. This information formed the premise for Chapter 9.

The reliability and variability of joint stiffness (JS) measures of the dominant and non-dominant stance leg during unanticipated straight run and unanticipated 180° turning tasks performed by netballers was examined in Chapter 7. Such an analysis had previously not been performed at least for the reliability of JS measures during any unanticipated athletic manoeuvres calculated using the torsional joint stiffness method. The ankle frontal plane stiffness measure was the most reliable measure throughout all four unanticipated tasks. Knee sagittal plane stiffness was reliable during the unanticipated 180° turn performed on the dominant leg. Consequently, these JS measures were used throughout the thesis research in later chapters.

Chapter 8 examined the effect of limb dominance, gender and netball playing ability on lower extremity JCV and JS during unanticipated straight run and unanticipated 180° turning tasks. Twelve elite female, 12 non-elite female, and 12 male netball players performed 20 to 30 trials of the unanticipated sprinting tasks (straight sprints and sprints with a 180° turn) on their dominant and non-dominant legs in the motion analysis laboratory from a 10 m approach. JCV and JS strategies were context movement specific when comparing netballers of differing abilities. Female netballers demonstrated substantially less JCV during unanticipated turning than male netballers. JS was also substantially less during all unanticipated tasks for female netballers compared to male netballers. The dominant leg utilised less variable joint coupling strategies compared to the non-dominant leg during the unanticipated straight task. Comparisons between limb JS measures suggested differences in JS to be both population and movement specific. All of the findings of Chapter 8 further heightened the need for a prospective study to be conducted for Chapter 9.

Chapters 5 and 9 investigated the association between injury occurrence and JCV and JS during unanticipated tasks performed by netballers. JCV and JS data were collected from injury free netballers prior to prospectively monitoring injuries sustained

over six months of a netball competition season. Variable coupling strategies were associated differently with injury occurrence for males and females. This was also the case for JS measures.

Chapter 10 consists of a general discussion of the key findings from the thesis, comments on limitations of the research studies conducted, and areas for future research.

The appendices contain material from chapters 2 and 9 that were presented as conference presentations (see Appendices 1-5). Appendix 6 and 7 provides a number of figures applicable to chapter 3 to 5 and 7 to 9. A sample subject information pack and consent form are provided in Appendix 8 and 9. Appendix 10 is notification from the Auckland University of Technology Ethics Committee (AUTEC) regarding ethical approval where required.

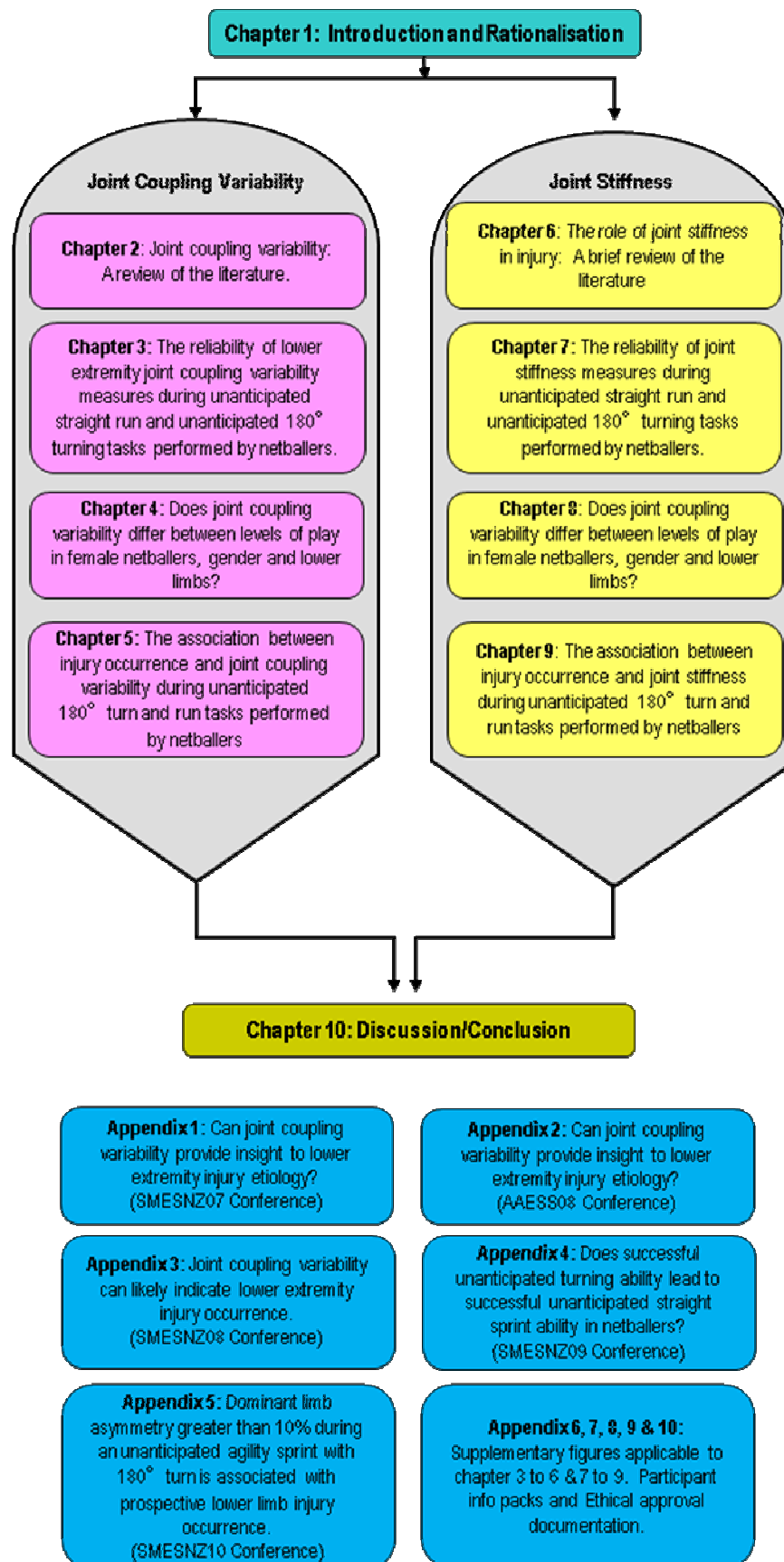


Figure 1: Overview of doctoral thesis chapter flow.

CHAPTER 2: JOINT COUPLING VARIABILITY: A REVIEW OF THE LITERATURE

Overview

This chapter explores the paradigm of movement coordination (joint coupling variability), focusing upon its potential role in lower extremity injury prevention during dynamic sporting tasks. The joint coupling relationship between the rearfoot and shank segments, and shank and thigh appear important during the stance phase of sporting movements such as running and jumping. Low variability in a variety of lower extremity intra-limb couplings during the stance phase of running can be a sign of current lower extremity injury. It is not known whether this decreased variability is a result of pain or is a contributing factor to the development of injury. Females have less variable coupling relationships than males possibly predisposing them to a higher risk of injury. Studies with a prospective design assessing lower extremity movement variability patterns may offer better insight into the causation of lower extremity injury occurrence.

Introduction

Traditionally a more variable movement pattern has been perceived as being detrimental to an individual due to the assumption that movement patterns for highly skilled performers are invariant (Bartlett et al., 2007). This view of variability in a biological system is overly simplistic. Dependent on the context, variability may be detrimental or even advantageous to an individual's musculoskeletal function and task performance. The purpose of this review was to clarify the difference between *task executions* and *coupling* variability with the latter being the primary focus. The role coupling variability may play in task execution and injury prevention is explored. Descriptions of how variability can be measured, technological and biological noise as a source of variability, the coupling of joints and segments within movement tasks, and the association between coupling variability and injury are discussed.

Methods

A systematic review approach was used to evaluate the paradigm of movement coordination (joint coupling variability), focusing upon its potential role in lower extremity injury prevention during dynamic sporting tasks. Web of Knowledge, Scopus, Medline, SportsDiscus, ProQuest Direct, Google Scholar, Cinahl, Scirus Current Contents, ABI/INFORM Global and ProQuest Direct databases from 1975 to November 2010, and the internet (e.g., Journal of Biomechanics on line, Google Scholar) were searched using key words joint coupling variability, dynamical systems theory, lower extremity, and injury. Exclusion criteria were the article was unavailable in English and

not previously referred to by other sources, or did not add knowledge to the aim of the review. Additional supportive articles were sought through article reference lists.

Methodological limitations were associated with many of the studies reviewed such as a failure to clearly describe the characteristics of the cohort, specifications of methods used to calculate joint coupling variability, the environmental conditions, or the p-value associated with the outcome measure.

The difference between performance outcome variability and coupling variability

The variability within a biological system has been of interest to researchers for many years. Research has addressed variability from sports performance, clinical, and measurement perspectives. Dependent on the perspective of interest variability can be classified as either beneficial or detrimental with the latter being the dominant assumption to many irrespective of the perspective of interest. Coinciding with the interest of variability within a biological system, a diverse range of perspectives and terminologies in the literature has emerged. Terms such as movement variability, coordination variability and coupling variability (which are somewhat synonymous) have been used when considering the variability within a biological system. With a multitude of terminologies meaning a similar concept one can become confused therefore from this point in the review variability within a biological system during movement will be referred to as coupling variability.

Minimal variability of sports performance scores (e.g. 100-m sprint time) from competition to competition or trial to trial is a key factor for success in top ranked sporting individuals, especially when matched to athletes of similar ability (Bradshaw, Maulder & Keogh, 2007; Hopkins & Hewson, 2001). Bradshaw, Maulder, and Keogh (2007) reported that minimal variability in the generation of horizontal speed when leaving the starting blocks ($r = 0.683$, $p = 0.030$) was associated with sprint performance (best 10-m time). Furthermore, during pistol shooting, expert marksmen have been reported to achieve lower variability in the position of the pistol barrel (Arutyunyan, Gurfinkel & Mirskii, 1968) which enables a more accurate performance compared to novice marksmen. Not only is it important for the individual to exhibit minimal variability in the global outcome of the task executed, it is crucial in the assessment of such an outcome. When measuring and assessing an individual's task execution it is advantageous to have minimal variability in the *outcome* measurement as variability affects the precision of estimates of change in the outcome measure of interest (Hopkins, 2000). Consequently, the smaller the variability the easier it will be to measure a change in task execution after a period of training (Hopkins, 2000). Therefore, minimal variability is desirable in an individual's task execution along with

the means utilised to measure that particular outcome, whereas high variability would be classed as detrimental.

From a movement *coordination* perspective the presence of high variability in the movement coupling patterns that cause the overall performance of the task may be more favourable than absolute invariance in the coupling patterns during movement execution (Knight, 2004). High coupling variability during the execution phase of a task could enable the performer to adjust for various intrinsic factors such as confidence and fatigue, and extrinsic factors such as wind and temperature, which can influence their performance (Bartlett, 2004; Bradshaw & Aisbett, 2006; Bradshaw & Le Rossignol, 2004). This high variability is proposed to enhance the perception of information to support motor performance rather than interfering with it by providing the individual with the ability to accommodate for possible perturbations their system may experience (Buzzi, Stergiou, Kurz, Hageman & Heidel, 2003; Davids, Shuttleworth, Button, Renshaw & Glazier, 2004). Dynamical systems theory supports this concept as it suggests that consistent high-level performance across a variety of situations and conditions can only be achieved with a variable coupling pattern that can be adapted to suit the demands of the task at hand (Hamill et al., 1999). Bradshaw et al., (2007) showed that the better performing sprinters exhibited minimal performance variability and also exhibited higher variability for the joint velocities measured especially at the ankle joint. Therefore in principle, a multitude of different movement / coupling patterns could be employed to produce an identical performance outcome (Glazier, Wheat, Pease & Bartlett, 2006; Hamill, Haddad, Heiderscheit, Van Emmerik & Li, 2006). The basis for this adaptive variability could be attributed to the concept of movement system degeneracy (Edelman & Gally, 2001; Newell, Liu & Mayer-Kress, 2003). Not only can high coupling variability for a given task outcome be advantageous but it may also protect the individual from possible injury occurrence (Hamill et al., 1999; Heiderscheit, Hamill & Van Emmerik, 2002; Kurz et al., 2005). If movement patterns are invariant (performed identically) the same tissues would be maximally loaded each time (Bartlett, 2004). Therefore, high coupling variability may modify tissue loads between repetitions reducing injury risk (Bartlett, 2004).

Variability may be detrimental or even advantageous to an individual's musculoskeletal function and task performance depending on the context. Minimal / low variability appears to be critical in an individual's performance outcome measure (e.g. sprint time). On the other hand an individual's high variability in joint coupling for a given task appears to aid performance and possibly reduce the risk of injury.

The potential role of joint coupling variability

The role coupling variability may have in movement is not clear due to often contradictory beneficial or detrimental effects (Hamill et al., 2006). Coupling variability has been suggested to serve opposing roles during functions of gait such as walking and running (Heiderscheit, 2000). Recent research has also identified the potential benefits of coupling variability in preventing injury during such movement tasks (Bartlett, 2004; Button, MacLeod, Sanders & Coleman, 2003; Davids et al., 2004; Heiderscheit, 2000; Pollard, Heiderscheit, Van Emmerik & Hamill, 2005; Van Emmerik, Hamill & McDermott, 2005), compared to detrimental effects discovered in earlier studies (Gabell & Nayak, 1984; Hausdorff, Cudkowicz, Firtion, Wei & Goldberger, 1998).

Coupling variability can be functional in practical programmes to offset negative effects of losses in sensory sensitivity through injury (Davids et al., 2004) with people rapidly habituating to constant background information, and tuning out the signals after short periods of time (Givois & Pollack, 2000). Responses to such signals decline unless variability is increased (Lackner & Dizio, 2000). Variability in joint coupling can be an essential component, providing the necessary flexibility for successful task execution (Clark & Phillips, 1993; Turvey, 1990; Van Emmerik, Wagenaar, Winogrodzka & Wolters, 1999). Additionally, individuals can exploit coupling variability within the movement system in different ways to adapt to changing task constraints over time (Davids et al., 2004). The addition of technique variability may modify tissue loads between repetitions, reducing injury risk (Bartlett, 2004). Therefore, coupling variability in practice and rehabilitation sessions may enhance the capacity of a performer to pick up signals from background noise, which is considered a vital task in rehabilitation from injury (Davids et al., 2004).

Past research identified the role of coupling variability as being detrimental in the function of movement. Current research has identified the potential benefits coupling variability can have in the function of movement especially in regards to injury either from a rehabilitation or prevention perspective.

Measurements of variability

Statistically, variability is usually quantified by the magnitude of the standard deviation (Riley & Turvey, 2002) and can be defined as the variance of data dispersed about the mean (Button, Davids & Schollhorn, 2006). The coefficient of variation (CV) is also often used as an index of intra and inter-individual variability (Hausdorff, Zeman, Peng & Goldberger, 1999) and can be calculated from the following formula:

$$CV = \left(\frac{SD}{mean} \right) \times 100\%$$

The standard deviation (SD) and the CV have the advantage of being very simple techniques for deriving variability (White, Agouris, Selbie & Kirkpatrick, 1999). While SD and CV provide accurate measures of variability within a movement system, they are not explanatory of the underlying neural processes of human movement (Buzzi et al., 2003). Further, CV is an expression of both true variance and error variance (White et al., 1999). Such a measure may include variable percentages of both technological error (e.g., due to the videoing set-up, environmental changes during field testing, digitization) and variability of a biological nature within a movement system (Bartlett, Bussey & Flyger, 2006; Rodano & Squadrone, 2002). Separating these two components is arguably not necessary when the purpose is to establish reliability of the measures. A method that quantifies the true variability within a biological system in intra-individual analysis is needed in studies examining coupling variability as technological measurement error can highly inflate traditional measures of variability (CV%) by up to 72% (Bradshaw et al., 2007).

In a study examining the biological variability within a movement system of male track sprinters performing block starts, Bradshaw et al. (2007) devised a method for separating variability from technological error. The method involved the calculation of individual athlete means (\bar{X}) and standard deviations (SD), then the calculation of the standard error of the mean ($SEM\% = \left[\frac{SD/\sqrt{n}}{\bar{X}} \right] \times 100$, where n is the number of trials) and coefficient of variations ($CV\% = SD/\bar{X} \times 100$). The biological coefficient of variation ($BCV\% = CV\% - SEM\%$) was then calculated. Bradshaw et al. (2007) advocated that by calculating the SEM%, inter-subject differences in the mean scores could be controlled for, allowing a more valid comparison (and grouping) of subjects than obtained by using the absolute SEM. The limitation of this method is that both the standard error of the mean and the coefficient of variation can be affected by heterostaticity where the data shows departures from a normal distribution (negative skewness) (Atkinson & Nevill, 1998).

Variability can be measured in a variety of ways statistically. Methods include the standard deviation, coefficient of variation, and biological coefficient of variation. Consideration should be taken when determining which method of measurement will be used to quantify variability, as the methods outlined in this review all have their limitations.

Noise as a source of variability

Noise expressed as high levels of variability is an essential part of the human movement system (Davids et al., 2004). This inherent noise results in variability being omnipresent, unavoidable and yet functional in helping to produce stable movement outcomes (Davids, Glazier, Araujo & Bartlett, 2003; Davids et al., 2004). Noise within a system may be attributed to several sources, including dynamical noise or measurement noise (Buzzi et al., 2003; Kantz & Schreiber, 1997).

Dynamical noise emerges from underlying nonlinearities and is considered important in pattern formation in biological systems (Glass, 2001). Dynamical noise is an integral part of the system dynamics thus no separation between the original signal and noise can occur (Van Emmerik et al., 2005).

Measurement noise can be considered the magnification of error over time in performing a specific task (Mullineaux, Bartlett & Bennett, 2001). Measurement noise in a signal is usually formed by fluctuations that are independent of and additive to the dynamics of interest (Van Emmerik et al., 2005). Examples of measurement noise are technological noise, joint/segment marker movement, and electrical interference. During kinematic analyses, technological error can occur during both data collection and data analyses. During data collection, the markers (even if positioned appropriately) may move in relation to the skin and the position of the joint centers also changes throughout the range of motion. If this data is then manually digitized, the operators (digitizers) may not always select the centroid of the markers. Fortunately with the advancement in analyses software, the biomechanics or motor control researcher can utilize data filtering procedures that will generally separate measurement noise from the original signal (Van Emmerik et al., 2005).

It appears that noise in the form of variability is an essentially functional part of movement. Within a movement system there can be dynamical noise and measurement noise. The former is an integral part of the system's dynamics whereas the latter is the addition of unwanted magnified error.

Coupling of joints and segments within movement

The human body is a vastly complex system that is composed of many moving segments that are connected through more than one hundred joints, the vast majority with several axes of rotation, and powered by hundreds of muscles (Bernstein, 1967). Movement patterns are distinguished by the coupling relationships between limbs or between segments within a limb (Tepavac & Field-Fote, 2001). Such coupling relationships have been defined as the mastering of redundant degrees of freedom to produce a controllable system (Bernstein, 1967).

There are a variety of techniques used to examine the coupling between two body segments and joints. Trying to quantify the coupling patterns can be difficult (Tepavac & Field-Fote, 2001; Wheat & Glazier, 2006). Techniques that attempt to examine joint coupling include relative motion plots, continuous relative phase (CRP), and vector coding methods. The methods used to measure joint coupling and its variability have been extensively and recently addressed elsewhere (see, for example, reviews by (Hamill, Haddad & McDermott, 2000; Wheat & Glazier, 2006). Limitations from a clinical perspective have been presented for the continuous relative phase technique. Specifically, CRP proves difficult to explain / interpret as the CRP angle is a function of the position and velocity of one segment relative to the position and velocity of another segment. The vector coding method may be more appropriate to utilise if attempting to provide meaningful clinical interpretations as the technique describes the relative motion of the segments to each other. For example a 45° indicates equal amounts of motion from both segments whereas $>45^\circ$ indicates more of the y axis plotted segment. There are no suggested preferences for the use of one method over the other, it is only acknowledged that when comparing findings from the differing methods it be done so cautiously.

Lower extremity coupling patterns during various sporting movement tasks

The actions of the legs in running are cyclic, each foot in turn lands on the ground, passes beneath and behind the body, and then leaves the ground to move forward again ready for the next landing (Williams, 1985). Based on the events of a single leg during the cycle of a stride there is a stance phase and a swing phase. The stance phase is where the individual is in contact with the ground, i.e., from touchdown of the foot to the takeoff of the foot. Two functional phases of braking (negative “eccentric” reaction force) and propulsion (positive “concentric” reaction force) form the basis of the stance phase (DeLeo, Dierks, Ferber & Davis, 2004; Mero, Luhtanen & Komi, 1983). Immediately after the initial contact with the ground, pronation of the rearfoot, tibial internal rotation, and knee flexion occur relatively synchronously (DeLeo et al., 2004). While the individual progresses into propulsion the motions of the rearfoot, tibia, and knee reverse (DeLeo et al., 2004). In one of the first studies to utilize the continuous relative phase method to quantify joint coupling relationships during running, Hamill et al. (1999) reported an in phase relationship (continuous relative phase approximately 10°) between rearfoot pronation/eversion and tibial internal rotation during stance of running. It has been proposed that rearfoot motion is likely to influence the motion of the knee during running (Ferber, McClay-Davis & Williams III, 2005). During landing tasks Tillman et al. (2005) found the ratio of rearfoot pronation/eversion and tibial internal rotation to be greater than that of running. This

suggests that increased loading demands of an activity require increased foot motions. Further these findings indicated that the ratio of knee flexion to knee internal rotation increases significantly from running to landing tasks.

Movement patterns are distinguished by the coupling relationships between limbs or between segments within a limb. The coupling relationships between the rearfoot and shank, and shank and thigh appear important during the stance phase of sporting tasks.

Joint coupling variability in injury related research

The incidence of injuries in court sports (e.g., netball, basketball, volleyball) has been well documented with the ankle and knee joints being identified as the primary anatomical locations injured (Arendt & Dick, 1995; Hopper et al., 1995; Hume, 1993). Of these acute injuries most occur as a result of play involving combinations of movements such as a change of direction whilst sprinting (Hume & Steele, 2000). Female athletes reportedly are four to six times more likely to sustain a serious knee injury than male athletes participating in the same sports that require explosive change of direction maneuvers whilst sprinting (Griffin et al., 2000; Hutchinson & Ireland, 1995; Ireland, 1999). Interestingly, during an unanticipated explosive change of direction manoeuvre Pollard et al. (2005) reported lower extremity segment and coupling variability differences between healthy males (N = 12) and females (N = 12). The female participants exhibited decreased variability in four of the couplings (32% less thigh rotation - leg rotation variability; 40% less thigh abduction/adduction - leg abduction/adduction variability; 46% less knee flexion/extension - knee rotation variability; and 44% less knee flexion/extension - hip rotation variability) calculated using the vector coding method. To help the reader put this in perspective, researchers interested in the relationship between joint / segment coupling variability and injury have provided information that tends to support the notion that low coupling variability is associated with lower extremity injury (Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005). Such studies have used a dynamic systems approach to examine lower extremity injuries (retrospectively) in relation to running tasks. For example, Kurz et al. (2005) compared stance phase sagittal continuous relative phase for the couplings of shank – thigh, and foot – shank between individuals with and without a reconstructed anterior cruciate ligament (ACL). The reconstructed ACL group demonstrated lower continuous relative phase measures for the intra-limb coupling between the foot and shank during treadmill running at a self selected speed. Hamill et al. (1999) indicated that individuals suffering from patellofemoral pain syndrome exhibited less continuous relative phase variability for intra-limb joint couplings of thigh flexion/extension - tibial rotation, thigh

adduction/abduction - tibial rotation, and tibial rotation - foot inversion/eversion measured during the stance phase of running than their healthy counterparts. Heiderscheit et al. (2002) also reported the coupling variability of thigh rotation - tibial rotation during heel-strike to be significantly lower in the injured leg of patellofemoral pain syndrome suffering females compared to their uninjured leg and legs of an uninjured group of females. Interestingly, the low coupling variability in the thigh rotation - tibial rotation coupling during an unanticipated explosive change of direction manoeuvre reported by Pollard et al. (2005) for the healthy injury free females was similar to that reported by Hamill et al. (1999) and Heiderscheit et al. (2002) for the individuals suffering from patellofemoral pain. These findings may somewhat explain the increased incidence of lower extremity injuries in females as compared to males.

Conversely, Ferber et al. (2005) reported that individuals with a variety of lower limb pathologies such as plantar fasciitis, anterior compartment syndrome, and patellofemoral pain syndrome, exhibited similar rearfoot inversion/eversion and tibial internal/external rotation intra-limb joint coupling patterns and variability during the stance phase of running over ground compared to uninjured individuals. The statistical power to detect differences may have been decreased in this study as a result of inter-subject variability due to the variety of running injuries carried by their participants.

Low coupling variability of the lower extremity may be possibly related to a loss of sensory information about joint position and velocity (Kurz et al., 2005). Individuals suffering from injury that demonstrate low coupling variability may employ segment interactions that are repeatable within a very narrow range thus enabling the individual to accomplish the specific task with minimum pain by avoiding painful coupling patterns (Hamill et al., 1999).

Though studies (Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005) have reported low intra-limb coupling variability to indicate the presence of injury, they do not determine the cause of injury due to the case-cohort study designs incorporated. Information pertaining to whether or not the reduced variability identified in the injured individuals' system was observed as a result of pain, or possibly existed prior to the onset of pain placing them at greater risk of injury, warrants further investigation. Studies with a prospective design assessing lower extremity coupling variability patterns may offer a better insight into the causation of lower extremity injury occurrence.

Conclusions

Traditionally variability has been perceived as being more detrimental than advantageous to an individual's musculoskeletal function and task performance. Dependent on the context, high variability can be detrimental in terms of performance

outcomes and measurement strategies, but be advantageous from a coupling perspective particularly when considering injury prevention. The role of high coupling variability in an individual's system has potential benefits in the rehabilitation from injury and the prevention of injury.

Females are more at risk of lower extremity injury performed during sports involving explosive change of direction tasks compared to males. Interestingly, males exhibit higher joint coupling variability than females in these types of tasks. Of the couplings demonstrating significant reductions in variability among females, all involved either a transverse (rotational) or frontal (medial-lateral) plane component of motion. If females exhibit less variable coupling patterns during competition, they may be less able to adapt to the environmental perturbations experienced during sports therefore predisposing them to greater injury risk. This assumption has not been validated through research.

Studies have identified a variety of lower extremity intra-limb couplings during the stance phase of running to be a sign of current lower extremity injury. Though these studies show low intra-limb joint coupling variability to indicate the presence of injury they do not determine the cause of injury due to the case-cohort study designs incorporated. Information pertaining to whether or not the reduced variability identified in the injured individuals' system was observed as a result of pain, or possibly existed prior to the onset of pain placing them at greater risk of injury, warrants investigation. Studies with a prospective design assessing lower extremity movement variability patterns may offer a better insight into the causation of lower extremity injury occurrence.

CHAPTER 3: THE RELIABILITY OF LOWER EXTREMITY JOINT COUPLING VARIABILITY MEASURES DURING UNANTICIPATED STRAIGHT RUN AND UNANTICIPATED 180° TURNING TASKS PERFORMED BY NETBALLERS

Overview

The reliability of joint coupling variability measures has not yet been adequately established. Despite this there has been a growing interest in the area of joint coupling variability dynamics that has revealed promising patterns with injury. The purpose of this study was to determine the reliability of various lower extremity joint coupling variability measures of the dominant and non-dominant stance leg during unanticipated straight run and unanticipated 180° turning tasks performed by netballers. Ten elite netball players completed the four tasks in random order until five trials were captured for each task using three dimensional cameras and a force platform. A variety of reliability measures were calculated along with qualitative outcomes to provide a robust conclusion. Specifically, the percentage difference in the mean and Cohen's effect sizes were calculated for reliability assessment and intra-class correlation coefficients, and the coefficient of variation percentages were calculated for variability assessment. Across the 24 combinations of tasks and joint coupling variability measures, eight (~33%) exhibited an acceptable level of reliability and variability (average measurement reliability and average measurement variability qualitative interpretations indicated 'good' to 'moderate' reliability and 'small' to 'moderate' variability respectively). Specifically, the rearfoot_(eversion/inversion)–knee_(flexion/extension), rearfoot_(eversion/inversion)–knee_(rotation) and tibial_(rotation)–knee_(flexion/extension) joint coupling variability of the dominant leg during an unanticipated straight run task, the rearfoot_(eversion/inversion)–tibial_(rotation) and rearfoot_(eversion/inversion)–knee_(rotation) joint coupling variability of the non-dominant leg during unanticipated straight run task, and the rearfoot_(eversion/inversion)–tibial_(rotation), rearfoot_(eversion/inversion)–knee_(rotation) and tibial_(rotation)–knee_(rotation) joint coupling variability of the non-dominant leg during an unanticipated 180° turning task were deemed to have acceptable levels of measurement reliability and measurement variability. The use of these measures to quantify joint coupling variability in the lower extremity across testing sessions during unanticipated straight run and unanticipated 180° turning tasks appears to be justified. Therefore it would be appropriate for these measures to be utilised in future investigations.

Introduction

Retest reliability concerns the reproducibility of the observed value when the measurement is repeated (Hopkins, 2000). A reliable test is characterized by small changes in the mean, small within-individual variation (Standard Error of the Mean [SEM] or Typical Error [TE]) and a high test-retest correlation (intraclass correlation coefficient [ICC]; (Atkinson & Nevill, 1998; Hopkins, 2000). Therefore, the smaller the error, the better the measure (Hopkins, 2000). Reliability provides an indication of the degree of precision associated with a particular measure and is a vital element in the biomechanical or physiological assessment of athletes (Moir, Button, Glaister & Stone, 2004). Despite every effort to ensure optimal reliability of a single measurement, some measures may still not be reliable enough for the intended use (e.g., monitoring small changes in performance; (Hunter, Marshall & McNair, 2004). It is up to the researcher to judge whether a measurement is reliable enough for its intended use (Atkinson & Nevill, 1998).

The human body is a vastly complex system that is composed of many moving segments that are connected through more than one hundred joints, the vast majority with several axes of rotation, and powered by hundreds of muscles (Bernstein, 1967). Motor behaviours or movement tasks are distinguished by the coupling or coordination relationships between limbs or between segments within a limb (Tepavac & Field-Fote, 2001). There are two methods that are currently being utilised by researchers to quantify the coupling of two segments during athletic tasks. One method is the continuous relative phase (CRP) plots (Dierks & Davis, 2007; Hamill et al., 1999; McGrath, Padua & Thigpen, 2008), and the other method is vector coding (Dierks & Davis, 2007; Ferber et al., 2005; Heiderscheit et al., 2002; Pohl & Buckley, 2008; Pollard et al., 2005). CRP is defined as the difference between the respective phase angles of each segment (Wheat & Glazier, 2006) and is calculated using the following steps. Initially, the phase angle is obtained by plotting the angle of one segment versus the angular velocity of that same segment in what is known as a 'phase-plane' (Hamill et al., 1999). Hamill et al. (2000) advocated that segment displacements and velocities need to be normalised and rectified before CRP can be calculated. Once the segment data has been normalised and rectified, a phase-plane portrait can be constructed with displacement data consisting the abscissa and velocity data consisting the ordinate axis of the portrait (Wheat & Glazier, 2006). Phase angles are then calculated for all points in the phase-plane portrait (DeLeo et al., 2004) using the following equation:

$$\varphi(t) = \tan^{-1} \left(\frac{\dot{\theta}(t)}{\theta(t)} \right)$$

where φ is the phase angle, $\dot{\theta}$ is normalised angular velocity, and θ is normalised angular displacement at time t . Once the phase angles have been calculated for the segments of interest, CRP can be calculated as the difference between the two segment phase angles. Researchers have generally subtracted the phase angle of the distal segment from that of the proximal segment (Hamill et al., 1999; Kao, Ringenbach & Martin, 2003). For example the CRP between the thigh and the shank during the stance phase of a cutting manoeuvre can be calculated using the following equation:

$$\Phi(t) = \varphi_{thigh}(t) - \varphi_{shank}(t)$$

where Φ is the CRP, φ_{thigh} is the phase angle of the thigh, and φ_{shank} is the phase angle of the shank at time t . A CRP of 0° indicates that the respective segments are in-phase or symmetrical. As the CRP increases the segments become more out-of-phase until a CRP of 180° which indicates an anti-phase or asymmetrical coupling. A positive CRP indicates that the proximal segment has a greater phase angle while a negative CRP indicates that the distal segment has a greater phase angle (Hamill et al., 1999).

The vector coding technique is typified by the creation of an angle-angle plot of two joints or segments of interest (DeLeo et al., 2004). Generally the coupling angles are calculated using the orientation of the resultant vector to the right horizontal between two adjacent data points of the angle-angle plot (Pollard et al., 2005). Researchers (DeLeo et al., 2004; Ferber et al., 2005) have provided a method for calculating the resultant vector between the two adjacent data points which is provided below:

$$\Phi_i = \text{abs}[\tan^{-1}(y_{i+1} - y_i / x_{i+1} - x_i)]$$

where i = point 1, 2 and n . The procedure is continued for all successive points (DeLeo et al., 2004). Following conversion from radians to degrees, the resulting range of values for coupling angles will be between $0-90^\circ$ (Ferber et al., 2005; Pollard et al., 2005). Ferber et al. (2005) provided guidelines for interpreting the coupling angle values. From their example, the coupling between rearfoot eversion/inversion (RF) and tibial internal/external rotation (TIB) during the stance phase of running was provided. RF motion was plotted on the abscissa and TIB motion was plotted on the ordinate of the angle-angle plot, a coupling angle of 45° indicated equal amounts of rearfoot frontal plane and tibial transverse plane motion. An angle greater than 45° indicated greater tibial transverse plane motion relative to rearfoot frontal plane motion.

Whilst coupling between joints/segments within a limb can distinguish motor behaviours or movement tasks (Tepavac & Field-Fote, 2001), it is the variability of such

couplings for the relationship between joint/segment coupling variability and injury during running tasks from standard deviation statistics that has been of growing interest to researchers recently (Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005). Though information on this measure is presently scarce, studies using a dynamical systems approach have identified a variety of lower extremity intra-limb couplings during the stance phase of running to be a marker of current lower extremity injury (Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005). These have all involved either a transverse/rotational or frontal/medial-lateral plane component of motion. Despite these findings only one study by McGrath, Padua and Thigpen (2008) has reported the reliability of these methods. McGrath, Padua and Thigpen (2008) reported fair to excellent intraclass correlation coefficients for foot and shank (0.82), shank and thigh (0.55), and thigh and trunk (0.96) sagittal plane joint couplings during jump landings. Whilst, McGrath, Padua and Thigpen (2008) provided sufficient justification for utilising coupling measures calculated from relative phase angles during jump landings, the reliability of methods to assess lower extremity joint coupling variability has not yet been established for running tasks.

A limitation of the CRP coupling quantification technique is that the outcomes can be very difficult to interpret with respect to injury or function (DeLeo et al., 2004; Tepavac & Field-Fote, 2001). Additionally, Heiderscheit et al. (2002) suggested that the use of the CRP method can elicit inaccurate results during running tasks due to the non-sinusoidal time series of the coupling relationships. The concept of CRP assumes data is sinusoidal in nature which is a somewhat limiting factor (DeLeo et al., 2004). The vector coding method may be more appropriate to assess the coupling strategies and in particular the variability of such strategies during running tasks (Heiderscheit et al., 2002). To the best of our knowledge no one has reported the reliability of coupling measures during any athletic manoeuvres calculated using the vector coding method.

Aim

This study aimed to determine the reliability of various lower extremity joint coupling variability measures (as derived from the vector coding method) of the dominant and non-dominant stance leg during unanticipated straight run and unanticipated 180° turning tasks performed by netballers.

Methods

Netball player characteristics

Ten elite (International = 6; National = 4) female netballers (mean \pm SD: age 22.2 \pm 4.2 yrs; height 1.79 \pm 0.08 m; mass 78.2 \pm 12.6 kg) volunteered to participate in the study. All had at least nine years experience playing netball (12.6 \pm 2.9 yrs). All netballers were in their pre-competition phase which consisted of four to seven (5.5 \pm 0.8) training sessions for a total of six to ten training hours (8.8 \pm 1.7 hrs) per week during data collection. The netballers had no history of significant lower extremity injury six months prior to testing and were injury free at the time of data collection. Each netballer gave informed consent in writing to participate in this study prior to testing. Ethical approval was obtained for all testing procedures from the Auckland University of Technology Ethics Committee. All netballers wore spandex shorts or pants and ASICS (Gel-Rocket) court shoes during the data collection.

Procedures

Study design

A test-retest between day protocol on two separate days was performed. There was a maximum of seven days between tests.

Netball player limb dominance

Limb dominance was determined via a series of questions and practical tests. The netballers were asked which leg was preferred for kicking a ball, and hopping on, with the preferred leg being considered the dominant leg (Maulder & Cronin, 2005). Furthermore, additional tests were used to identify which limb moved first; walking from a stationary position and stepping off a 0.3 m high step from a stationary position. The limb that moved first was considered the dominant limb. This movement behaviour information in conjunction with the question data allowed for a comprehensive decision to be made on the netballer's limb dominance. The dominant limb was determined as the limb on the side of the body that was identified in the four assessments the majority of the time.

Unanticipated straight run task and unanticipated 180° turn tasks

The netballers performed three tasks from a 10 m approach that utilised a self selected start stance: a left leg plant and 180° turn; a straight ahead run (left or right foot placement); and a right leg plant and 180° turn. The tasks were presented as options in order to obtain an unanticipated / decision made movement response. Unanticipated movements have been demonstrated to elicit up to two times greater

knee varus/valgus and internal/external rotation joint moments than anticipated movements (Besier, Lloyd, Ackland & Cochrane, 2001). Movements during game situations are generally not always anticipated due to an external stimulus (Besier et al., 2001), thus unanticipated movements may offer a better reflection of the loads experienced around lower extremity joints during a sporting scenario. Therefore, a visual cue was displayed on a 19" computer screen which was triggered manually when the netballer was approximately 1 m away from the force platform. The screen was placed 0.5 m to the right side of the force platform. Testing tasks were assigned a colour consisting of green, yellow, and red which represented the 180° left leg plant and turn, straight ahead, and 180° right leg plant and turn respectively. Visual cues were created and presented using PowerPoint (Microsoft, Office, version 2003, California) slides.

Several pre-planned and unanticipated trials of each task were performed before data collection started in order to provide the netballers with the opportunity to familiarise themselves with the testing tasks. Each netballer completed all four tasks randomly, as cued by the computer monitor. This included foot placement of the left foot and right foot during the unanticipated straight run task, and pivoting on the left foot and right foot during the unanticipated 180° turn tasks. Bates et al. (1992) suggested that a minimum of five trials are needed to achieve 90% power for sample sizes of at least ten participants. To enable the five trials needed for data analysis to be collected for each task, a total of 20 successful trials were needed (Dierks & Davis, 2007). A maximum of 30 trials were completed by the participants to achieve the required data set. No feedback on trials performed previously in the testing session was provided to the participants as to avoid the possibility of the trials becoming planned. A 180° left (or right) leg plant and turn trial was deemed successful if: (a) the approach speed fell between 3.5 and 5 m.s⁻¹; (b) the left (or right) foot came in contact with the force platform; and (c) the exit speed was between 2.5 and 3.5 m.s⁻¹. A straight-ahead trial was deemed successful if (a) the approach speed was between 3.5 and 5 m.s⁻¹; (b) the left (or right) foot came into contact with the force platform; and (c) the netballer continued along the straight-ahead path and did not decelerate until at least 1 m after the centre of the force platform. The turning tasks were utilised in this study due to the use of the movement in field test assessment for the sport of netball. Specifically the 505 assessment (180° turn) is utilised to assess an individual's change of direction ability. Furthermore, anecdotally this type of turn is frequently utilised in netball. The approach and exit speeds were based on unpublished field testing scores typical in sprint and agility assessment in New Zealand netballers. Each netballer was given approximately 45 - 90 s of rest between trials to reduce the potential effects of fatigue.

Kinematic and kinetic data collection

Following the practice trials, four moulded thermoplastic shells were securely placed on the lateral surface of both the netballer's thighs and shanks. Each thermoplastic shell had four retro-reflective tracking markers attached. Additional tracking markers were placed on both anterior superior iliac spines, both iliac crests, and the mid-point of both posterior superior iliac spines to define the pelvis. Tracking markers were also placed on the heels of both feet, and the first and fifth metatarsal heads in order to define the foot. Calibration markers were placed on both greater trochanters (bilateral), both medial and lateral femoral condyles, and both medial and lateral malleoli to locate the segment origins. The marker placement protocol was based on those used by others previously (Dierks & Davis, 2007; Ferber et al., 2005; Pollard, Davis & Hamill, 2004; Pollard et al., 2005). For a depiction of the marker set see Appendix 6. Once the markers were placed, a standing calibration trial was recorded to establish anatomical neutral. The netballers stood in a neutral position on the force plate at the centre of the camera capture space for approximately 1 minute. The calibration markers were removed after the standing trial, while the tracking markers remained on the netballer throughout the data collection session. The same individual placed the markers for all netballers and testing sessions.

A nine-camera motion capture system (Qualisys, Sweden) was used to record three dimensional (3-D) kinematic data at a sampling rate of 240 Hz as used by Pollard et al. (2005). The cameras were positioned so that each marker was visible in multiple cameras throughout the stance phase (heel strike to toe off). The cameras encircled a force platform (~0.48m x ~0.51m) embedded within the floor (Advanced Mechanical Technology Inc., USA). The force platform, sampling at a rate of 1200 Hz, recorded the magnitude of three-dimensional ground reaction forces and was only used to identify the stance phase and foot strike region for the various tasks. The cameras and force platform were interfaced to a personal computer that allowed for synchronization of kinematic and kinetic data using the motion analysis software (Qualisys Track Manager, Sweden, version 1.10.283). Prior to testing, the nine-camera motion capture system was calibrated as per the manufacturer's protocol (Qualisys, Sweden), with a right-handed lab coordinate system being defined using a rigid L-frame containing four markers of known locations. A two-marker wand of known length was used within the calibration frame to scale the individual camera views of the measurement volume. The average movement residue for the retro-reflective markers during system calibration was minimal (less than 2 mm). The AMTI force platform was zeroed and calibrated for laboratory position and axis orientation. A two gate SWIFT® timing light system (SWIFT, Australia) was used to measure and monitor approach, performance and exit

velocities. One timing light gate consisted of a dual beam modulated visible RED light sensor / reflector set up collecting at 4 MHz \pm 80 Hz. The timing lights were set at a height of 1.1 m (approximately hip height) and placed parallel to the approach runway with one gate located 3 m prior to the force platform and the other located 1 m prior (2 m apart). To view a schematic of the experimental set up see Appendix 7.

Kinematic data processing & analyses

The following data reduction procedures were performed on the data for all five trials for each of the four unanticipated tasks. Q-Trac software (Qualisys, Sweden) was used to digitize the marker coordinates. Digitized coordinate data were then exported to Visual 3D™ software (C-Motion, Inc., Rockville, MD, USA) where it was low-pass filtered using a fourth-order Butterworth filter with an 8 Hz cut-off frequency (Pollard et al., 2005). Ground reaction force data were low-pass filtered using a fourth-order Butterworth filter with a 50 Hz cut-off frequency (Dierks & Davis, 2007; Pollard et al., 2004; Pollard et al., 2005). Three-dimensional kinematics, namely angles, were created from the coordinate data for the hip, knee and ankle joint angles as well as for the thigh, shank, and rearfoot (calcaneal) segment angles in the sagittal, frontal and transverse planes. Kinematic and ground reaction force data were exported to customised LabVIEW software (National Instruments, Austin, Texas, USA, version 6) where all angle data were linearly interpolated to 101 data points in order to normalize stance to 100%. This meant that each data point represented one percent of the stance phase (0 – 100%). Intra limb joint couplings of the stance leg for each task were generated using a vector coding method of Sparrow et al. (1987) and utilised in the literature recently by (Dierks & Davis, 2007; Ferber et al., 2005; Pollard et al., 2005). Segment and joint couplings of interest were derived from the work of Dierks et al. (2007) and Ferber et al. (2005) as outlined in Table 1. Angle–angle plots were constructed for each coupling of interest with the distal motion on the vertical axis and the proximal motion on the horizontal axis. Coupling angles were then calculated using the orientation of the resultant vector to the right horizontal between two adjacent data points in the stance phase. The standard deviation of the coupling angles across the five trials for a task was calculated for each percent of stance, providing a measure of between-trial, within-participant variability. Group means for joint coupling variability were calculated using an average of the variances method so coupling data could be plotted. Joint coupling variability was averaged within one period of stance based on discrete events in the vertical ground reaction force (Dierks & Davis, 2007; Ferber et al., 2005). The period was defined from foot-strike to the maximum vertical ground reaction force and is referred to as stance throughout the findings of this study. These

procedures were repeated for each intra-limb coupling within each movement task for each netballer. Data was then categorised / reallocated based upon limb dominance.

Statistical analyses

Descriptive statistics including overall group mean and standard deviations were calculated for all variables of interest. The measurement reliability (performance consistency) and measurement variability (performance flexibility) of the average joint coupling variability for the six joint couplings of interest during four unanticipated movement tasks was assessed using similar methods to that of Bradshaw, Hume, Carlton and Aisbett (2010). Joint coupling variability data were log transformed in order for measurement reliability and measurement variability outcomes to be presented as percentage changes where appropriate (Hopkins, 2000).

Reliability measures included the difference in the mean (MDiff) between the two days as a percentage, and Cohen's effect sizes (ES). Effect sizes were interpreted as 0 – 0.2 trivial, 0.2 – 0.6 small, 0.6 – 1.2 moderate, 1.2 – 2.0 large, and 2.0 – 4.0 very large (Hopkins, 2007b). An overall interpretation of the average measurement reliability of the joint coupling variability outcomes was based on the methods of Bradshaw et al. (2010). Average reliability was interpreted as 'good' when the difference in the mean was less than 5% and the effect size was trivial to small. Average reliability was interpreted as 'moderate' when the aforementioned criteria for 'good' was breached for either the difference in the mean or the effect size (MDiff > 5% or ES = moderate to large). Average reliability was categorised as 'poor' when both the difference in the mean and the effect size criteria were breached (MDiff > 5% and ES = moderate to large).

Measurement variability outcomes included intraclass correlation coefficients (ICC) (Bradshaw et al., 2010), and the typical error of the measurement expressed as a coefficient of variation percentage (Hopkins, 2000). Based on 10 participants an ICC close to 1.00 indicates 'perfect' agreement with minimal variation (Atkinson & Nevill, 1998) whereas an ICC less than 0.70 is indicative of 'poor' agreement and high measurement variability, $0.7 \leq \text{ICC} \leq 0.80$ represents a questionable outcome, and $\text{ICC} > 0.8$ represents an excellent outcome (Hopkins & Manly, 1989; Morrow & Jackson, 1993; Shrout & Fleiss, 1979). A typical error (CV) of less than 10% is considered small variation (Cormack, Newton, McGuigan & Doyle, 2008). An overall interpretation of the average measurement variability of the joint coupling variability measures was based on the methods of Bradshaw et al. (2010). Average measurement variability was interpreted as 'small' when the ICC was > 0.70 and the CV was $< 10\%$. Average measurement variability was interpreted as 'moderate' when ICC was < 0.70 or CV was $> 10\%$, and 'large' when $\text{ICC} < 0.70$ and $\text{CV} > 10\%$.

The use of a variety of measurement reliability and measurement variability outcomes which exceeds the recommendations of Atkinson and Neville (1998), allows for a robust decision to be made on the appropriateness to utilise a test measure of interest. In order for a joint coupling variability measure to be considered acceptable for future use the average measurement reliability and average measurement variability qualitative interpretations had to indicate 'good' to 'moderate' reliability and 'small' to 'moderate' measurement variability respectively. In any instances where the average reliability outcome was 'poor' or the average measurement variability was 'large' the measure was considered inappropriate for future use.

Results

The measurement reliability and measurement variability outcomes are reported for each joint coupling variability measure and associated movement task in Table 2. Overall there were eight (~33%) instances where the joint coupling variability measures assessed during the four different movement tasks were identified as being acceptable (average reliability and average measurement variability qualitative interpretations indicated 'good' to 'moderate' reliability and 'small' to 'moderate' measurement variability respectively) for future use.

Good average reliability and moderate average measurement variability was demonstrated for the rearfoot_(eversion/inversion)–tibial_(rotation) joint coupling variability measure during the unanticipated 180° turn task. Moderate average reliability and moderate average measurement variability was demonstrated for the rearfoot_(eversion/inversion)–tibial_(rotation) joint coupling variability measure of the non-dominant leg during the unanticipated straight task. During the unanticipated straight task, the dominant leg demonstrated moderate average reliability and moderate average measurement variability for the rearfoot_(eversion/inversion)–knee_(flexion/extension) joint coupling variability measure. For all movement tasks with the exception of the unanticipated 180° turn task performed on the dominant leg the rearfoot_(eversion/inversion)–knee_(rotation) joint coupling variability measure demonstrated moderate average reliability and moderate average measurement variability in all cases. Tibial_(rotation)–knee_(flexion/extension) joint coupling variability demonstrated moderate average reliability and moderate average measurement variability in the dominant leg during the unanticipated straight task. During the unanticipated 180° turn performed on the non-dominant leg, moderate average reliability and moderate average measurement variability was demonstrated for the tibial_(rotation)–knee_(rotation) joint coupling variability measure.

Table 1: Definition of terms for joint motions and joint coupling relationships

Joint Motions	Definition
<i>Sub-Talar (Ankle):</i>	
Rearfoot eversion/inversion	Calcaneus with respect to the tibia in the frontal plane. Eversion is lateral rotation of the calcaneus relative to the tibia. Inversion is the opposite of eversion.
Tibial rotation	Calcaneus with the respect to the tibia in the transverse plane. This describes the internal and external rotation of the tibia at the distal endpoint.
<i>Tibio-Femoral (Knee):</i>	
Knee Flexion/Extension	Tibia with respect to the femur in the sagittal plane.
Knee Rotation	Tibia with respect to the femur in the transverse plane. This describes the tibial rotation at the proximal endpoint.
<i>Femoral-Pelvic (Hip):</i>	
Thigh Rotation	Femur with respect to the pelvis in the transverse plane. This describes the femur rotation at the proximal endpoint.
Joint coupling relationship	Definition
Rearfoot _(eversion/inversion) –Tibial _(rotation)	Eversion and inversion of the rearfoot coupled with internal and external rotation of the tibia.
Rearfoot _(eversion/inversion) –Knee _(flexion/extension)	Eversion and inversion of the rearfoot coupled with flexion and extension of the knee
Rearfoot _(eversion/inversion) –Knee _(rotation)	Eversion and inversion of the rearfoot coupled with internal and external rotation of the knee.
Tibial _(rotation) – Knee _(flexion/extension)	Internal and external rotation of the tibia coupled with flexion and extension of the knee.
Tibial _(rotation) – Knee _(rotation)	Internal and external rotation of the tibia coupled with internal and external rotation of the knee.
Tibial _(rotation) –Thigh _(rotation)	Internal and external rotation of the tibia coupled with internal and external rotation of the thigh.

Table 2: Measurement reliability and measurement variability of joint coupling variability measures during the unanticipated movement tasks.

Couplings (°)	Reliability Statistics					Variability Statistics			
	Day 1	Day 2	MDiff (%)	ES	Rating	ICC	Typical	Rating	Use
	Mean ±SD	Mean ±SD					error as a CV (%)		
Rearfoot_(eversion/inversion)–tibial_(rotation)									
Straight run: dominant leg contact	21.6 ±7.2	22.7 ±12.8	-2.7	0.11	Good	0.13	54.3	Large	No
Straight run: non-dominant leg contact	26.2 ±15.1	19.8 ±9.2	-21.3	-0.51	Moderate	0.85	27.0	Moderate	Yes
180° turn on the dominant leg task	34.1 ±6.2	32.0 ±8.5	-7.3	-0.28	Moderate	0.05	23.0	Large	No
180° turn on the non-dominant leg task	31.3 ±13.7	30.8 ±11.2	4.1	-0.04	Good	0.89	24.4	Moderate	Yes
Rearfoot_(eversion/inversion)–knee_(flexion/extension)									
Straight run task: dominant leg	29.4 ±15.8	24.8 ±15.1	-19.4	-0.30	Moderate	0.92	31.3	Moderate	Yes
Straight run task: non-dominant leg	32.3 ±19.6	23.7 ±16.9	-31.7	-0.47	Moderate	0.47	93.3	Large	No
180° turn on the dominant leg task	18.4 ±8.4	15.8 ±7.9	-11.2	-0.31	Moderate	0.29	53.4	Large	No
180° turn on the non-dominant leg task	19.3 ±12.8	18.7 ±8.6	7.6	-0.05	Moderate	0.54	55.3	Large	No
Rearfoot_(eversion/inversion)–knee_(rotation)									
Straight run task: dominant leg	20.7 ±8.2	19.7 ±9.6	-8.9	-0.12	Moderate	0.75	37.2	Moderate	Yes
Straight run task: non-dominant leg	23.8 ±15.8	18.3 ±11.8	-24.0	-0.39	Moderate	0.72	48.0	Moderate	Yes
180° turn on the dominant leg task	35.0 ±10.1	33.3 ±10.3	-3.7	-0.16	Good	0.21	39.6	Large	No
180° turn on the non-dominant leg task	37.9 ±10.3	34.4 ±7.0	-7.8	-0.40	Moderate	0.70	17.9	Moderate	Yes

Table 2: continued

Tibial_(rotation)– knee_(flexion/extension)										
Straight run task: dominant leg	32.4 ±13.4	27.2 ±14.8	-20.7	-0.37	Moderate	0.82	35.2	Moderate	Yes	
Straight run task: non-dominant leg	32.7 ±17.8	26.0 ±16.8	-24.8	-0.39	Moderate	0.47	78.8	Large	No	
180° turn on the dominant leg task	19.4 ±6.3	19.1 ±7.6	-2.6	-0.05	Good	0.57	32.3	Large	No	
180° turn on the non-dominant leg task	22.1 ±10.7	20.8 ±7.0	0.3	-0.14	Good	0.23	46.1	Large	No	
Tibial_(rotation)– knee_(rotation)										
Straight run task: dominant leg	20.2 ±7.5	18.3 ±9.0	-17.5	-0.23	Moderate	0.26	62.2	Large	No	
Straight run task: non-dominant leg	22.4 ±12.8	18.5 ±12.7	-18.5	-0.31	Moderate	0.45	68.4	Large	No	
180° turn on the dominant leg task	33.1 ±9.1	34.9 ±10.0	5.9	0.19	Moderate	0.22	31.9	Large	No	
180° turn on the non-dominant leg task	37.1 ±9.3	33.5 ±6.9	-7.9	-0.43	Moderate	0.81	16.5	Moderate	Yes	
Tibial_(rotation)–thigh_(rotation)										
Straight run task: dominant leg	21.8 ±10.6	20.3 ±10.7	-10.5	-0.14	Moderate	0.49	64.0	Large	No	
Straight run task: non-dominant leg	20.4 ±13.3	18.5 ±9.6	-2.5	-0.17	Good	0.40	68.6	Large	No	
180° turn on the dominant leg task	31.4 ±9.0	35.1 ±8.9	13.7	0.41	Moderate	0.01	35.8	Large	No	
180° turn on the non-dominant leg task	35.0 ±10.8	33.8 ±9.0	-1.4	-0.12	Good	0.42	31.2	Large	No	

Notes: SD, standard deviation; MDiff, inter-day difference in mean scores as a percentage; ES, Cohen's inter-day effect size; ICC, intraclass correlation coefficient; CV, typical error of measurement as a coefficient of variation; Use, indicates acceptable for future use.

Discussion

Reports of the measurement reliability and measurement variability of lower extremity joint coupling variability during athletic movements are scarce. The purpose of this study was to determine the measurement reliability and measurement variability of various lower extremity joint coupling variability measures of the dominant and non-dominant stance leg during unanticipated straight run and unanticipated 180° turning tasks performed by netballers. The results of the present study indicate eight out of 24 (~33%) measures investigated exhibited an acceptable level of measurement reliability and measurement variability for joint coupling variability between testing sessions conducted on two days seven days apart.

Measurement reliability and measurement variability of joint coupling variability

The intraclass correlation coefficient (ICC) in the present study reported for the joint coupling variability of the rearfoot_(eversion/inversion)–tibial_(rotation) coupling was excellent for the non-dominant leg during both the unanticipated tasks with ICC values being similar to that reported in the literature. For example, McGrath, Padua & Thigpen (2008) reported an excellent intraclass correlation coefficient of 0.82, for the foot and shank coupling during a jump-landing task. Interestingly, the present study revealed the rearfoot_(eversion/inversion)–tibial_(rotation) joint coupling variability in the dominant leg during both the unanticipated tasks to have very poor ICCs and overall unacceptable combined measurement reliability and measurement variability outcomes. Based on the preferential use of the dominant limb for motor patterns (Sadeghi, Allard, Prince & Labelle, 2000) it is surprising that very different joint coupling strategies would be used on different testing occasions especially during a simple movement pattern like straight sprint running.

There was only one instance each where rearfoot_(eversion/inversion)–knee_(flexion/extension) and tibial_(rotation)–knee_(flexion/extension) joint coupling variability measures of the dominant leg during the straight run task were identified as being both acceptably reliable and variable. During straight running immediately after the initial contact with the ground, pronation of the rearfoot occurs relatively synchronously with tibial internal rotation and knee flexion (DeLeo et al., 2004). This established synchronous relationship in conjunction with the preferential characteristics of the dominant limb and the simplistic nature of a straight running task would somewhat explain the reasons for the rearfoot_(eversion/inversion)–knee_(flexion/extension) and tibial_(rotation)–knee_(flexion/extension) joint coupling variability measures having such excellent ICC outcomes. The tibial_(rotation)–knee_(rotation) joint coupling variability during an unanticipated 180° turn performed on the non-dominant leg was also revealed as having excellent ICC outcomes in the present

study. All the aforementioned joint coupling variability measures are encouraged for researchers to use in future investigations to broaden the scope of the joint coupling variability paradigm.

The rearfoot_(eversion/inversion)–knee_(rotation) joint coupling variability measure was identified as both acceptably reliable and variable for most unanticipated tasks with the exception of the unanticipated 180° turn task performed on the dominant leg. Specifically, the rearfoot_(eversion/inversion)–knee_(rotation) joint coupling variability of the dominant leg and non-dominant leg during the unanticipated straight run tasks, and the dominant leg during the unanticipated 180° turn task should be considered as joint coupling variability measures of interest in future study. In particular such measures may be of interest during studies investigating knee joint stress during running activities. Hamill et al. (1999) suggested antagonistic counter-rotations of the tibia at the proximal and distal ends such as that experienced during rearfoot_(eversion/inversion)–knee_(rotation) joint coupling may lead to excessive stress at the knee joint and potentially lead to knee injury.

Dominant leg versus non-dominant leg

The dominant leg was found to have the least number of acceptably reliable and variable joint coupling variability measures. Intuitively it would be expected that such a preferential limb for tasks would demonstrate improved stability / reliability / invariability in the movement patterns utilised. The dominant limb which is prominent during mobilisation of movement tasks via enhanced power outputs or propulsion, whilst the other limbs acts as the stabiliser (Sadeghi et al., 2000), has been found to be more variable as speed of mobilisation increases (Masani, Kouzaki & Fukunaga, 2002). It is plausible that asymmetrical behaviour (dominant vs. non-dominant limb) may be associated with different contributions of limbs in carrying out propulsion and control tasks (Sadeghi et al., 2000) which may explain discrepancies in variability outcomes.

When considering the dominant limb the measurement reliability and measurement variability outcomes appear to be task specific. For example, during the unanticipated straight run task three joint coupling variability measures of the dominant leg were identified as having both acceptable measurement reliability and measurement variability, whereas no joint coupling measures were identified for the dominant leg during an unanticipated 180° turn.

During the unanticipated 180° turn tasks the acceptable measurement reliability and measurement variability outcomes appear to be limb specific with none of the joint coupling variability measures during the unanticipated 180° turn performed on the dominant leg indicating both acceptable measurement reliability and measurement variability. An example is the rearfoot_(eversion/inversion)–tibial_(rotation) joint coupling variability

measure which had acceptable reliability during the unanticipated task utilising the non-dominant leg but poor reliability when utilising the dominant leg.

Only one joint coupling variability measure was identified as having both acceptable measurement reliability and measurement variability in both the dominant and non-dominant limb for the unanticipated tasks. Specifically, the rearfoot_(eversion/inversion)–knee_(rotation) joint coupling variability measure during the unanticipated straight run tasks demonstrated both acceptable measurement reliability and measurement variability. It is possible that this particular joint coupling variability measure could be used in limb comparisons between various athletic population in future study. Furthermore such a measure may be a precursor to tibial stress type injuries during running or even patellofemoral pain (PFP). Based on the lower magnitudes in knee kinematics demonstrated by participants with PFP (Dillon, Updyke & Allen, 1983), Heiderscheit et al. (2002) compared a rearfoot_(eversion/inversion)–knee_(rotation) joint coupling variability measure between injury free and PFP sufferers. No substantial link was identified between this coupling and the PFP sufferers. This may have been due to a preferred running speed on a treadmill incorporated by Heiderscheit et al. (2002) instead of a more realistic maximal effort being utilised. Further research should investigate the latter speed concept in this context.

Unanticipated straight run tasks versus unanticipated 180° turn tasks

Overall the straight tasks presented with the most acceptable outcomes in the present study compared to 180° turn tasks (5 versus 3). Such a finding would be expected given the more complex nature of the turn (agility) task. The variability of the couplings during the unanticipated 180° turning tasks reported in this study were mostly larger compared to the straight tasks which demonstrates a more flexible nature in outcomes during a turning task. This greater flexibility in the motor pattern of the turning task would somewhat explain the discrepancy in reliability outcomes between the straight and turning tasks. Physical demands and motor pattern coordination for agility tasks are greater than that of straight sprint tasks (Young, McDowell & Scarlett, 2001) therefore these tasks are independent of each other. This independence is mostly apparent in this study's findings as only one joint coupling variability measure (rearfoot_(eversion/inversion)–knee_(rotation)) was acceptably reliable in both the unanticipated straight run and unanticipated 180° turn tasks.

Unreliable and highly variable joint coupling variability measures

The combined measurement reliability and measurement variability of a measure determines whether or not that particular measure may be of use in biomechanical research. Unfortunately, many (17; ~67%) of the lower extremity joint

coupling variability measures investigated in the current study demonstrated both unacceptable measurement reliability and measurement variability during unanticipated straight run and unanticipated 180° turning tasks. Of the six coupling variability measures the joint coupling variability measure for the tibial_(rotation)–thigh_(rotation) coupling exhibited both unacceptable reliability and variability for all unanticipated tasks. It is up to the researcher to judge whether a measurement is appropriate enough for its intended use (Atkinson & Nevill, 1998). It is acknowledged that the researcher ultimately decides whether or not to use such variables. It is recommended that the joint coupling variability measures with low measurement reliability and high measurement variability found in the present study be considered cautiously as these variables are probably too unreliable and variable to monitor small changes in an athlete's couplings during athletic performance following a period of training intervention.

Recommendations for future research

For the joint coupling variability measures identified as both acceptably reliable and variable in this study, future research should investigate the associations these measures may have with lower extremity injuries. Furthermore, the use of these measures in comparison investigations between genders, athletic populations, and athletic performance level would broaden the knowledge base of the joint coupling variability paradigm. Given the limited amounts of acceptable outcomes for joint coupling variability measures assessed in this study in particularly for the unanticipated 180° turn task on the dominant leg it is recommended more research is conducted that investigates the measurement reliability and measurement variability of other lower extremity coupling relationships during this type of task.

Conclusion

A variety of lower extremity joint coupling variability measures during unanticipated straight run and unanticipated 180° turning tasks can be achieved with an acceptable degree of measurement reliability and measurement variability. Specifically, the rearfoot_(eversion/inversion)–knee_(flexion/extension), rearfoot_(eversion/inversion)–knee_(rotation) and tibial_(rotation)–knee_(flexion/extension) joint coupling variability of the dominant leg during an unanticipated straight run task, the rearfoot_(eversion/inversion)–tibial_(rotation) and rearfoot_(eversion/inversion)–knee_(rotation) joint coupling variability of the non-dominant leg during unanticipated straight run task, and the rearfoot_(eversion/inversion)–tibial_(rotation), rearfoot_(eversion/inversion)–knee_(rotation) and tibial_(rotation)–knee_(rotation) joint coupling variability of the non-dominant leg during an unanticipated 180° turning task were deemed to have acceptable levels of measurement reliability and measurement variability. The use of

these measures to quantify joint coupling variability in the lower extremity across testing sessions during unanticipated straight run and unanticipated 180° turning tasks appears to be justified. Therefore it would be appropriate for these measures to be recommended for future use.

CHAPTER 4: DOES JOINT COUPLING VARIABILITY DIFFER BETWEEN LEVELS OF PLAY IN FEMALE NETBALLERS, GENDER AND LOWER LIMBS?

Overview

The purpose of this study was to examine the effect of limb dominance, gender and netball playing ability on lower extremity joint coupling variability during unanticipated straight run and unanticipated 180° turning tasks. Twelve elite female, 12 non-elite female, and 12 male netball players performed 20 to 30 trials of the unanticipated sprinting tasks (straight sprints and sprints with a 180° turn) on their dominant and non-dominant legs in the motion analysis laboratory from a 10 m approach. Non-elite netballers demonstrated 33% less rearfoot_(eversion/inversion)–knee_(rotation) coupling variability during the stance phase of the dominant leg during a straight sprint when compared with elite netballers. During stance of the unanticipated turn performed on the non-dominant leg, non-elite netballers demonstrated 43% greater rearfoot_(eversion/inversion)–tibial_(rotation) coupling variability than the elite netballers. These findings suggest JCV to be context-specific and likely related to the nature of the movement. Further research is needed to better appreciate the context-specificity of JCV in athletes of varying ability. During an unanticipated 180° turn performed on the non-dominant leg, non-elite female netballers demonstrated -15.5% substantially less tibial_(rotation)–knee_(rotation) coupling variability during the stance phase of the pivot than male netballers which is in accordance with existing research investigating 45° cutting movements. For both dominant and non-dominant leg ground contacts during the unanticipated straight task compared to the males the elite females demonstrated substantially greater (31.7% to 106.1%) JCV magnitudes for all JCV measures with the exception of rearfoot_(eversion/inversion)–knee_(rotation) JCV, whereas during the unanticipated 180° turn performed on the non-dominant leg the elite females demonstrated substantially less rearfoot_(eversion/inversion)–knee_(rotation) JCV (-17.2%) and rearfoot_(eversion/inversion)–knee_(rotation) JCV (-20.6%). Further research is required investigating gender differences in JCV for other forms of sporting movements such as abrupt stops, landings and straight running. Other sporting population samples may offer more insight into gender discrepancies in JCV as well. Rearfoot_(eversion/inversion)–knee_(rotation) coupling variability during unanticipated straight sprints was 16.8% (effect size = 0.2) larger in the non-dominant leg than the dominant leg. The greater bandwidth of coupling strategies the non-dominant leg has access to, may allow a more explorative nature within a movement task in order to optimize performance and reduce the risk of injury.

Introduction

In Australasia netball is considered the primary team sport played both recreationally and competitively by females (McManus et al., 2006), and is also growing in interest and participation rate for males as well (Tagg, 2008). Some men's netball teams in New Zealand and Australia treat the game very seriously, training and competing with some of the best women's teams in the world (Tagg, 2008). Netball is a high-strategy sport requiring many explosive sprints, abrupt stops, change of direction and landing movements (Bock-Jonathan et al., 2007; McManus et al., 2006). Given the physical demands of netball there is a large exposure for risk of injury (Hume & Steele, 2000).

The incidence of injuries in court sports (e.g., netball, basketball, volleyball) has been well documented with the ankle and knee joints being identified as the primary anatomical locations injured (Hopper et al., 1995; Hume, 1993; Hume & Steele, 2000). Of these acute injuries, most occur as a result of play involving combinations of movements such as a change of direction whilst sprinting (Hume & Steele, 2000). Female athletes reportedly are four to six times more likely to sustain a serious knee injury than male athletes participating in the same sports that require explosive change of direction maneuvers whilst sprinting (Griffin et al., 2000; Hutchinson & Ireland, 1995; Ireland, 1999). Research into the mechanisms that cause injury is ongoing with attention currently focused upon the paradigm of joint coupling variability (JCV) strategies within a movement pattern (Dierks & Davis, 2007; Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 1999; Pollard et al., 2005).

Joint coupling variability

Variability in joint coupling can be an essential component, providing the necessary flexibility for successful task execution and enhanced performance (Clark & Phillips, 1993; Turvey, 1990; Van Emmerik et al., 1999). Furthermore, individuals can exploit JCV within the movement system in different ways to adapt to changing task constraints over time (Davids et al., 2004), thus reducing the risk of injury (Hamill et al., 1999; Pollard et al., 2005). Due to the infancy of the JCV paradigm, information on JCV is scarce with empirical evidence in the form of normative data being limited or nonexistent presently for athletes of various athletic ability, genders or limbs (e.g. legs).

Athletic ability comparisons of joint coupling variability

Highly variable JCV strategies have been linked to superior sprint performance (Bradshaw et al., 2007), and appear more prevalent in superior performances of javelin and basketball shooting tasks (Bartlett et al., 2007). To date no studies have investigated differences in coupling variability between athletes of varying ability (elite

vs. non-elite). One study has offered insight into training status differences for aspects of variance within movement and muscle recruitment patterns during cycling (Chapman, Vicenzino, Blanch & Hodges, 2009). Specifically lesser trained cyclists were reported to demonstrate more variability in movement and muscle recruitment patterns during cycling compared to highly trained cyclists. These findings are in contrast to the findings presented previously (Bartlett et al., 2007; Bradshaw et al., 2007), suggesting that coupling variability is likely context-specific and likely related to the nature of the movement (Chapman et al., 2009). Such a premise warrants further investigation.

Gender comparisons of joint coupling variability

Females have been reported to exhibit much less coupling variability during an agility task compared to males (Pollard et al., 2005), which may partially explain the disproportional occurrences of lower extremity injuries presented by females compared to males, especially for anterior cruciate ligament ruptures (Griffin et al., 2000; Hutchinson & Ireland, 1995; Ireland, 1999). The findings of Pollard et al. (2005) provide an awareness that during 45° cutting movements, gender differences exist for lower extremity couplings predominantly in the frontal plane of injury free individuals. Specifically, females demonstrated 32% less thigh rotation - leg rotation variability, 40% less thigh abduction/adduction - leg abduction/adduction variability, 46% less knee flexion/extension - knee rotation variability, and 44% less knee flexion/extension - hip rotation variability. Based on the outcomes of Pollard et al. (2005) it could be assumed that athletes, and in particular female athletes, that demonstrate low coupling variability within the lower extremity may possess an inability to utilise a movement pattern that meets the needs of potential scenarios that may be encountered during their chosen sporting pursuit, thus increasing the risk of injury and diminished performance. Dynamical systems theory supports this concept as it suggests that consistent high-level performance across a variety of situations and conditions can only be achieved with a variable coupling pattern that can be adapted to suit the demands of the task at hand (Hamill et al., 1999). Given that Pollard et al. (2005) examined coupling variability during a 45° cut movement pattern it is unknown whether similar gender differences would exist for movement patterns such as straight sprinting and 180° turns. These types of movements are common in netball therefore warrant investigation.

Limb comparisons of joint coupling variability

The presence of functional asymmetry due to limb dominance may be one of the factors responsible for mechanical overload affecting movement technique

(Maupas, Paysant, Datie, Martinet & André, 2002). Additionally, the dependence on the dominant limb can increase stress on the joints of that extremity (Murphy, Connolly & Beynon, 2003) which may increase the likelihood of injury (Negrete, Schick & Cooper, 2007). Research has identified an association between limb dominance and injury (Chomiak, Junge, Peterson & Dvorak, 2000; Ekstrand & Gillquist, 1983; Orchard, 2001) in particular for ankle and knee related injury occurrences. Such injuries are prevalent in court sports such as netball (Hume, 1993; Hume & Steele, 2000) and are also more likely to occur in females compared to males (Griffin et al., 2000; Hutchinson & Ireland, 1995; Ireland, 1999). It may be possible that the dominant limb demonstrates reduced lower extremity JCV which may explain a higher likelihood of injury. Investigation into the differences in JCV measures that may exist between the dominant and non-dominant limbs would broaden the knowledge base of the JCV paradigm which may offer insight into the injury associated parameters.

Aim

The aim of this study was to examine the effect of limb dominance, gender and netball playing ability on lower extremity joint coupling variability during unanticipated straight run and unanticipated 180° turning tasks.

Netball player characteristics

Thirty six netball players, consisting of three sub-groups of elite females ($N = 12$), non-elite females ($N = 12$) and males ($N = 12$), volunteered to participate in the study (see Table 3). Using data from Pollard et al. (2005) 12 participants per group were deemed adequate for the sample size based on a minimal statistical power of 80% ($p = 0.05$). Sample size and power calculations were completed using G*Power Software (Erdfelder, Faul & Buchner, 1996).

Elite female netballers were classified as players who had represented their region or country at a senior level, whereas non-elite were classified as players who had participated in senior club level netball teams. Male netballers consisted mostly of regional representative level players and some high level competitive indoor netball players. All netballers had no history of significant lower extremity injury six months prior to testing and were injury free at the time of data collection. Each netballer gave informed consent in writing to participate in this study prior to testing. Ethical approval was obtained for all testing procedures from the Auckland University of Technology Ethics Committee. All netballers wore spandex shorts or pants and ASICS (Gel-Rocket) court shoes during the data collection.

Table 3: Netball player characteristics.

	Elite females (<i>N</i> = 12) Mean ±SD	Non-elite females (<i>N</i> = 12) Mean ±SD	Males (<i>N</i> = 12) Mean ±SD	All netballers (<i>N</i> = 36) Mean ±SD
Age (yrs)	22.3 ±3.8	20.9 ±2.3	23.7 ±4.2	22.3 ±3.6
Height (m)	1.79 ±0.08	1.72 ±0.05	1.78 ±0.07	1.76 ±0.07
Mass (kg)	79.2 ±11.6	69.5 ±9.8	88.8 ±23.2	79.2 ±17.5
Playing history (yrs)	13.0 ±2.8	13.2 ±2.4	4.9 ±5.2	10.4 ±5.3
Training load (hours/week)	8.8 ±1.6	8.8 ±2.9	5.7 ±3.4	7.8 ±3.1
Training load (sessions/week)	5.5 ±0.8	5.3 ±2.0	3.5 ±2.3	4.8 ±2.0

Procedures

Netball player limb dominance

Limb dominance was determined via verbal questions and practical tests. The netballers were asked which leg was preferred for kicking a ball, and hopping on, with the preferred leg being considered the dominant leg (Maulder & Cronin, 2005). Furthermore, additional tests were used to identify which limb moved first; walking from a stationary position and stepping off a 0.3 m high step from a stationary position. The limb that moved first was considered the dominant limb. This information in conjunction with the question data allowed for a comprehensive decision to be made on limb dominance. The dominant limb was determined as the limb on the side of the body that was identified in the four assessments the majority of the time.

Unanticipated straight run task and unanticipated 180° turn tasks

The netballers performed three tasks from a 10 m approach that utilised a self selected start stance: a left leg plant and 180° turn; a straight ahead run (left or right foot placement); and a right leg plant and 180° turn. The tasks were presented as options in order to obtain an unanticipated / decision made movement response. Unanticipated movements have been demonstrated to elicit up to two times greater knee varus/valgus and internal/external rotation joint moments than anticipated movements (Besier et al., 2001). Movements during game situations are generally not always anticipated due to an external stimulus (Besier et al., 2001), thus unanticipated movements may offer a better reflection of the loads experienced around lower extremity joints during a sporting scenario. Therefore, a visual cue was displayed on a

19" computer screen which was triggered manually when the netballer was approximately 1 m away from the force platform. The screen was placed 0.5 m to the right side of the force platform. Testing tasks were assigned a colour consisting of green, yellow, and red which represented the 180° left leg plant and turn, straight ahead, and 180° right leg plant and turn respectively. Visual cues were created and presented using PowerPoint (Microsoft, Office, version 2003, California) slides.

Several pre-planned and unanticipated trials of each task were performed before data collection started in order to provide the netballers with the opportunity to familiarise themselves with the testing tasks. Each netballer completed all four tasks randomly, as cued by the computer monitor. This included foot placement of the left foot and right foot during the unanticipated straight run task, and pivoting on the left foot and right foot during the unanticipated 180° turn tasks. Bates et al. (1992) suggested that a minimum of five trials are needed to achieve 90% power for sample sizes of at least ten participants. To enable the five trials needed for data analysis to be collected for each task, a total of 20 successful trials were needed (Dierks & Davis, 2007). A maximum of 30 trials were completed by the participants to achieve the required data set. No feedback on trials performed previously in the testing session was provided to the participants as to avoid the possibility of the trials becoming planned. A 180° left (or right) leg plant and turn trial was deemed successful if: (a) the approach speed fell between 3.5 and 5 m.s⁻¹; (b) the left (or right) foot came in contact with the force platform; and (c) the exit speed was between 2.5 and 3.5 m.s⁻¹. A straight-ahead trial was deemed successful if (a) the approach speed was between 3.5 and 5 m.s⁻¹; (b) the left (or right) foot came into contact with the force platform; and (c) the netballer continued along the straight-ahead path and did not decelerate until at least 1 m after the centre of the force platform. The turning tasks were utilised in this study due to the use of the movement in field test assessment for the sport of netball. Specifically the 505 assessment (180° turn) is utilised to assess an individual's change of direction ability. Furthermore, anecdotally this type of turn is frequently utilised in netball. The approach and exit speeds were based on unpublished field testing scores typical in sprint and agility assessment in New Zealand netballers. Each netballer was given approximately 45 - 90 s of rest between trials to reduce the potential effects of fatigue.

Kinematic and kinetic data collection

Following the practice trials, four moulded thermoplastic shells each with four retro-reflective tracking markers attached were securely placed on the lateral surface of both the netballer's thighs and shanks. Additional tracking markers were placed on both anterior superior iliac spines, both iliac crests, and the mid-point of both posterior

superior iliac spines to define the pelvis. Tracking markers were also placed on both heels, first and fifth metatarsal heads to define the foot. Calibration markers were placed on both greater trochanters (bilateral), both medial and lateral femoral condyles, both medial and lateral malleoli, to locate the segment origins. All markers were based on those used by others previously (Dierks & Davis, 2007; Ferber et al., 2005; Pollard et al., 2004; Pollard et al., 2005). For a depiction of the marker set see Appendix 6. Once the markers were placed, a standing calibration trial was recorded to establish anatomical neutral. Netballers stood in a neutral position on the force plate at the centre of the camera set-up. The calibration markers were removed after the standing trial, while the tracking markers remained on the netballer throughout the data collection session. The same individual placed the markers for all netballers.

A nine-camera motion capture system (Qualisys, Sweden) was used to record 3-D kinematic data at a sampling rate of 240 Hz as used by Pollard et al. (2005). The cameras were positioned so that each marker was visible in multiple cameras throughout the stance phase (heel strike to toe off). The cameras encircled a force platform (~0.48m x ~0.51m) embedded within the floor (Advanced Mechanical Technology Inc., USA). The force platform, sampling at a rate of 1200 Hz, recorded the magnitude of three-dimensional ground reaction forces and was only used to identify the stance phase and foot strike region for the various tasks. The cameras and force platform were interfaced to a personal computer that allowed for synchronization of kinematic and kinetic data using the motion analysis software (Qualisys Track Manager, Sweden, version 1.10.283). Prior to testing the nine-camera motion capture system was calibrated as per the manufacturer's protocol (Qualisys, Sweden), with a right-handed lab coordinate system being defined using a rigid L-frame containing four markers of known locations. A two-marker wand of known length was used within the calibration frame to scale the individual camera views of the measurement volume. The average movement residue for the retro-reflective markers during system calibration was minimal (less than 2 mm). The AMTI force platform was zeroed and calibrated for laboratory position and axis orientation. A two gate SWIFT® timing light system (SWIFT, Australia) was used to measure / monitor approach, performance and exit velocities. One timing light gate consisted of a dual beam modulated visible RED light sensor / reflector set up collecting at 4 MHz \pm 80 Hz. The timing lights were set at a height of 1.1 m and placed parallel to the approach runway with one gate located 3 m prior to the force platform and the other located 1 m prior. To view a schematic of the experimental set up see Appendix 7.

Kinematic data processing & analyses

The following data reduction procedures were performed on data for all five trials for each of the four unanticipated tasks. Q-Trac software (Qualisys, Sweden) was used to digitize the marker coordinates. Digitized coordinate data were then exported to Visual 3D™ software (C-Motion, Inc., Rockville, MD, USA) where they were low-pass filtered using a fourth-order Butterworth filter with an 8 Hz cut-off frequency. Ground reaction force data were low-pass filtered using a fourth-order Butterworth filter with a 50 Hz cut-off frequency (Dierks & Davis, 2007; Pollard et al., 2004; Pollard et al., 2005).

Joint coupling variability

Three-dimensional kinematics, namely angles, were created from the coordinate data for the hip, knee and ankle joint angles as well as for the thigh, shank, and rearfoot (calcaneal) segment angles in the sagittal, frontal and transverse planes. Kinematic and ground reaction force data were exported to a customised LabVIEW software (National Instruments, Austin, Texas, USA, version 6) where all angle data were linearly interpolated to 101 data points in order to normalize stance to 100%, with meant each point represented one percent of the stance phase (0 – 100%). Intra limb joint couplings of the stance leg for each task were generated using a vector coding method of Sparrow et al., (1987) and utilised in the literature recently by (Dierks & Davis, 2007; Ferber et al., 2005; Pollard et al., 2005). Joint couplings of interest were derived from the work of Dierks et al., (2007) and Ferber et al., (2005) as outlined in Table 4. Reliability was established for these measures in work reported in Chapter 3 with acceptable intraclass correlation coefficients ranging between 0.70 and 0.92.

Table 4: Joint couplings of interest.

Movement task	Joint coupling variability	ICC
Unanticipated straight run: dominant leg contact	Rearfoot _(eversion/inversion) –knee _(flexion/extension)	0.92
	Rearfoot _(eversion/inversion) –knee _(rotation)	0.75
	Tibial _(rotation) – knee _(flexion/extension)	0.82
Unanticipated straight run: non-dominant leg contact	Rearfoot _(eversion/inversion) –tibial _(rotation)	0.85
	Rearfoot _(eversion/inversion) –knee _(rotation)	0.72
Unanticipated 180° turn on the non-dominant leg:	Rearfoot _(eversion/inversion) –tibial _(rotation)	0.89
	Rearfoot _(eversion/inversion) –knee _(rotation)	0.70
	Tibial _(rotation) – knee _(rotation)	0.81

Angle–angle plots were constructed for each coupling of interest with the distal motion on the vertical axis and the proximal motion on the horizontal axis. Coupling angles were then calculated using the orientation of the resultant vector to the right horizontal between two adjacent data points in the stance phase. The standard deviation of the coupling angles across the five trials for a task was calculated for each percent of stance, providing a measure of between-trial, within-participant variability. Group means for joint coupling variability (JCV) were calculated using an average of the variances method so coupling data could be plotted. JCV was averaged within one period of stance based on discrete events in the vertical ground reaction force (Dierks & Davis, 2007; Ferber et al., 2005). The period was defined from foot-strike to the maximum vertical ground reaction force and is referred to as stance throughout the findings of this study. These procedures were repeated for each intra-limb coupling within each movement task for each netballer. Data were then categorised / reallocated based upon limb dominance.

Statistical analyses

Comparisons were made between all JCV measures (see Table 4) exhibited by the elite female, non-elite female and male netballers using the methods of Hopkins (2007b). In order to make comparisons between dominant and non-dominant limbs this could only be done for the rearfoot_(eversion/inversion)–knee_(rotation) JCV measure during unanticipated straight runs. This was due to this JCV measure being the only one that was reliable in both limbs for a given task (i.e. the unanticipated straight run; see Table 4). Comparisons were conducted using the methods of Hopkins (2006). All of Hopkins' (2006 & 2007) analyses allowed for Cohen effect sizes, 90% confidence intervals, and qualitative inferences to be presented, which is currently considered best practice for statistical use in sports medicine and the exercise sciences (Hopkins, Marshall, Batterham & Hanin, 2009).

Differences between groups and differences between dominant and non-dominant limbs were expressed as a percentage via analysis of log-transformed values using natural logarithms. Logarithmic transformation allowed for uniformity of error and was used to reduce bias arising from non-uniformity of error raw values (differences) of the variables of interest. Inferential statistics were based on interpretation of magnitude of effects (differences), as described by Batterham & Hopkins (2006). The likelihood of differences (effect unit) was interpreted using the Cohen scale of magnitudes for the standardized differences in the mean. The Cohen scale is divided into different effect sizes (ES) which are used to quantify the differences between conditions (Hopkins et al., 2009). To make inferences about the true values of the percentage differences and effect sizes between the groups of netballers, and the limbs, the uncertainty in the

percentage differences and ES were expressed as 90% confidence intervals and as likelihoods that the true value of the difference is substantial (Batterham & Hopkins, 2006). A difference was deemed unclear if its confidence interval of the effect statistic overlapped substantially positive and negative values and the threshold for the smallest worthwhile effect, otherwise, when a result was above the threshold for the smallest worthwhile effect the results could be given as: 0 – 0.2 trivial; 0.2 – 0.6 small; 0.6 – 1.2 moderate; 1.2 – 2.0 large; 2.0 – 4.0 very large. An effect size of 0.2 was chosen to be the smallest worthwhile difference in the means in standardized (Cohen) units as it gave likelihoods that the true effect would at least be small (Cohen, 1990).

Results

Differences in joint coupling variability (JCV) are presented in Tables 5 to 8. For ease of interpretation and appreciation the results have been presented in the sub-categories of analysis throughout this results section.

Figures 2 to 14 present the mean JCV normalised to stance for the various couplings during the three performance tasks of interest. These figures are provided to give the reader a qualitative, visual appreciation of the JCV measure differences between the two groups or limbs. The numerical representation of JCV is a discrete measure of the mean JCV from touch-down of stance to the occurrence of the peak active vertical ground reaction force for the respective group. Whilst visually in the figures it may appear that a difference is present this must be interpreted cautiously without consideration for the numerical outcomes. Additionally, Figures 4, 7 and 10 data traces appear noisy which is due to the nature of the movement and wide variety of individual variation in the coupling as made evident by the larger magnitudes in the group ensemble data compared to the unanticipated straight tasks. Note raw angular data from which JCV measures were derived were filtered. Please refer to the methods for specific details of the filtering technique used to process the kinematic data appropriately.

Comparisons between joint coupling variability of elite female and non-elite female netballers

Two of the eight couplings demonstrated trivial to large differences (see Table 5). Specifically, non-elite netballers demonstrated 33.1% (12.6 to 60.3%) less rearfoot_(eversion/inversion)–knee_(rotation) JCV during the stance phase of the dominant leg during an unanticipated straight run when compared with elite netballers. The case was reciprocated during stance of the unanticipated 180° turn performed on the non-dominant leg as non-elite netballers demonstrated 42.9% (6.3 to 92.0%) greater rearfoot_(eversion/inversion)–tibial_(rotation) JCV than the elite netballers. See Figures 2 to 4 for a visual appreciation of the JCV measure differences between the two groups.

Comparisons between joint coupling variability of male and non-elite female netballers

Only one of the eight couplings demonstrated a clear difference between male and non-elite female netballers (see Table 6). Specifically, during stance of the unanticipated 180° turn performed on the non-dominant leg, non-elite female netballers demonstrated 15.4% (-29.8 to 1.9%) less tibial_(rotation)–knee_(rotation) coupling variability than males which was substantially different as indicated by the negative large to trivial outcome (Effect size = - 0.61). See Figures 5 to 7 for a visual appreciation of the JCV measure differences between the two groups.

Table 5: Differences in joint coupling variability[#] for various couplings during unanticipated tasks between elite female ($N = 12$) and non-elite female ($N = 12$) netballers and the qualitative inferences about the effect of the differences.

	Elite Females Mean \pm SD	Non-elite Females Mean \pm SD	p value	Diff. in means as Percentage (%)	Diff. in means as % 90% Confidence levels		Cohen ES	Qualitative inference of ES
					lower	upper		
<i>Straight run: dominant leg contact</i>								
Rearfoot _(eversion/inversion) –Knee _(flexion/extension)	28.5 \pm 16.2	23.5 \pm 19.9	0.384	-23.3	-54.1	28.1	-0.35	unclear
Rearfoot _(eversion/inversion) –Knee _(rotation)	20.9 \pm 9.6	17.4 \pm 17.4	0.198	-33.1	-60.3	12.6	-0.52	large-trivial –ive
Tibial _(rotation) –Knee _(flexion/extension)	30.6 \pm 13.9	25.7 \pm 18.7	0.333	-22.6	-50.5	20.8	-0.39	unclear
<i>Straight run: non-dominant leg contact</i>								
Rearfoot _(eversion/inversion) –Tibial _(rotation)	25.9 \pm 13.9	26.3 \pm 9.9	0.792	5.0	-23.2	46.3	0.11	unclear
Rearfoot _(eversion/inversion) –Knee _(rotation)	21.7 \pm 15.3	22.0 \pm 15.0	0.859	-5.1	-42.2	55.9	-0.07	unclear
<i>180° turn on the non-dominant leg task</i>								
Rearfoot _(eversion/inversion) –Tibial _(rotation)	33.0 \pm 13.3	43.2 \pm 8.5	0.050*	42.9	6.3	92.0	0.82	trivial-large +ive
Rearfoot _(eversion/inversion) –Knee _(rotation)	38.9 \pm 12.5	42.3 \pm 13.5	0.576	8.1	-14.5	36.6	0.22	unclear
Tibial _(rotation) –Knee _(rotation)	37.9 \pm 9.9	40.3 \pm 10.5	0.619	6.6	-14.2	32.4	0.20	unclear

Key: [#] = Coupling variability (°) is a discrete measure of the average coupling variability from touchdown to peak active vertical ground reaction force; SD = standard deviation; Diff. = difference; ES = effect size; * = $p < 0.05$; -ive = negative; +ive = positive.

Table 6: Differences in joint coupling variability[#] for various couplings during unanticipated tasks between male ($N = 12$) and non-elite female ($N = 12$) netballers and the qualitative inferences about the effect of the differences.

	Males	Non-elite Females		Diff. in means as Percentage	Diff. in means as % 90% Confidence levels		Cohen ES	Qualitative inference of ES
	Mean \pmSD	Mean \pmSD	p value	(%)	lower	upper		
<i>Straight run: dominant leg contact</i>								
Rearfoot _(eversion/inversion) –Knee _(flexion/extension)	18.0 \pm 8.4	23.5 \pm 19.9	0.710	10.2	-29.2	71.5	0.15	unclear
Rearfoot _(eversion/inversion) –Knee _(rotation)	10.4 \pm 5.6	17.4 \pm 17.4	0.308	37.9	-18.8	134.1	0.41	unclear
Tibial _(rotation) –Knee _(flexion/extension)	22.4 \pm 9.5	25.7 \pm 18.7	0.939	1.9	-32.4	53.4	0.03	unclear
<i>Straight run: non-dominant leg contact</i>								
Rearfoot _(eversion/inversion) –Tibial _(rotation)	24.3 \pm 13.7	26.3 \pm 9.9	0.471	15.8	-17.9	63.6	0.29	unclear
Rearfoot _(eversion/inversion) –Knee _(rotation)	16.1 \pm 12.5	22.0 \pm 15.0	0.302	40.9	-19.3	145.9	0.42	unclear
<i>180° turn on the non-dominant leg task</i>								
Rearfoot _(eversion/inversion) –Tibial _(rotation)	38.6 \pm 12.5	43.2 \pm 8.5	0.240	16.0	-6.1	43.2	0.48	unclear
Rearfoot _(eversion/inversion) –Knee _(rotation)	47.1 \pm 13.6	42.3 \pm 13.5	0.442	-10.5	-29.9	14.2	-0.31	unclear
Tibial _(rotation) –Knee _(rotation)	46.9 \pm 9.7	40.3 \pm 10.5	0.137	-15.4	-29.8	1.9	-0.61	large-trivial –ive

Key: [#] = Coupling variability (°) is a discrete measure of the average coupling variability from touchdown to peak active vertical ground reaction force; SD = standard deviation; Diff. = difference; ES = effect size; -ive = negative.

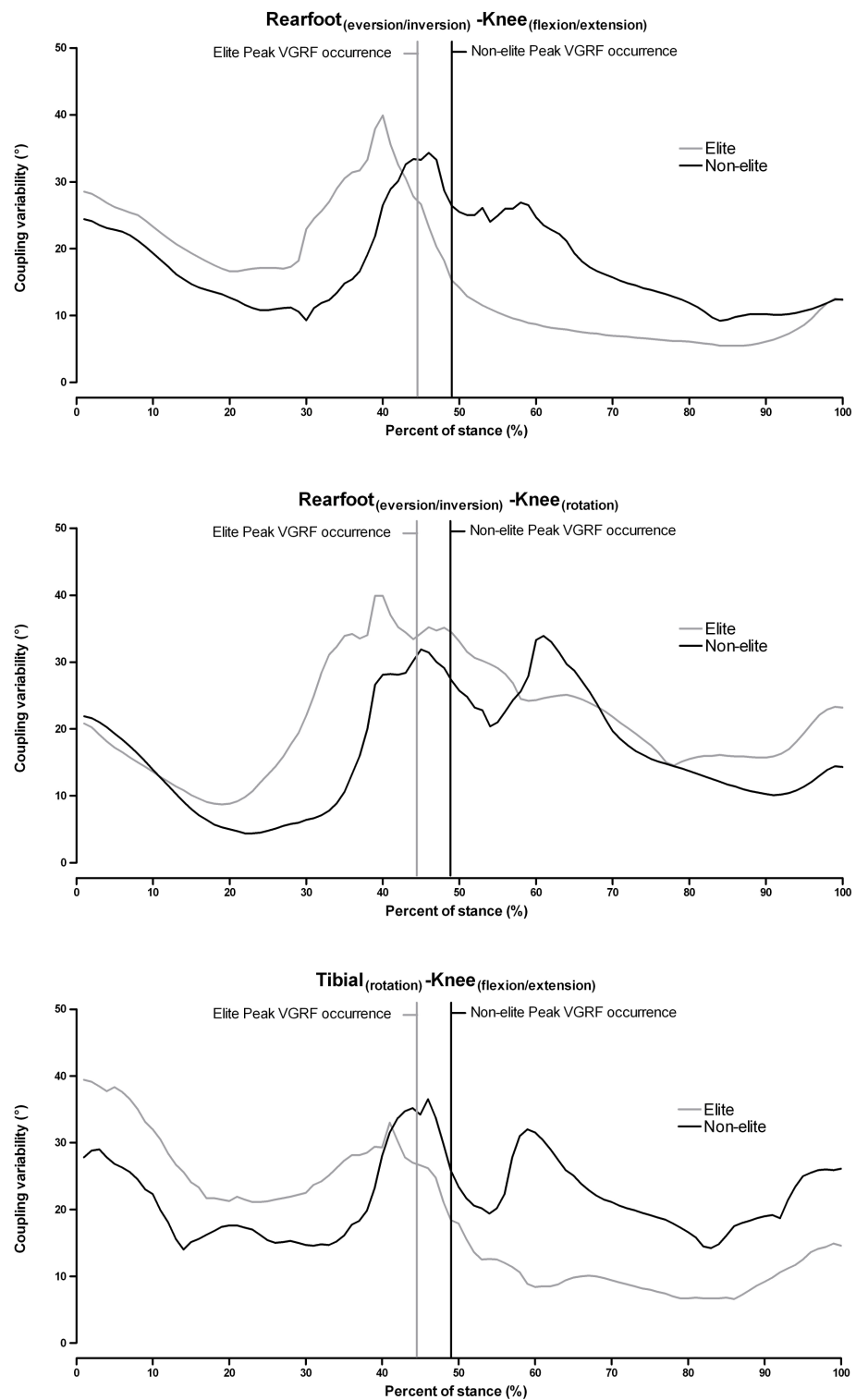


Figure 2: Group mean joint coupling variability of three couplings across the stance phase of the dominant leg during unanticipated straight runs performed by elite female ($N = 12$) and non-elite female ($N = 12$) netballers.

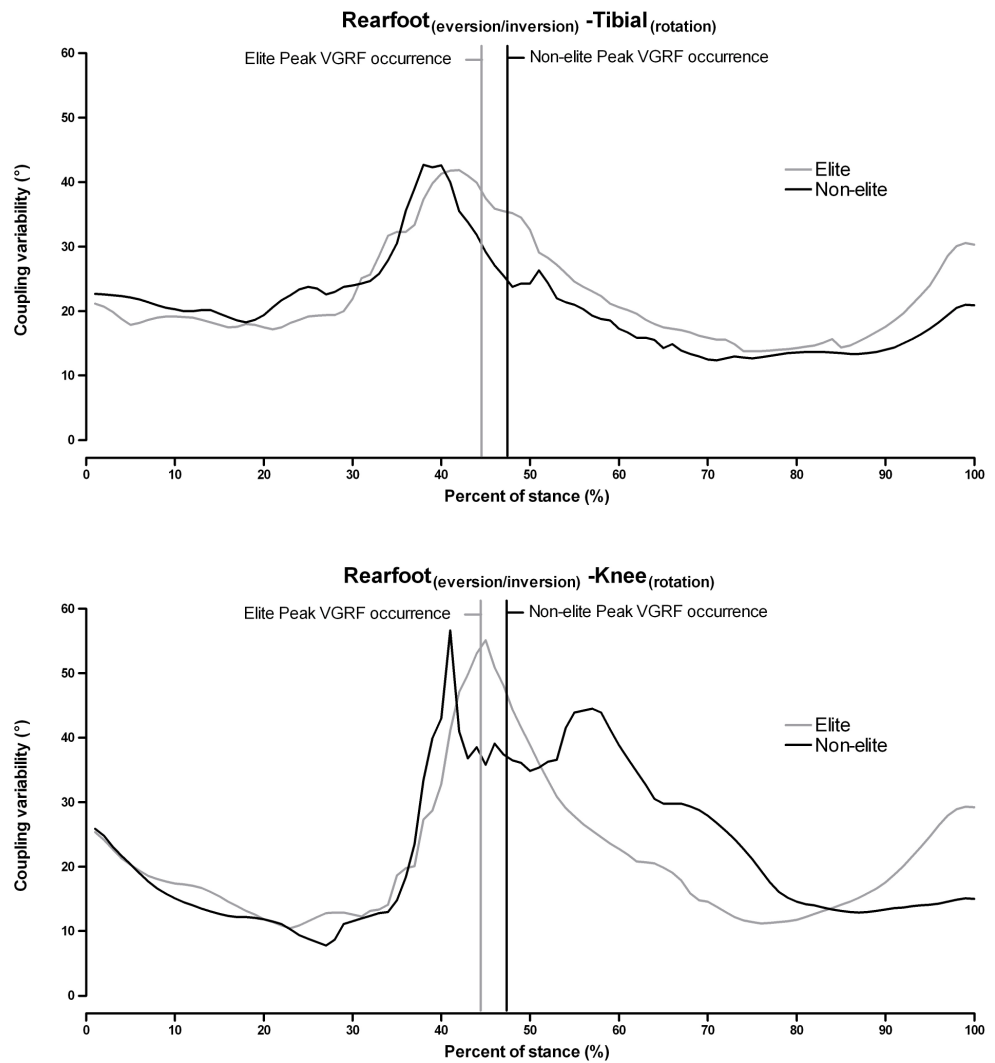


Figure 3: Group mean joint coupling variability of two couplings across the stance phase of the non-dominant leg during unanticipated straight runs performed by elite female ($N = 12$) and non-elite female ($N = 12$) netballers.

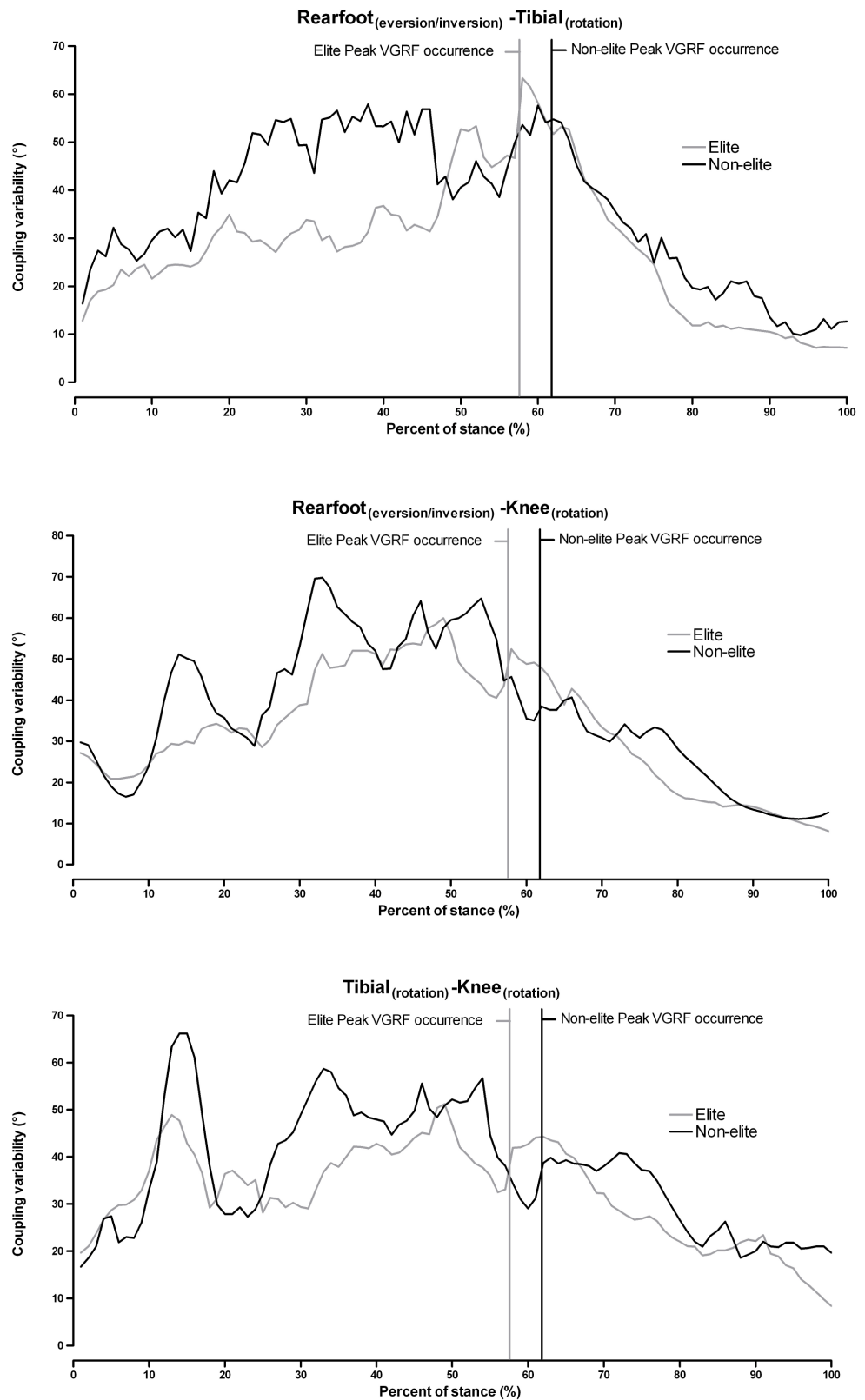


Figure 4: Group mean joint coupling variability of three couplings across the stance phase of the non-dominant leg during an unanticipated 180° turn performed by elite female ($N = 12$) and non-elite female ($N = 12$) netballers.

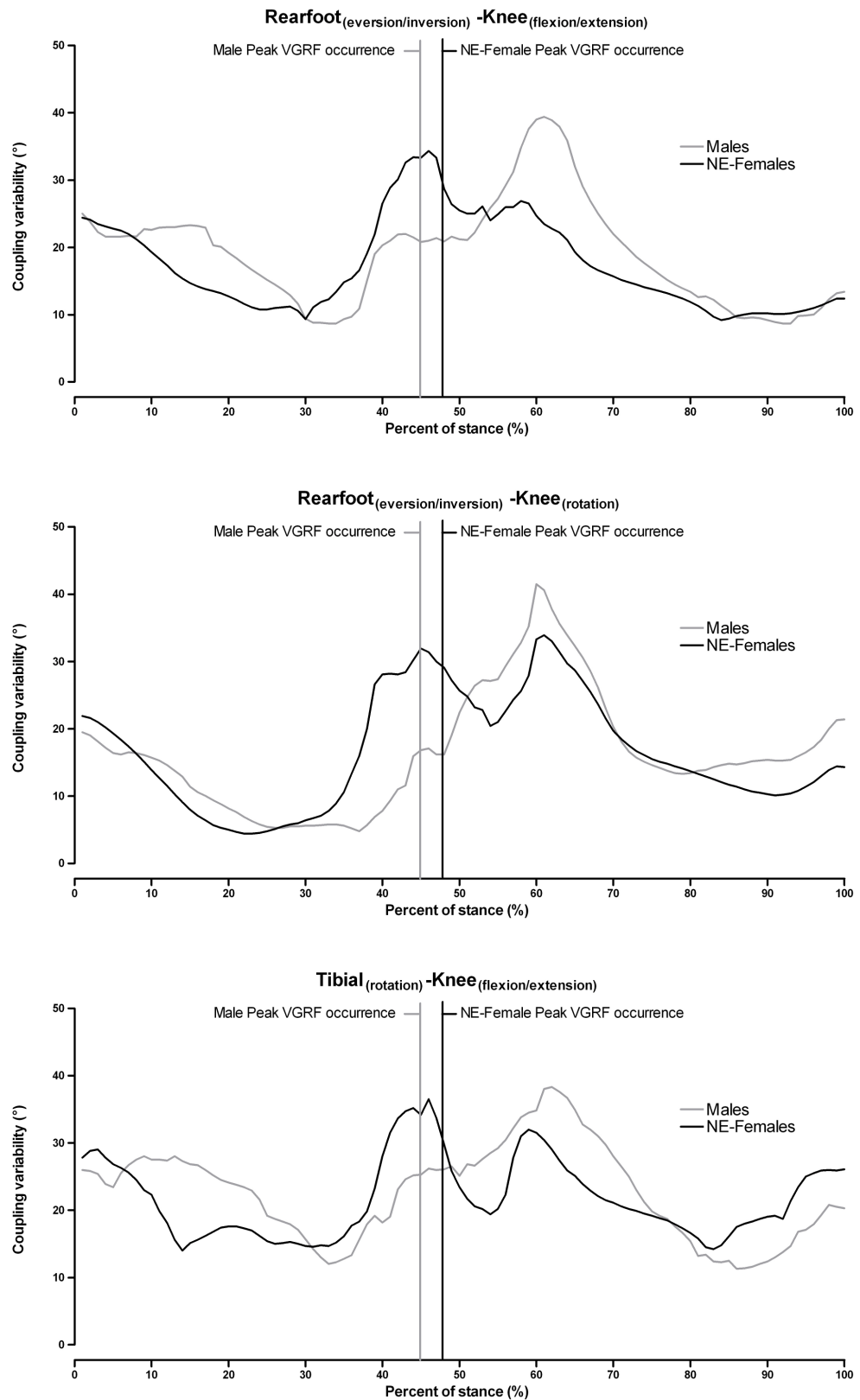


Figure 5: Group mean joint coupling variability of three couplings across the stance phase of the dominant leg during an unanticipated straight run performed by male ($N = 12$) and non-elite (NE) female ($N = 12$) netballers.

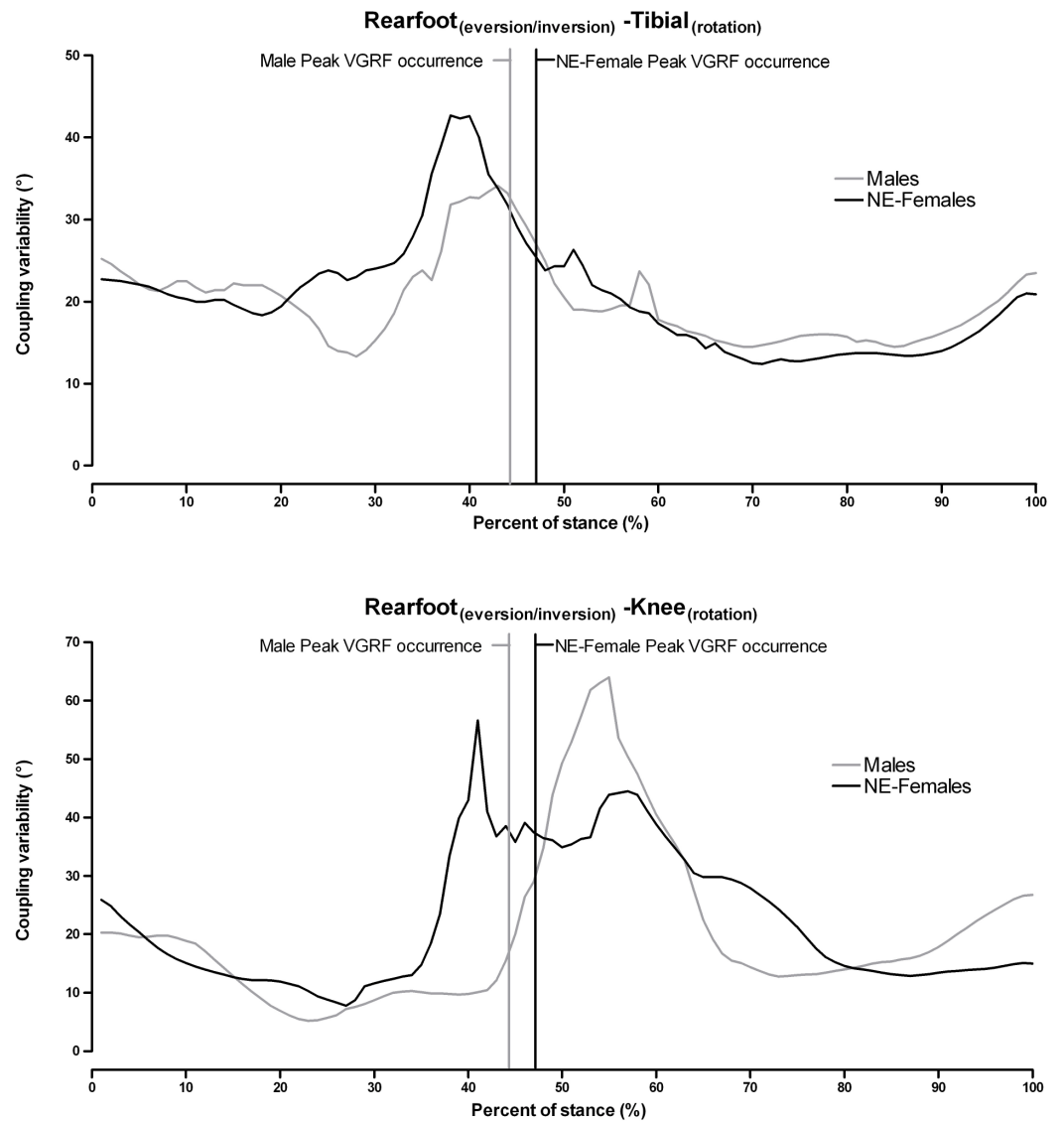


Figure 6: Group mean joint coupling variability of two couplings across the stance phase of the non-dominant leg during an unanticipated straight run performed by male ($N = 12$) and non-elite (NE) female ($N = 12$) netballers.

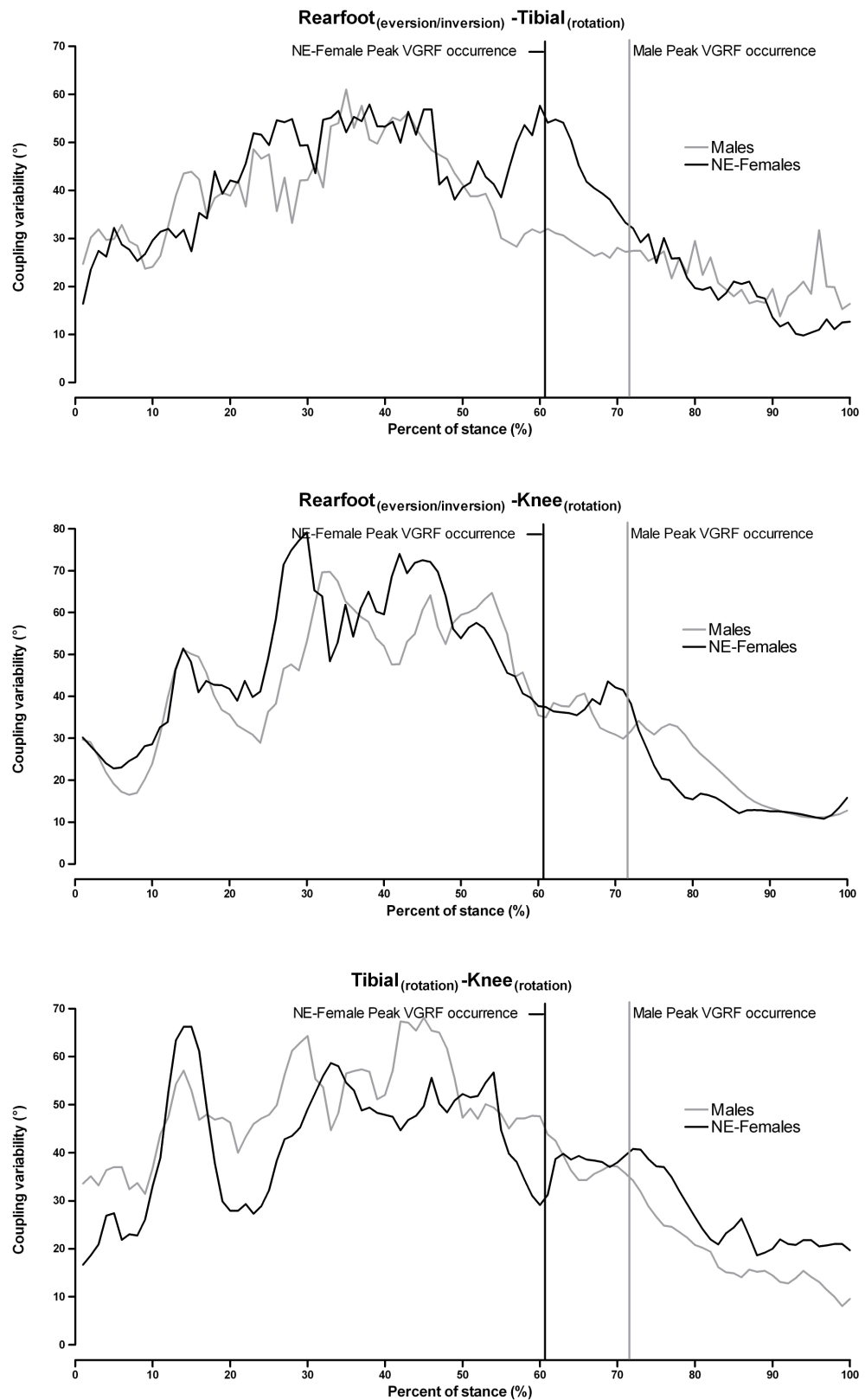


Figure 7: Group mean joint coupling variability of three couplings across the stance phase of the non-dominant leg during an unanticipated 180° turn performed by male ($N = 12$) and non-elite (NE) female ($N = 12$) netballers.

Comparisons between joint coupling variability of male and elite female netballers

Substantial differences were demonstrated for a variety of JCV measures between male netballers and elite female netballers (see Table 7). For both dominant and non-dominant leg ground contacts during the unanticipated straight task the elite females demonstrated substantially greater (31.7% to 106.1%) JCV magnitudes for all JCV measures with the exception of $\text{rearfoot}_{(\text{everversion/inversion})}-\text{knee}_{(\text{rotation})}$ JCV. During the unanticipated 180° turn performed on the non-dominant leg the elite females demonstrated substantially less $\text{rearfoot}_{(\text{everversion/inversion})}-\text{knee}_{(\text{rotation})}$ JCV (-17.2%) and $\text{rearfoot}_{(\text{everversion/inversion})}-\text{knee}_{(\text{rotation})}$ JCV (-20.6%). See Figures 8 to 10 for a visual appreciation of the JCV measure differences between the two groups.

Comparisons between joint coupling variability of dominant and non-dominant limbs

Unclear differences were identified when comparing limbs for the sub-categories of male netballers, elite female netballers and non-elite female netballers. However when the elite female and the non-elite female groups were combined to form a female netballers group ($N = 24$), $\text{rearfoot}_{(\text{everversion/inversion})}-\text{knee}_{(\text{rotation})}$ JCV during ground contact was 16.8% ($ES = 0.2$) larger in the non-dominant leg than the dominant leg during unanticipated straight runs which was deemed to be a substantial small effect according to Cohen's (Cohen, 1990) effect size classification (see Table 8). See Figures 11 to 14 for a visual appreciation of the JCV measure differences between the two limbs for the different groups.

Table 7: Differences in joint coupling variability[#] for various couplings during unanticipated tasks between male ($N = 12$) and elite female ($N = 12$) netballers and the qualitative inferences about the effect of the differences.

	Males	Elite Females		Diff. in means as Percentage (%)	Diff. in means as % 90% Confidence levels		Cohen ES	Qualitative inference of ES
	Mean \pm SD	Mean \pm SD	p value		lower	upper		
<i>Straight run: dominant leg contact</i>								
Rearfoot _(eversion/inversion) –Knee _(flexion/extension)	18.0 \pm 8.4	28.5 \pm 16.2	0.168	43.6	-7.2	122.2	0.56	trivial-large +ive
Rearfoot _(eversion/inversion) –Knee _(rotation)	10.4 \pm 5.6	20.9 \pm 9.6	0.008*	106.1	35.1	214.3	1.16	small-large +ive
Tibial _(rotation) –Knee _(flexion/extension)	22.4 \pm 9.5	30.6 \pm 13.9	0.221	31.7	-9.5	91.7	0.50	trivial-moder. +ive
<i>Straight run: non-dominant leg contact</i>								
Rearfoot _(eversion/inversion) –Tibial _(rotation)	24.3 \pm 13.7	25.9 \pm 13.9	0.642	10.3	-23.0	58.0	0.19	unclear
Rearfoot _(eversion/inversion) –Knee _(rotation)	16.1 \pm 12.5	21.7 \pm 15.3	0.196	48.4	-10.7	146.7	0.53	trivial-large +ive
<i>180° turn on the non-dominant leg task</i>								
Rearfoot _(eversion/inversion) –Tibial _(rotation)	38.6 \pm 12.5	33.0 \pm 13.3	0.278	-18.8	-41.2	12.1	-0.44	unclear
Rearfoot _(eversion/inversion) –Knee _(rotation)	47.1 \pm 13.6	38.9 \pm 12.5	0.442	-17.2	-34.4	4.6	-0.55	large-trivial -ive
Tibial _(rotation) –Knee _(rotation)	46.9 \pm 9.7	37.9 \pm 9.9	0.137	-20.6	-34.4	-3.9	-0.82	large-trivial -ive

Key: [#] = Coupling variability (°) is a discrete measure of the average coupling variability from touchdown to peak active vertical ground reaction force; SD = standard deviation; Diff. = difference; ES = effect size; * = $p < 0.05$; -ive = negative; +ive = positive; moder. = moderate.

Table 8: Differences in Rearfoot_(eversion/inversion)–Knee_(rotation) joint coupling variability between dominant and non-dominant legs during unanticipated straight runs and the qualitative inferences about the effect of the differences.

	Dominant		Non-dominant		<i>p</i> value	Diff. in	Diff. in means as a %		Cohen ES	Qualitative inference of ES
	Mean	±SD	Mean	±SD		means as Percentage (%)	90% Confidence levels lower	upper		
Male (N = 12)	10.4	±5.6	16.1	±12.5	0.327	36.2	-20.7	133.8	0.47	unclear
Elite females (N = 12)	20.9	±9.6	21.7	±15.3	0.916	-1.9	-29.1	35.7	-0.03	unclear
Non-elite females (N = 12)	17.4	±17.4	21.9	±15.0	0.283	39.2	-17.8	135.5	0.36	unclear
Females (N = 24)	19.1	±13.9	21.8	±14.8	0.376	16.8	-13.0	57.0	0.20	trivial-small +ive

Key: Females represent the combination of all female netballers that participated in the study; SD = standard deviation; Diff. = difference; ES = effect size; +ive = positive

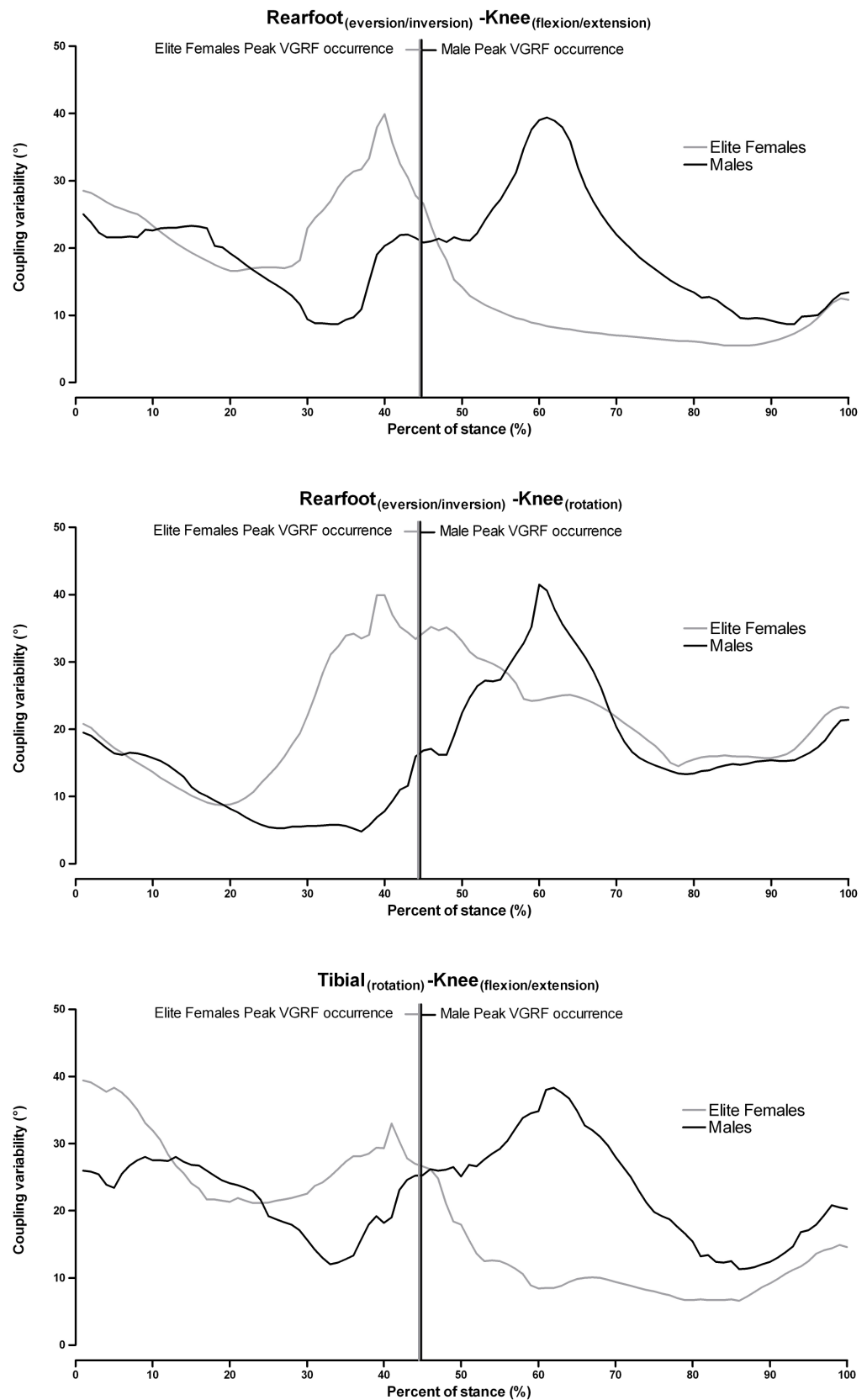


Figure 8: Group mean joint coupling variability of three couplings across the stance phase of the dominant leg during unanticipated straight runs performed by male ($N = 12$) and elite female ($N = 12$) netballers.

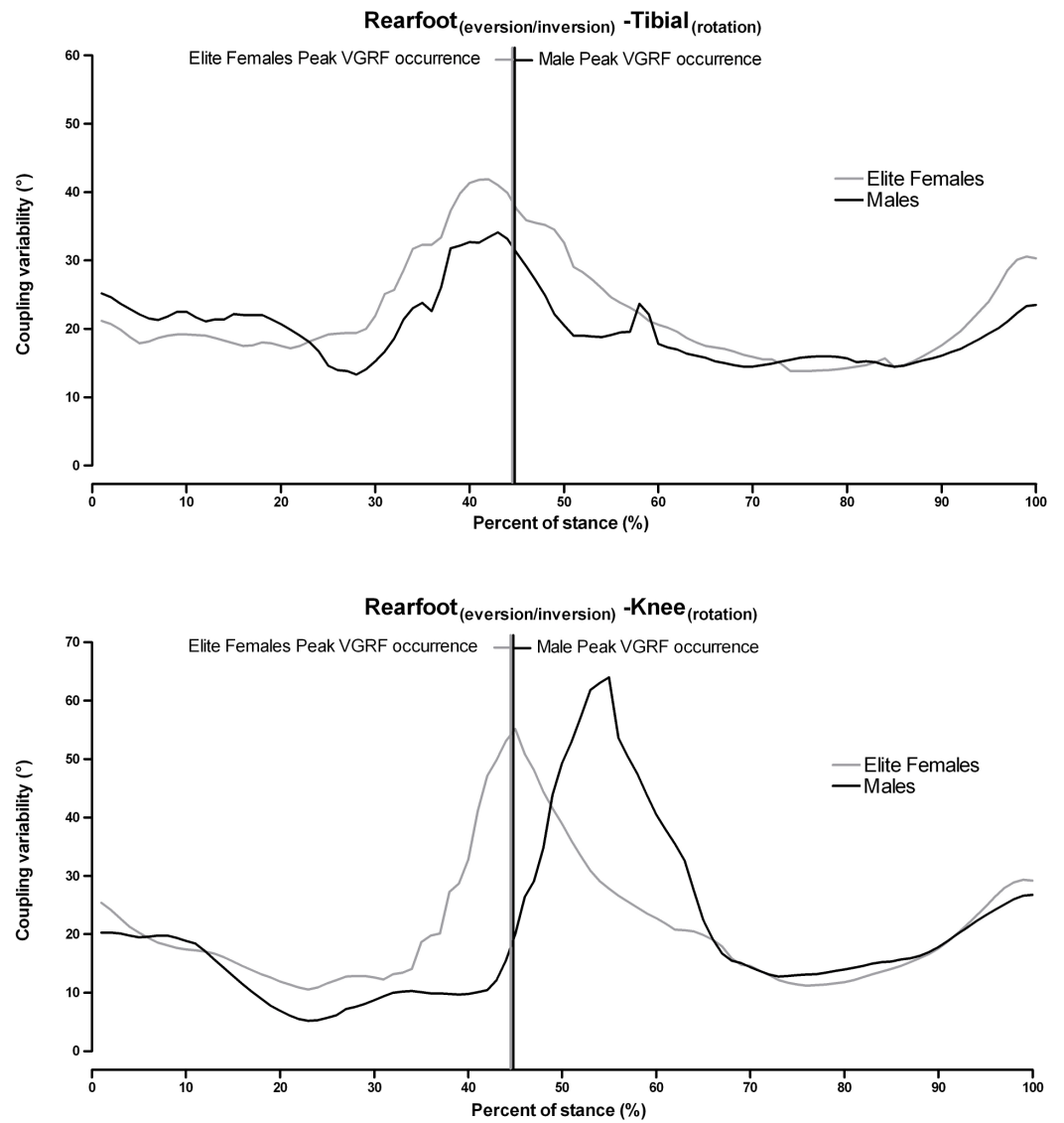


Figure 9: Group mean joint coupling variability of two couplings across the stance phase of the non-dominant leg during unanticipated straight runs performed by male ($N = 12$) and elite female ($N = 12$) netballers.

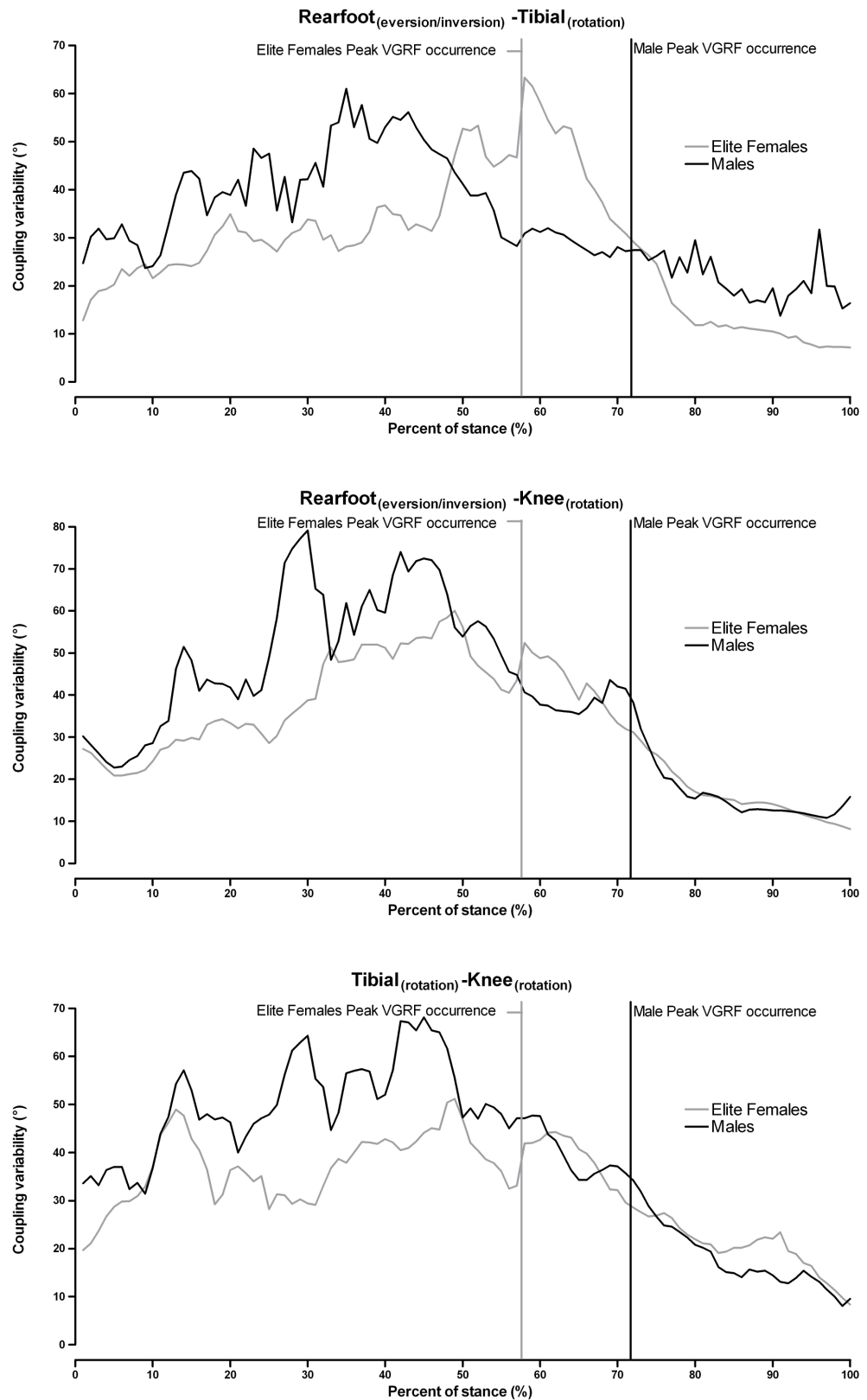


Figure 10: Group mean joint coupling variability of three couplings across the stance phase of the non-dominant leg during an unanticipated 180° turns performed by male ($N = 12$) and elite female ($N = 12$) netballers.

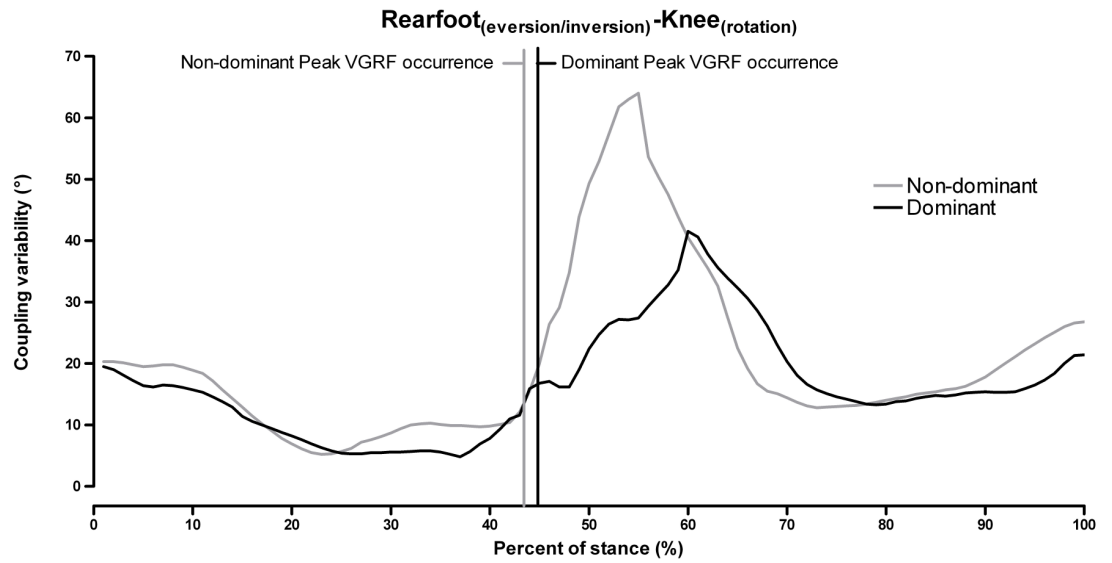


Figure 11: Mean rearfoot_(eversion/inversion)–knee_(rotation) coupling variability during the stance phase of the non-dominant and dominant leg ground contacts of unanticipated straight sprints performed by male netballers ($N = 12$).

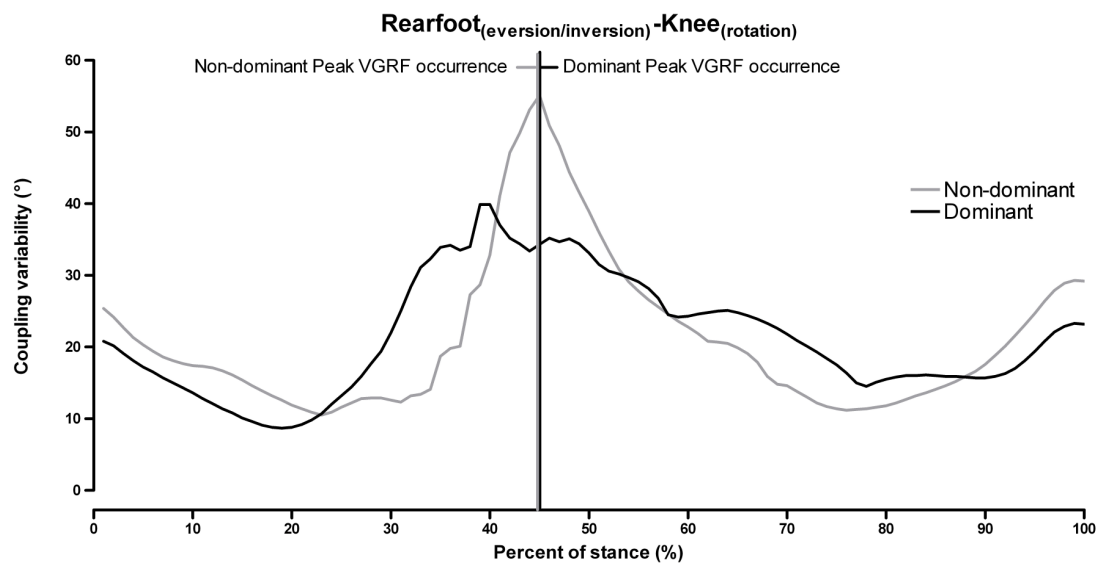


Figure 12: Mean rearfoot_(eversion/inversion)–knee_(rotation) joint coupling variability during the stance phase of the non-dominant and dominant leg ground contacts of unanticipated straight runs performed by elite female netballers ($N = 12$).

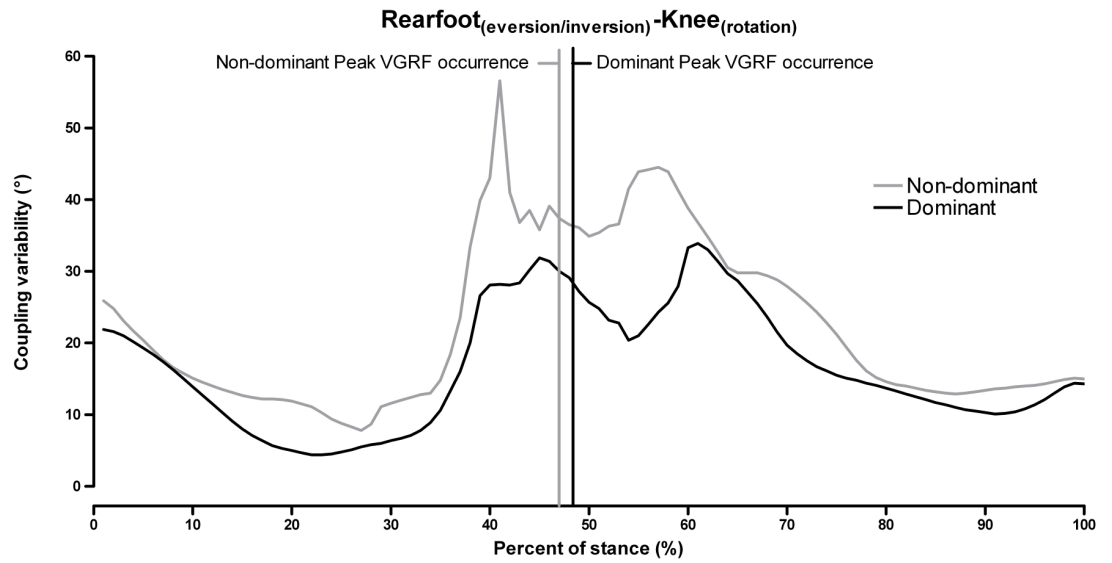


Figure 13: Mean rearfoot_(eversion/inversion)-knee_(rotation) coupling variability during the stance phase of the non-dominant and dominant leg ground contacts of unanticipated straight runs performed by non-elite female netballers ($N = 12$).

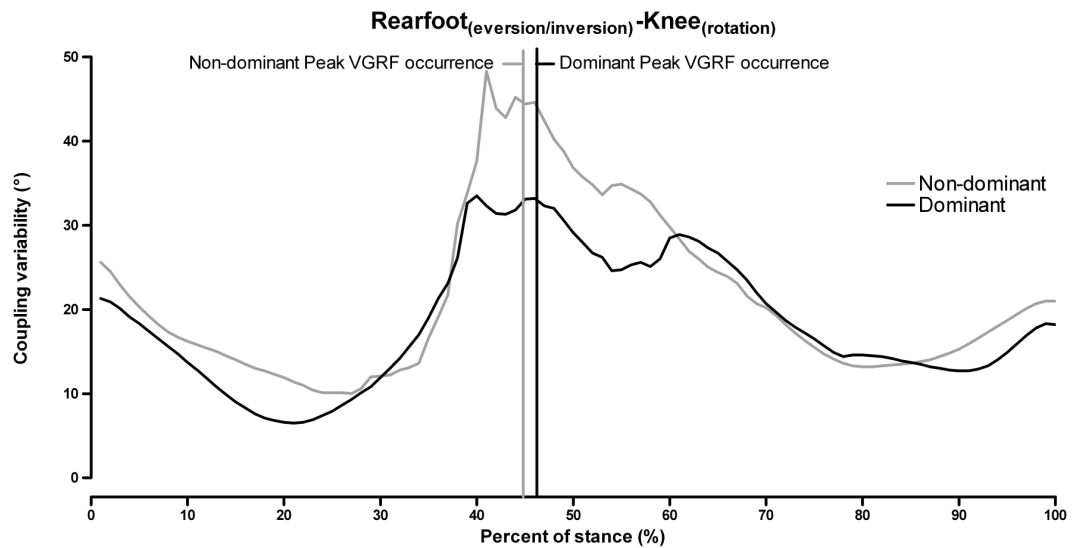


Figure 14: Mean rearfoot_(eversion/inversion)-knee_(rotation) coupling variability during the stance phase of the non-dominant and dominant leg ground contacts of unanticipated straight runs performed by all female netballers ($N = 24$).

Discussion

Comparisons between joint coupling variability of elite female and non-elite female netballers

Information pertaining to differences in joint coupling variability (JCV) between athletes of differing ability is equivocal (Bartlett et al., 2007; Bradshaw et al., 2007; Chapman et al., 2009). Therefore, to offer more insight into the potential role JCV may play in athletes of varying athletic status this study aimed to identify any substantial differences in lower extremity joint coupling variability between elite female and non-elite female netballers. It was expected that non-elite netballers would demonstrate less joint coupling variability than elite netballers. Based on the results of this study this expectation was supported as non-elite netballers demonstrated substantially less (-33.1%) variability for the rearfoot_(eversion/inversion)–knee_(rotation) coupling of the dominant stance leg during an unanticipated straight run. The true value of the percentage difference could indicate anything between a -60.3% and 12.6% difference as indicated by the 90% confidence limits. It appears that the non-elites are less variable for the rearfoot_(eversion/inversion)–knee_(rotation) coupling of the dominant leg during stance of an unanticipated straight run than the elite netballers. These results are in agreement with those of Bradshaw et al. (2007) in which faster (more elite) sprinters were identified to have more variable coupling strategies during a straight sprinting task. A more flexible repertoire (more variability) of coupling strategies may be linked to performance (Hamill et al., 1999; Pollard et al., 2005). Dynamical systems theory supports the concept that consistent high-level performance across a variety of situations and conditions can only be achieved with a variable coupling pattern that can be adapted to suit the demands of the task at hand (Hamill et al., 1999). Low JCV during straight running has been linked to injury retrospectively (Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005) and may be a potential cause of injury. The non-elite netballers in this study may be at greater risk of injury during straight sprint tasks due to their invariable JCV patterns. Prospective monitoring would be required to validate such an assumption. Training interventions that expose netballers to various straight running conditions so that they will be able to adapt their JCV strategies to circumstances they encounter during competition would be advantageous.

Whilst researchers (Arutyunyan et al., 1968; Bartlett et al., 2007; Bradshaw et al., 2007) and this study so far have indicated superior performance to be associated with higher JCV strategies, this is not universally the case. For example, novice cyclists have been reported to exhibit significantly greater variability in hip–ankle and knee–ankle joint couplings than expert cyclists (Chapman et al., 2009). These contrasting

findings seem to suggest that JCV may be context specific, an assumption originally made by Chapman et al. (2009). This premise is supported when considering the stance phase of the non-dominant leg during an unanticipated 180° turn task measured in the current study. Specifically, the non-elite group displayed substantially greater (42.9%) rearfoot_(eversion/inversion)–tibial_(rotation) coupling variability. The true value of the percentage difference (effect) could be trivial to large as indicated by the qualitative outcome of the 90% confidence limits of the effect size. It appears that the non-elite players are more variable for the rearfoot_(eversion/inversion)–tibial_(rotation) coupling of the non-dominant leg during stance of an unanticipated 180° turn task than the elite netballers, which is in accordance with the findings of Chapman et al. (2009). From an information processing theoretical perspective, this finding of the current study may support the idea that motor learning is characterised by the development towards invariance in motor output (Schmidt, 1985). Non-elite netballers performed the agility task substantially slower than the elites in the current study. This finding in conjunction with the JCV finding indicates learning, in the context of unanticipated 180° turns, to be characterized by a progression towards less variance in JCV. Perhaps a greater amount of variability in a movement task such as unanticipated turning is detrimental to performance due to the complexity of positioning the lower extremity segments appropriately during the turn to propel the body successfully in the intended direction. A greater repertoire of coupling strategies demonstrated by the non-elites may lead to them potentially utilising an inappropriate coupling movement that is not suitable for performance e.g. excessive internal rotation of the shank leading to an increase in pivot time with a substantial loss in momentum and propulsive impulse. It is unknown what mechanical movement strategies are important for 180° turning. Future analysis into the biomechanical determinants of 180° turning performance is required to provide insight as to what movement strategies may lead to superior performance.

Greater amounts of JCV regardless of playing level may be beneficial for avoiding injury. A lack of JCV within a movement pattern is thought to lead to less flexible movement strategies that can adapt adequately to meet the needs of an environment change or perturbation, thus increasing the risk for the individual attaining injury (Hamill et al., 1999). If movement patterns are invariant (performed identically) the same tissues would be maximally loaded each time (Bartlett, 2004). Therefore, high JCV may modify tissue loads between repetitions reducing injury risk (Bartlett, 2004). Low JCV during straight running has been linked to injury retrospectively (Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005) and may be a potential cause of injury. The more invariant coupling strategies for rearfoot-knee motion demonstrated during the straight sprints by the non-elite netballers of the current study may lead to the continual overload of the tissues surrounding the knee.

This may lead to possible overuse injuries such as patellofemoral pain, however, such an assumption needs to be validated in future research using a prospective study design.

Comparisons between joint coupling variability of male and female netballers

This study intended to identify whether or not differences exist between male and female (elite and non-elite) netballer's joint coupling variability (JCV) magnitudes of various lower extremity couplings, during unanticipated turning performance and unanticipated straight sprint performance. It was expected that females would demonstrate lower JCV compared to male netballers. The results of this study supported this expectation with female netballers demonstrating substantially less JCV in two of the eight couplings from the three performance tasks examined. When the unanticipated straight task was taken into consideration elite females demonstrated greater JCV than males in four out of the five couplings measured during both unanticipated straight tasks. These findings suggest that gender differences exist for JCV and they are movement context specific.

During stance of the unanticipated 180° turn performed on the non-dominant leg female netballers are less variable for the rearfoot_(rotation)–knee_(rotation) and tibial_(rotation)–knee_(rotation) couplings of the non-dominant leg during an unanticipated 180° turn than the male netballers. This finding is in accordance with those reported by Pollard et al. (2005). The magnitude of differences (15 - 21%) identified between males and females for rearfoot_(rotation)–knee_(rotation) and tibial_(rotation)–knee_(rotation) coupling variability during an unanticipated 180° turn performed on the non-dominant leg was slightly less than the differences reported by Pollard et al. (2005); 32% less thigh rotation - leg rotation variability; 40% less thigh abduction/adduction - leg abduction/adduction variability; 46% less knee flexion/extension - knee rotation variability; and 44% less knee flexion/extension - hip rotation variability during a 45° cutting movement. The slight difference in magnitudes between studies may be due to a difference in type of movement patterns and couplings assessed. The agility movements employed in both studies undoubtedly involve large loads at the ankle, knee and hip of the stance pivot leg in all planes of motion. Intuitively, a 45° cut would require more medial - lateral movement at the stance pivot leg whereas a 180° turn requires more rotational movement.

Couplings measured in the study of Pollard et al. (2005) involved more proximal hip thigh and knee couplings based around anterior cruciate ligament (ACL) loading patterns experienced at the knee joint. The present study investigated more distal rearfoot, tibia and knee couplings particularly from a rotational perspective due to the nature of the 180° turn. Such a turn requires large amounts of internal rotation and

flexion at the ankle and knee joints of the pivot leg whilst decelerating and breaking large forces during the initial part of stance. During the latter part of stance the inertia of the body is overcome with sufficient propulsive force as external rotations and extensions of the ankle and knee occur.

A lack of JCV within a movement pattern is thought to lead to less flexible movement strategies available to adapt adequately to meet the needs of an environment change or perturbation, thus increasing the risk for the individual attaining injury (Hamill et al., 1999). The present findings suggest that during an unanticipated 180° turn females may lack the flexibility required to adapt to challenges potentially experienced during netball. Due to the nature of netball being a high-strategy sport requiring many explosive sprints, abrupt stops, change of direction and landing movements (Bock-Jonathan et al., 2007; McManus et al., 2006) this can predispose the athlete to increased risk of injury (Hume & Steele, 2000). Due to the elevated likelihood of female athletes sustaining a serious lower extremity injury compared with male athletes participating in the same sports that require explosive change of direction maneuvers whilst sprinting (Griffin et al., 2000; Hutchinson & Ireland, 1995; Ireland, 1999) and the presence of low JCV in a movement pattern being linked to injury retrospectively (Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005), the present study further highlighted the potential of minimal JCV being a mechanism in lower extremity aetiology during agility movements. Whilst the former statement is speculative there is a great need for further understanding the role JCV may play in injury occurrence especially for female athletes participating in explosive sports such as netball. To date no prospective studies have been conducted attempting to identify an association between low JCV and injury occurrence. Such a study is warranted based on the findings of the present study and those of others (Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005; Pollard et al., 2005).

It was somewhat surprising that elite females demonstrated greater JCV than male netballers during unanticipated straight tasks. A greater amount of variability in ankle and knee motion in a movement task such as unanticipated straight sprinting may perhaps be detrimental to performance and the health of male netballers. This may lead to males potentially utilising an inappropriate coupling movement that is not suitable for performance or their health e.g. excessive or insufficient internal rotation of the shank in conjunction with excessive rearfoot pronation or external tibial rotation, which is a risk factor for injury (Heiderscheit et al., 1999). The differences identified between males and females in regards to JCV may be due to anatomical and neuromuscular differences between the sexes (Hewett, 2000; D. F. Murphy et al., 2003). Further research is needed to compare gender differences in JCV for other

forms of sporting movements such as abrupt stops, landings and straight running. Other sporting population samples may offer more insight into gender discrepancies in JCV.

Comparisons between joint coupling variability of dominant and non-dominant limbs

This study aimed to identify whether there were any substantial differences in lower extremity joint coupling variability between dominant or non-dominant limbs during an unanticipated straight run. The expectation was that the non-dominant leg would exhibit greater coupling variability than the dominant leg which was supported by the findings in this study when all the elite and non-elite female netballers were combined into an overall female group. The non-dominant leg was 16.8% more variable than the dominant leg for rearfoot_(eversion/inversion)–knee_(rotation) joint coupling during an unanticipated straight run. The true value of the percentage difference could be between -13% and 57% difference as indicated by the 90% confidence limits. It appears that the non-dominant leg was more variable than the dominant leg.

From an information processing theoretical perspective the findings of the current study (i.e. the dominant limb demonstrating less variability or more stability) may support the premise that motor learning is characterised by the development towards invariance in motor output (Schmidt, 1985). It is generally believed that participants can learn tasks better with their dominant limb than with their non-dominant limb (Davidson & Wolpert, 2003). The dominant limb therefore may have more stable invariant regions within the motor pattern leading to greater functional stability compared to the non-dominant limb. When considering motor learning from a dynamical systems theoretical perspective, consistent high-level performance across a variety of situations and conditions can only be achieved with a variable coupling pattern that can be adapted to suit the demands of the task at hand (Hamill et al., 1999), or the search for stable and functional states of coordination (Davids, Button & Bennett, 2008). Variability in joint coupling may be an essential component providing the necessary flexibility for successful task execution (Clark & Phillips, 1993; Turvey, 1990; Van Emmerik et al., 1999).

The non-dominant limb had more JCV than the dominant limb which may reflect a more explorative nature within a movement task in order to optimize future performance via enhanced learning (Chapman et al., 2009). Individuals that can exploit JCV within the movement system may benefit in different ways to adapting to changing task constraints over time (Davids et al., 2004). A lack of JCV demonstrated by the dominant limb in the current study may lead to less flexible movement strategies that can adapt adequately to meet the needs of an environment change or perturbation,

thus increasing the risk for the individual attaining injury (Hamill et al., 1999). If movement patterns are invariant (performed identically) the same tissues would be maximally loaded each time (Bartlett, 2004). Low coupling variability during straight running has been linked to injury retrospectively (Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005) and may be a potential cause of injury. Therefore, high coupling variability may modify tissue loads between repetitions reducing injury risk (Bartlett, 2004).

In certain sports, the dominant leg is preferentially used for kicking, pushing off, changing direction, jumping, or landing (D. F. Murphy et al., 2003). This unilateral demand might lead to functional asymmetry and differences in motor ability especially strength and coordination (Haaland & Hoff, 2003; Kearns, Isokawa & Abe, 2001). For example, Itoh et al. (1998) found healthy male participants had significantly more powerful (~5%; effect size = 0.49) dominant leg performances when compared to the non-dominant leg during a horizontal countermovement jump. The greater power output in the dominant limb may be due to greater muscle mass identified in the dominant limb compared to non-dominant limb (Chhibber & Singh, 1970). Overreliance on the dominant limb is considered a risk factor for lower extremity injury because most athletes place a greater demand on their dominant limb (Beynnon, Murphy & Alosa, 2002). An association between limb dominance and injury has been reported in the literature (Chomiak et al., 2000; Ekstrand & Gillquist, 1983; Orchard, 2001). The association between limb dominance and injury is controversial due to equivocal findings in the literature (Beynnon, Renström, Alosa, Baumhauer & Vacek, 2001; Matava, Freehill, Grutzner & Shannon, 2002; Negrete et al., 2007; Seil, Rupp, Tempelhof & Kohn, 1998; Surve, Schwellnus, Noakes & Lombard, 1994). The contrasting findings may have been the result of different study designs, participant type and numbers, injury location or the methods used for data analysis. If the dominant leg is less variable in terms of joint coupling as identified in the current study, and the dominant leg is also highly susceptible to injury (Chomiak et al., 2000; Ekstrand & Gillquist, 1983; Orchard, 2001), these factors may be linked. Such an association would offer insight to the mechanisms of injury. Prospective studies are required attempting to identify an association between low coupling variability and injury occurrence. Such studies are warranted based on the findings of the present study and those of others (Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005; Pollard et al., 2005). A greater demand of use of the dominant limb during athletic tasks in conjunction with low coupling variability may lead to a greater likelihood of injury for an individual. The greater bandwidth of coupling strategies the non-dominant leg has access to, may allow a more explorative nature

within a movement task in order to optimize performance and reduce the risk of injury. Further prospective research is required to validate such an assumption.

Range of motion may be a possible explanation for the increased coupling variability demonstrated by the non-dominant limb. The non-dominant limb has been reported to be more flexible than the dominant limb (Harvey, 1998). Greater flexibility may allow for a more dynamic range of motion to be present. Such an occurrence could allow for a greater bandwidth of movement strategies to occur, allowing greater coupling variability potential. Measurement of flexibility of the two legs was outside the scope of the current study. Additionally it is unknown if there was an association between flexibility and coupling variability, thus former statements are speculative and need to be validated in future research.

Conclusion

Joint coupling variability (JCV) strategies appear to be context specific when comparing athletic ability. For instance non-elite female netballers demonstrated less JCV within the dominant stance leg during an unanticipated straight run compared to elite female netballers. During unanticipated 180° turning elite female netballers exhibited lower JCV than non-elite females. This lower JCV in conjunction with the higher demands physically and mentally during elite netball game play compared to the non-elite level competition makes elites potentially even more susceptible to the likelihood of injury.

Gender differences in JCV exist but are movement task specific. Specifically, male netballers demonstrated greater JCV than all female netballers during the unanticipated turning task performed on the non-dominant leg. When the straight task was examined females (in particular the elite players) demonstrated greater JCV than male netballers during the unanticipated straight task stance phases of both the dominant and non-dominant legs.

Differences in JCV are apparent between limbs. In particular rearfoot_(eversion/inversion)–knee_(rotation) joint coupling variability during an unanticipated straight run performed by female athletes to be less variable for dominant leg ground contacts compared to non-dominant leg ground contacts. A greater demand of use of the dominant limb during athletic tasks in conjunction with low coupling variability may lead to a greater likelihood of injury for an individual.

CHAPTER 5: THE ASSOCIATION BETWEEN INJURY OCCURRENCE AND JOINT COUPLING VARIABILITY DURING UNANTICIPATED 180° TURN AND RUN TASKS PERFORMED BY NETBALLERS

Overview

This study aimed to determine whether during unanticipated movements performed by netballers, lower extremity joint coupling variability measures were associated with prospective lower limb injury in netball players. Twelve elite female, 12 non-elite female, and 12 male injury-free netballers performed 20 to 30 trials of unanticipated sprinting tasks in the motion analysis laboratory from a 10 m approach. The tasks included straight sprints and sprints with a 180° turn on their dominant and non-dominant legs. All netballers were monitored prospectively for a period of six months (one competitive season) for the occurrence of lower limb injury. Joint coupling variability measures of the lower extremity were calculated for all movement tasks, and then compared between the 13 (36%) injured and 23 (64%) non-injured netball players. The majority of lower limb injuries (~92.3%; N = 12/13) occurred in the dominant leg. Low joint coupling variability was associated with injury occurrence in elite ($r = 0.66$) and non-elite ($r = 0.33$ to 0.47) female netballers, whereas high joint coupling variability was associated with injury occurrence in male netballers ($r = -0.35$ to -0.54). Ideal ranges of joint coupling variability for particular movements that allow players to minimize the risk for injury may exist. This 'safe zone' may be independent of gender, joint or movement task.

Introduction

In New Zealand and Australia, netball is considered the primary team sport played both recreationally and competitively by females (McManus et al., 2006) and is also experiencing an increased participation rate for males (Tagg, 2008). Netball is a high-strategy sport requiring many explosive sprints, abrupt stops, changes of direction and landing movements (Bock-Jonathan et al., 2007; McManus et al., 2006). Given the physical demands of netball there is a heightened risk of injury (Hume & Steele, 2000). Potential injury mechanisms of interest to researchers are the concepts of intra-limb coupling variability within a movement pattern (Dierks & Davis, 2007; Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 1999; Pollard et al., 2005).

Variability in joint coupling can be an essential component, providing the necessary flexibility for successful task execution (Clark & Phillips, 1993; Turvey, 1990; Van Emmerik et al., 1999). Individuals can exploit joint coupling variability within the movement system in different ways to adapt to changing task constraints over time (Davids et al., 2004). A more flexible repertoire (more variability) of coupling strategies may be associated with better performance and reduced injury risk (Hamill et al., 1999; Pollard et al., 2005).

Researchers interested in the relationship between joint / segment coupling variability and injury have provided information that moderately supports the notion that low joint coupling variability is associated with lower extremity injury (Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005). Such studies have used a dynamic systems approach to examine lower extremity injuries (retrospectively) in relation to running tasks. For example, Kurz et al. (2005) compared the sagittal plane continuous relative phase of stance for the couplings of shank - thigh, and foot - shank between individuals with and without a reconstructed anterior cruciate ligament. The reconstructed anterior cruciate ligament group demonstrated lower continuous relative phase measures for the intra-limb coupling between the foot and shank during treadmill running at a self selected speed. Hamill et al. (1999) indicated that individuals suffering from patellofemoral pain syndrome exhibited less continuous relative phase variability for intra-limb joint couplings of thigh flexion/extension - tibial rotation, thigh adduction/abduction - tibial rotation, and tibial rotation - foot inversion/eversion measured during the stance phase of running than their healthy counterparts. Heiderscheit et al. (2002) also reported the joint coupling variability of thigh rotation - tibial rotation during heel-strike to be significantly lower in the injured leg of patellofemoral pain syndrome suffering females compared to their uninjured leg and legs of an uninjured group of females. Interestingly, the low joint coupling variability in the thigh rotation - tibial rotation coupling during an unanticipated explosive change of

direction manoeuvre reported by Pollard et al. (2005) for healthy injury free females, was similar to that reported by Hamill et al. (1999) and Heiderscheit et al. (2002) for the individuals suffering from patellofemoral pain. These findings may somewhat explain the increased incidence of lower extremity injuries in females as compared to males.

Conversely, Ferber et al. (2005) reported that individuals with a variety of lower limb pathologies such as plantar fasciitis, anterior compartment syndrome, and patellofemoral pain syndrome, exhibited similar rearfoot inversion/eversion and tibial internal/external rotation intra-limb joint coupling patterns and variability during the stance phase of running over ground compared to uninjured individuals. The statistical power to detect differences may have been decreased in this study as a result of inter-participant variability, due to the variety of running injuries sustained by their participants ($N = 11$).

Though studies (Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005) have reported low intra-limb joint coupling variability to indicate the presence of injury, they do not determine the cause of injury due to the case-cohort study designs incorporated. Information pertaining to whether or not the reduced variability identified in the injured individuals system was observed as a result of pain, or possibly existed prior to the onset of pain placing them at greater risk of injury, warrants further investigation. Studies with a prospective design assessing lower extremity joint coupling variability patterns may offer a better insight into the causation of lower extremity injury occurrence.

Aim

This study aimed to determine whether during unanticipated movements performed by netballers, lower extremity joint coupling variability measures were associated with prospective lower limb injury in netball players. It was expected that netballers who exhibited low joint coupling variability would likely incur an injury to the lower extremity.

Methods

Netball player characteristics

Using data from pilot work (ten netballers monitored during six months of a competitive netball season) it was considered that 36 netballers were adequate for the sample size based on a minimal statistical power of 80% ($p = 0.05$). Sample size and power calculations were completed using G*Power Software (Erdfeider et al., 1996).

Thirty six netball players, consisting of three sub-groups of elite females ($N = 12$), non-elite females ($N = 12$) and males ($N = 12$), volunteered to participate in the

study (see Table 9). Elite female netballers were classified as players who were representing their region or country at a senior level, whereas non-elite were classified as players who were participating in senior club level netball teams. Male netballers consisted mostly of regional representative level players and some high level competitive indoor netball players. All netballers had no history of significant lower extremity injury six months prior to testing and were injury free at the time of data collection. Each netballer gave informed consent in writing to participate in this study prior to testing. Ethical approval was obtained for all testing procedures from the Auckland University of Technology Ethics Committee. All netballers wore spandex shorts or pants and ASICS (Gel-Rocket) court shoes during the data collection.

Table 9: Netball player characteristics.

	Elite females (<i>N</i> = 12) mean ±SD	Non-elite females (<i>N</i> = 12) mean ±SD	Males (<i>N</i> = 12) mean ±SD	All netballers (<i>N</i> = 36) mean ±SD
Age (yrs)	22.3 ±3.8	20.9 ±2.3	23.7 ±4.2	22.3 ±3.6
Height (m)	1.79 ±0.08	1.72 ±0.05	1.78 ±0.07	1.76 ±0.07
Mass (kg)	79.2 ±11.6	69.5 ±9.8	88.8 ±23.2	79.2 ±17.5
Playing history (yrs)	13.0 ±2.8	13.2 ±2.4	4.9 ±5.2	10.4 ±5.3
Training load (hours/week)	8.8 ±1.6	8.8 ±2.9	5.7 ±3.4	7.8 ±3.1
Training load (sessions/week)	5.5 ±0.8	5.3 ±2.0	3.5 ±2.3	4.8 ±2.0

Procedures

Netball player limb dominance

Limb dominance was determined via questions and practical tests. The netballers were asked which leg was preferred for kicking a ball, and hopping on, with the preferred leg being considered the dominant leg (Maulder & Cronin, 2005). Furthermore, additional tests were used to identify which limb moved first; walking from a stationary position and stepping off a 0.3 m high step from a stationary position. The limb that moved first was considered the dominant limb. This information in conjunction with the question data allowed for a comprehensive decision to be made on limb dominance. The dominant limb was determined as the limb on the side of the body that was identified in the four assessments the majority of the time.

Unanticipated 180° turn and straight run task

The netballers performed three tasks from a 10 m approach that utilised a self selected start stance: a left leg plant and 180° turn; a straight ahead run (left or right foot placement); and a right leg plant and 180° turn. The tasks were presented as options in order to obtain an unanticipated / decision made movement response. Unanticipated movements have been demonstrated to elicit up to two times greater knee varus/valgus and internal/external rotation joint moments than anticipated movements (Besier et al., 2001). Movements during game situations are generally not always anticipated due to an external stimulus (Besier et al., 2001), thus unanticipated movements may offer a better reflection of the loads experienced around lower extremity joints during a sporting scenario. Therefore, a visual cue was displayed on a 19" computer screen which was triggered manually when the netballer was approximately 1 m away from the force platform. The screen was placed 0.5 m to the right side of the force platform. Testing tasks were assigned a colour consisting of green, yellow, and red which represented the 180° left leg plant and turn, straight ahead, and 180° right leg plant and turn respectively. Visual cues were created and presented using PowerPoint (Microsoft, Office, version 2003, California) slides.

Several pre-planned and unanticipated trials of each task were performed before data collection started in order to provide the netballers with the opportunity to familiarise themselves with the testing tasks. Each netballer completed all four tasks randomly, as cued by the computer monitor. This included foot placement of the left foot and right foot during the unanticipated straight run task, and pivoting on the left foot and right foot during the unanticipated 180° turn tasks. Bates et al. (1992) suggested that a minimum of five trials are needed to achieve 90% power for sample sizes of at least ten participants. To enable the five trials needed for data analysis to be collected for each task, a total of 20 successful trials were needed (Dierks & Davis, 2007). A maximum of 30 trials were completed by the participants to achieve the required data set. No feedback on trials performed previously in the testing session was provided to the participants as to avoid the possibility of the trials becoming planned. A 180° left (or right) leg plant and turn trial was deemed successful if: (a) the approach speed fell between 3.5 and 5 m.s⁻¹; (b) the left (or right) foot came in contact with the force platform; and (c) the exit speed was between 2.5 and 3.5 m.s⁻¹. A straight-ahead trial was deemed successful if (a) the approach speed was between 3.5 and 5 m.s⁻¹; (b) the left (or right) foot came into contact with the force platform; and (c) the netballer continued along the straight-ahead path and did not decelerate until at least 1 m after the centre of the force platform. The turning tasks were utilised in this study due to the use of the movement in field test assessment for the sport of netball.

Specifically the 505 assessment (180° turn) is utilised to assess an individual's change of direction ability. Furthermore, anecdotally this type of turn is frequently utilised in netball. The approach and exit speeds were based on unpublished field testing scores typical in sprint and agility assessment in New Zealand netballers. Each netballer was given approximately 45 - 90 s of rest between trials to reduce the potential effects of fatigue.

Injury data collection & analyses

The prospective nature of the study involved all netballers being monitored for six months (one competitive season) for the occurrence of lower limb injury. Prospective study designs are considered powerful for determining the risk factors of injury (Hagglund, Walden, Bahr & Ekstrand, 2005). Injury was defined as that which interfered with performance and required professional treatment, causing the player to miss training and/or game time (McKay, Goldie, Payne, Oakes & Watson, 2001). A training session was defined as any coach directed scheduled physical activity carried out with the team, whereas a game was considered friendly or competitive (Hagglund, Walden & Ekstrand, 2006).

Netball players were contacted regularly (fortnightly) via email and telephone to enquire if a lower limb injury had occurred. If an injury had occurred, information about the injury type and location (Hagglund et al., 2005) was recorded by the principal researcher, as communicated by the netballer. Injury was diagnosed by clinicians that were outside the research party. For reasons such as clinician client confidentiality, verification of the injury from the clinician was unable to be obtained by the principal researcher. It was presumed that the information that the netballers were communicating were accurate.

For analyses purposes, injured player data were grouped into an injured group with all remaining participant data being grouped into the non-injured group category. Data classification allowed comparisons in mechanical concepts to be made of which the procedures are outlined in subsequent sections.

Kinematic and kinetic data collection

Following the practice trials of unanticipated 180° turn and straight run tasks, four moulded shells each with four retro-reflective tracking markers attached were securely placed on the lateral surface of both the netballer's thighs and shanks. Additional tracking markers were placed on both anterior superior iliac spines, both iliac crests, and the mid-point of both posterior superior iliac spines to define the pelvis. Tracking markers were also placed on both heels, and first and fifth metatarsal heads to define the foot. Calibration markers were placed on both (bilateral) greater

trochanters, both medial and lateral femoral condyles, and both medial and lateral malleoli in order to locate the segment origins. All markers were based on those used by others previously (Dierks & Davis, 2007; Ferber et al., 2005; Pollard et al., 2004; Pollard et al., 2005). For a depiction of the marker set see Appendix 6. Once the markers were placed, a standing calibration trial was recorded to establish anatomical neutral. Netballers stood in a neutral position on the force plate at the centre of the camera set-up. The calibration markers were removed after the standing trial, while the tracking markers remained on the netballer throughout the data collection session. The same individual placed the markers for all netballers.

A nine-camera motion capture system (Qualisys, Sweden) was used to record three dimensional (3-D) kinematic data at a sampling rate of 240 Hz as used by Pollard et al. (2005). The cameras were positioned so that each marker was visible in multiple cameras throughout the stance phase (heel strike to toe off). The cameras encircled a force platform (~0.48m x ~0.51m) embedded within the floor (Advanced Mechanical Technology Inc., USA, 1200 Hz). The force platform recorded the magnitude of the three-dimensional ground reaction forces and was only used to identify the stance phase and foot strike region for the various sprint tasks. The cameras and force platform were interfaced to a personal computer that allowed for synchronization of the kinematic and kinetic data using the motion analysis software (Qualisys Track Manager, Version 1.10.283). Prior to testing, the nine-camera motion capture system was calibrated as per the manufacturer's protocol (Qualisys, Sweden), with a right-handed lab coordinate system being defined using a rigid L-frame containing four markers of known locations. A two-marker wand of known length was used within the calibration frame to scale the individual camera views of the measurement volume. The average movement residue for the retro-reflective markers during system calibration was minimal (less than 2 mm). The AMTI force platform was zeroed and calibrated for laboratory position and axis orientation. A two gate SWIFT® timing light system (SWIFT, Australia) was used to measure / monitor approach, performance and exit velocities. One timing light gate consisted of a dual beam modulated Visible RED Light sensor / reflector set up collecting at 4 MHz \pm 80 Hz. The timing lights were set at a height of 1.1 m and placed parallel to the approach runway with one gate located 3 m prior to the force platform and the other located 1 m prior. To view a schematic of the experimental set up see Appendix 7.

Kinematic and kinetic data processing & analyses

The following data reduction procedures were performed on data for all five trials for each of the four tasks. Q-Trac software (Qualisys, Sweden) was used to digitize the marker coordinates. Digitized coordinate data were then exported to Visual

3DTM software (C-Motion, Inc., Rockville, MD, USA) where they were low-pass filtered using a fourth-order Butterworth filter with an 8 Hz cut-off frequency. Ground reaction force data were low-pass filtered using a fourth-order Butterworth filter with a 50 Hz cut-off frequency (Dierks & Davis, 2007; Pollard et al., 2004; Pollard et al., 2005).

Joint coupling variability

Three-dimensional kinematics, namely angles, was created for the hip, thigh, knee, shank, ankle and rearfoot in the sagittal, frontal and transverse planes from the coordinate data. Kinematic and ground reaction force data were then exported to a customised LabVIEW software (National Instruments, Austin, Texas, USA) where all angle data were linearly interpolated to 101 data points in order to normalize stance to 100%, with meant each point represented one percent of the stance phase (0 – 100%). Intra limb joint couplings of the stance leg for each task were generated using a vector coding method of Sparrow et al., (1987) and utilised in the literature recently (Dierks & Davis, 2007; Ferber et al., 2005; Pollard et al., 2005). Joint couplings of interest were derived from the work of Dierks et al. (2007) and Ferber et al. (2005) as outlined in Table 10. Reliability was established for these measures in pilot work with acceptable intraclass correlation coefficients ranging between 0.70 and 0.92. Whilst an unanticipated 180° turn on the dominant leg was utilised as a movement task in this study, no joint coupling variability measures were assessed due to a lack of reliability calculated during work reported in Chapter 3.

Table 10: Joint couplings of interest.

Movement task	Joint couplings	ICC
Straight sprint dominant leg:	Rearfoot _(eversion/inversion) –knee _(flexion/extension)	0.92
	Rearfoot _(eversion/inversion) –knee _(rotation)	0.75
	Tibial _(rotation) – knee _(flexion/extension)	0.82
Straight sprint non-dominant leg:		
	Rearfoot _(eversion/inversion) –tibial _(rotation)	0.85
	Rearfoot _(eversion/inversion) –knee _(rotation)	0.72
180° turn on the non-dominant leg:		
	Rearfoot _(eversion/inversion) –tibial _(rotation)	0.89
	Rearfoot _(eversion/inversion) –knee _(rotation)	0.70
	Tibial _(rotation) – knee _(rotation)	0.81

Angle–angle plots were constructed for each coupling of interest with the distal motion on the vertical axis and the proximal motion on the horizontal axis. Coupling angles were then calculated using the orientation of the resultant vector to the right

horizontal between two adjacent data points in the stance phase. The standard deviation of the coupling angles across the five trials for a task was calculated for each percent of stance, providing a measure of between-trial, within-participant variability. Group means for joint coupling variability were calculated using an average of the variances method so coupling data could be plotted. Joint coupling variability was averaged within one period of stance based on discrete events in the vertical ground reaction force (Dierks & Davis, 2007; Ferber et al., 2005). The period was defined from foot-strike to the maximum vertical ground reaction force and is referred to as stance throughout the findings of this study. These procedures were repeated for each intra-limb coupling within each movement task for each netballer. Data were then categorised / reallocated based upon limb dominance.

Statistical analyses

Comparisons were made between physical characteristics, stance based parameters, joint coupling variability measures exhibited by the injured and non-injured netballers using the methods of Hopkins (2007b). These analyses allowed for Cohen effect sizes, 90% confidence intervals, and qualitative inferences to be presented, which is currently considered best practice for statistical use in sports medicine and the exercise sciences (Hopkins et al., 2009). Differences between injured and non-injured netballers were expressed as a percentage via analysis of log-transformed values using natural logarithms. Logarithmic transformation allowed for uniformity of error and was used to reduce bias arising from non-uniformity of error raw values (differences) of the variables of interest. Inferential statistics were based on interpretation of magnitude of effects (differences) as described by Batterham & Hopkins (Batterham & Hopkins, 2006). The likelihood of the differences (effect unit) was interpreted using the Cohen scale of magnitudes for the standardized differences in the mean. The Cohen scale is divided into different effect sizes which are used to quantify the differences between conditions (Hopkins et al., 2009). To make inferences about the true values of the percentage differences and effect sizes between injured and non-injured netballers the uncertainty in the percentage differences and effect sizes were expressed as 90% confidence intervals and as likelihoods that the true value of the difference is substantial (Batterham & Hopkins, 2006). A difference was deemed unclear if its confidence interval of the effect statistic overlapped substantially positive and negative values and the threshold for the smallest worthwhile effect, otherwise, when a result was above the threshold for the smallest worthwhile effect the results could be given as: 0 – 0.2 trivial; 0.2 – 0.6 small; 0.6 – 1.2 moderate; 1.2 – 2.0 large; 2.0 – 4.0 very large. An effect size of 0.2 was chosen to be the smallest worthwhile difference in the

means in standardized (Cohen) units as it gave likelihoods that the true effect would at least be small (Cohen, 1990).

SPSS version 18 was used to calculate Pearson correlation coefficients to identify associations between joint coupling variability measures and injury occurrence. The magnitude of the associations was qualitatively interpreted utilising the following criteria: 0.0 – 0.1 poor; 0.1 – 0.3 small; 0.3 – 0.5 moderate; >0.5 large (Cohen, 1990). Confidence intervals (90% CI) were processed for these correlations to show the likely range of the true correlation using the methods of Hopkins (2007a). Furthermore, clinical inferences were also provided on the likelihood these relationships were clinically substantial.

Results

Player characteristics

The non-injured group were substantially shorter (MDiff: -2.4% [90% Confidence limit: -4.6 to -0.2%], ES=-0.65 [moderate]) than the injured group. There were no other notable differences for the other physical and training characteristics (see Table 11).

Lower limb injuries

Lower limb injury occurred in ~36% (N = 13/36) of the netballers which required them to miss either training and/or game time. The injuries included five ankle sprains, two cases of patellar tendonitis, two calf strains, an Achilles strain, an adductor strain, and two cases of shin splints. The majority of injuries (~92.3%; N = 12/13) occurred on the netballer's dominant leg (see Table 12).

Comparisons between kinematic and kinetic measures of injured and non-injured netballers

Non-injured netballers demonstrated substantially smaller temporal variables during the straight non-dominant leg condition compared with the injured netballers. Specifically ground contact time was less (MDiff = -7.6% [-14.8 to 0.1%], ES = -0.59 [small]), time to peak active vertical ground reaction force (VGRF) was less (MDiff = -14.0% [-24.1 to -2.6%], ES = -0.72 [moderate]), and time to peak active VGRF as a percentage of ground contact (stance) was less (MDiff = -6.0% [-12.3 to 0.6%], ES = -0.51 [small]). The statistical outcomes were unclear for these temporal variables during the straight dominant leg and turn on the non-dominant leg tasks (see Table 13).

Table 11: Player characteristics between injured ($N = 13$) and non-injured ($N = 23$) netballers.

	Injured		Non-injured			MDiff	90% Confidence levels		Cohen	Clinical inference
	Mean	\pm SD	Mean	\pm SD	p value	(%)	lower	upper	ES	
Age (years)	21.6	± 2.2	22.7	± 4.2	0.587	2.7	-5.5	11.6	0.18	unclear
Height (m)	1.79	± 0.07	1.75	± 0.07	0.075	-2.4	-4.6	-0.2	-0.65	large-trivial -ive
Mass (kg)	79.9	± 14.6	78.8	± 19.2	0.469	-4.9	-15.3	6.8	-0.25	unclear
Playing history (years)	10.8	± 4.8	10.1	± 5.6	0.618	-14.8	-50.3	46.1	-0.17	unclear
Training per week (hours)	7.8	± 3.1	7.7	± 3.2	0.352	-13.8	-34.0	12.6	-0.30	unclear

Key: SD = standard deviation; MDiff. = difference in the group means; ES = effect size; -ve = negative.

Table 12: Injured player characteristics ($N = 13$; ~36%).

Player	Gender	Sub-group	Age (yr)	Height (m)	Mass (kg)	Dominant limb	Injured limb	Injury type
1	F	Elite	25	1.94	85.0	R	D	Ankle sprain
2	F	Elite	18	1.72	75.0	R	D	Patella tendonosis
3	F	Elite	21	1.80	77.0	R	D	Ankle sprain
4	F	Elite	22	1.79	66.0	L	D	Calf strain
5	F	Elite	21	1.87	111.0	R	D	Patella tendonosis
6	F	Non-elite	23	1.71	82.4	R	D	Achilles strain
7	F	Non-elite	24	1.78	83.0	R	D	Calf strain
8	F	Non-elite	18	1.80	71.0	R	D	Adductor strain
9	F	Non-elite	21	1.68	70.0	R	D	Shin splints
10	M	Male	21	1.84	107.7	R	D	Shin splints
11	M	Male	24	1.77	69.8	R	D	Ankle sprain
12	M	Male	23	1.77	77.0	R	ND	Ankle sprain
13	M	Male	20	1.80	64.0	R	D	Ankle sprain

Key: F = female; M = male; R = right leg; L = left leg; D = dominant leg; ND = non-dominant leg

Table 13: Differences in stance based parameters during unanticipated tasks between injured (N = 13) and non-injured (N = 23) netballers and the qualitative inferences about the effect of the differences.

	Injured		Non-injured			MDiff	90% Confidence levels		Cohen	Clinical inference
	Mean	±SD	Mean	±SD	p value	(%)	lower	upper	ES	
<i>Straight dominant leg</i>										
Contact time (s)	0.203	±0.028	0.197	±0.028	0.593	-2.7	-10.9	6.2	-0.19	unclear
Time to Peak active VGRF (s)	0.092	±0.020	0.092	±0.020	0.926	0.7	-11.7	14.9	0.03	unclear
Time to Peak active VGRF (%)	45.7	±3.1	46.3	±4.9	0.744	1.0	-4.1	6.4	0.11	unclear
<i>Straight non-dominant leg</i>										
Contact time (s)	0.211	±0.029	0.194	±0.023	0.105	-7.6	-14.8	0.1	-0.59	moderate-trivial -ive
Time to Peak active VGRF (s)	0.098	±0.020	0.085	±0.016	0.048*	-14.0	-24.1	-2.6	-0.72	large-trivial -ive
Time to Peak active VGRF (%)	46.2	±4.0	44.0	±5.6	0.134	-6.0	-12.3	0.6	-0.51	moderate-trivial -ive
<i>Turn non-dominant leg</i>										
Performance time (s)	0.872	±0.114	0.893	±0.087	0.608	2.2	-4.9	9.9	0.18	unclear
Contact time (s)	0.464	±0.088	0.460	±0.092	0.822	-1.5	-12.3	10.6	-0.08	unclear
Time to Peak active VGRF (s)	0.315	±0.088	0.340	±0.245	0.862	-2.3	-22.4	22.9	-0.06	unclear
Time to Peak active VGRF (%)	63.6	±8.2	62.8	±10.9	0.318	-5.5	-14.1	3.9	-0.34	unclear

Key: SD = standard deviation; MDiff. = difference in the group means; ES = effect size; * = $p < 0.05$; -ive = negative.

Comparisons between joint coupling variability measures of injured and non-injured netballers

Small unclear statistical outcomes were computed for all joint coupling variability measures during the three testing tasks demonstrating no substantial differences between injured and non-injured netballers (see Table 14). Figures 15 to 17 present the mean coupling variability of all eight couplings from the three performance tasks. Due to the majority of injury occurrences occurring on the dominant leg, the following information will focus on the straight dominant leg task only. During the straight dominant task, the non-injured group's coupling variability data trace appeared to be noticeably larger around the point at which peak active VGRF occurred and to the 75% mark of stance for the couplings of rearfoot_(eversion/inversion)–knee_(flexion/extension), rearfoot_(eversion/inversion)–knee_(rotation), and tibial_(rotation)–knee_(flexion/extension) when compared to the injured group.

Associations between joint coupling variability measures and the occurrence of injury in netballers

Due to the majority of injury occurrences occurring on the dominant leg, the following information will focus on the straight dominant leg and dominant leg turn tasks only. The associations between coupling variability measures during the straight dominant leg task and dominant leg injury occurrences are presented in Table 15. Poor correlations existed between injury occurrence and various coupling variability measures when considering all netballers that participated in this study. When categorised into sub groups, the correlations increased in magnitude. A large correlation ($r > 0.50$) existed between rearfoot_(eversion/inversion)–knee_(rotation) coupling variability and injury occurrence for elite female netballers. The non-elite female netballers demonstrated moderate likely probable associations between injury occurrence and all three coupling variability measures. Male netballers demonstrated moderate likely probable associations between injury occurrence and rearfoot_(eversion/inversion)–knee_(flexion/extension) coupling variability and rearfoot_(eversion/inversion)–knee_(rotation) coupling variability respectively. A large correlation existed between tibial_(rotation)–knee_(flexion/extension) coupling variability and injury occurrence for male netballers.

Table 14: Differences in mean coupling variability from foot contact to peak active vertical ground reaction force for each coupling during unanticipated tasks between injured (N = 13) and non-injured (N = 23) netballers and the qualitative inferences about the effect of the differences.

	Injured Mean \pm SD	Non-injured Mean \pm SD	<i>p</i> value	MDiff (%)	90% Confidence levels		Cohen ES	Qualitative inference of ES
					lower	upper		
<i>Straight dominant leg</i>								
Rearfoot _(eversion/inversion) –Knee _(flexion/extension)	20.0 \pm 12.4	25.2 \pm 17.3	0.396	22.3	-17.8	81.9	0.29	unclear
Rearfoot _(eversion/inversion) –Knee _(rotation)	12.7 \pm 6.1	18.2 \pm 14.6	0.440	22.0	-20.7	87.6	0.26	unclear
Tibial _(rotation) –Knee _(flexion/extension)	26.0 \pm 10.8	26.3 \pm 16.5	0.742	-6.1	-32.2	29.8	-0.11	unclear
<i>Straight non-dominant leg</i>								
Rearfoot _(eversion/inversion) –Tibial _(rotation)	25.3 \pm 15.5	25.6 \pm 10.5	0.785	5.2	-23.4	44.4	0.10	unclear
Rearfoot _(eversion/inversion) –Knee _(rotation)	20.5 \pm 16.2	19.6 \pm 13.3	0.959	1.4	-35.3	58.9	0.02	unclear
<i>Turn non-dominant leg</i>								
Rearfoot _(eversion/inversion) –Tibial _(rotation)	39.8 \pm 11.1	37.4 \pm 12.7	0.354	-12.7	-31.7	11.5	-0.32	unclear
Rearfoot _(eversion/inversion) –Knee _(rotation)	40.4 \pm 13.2	44.2 \pm 13.4	0.543	7.8	-12.5	32.7	0.21	unclear
Tibial _(rotation) –Knee _(rotation)	40.1 \pm 11.1	42.6 \pm 10.2	0.594	6.1	-12.1	28.2	0.19	unclear

Key: SD = standard deviation; MDiff. = difference in the group means; ES = effect size.

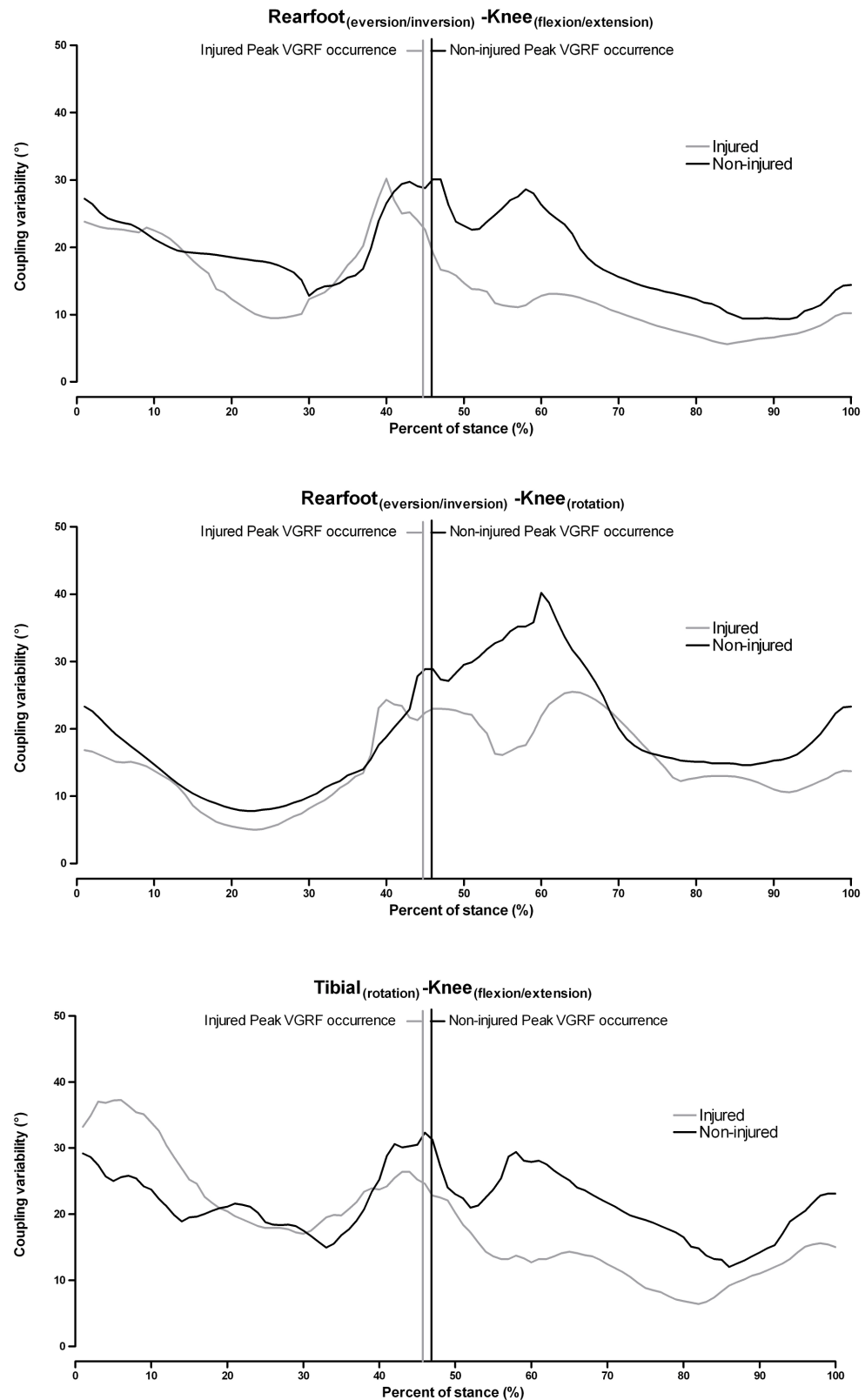


Figure 15: Mean coupling variability of three couplings across the stance phase of the dominant leg during unanticipated straight sprints performed by injured ($N = 13$) and non-injured ($N = 23$) netballers before the period of observation where injury occurred.

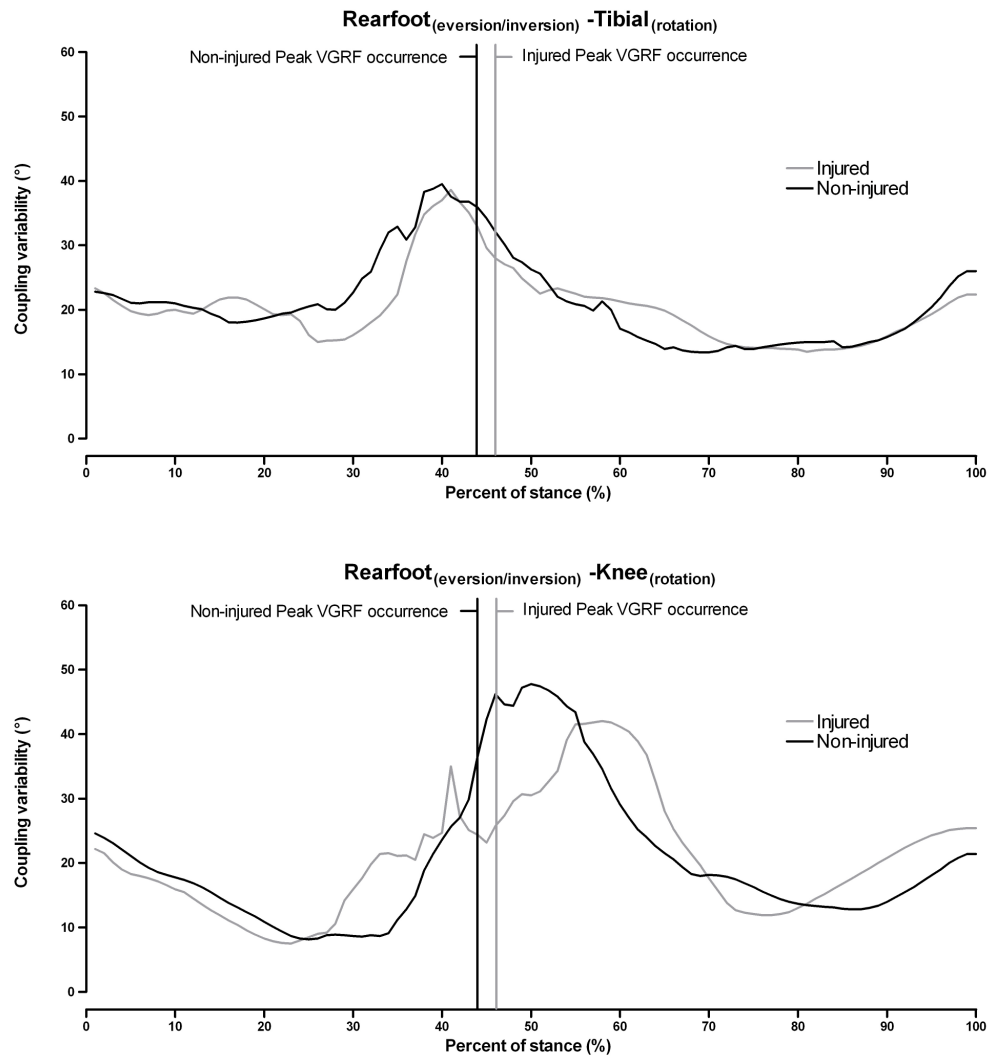


Figure 16: Mean coupling variability of two couplings across the stance phase of the non-dominant leg during unanticipated straight sprints performed by injured ($N = 13$) and non-injured ($N = 23$) netballers before the period of observation where injury occurred.

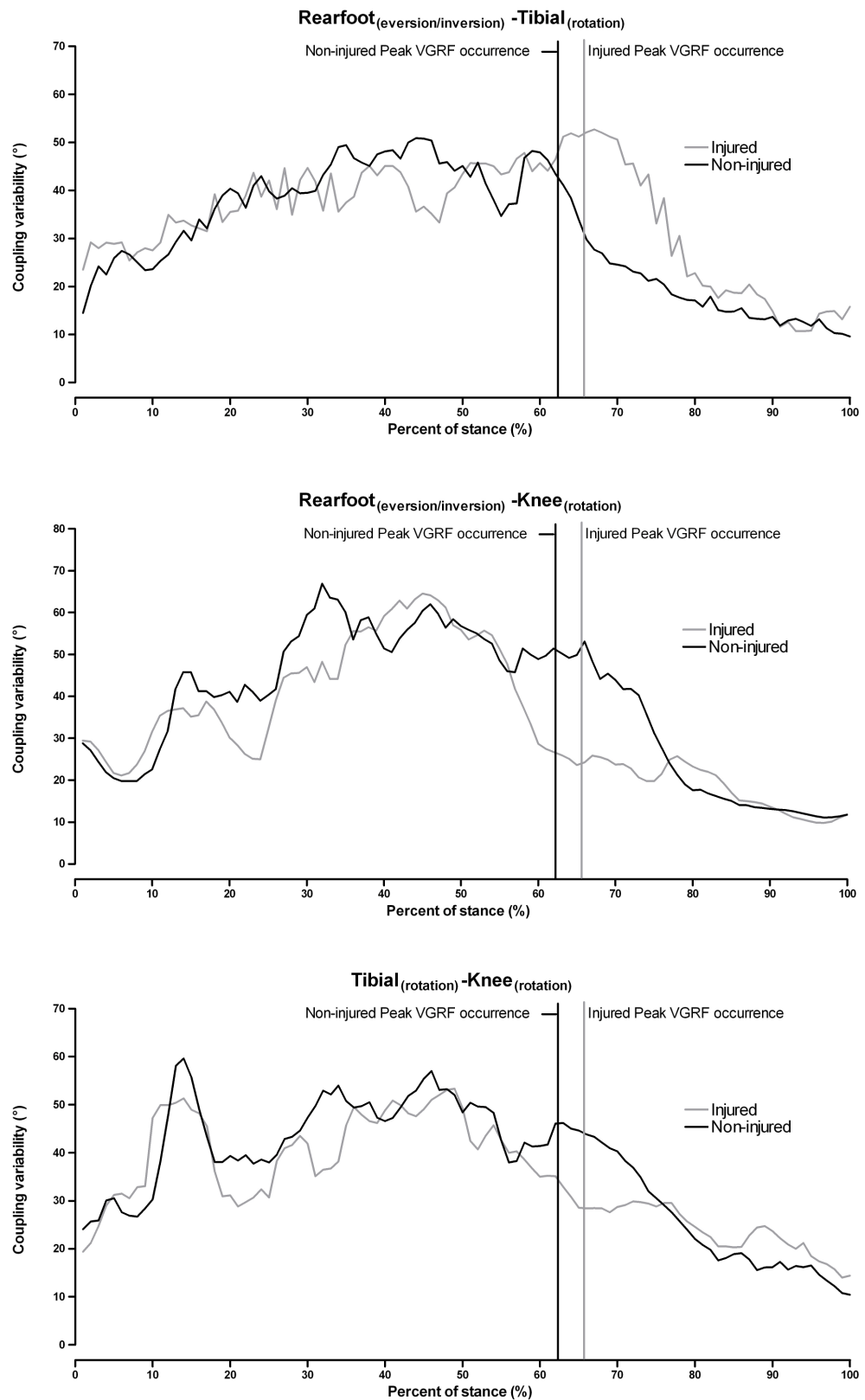


Figure 17: Mean coupling variability of three couplings across the stance phase of the non-dominant leg during an unanticipated 180° turning sprint performed by injured ($N = 13$) and non-injured ($N = 23$) netballers before the period of observation where injury occurred.

Table 15: Correlations between straight dominant leg couplings and dominant leg injury occurrences.

	Rearfoot _(eversion/inversion) –Knee _(flexion/extension)	Rearfoot _(eversion/inversion) –Knee _(rotation)	Tibial _(rotation) –Knee _(flexion/extension)
Group (N=35*)			
r (90%CL upper – lower)	0.16 (-0.12 to 0.42)	0.22 (-0.06 to 0.43)	0.01 (-0.18 to 0.37)
Clinical inference	Possibly may not be associated	Possibly may not be associated	Possibly may not be associated
Elite (N=12)			
r (90%CL upper – lower)	0.29 (-0.25 to 0.69)	0.66 (0.24 to 0.87)	0.12 (-0.40 to 0.58)
Clinical inference	Possibly may not be associated	Association is very likely	Possibly may not be associated
Non-Elite (N=12)			
r (90%CL upper – lower)	0.47 (-0.04 to 0.79)	0.39 (-0.14 to 0.74)	0.33 (-0.20 to 0.71)
Clinical inference	Association is likely probable	Association is likely probable	Association is likely probable
Male (N=11*)			
r (90%CL upper – lower)	-0.46 (-0.78 to 0.05)	-0.35 (-0.72 to 0.18)	-0.54 (-0.82 to 0.06)
Clinical inference	Association is likely probable	Association is likely probable	Association is likely probable

Key: r = correlation coefficient; CL = confidence limits; * = only 35 from 36 and 11 from 12 due to one netballer attaining injury on the non-dominant leg

Discussion

Sports injuries result in pain, loss of playing or working time, as well as medical expenditure (Fong, Hong, Chan, Yung & Chan, 2007). Research attempting to understand the mechanisms behind injuries is warranted as the identification of risk factors for injury is critical for the effective prevention of injury (DeLeo et al., 2004; Dierks & Davis, 2007; Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 1999; Pollard et al., 2005). The literature suggests that there is an association between low coupling variability and the presence of injury (Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005). All of these studies tested participants who currently or very recently had been injured and thus the studies were retrospective in terms of study design. A prospective study, which follows participants going forward in time, is generally viewed as more meaningful compared to a retrospective study (Hamill & Davis, 2006), thus the inclusion of a prospective design in the present study. The purpose of this study was to identify whether or not there was an association between lower limb injury occurrence measured prospectively and joint coupling variability measures during unanticipated movements performed by netballers.

Injury occurrence

Lower limb injury, as defined by McKay et al. (2001), occurred in ~36% of the netballers tested in the present study which required them to miss either training or game time. The ~39% of ankle sprains in our netballers were consistent with the frequency of ankle ligament sprains reported in the literature (Handoll, Rowe, Quinn & de Bie, 2001; Hopper et al., 1995; Hume, 1993). Additionally, Hume and Steele (2000) identified muscle strains within the lower extremity to be common in netball which is in agreement with the 8% adductor strains for the players in our study. Netball is a high-strategy sport requiring many explosive sprints, abrupt stops, change of direction and landing movements (Bock-Jonathan et al., 2007; McManus et al., 2006). Therefore, it is no surprise that the ankle complex would be the most commonly injured site due to amount of stress it would encounter as a major pivot point in the kinetic link system during such movement tasks.

Limb dominance is considered a risk factor for lower extremity injury because most athletes place a greater demand on their dominant limb (Beynnon et al., 2002). In certain sports, the dominant leg is preferentially used for kicking, pushing off, changing direction, jumping, or landing (D. F. Murphy et al., 2003). This can lead to an increased frequency and magnitude of moments about the knee and ankle, particularly during high-demand activities that place the ankle and knee at risk (Beynnon et al., 2002). In the present study the majority of injuries (~92.3%) occurred in the netballer's dominant

leg which is consistent with the findings of others (Chomiak et al., 2000; Ekstrand & Gillquist, 1983; Orchard, 2001). It must be acknowledged that the association between limb dominance and injury is controversial due to equivocal findings in the literature (Beynnon et al., 2001; Matava et al., 2002; Negrete et al., 2007; Seil et al., 1998; Surve et al., 1994). The contrasting findings may have been the result study designs, participant type and numbers, injury location or the methods used for data analysis.

Associations between joint coupling variability measures and the occurrence of injury in netballers

Due to the majority of injury occurrences occurring on the dominant leg in the present study, the following discussion will focus on the coupling variability measures during the straight dominant leg task. An expectation of the present study was that netballers who exhibited low coupling variability were likely to incur an injury to the lower extremity throughout the six month / competitive season period. This was not the case as indicated by the poor correlations between injury occurrence and various coupling variability measures when considering all netballers that participated in this study. When categorised into sub groups, the correlations increased in magnitude for the two female sub-categories of elite and non-elite netballers, which then offered support for our expectation. Specifically, a large correlation was observed between rearfoot_(eversion/inversion)–knee_(rotation) coupling variability and injury occurrence for elite female netballers whereas moderate likely probable associations between injury occurrence and all three coupling variability measures were observed for the non-elite female netballers. These findings were indicative of an association between low coupling variability and injury. It must be acknowledged that the true values of the correlations could indicate anything between a trivial and very strong association between low coupling variability and injury occurrence as indicated by the 90% confidence limits.

Low coupling variability during straight running has been associated retrospectively with the presence of injury (Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005). High amounts of coupling variability regardless of playing level appears to be beneficial for avoiding injury which is confirmed prospectively utilising female netballers in the present study. Variability in joint coupling is considered an essential component, providing the necessary flexibility for successful task execution (Clark & Phillips, 1993; Turvey, 1990; Van Emmerik et al., 1999). A more flexible repertoire (more variability) of coupling strategies an individual can exploit within the movement task allowing for changing task constraints may be beneficial for reducing injury risk (Davids et al., 2004; Hamill et al., 1999; Pollard et al., 2005). In fact, a lack of coupling variability within a movement pattern is thought to lead to less flexible

movement strategies that can adapt inadequately to meet the needs of an environment change or perturbation, thus increasing the risk for the individual attaining injury (Hamill et al., 1999). If movement patterns are invariant (performed identically) the same tissues would be maximally loaded each time and thus high coupling variability may modify tissue loads between repetitions reducing injury risk (Bartlett, 2004). Dynamical systems theory supports this concept as it suggests that consistent high-level performance across a variety of situations and conditions can only be achieved with a variable coupling pattern that can be adapted to suit the demands of the task at hand (Hamill et al., 1999).

When considering rearfoot_(eversion/inversion)–knee_(rotation) coupling variability the fact that elite female netballers presented with a stronger association between low variability and injury occurrence compared to the non-elites is interesting. The stronger association found in this study for the elite group suggests that having low coupling variability and playing netball at an elite level may increase the likelihood of injury compared to playing at a non-elite club competition level. Intuitively, elite netball is played at a more physically and mentally intense level than non-elite netball thus it is possible that greater demands experienced physically by the elites may make them even more susceptible to injury than the non-elites.

During an unanticipated explosive change of direction manoeuvre Pollard et al. (2005) reported lower extremity segment and joint coupling variability differences between healthy uninjured males and females. Specifically, healthy uninjured male athletes demonstrated substantially more coupling variability than similar female athletes. To help the reader to put this in perspective, Pollard et al. (2005) proposed that the lesser coupling variability demonstrated by females may be a possible cause for the large discrepancies in injury occurrences for females compared to males that has been reported previously (Griffin et al., 2000; Hutchinson & Ireland, 1995; Ireland, 1999). The findings of the present study suggest the proposition of Pollard et al. (2005) are somewhat true. This was not the case for male netballers whose findings were contrary to the theories and findings presented in the literature (Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005). Interestingly an association between high coupling variability and injury occurrence was identified for the male netballers during an unanticipated straight task. The inverse correlation outcomes demonstrated by males may explain the poor correlations calculated between injury occurrence and various coupling variability measures when considering all netballers (females and males) that participated in this study.

Male netballers demonstrated moderate likely probable associations between injury occurrence and high rearfoot_(eversion/inversion)–knee_(flexion/extension) coupling variability and high rearfoot_(eversion/inversion)–knee_(rotation) coupling variability, and a large association

between high tibial_(rotation)– knee_(flexion/extension) coupling variability and injury occurrence . These findings seem to suggest that gender plays a role in how injury is associated with coupling variability. Perhaps a high amount of variability in ankle and knee motion in a movement task such as unanticipated straight sprinting is detrimental to performance and the health of male netballers. This may lead to males potentially utilising an inappropriate coupling movement that is not suitable for performance or their health e.g. excessive or insufficient internal rotation of the shank in conjunction with excessive rearfoot pronation or external tibial rotation, which is a risk factor for injury (Heiderscheit et al., 1999). The differences identified between males and females in regards to an association between coupling variability and injury may be due to anatomical and neuromuscular differences between the sexes (Hewett, 2000; D. F. Murphy et al., 2003). Based on the findings of this study it is possible that there may be optimal levels of coupling variability for both females and males. More prospective studies are required to better understand the associations between coupling variability and injury occurrence in both males and females.

Additional findings

Height has been implicated as a risk factor for injury and in particularly ankle injury (Beynnon et al., 2002) in netballers. In the present study the non-injured group were substantially shorter (-2.4% (90% Confidence limit: -4.6 to -0.2%) which was confirmed by a moderate effect size (ES = -0.65). This finding is consistent with those of Milgrom et al.(1991) and Watson et al. (1999). Specifically, Milgrom et al (1991) reported that during basic training, taller military recruits were at increased risk of suffering an ankle injury. Watson et al. (1999) reported taller soccer athletes more likely attain ankle sprains than those who were shorter. A taller athlete may be at more of an at-risk position for inversion ankle injury during dynamic tasks, as the increase in height may proportionally increase the magnitude of inversion torque that must be resisted by the ligaments and muscles that span the ankle complex.

Recommendations for future research

Future research investigating training interventions aimed at adapting JCV are needed. The gender differences observed in this group of netballers suggests that an intervention program designed for women should be focused more on developing a greater repertoire of coupling strategies whereas for males the intervention should focus on minimising coupling variability. Research that monitors changes in JCV post injury, then following treatment and rehabilitation would be of great worth to the JCV body of knowledge.

Conclusion

Low joint coupling variability for the lower limb segments was associated with lower limb injury occurrence in elite and non-elite female netballers, whereas high joint coupling variability was associated with injury occurrence in male netballers. It is possible that an ideal range of joint coupling variability for particular movements that allows players to minimize the risk for injury, may exist independently between the genders. More prospective studies are required to better understand the associations between joint coupling variability and injury occurrence in both males and females.

CHAPTER 6: THE ROLE OF JOINT STIFFNESS IN INJURY: A BRIEF REVIEW OF THE LITERATURE.

Overview

Lower extremity joint stiffness has been given recent attention in the literature especially for performance associations. Information relating to joint stiffness and injury has received less attention. The purpose of this review was to provide a brief review of literature evaluating stiffness and performance and any associations with injury. The associations between injury occurrence and too little or too much joint stiffness were equivocal. More prospective investigations are needed to quantify and evaluate the role of joint stiffness in injury aetiology.

Introduction

Lower extremity joint stiffness studies are becoming more prevalent. In particular, sports and clinical biomechanists are typically interested in the role of stiffness as it relates to both performance and injury (Butler et al., 2003). While some stiffness may be necessary for performance, either too much or too little stiffness may lead to injury (Williams et al., 2004; Williams et al., 2001). The purpose of this review was to provide a brief review of literature evaluating stiffness and performance and any associations with injury.

Methods

A systematic review approach was used to evaluate the paradigm of Joint stiffness, focusing upon its potential role in lower extremity injury prevention during dynamic sporting tasks. Web of Knowledge, Scopus, Medline, SportsDiscus, ProQuest Direct, Google Scholar, Cinahl, Scirus Current Contents, ABI/INFORM Global and ProQuest Direct databases from 1975 to November 2010, and the internet (e.g., Journal of Biomechanics on line, Google Scholar) were searched using key words joint stiffness, lower extremity, and injury. Exclusion criteria were the article was unavailable in English and not previously referred to by other sources, or did not add knowledge to the aim of the review. Additional supportive articles were sought through article reference lists.

Methodological limitations were associated with many of the studies reviewed such as a failure to clearly describe the characteristics of the cohort, specifications of

methods used to calculate joint coupling variability, the environmental conditions, or the p-value associated with the outcome measure.

What is stiffness?

Stiffness can be defined as the amount of deformation experienced by a body per unit of force (Butler et al., 2003) or more specifically an estimate of the resistive force that a muscle exerts in response to a given length change (Blackburn, Riemann, Padua & Guskiewicz, 2004; Hill, 1938; Shorten, 1987). Mathematically stiffness equals the slope of the applied force plotted as a function of displacement (Davis & DeLuca, 1996) and is calculated as the change in muscle force divided by the change in muscle length (Hill, 1938; Shorten, 1987).

Stiffness can be measured at the level of a single muscle fibre, joint, to the modelling of the entire body as a mass and spring (Owen, Cronin, Gill & McNair, 2005). Stiffness has been suggested to provide a measure well-suited to quantify the behaviour of many components, namely joints, ligaments, tendons, cartilages, muscles and bones because it describes the resistance of a body to applied forces (Kupper, Loitz-Ramage, Corr, Hart & Ronsky, 2007).

Types of stiffness

A measure of stiffness can be determined under both passive and active conditions. Passive stiffness serves as a baseline level above which voluntary and/or reflexive muscle activation increase total stiffness, insufficient passive stiffness may predispose an individual to insufficient active stiffness (Blackburn, Padua, Riemann & Guskiewicz, 2004).

The physiological determinants of active stiffness are comprised of intrinsic and extrinsic components (Huston, Greenfield & Wojtys, 2000). The intrinsic component includes contributions from the muscular component and is largely dependent on the number of active actin-myosin cross-bridges in the muscles at a specified point (Huston et al., 2000; Komi, 1986; Morgan, 1977). The number of cross-bridges formed in the muscular component is the primary determinant of active stiffness (Morgan, 1977). The extrinsic component includes contributions from the muscular component, length-feedback component (muscle spindles) and force-feedback-component (Golgi tendon organ) (Komi, 1986) and is dependent on the excitation provided by the alpha and gamma motoneurons (Huston et al., 2000).

Active muscle stiffness contributes to musculoskeletal behaviour and is essential for the maintenance of joint stability (Wagner & Blickhan, 1999). Muscles serve as the primary active stabilizers during functional loading conditions, protecting

against musculoskeletal injury (Louie & Mote, 1987). A muscle's intrinsic muscle stiffness is probably the knee's first line of protection. While the potential of the extrinsic component's protection is greater (Huston et al., 2000), it is the active condition of stiffness that is of interest within this review. Therefore, the term active stiffness is referred to as "stiffness" from this point onwards.

Assessing stiffness

The methods used for assessing and calculating stiffness have been well reviewed by Butler et al. (2003). Therefore this review will provide a brief overview of the ways stiffness can be assessed. Lower extremity stiffness can be calculated in several ways including vertical and torsional leg stiffness. Vertical stiffness is used to describe linear movements that occur in the vertical direction such as hopping and jumping (Butler et al., 2003; McMahon & Cheng, 1990; McMahon, Valiant & Frederick, 1987). This method involves peak vertical ground reaction force being divided by the maximal vertical displacement of the centre of mass during contact with the ground (Butler et al., 2003; McMahon & Cheng, 1990). If the joints are of interest it has been suggested that torsional leg stiffness be evaluated (Butler et al., 2003). Angular or "torsional" stiffness is represented by the slope of the moment applied to the spring plotted as a function of angular / rotational displacement of the joint (Davis & DeLuca, 1996; Farley, Houdijk, Van Strien & Louie, 1998), or more simply the change in joint moment divided by the change in joint angle (Farley & Gonzalez, 1996).

The association between stiffness and performance

Lower extremity stiffness is considered to be a critical factor in musculoskeletal performance (Butler et al., 2003) and has been suggested to be very important in stretch shorten cycle exercises (Komi, 1986). Stiffness may be an important factor during running as it represents the ability of the entire lower extremity to attenuate the excessive forces generated during the stance phase (Williams et al., 2004). The association between stiffness and running speed is assumed to be strong, as authors have speculated that a stiff musculotendinous unit will enhance the rapid transmission of force (Aura & Komi, 1987; Komi, 1986). A "stiff" runner has been shown to spend less time in contact with the ground (Farley & Gonzalez, 1996) and attenuate less shock (McMahon et al., 1987), both of which are important to sprint performance (Mero et al., 1983; Murphy, Lockie & Coutts, 2003). Furthermore, increased stiffness has been reported to be associated with land based sprint performance (Bret, Rahmani, Dufour, Mesonnier & Lacour, 2002; Chelly & Denis, 2001) and increasing running speed in studies investigating actual participants (Arampatzis, Bruggemann & Metzler, 1999; Kuitunen, Komi & Kyrolainen, 2002) and from simulations (Seyfarth, Geyer,

Gunther & Blickhan, 2002). Additionally, stiffness has been reported to be significantly higher in sprinters compared with endurance runners (Harrison, Keane & Coglan, 2004), suggesting that it is possible that different types of athletes do differ in level of stiffness. Though the role of stiffness within performance could be further addressed it is beyond the scope of this particular review.

Stiffness and gender

Males have been reported to possess greater stiffness compared to females (Blackburn, Padua, Weinhold & Guskiewicz, 2006; Rozzi, Lephart, Gear & Fu, 1999), specifically in knee flexor (Blackburn, Riemann et al., 2004; Granata, Wilson, Massimini & Gabriel, 2004) and total leg comparisons (Granata et al., 2004). Padua et al. (2005) reported females to demonstrate ~18% less stiffness during hopping in comparison with that of males. These findings seem to support the notion that male musculature is more effective at resisting changes in its length (Blackburn et al., 2006). Butler et al. (2003) proposed that too little stiffness may lead to soft tissue injuries and knee pathology. Research has revealed female athletes who participate in jumping and running sports reportedly are four to six times more likely to sustain a serious knee injury than male athletes participating in the same sports (Griffin et al., 2000; Hutchinson & Ireland, 1995; Ireland, 1999). Therefore, the torsional joint stiffness of the knee might be an important contributing factor for differences in ACL injury rates between genders (Hsu, Fisk, Yamamoto, Debski & Woo, 2006). Wojtys et al. (2003) showed that female athletes are less capable of increasing the torsional joint stiffness of the knee compared with size and sport matched male athletes using muscular contraction. This was also the case under passive conditions (Hsu et al., 2006). Utilising cadaveric knees Hsu et al. (2006) reported the torsional joint stiffness of female knees to be 25% lower than that of male knees at 15° of knee flexion. Whilst these findings do not present a definitive association between low stiffness and injury occurrence they do allow for the assumption that low stiffness may play a role in the occurrence of an injury.

The association between stiffness and injury

Recently studies interested in the association between stiffness and injuries have begun to emerge (Mahieu, Witvrouw, Stevens, Van Tiggelen & Roget, 2006; Milner et al., 2006; Milner, Hamill & Davis, 2007; Pollard et al., 2005), however, information is still scarce so formative conclusions are difficult. Initially the association between stiffness and injuries was assumed somewhat indirectly through a body of knowledge surrounding foot structure (Williams et al., 2004; Williams et al., 2001). Distinctively, foot structure is associated with different injury patterns when comparing

injured high-arched runners with injured low-arched runners (Williams et al., 2001). Specifically, high-arched runners appear more likely to develop bony type injuries such as tibial stress fractures and injuries to the lateral portion of the lower extremity such as lateral ankle sprains. Low-arched runners were reported to be more likely to develop soft tissue injuries on the medial side of the lower extremity particularly around the knee joint (Williams et al., 2001). Uninjured high-arched runners have been reported to demonstrate both higher sagittal leg stiffness (10%) and knee stiffness (14%) compared to uninjured low-arched runners (Williams et al., 2004). In light of the findings of Williams et al. (2001) and Williams et al. (2004) it seems that too much stiffness may lead to bony injuries and ankle pathology whereas too little stiffness may lead to soft tissue injuries and knee pathology. Studies have reported an inability of stiffness to discriminate between injured and uninjured individuals (Mahieu et al., 2006; Milner et al., 2006). Only one study showed a discriminative ability (Milner et al., 2007). For example, Mahieu et al. (2006) prospectively examined the relationship between stiffness of the Achilles tendon and the rate of Achilles tendon overuse injuries in male military cadets during six weeks of basic military training. Stiffness of the Achilles tendon was defined as the relationship between the supplied muscle force from an isometric maximal voluntary contraction and the elongation of the Achilles tendon. Ten of the 69 male participants (14.5%) sustained an Achilles tendon overuse injury during this study. Stiffness was not reported to be an intrinsic factor associated with this type of injury.

Sagittal plane stiffness of the knee and ankle joints have been reported to reveal no differences in individuals with and without tibial stress fractures (Milner et al., 2006). Despite this finding Milner et al. (2006) indicated a trend toward increased (9%) knee stiffness in the tibial stress fracture group ($p = 0.054$). The moderate effect size (0.54) reported by Milner et al. (2006) indicated that stiffness of the knee joint may be an important factor in tibial stress fracture aetiology. Further work of Milner et al. (2007) did identify sagittal plane knee stiffness during the initial loading of stance to be significantly greater in the tibial stress fracture group compared with the uninjured group. The occurrence of a difference in stiffness between groups in the study of Milner et al. (2007) may be explained by the recruitment methods used. Female runners with a history of tibial stress fracture ($N = 23$) who were age and training mileage matched to uninjured females ($N = 23$) were recruited by Milner et al. (2007) whereas the earlier study of Milner et al. (2006) recruited running individuals of both genders ($N = 40$). Perhaps, single gender recruitment strategies should be considered when conducting research on the role stiffness may have in determining injury patterns.

Overall it is still unclear whether or not stiffness is directly related with injury. Information pertaining to whether or not high or low stiffness is directly associated to

any lower extremity injury warrants further investigation. Studies with a prospective design assessing lower extremity stiffness may offer a better insight into the causation of lower extremity injury occurrence. Additionally, the identification of an optimal range in which risk of injury is reduced would be a useful clinical tool.

Conclusions

Lower extremity joint stiffness has been shown to play a role in performance and injury occurrence. Several studies have demonstrated the importance of joint stiffness in functional performance. In terms of gender differences it is well reported that males possess greater stiffness compared to females during athletic tasks. Whilst, it appears joint stiffness is associated with injury retrospectively, it is still unclear whether or not joint stiffness is directly related with injury prospectively. More prospective research assessing lower extremity stiffness is needed to provide a better insight into the causation of lower extremity injury occurrence.

CHAPTER 7: THE RELIABILITY OF JOINT STIFFNESS MEASURES DURING UNANTICIPATED STRAIGHT RUN AND UNANTICIPATED 180° TURNING TASKS PERFORMED BY NETBALLERS

Overview

The reliability and variability of joint stiffness measures has not yet been adequately established. Despite this there has been a growing interest in the area of joint stiffness dynamics that has revealed promising possibilities for explaining the mechanisms of injury. This study aimed to determine the reliability and variability of joint stiffness measures of the dominant and non-dominant stance leg during unanticipated straight run and unanticipated 180° turning tasks performed by netballers. Ten elite netball players completed the four tasks in random order until five trials were captured for each task using three dimensional cameras and a force platform. A variety of reliability measures were calculated along with qualitative outcomes to provide a robust conclusion. Specifically, the percentage difference in the mean and Cohen's effect sizes were calculated for reliability assessment and intra-class correlation coefficients, and the coefficient of variation percentages were calculated for variability assessment. Across the 16 combinations of tasks and joint stiffness measures, five (~31%) exhibited an acceptable level of reliability and variability (average reliability and average variability qualitative interpretations indicated 'good' to 'moderate' reliability and 'small' to 'moderate' variability respectively). Specifically, the ankle frontal plane joint stiffness measure was found to have both acceptable levels of reliability and variability during unanticipated straight sprints and 180° turning tasks performed on both the dominant and non-dominant legs. Additionally, acceptable reliability and variability was demonstrated for the knee sagittal plane torsional stiffness measure during a 180° turn performed on the non-dominant leg. The use of these measures to quantify joint stiffness in the lower extremity across testing sessions during unanticipated straight run and unanticipated 180° turning tasks appears to be justified. Therefore it would be appropriate for these measures to be utilised in future investigations.

Introduction

Stiffness is a biomechanical parameter that characterizes the deformation of the soft-tissue structures connecting one bone to another in response to applied load or torques (Schmitz et al., 2008). It can be defined as the amount of deformation experienced by a body per unit of force (Butler et al., 2003). Simplistically, musculoskeletal stiffness is the resistive force that a muscle exerts in response to a given length change (Blackburn, Riemann et al., 2004; Hill, 1938; Shorten, 1987). Research has shown that stiffness is associated with performance (Arampatzis et al., 1999; Bret et al., 2002; Chelly & Denis, 2001) and, the presence of, or potential for injury (Milner et al., 2007).

Stiffness can be measured at the level of a single muscle fibre, joint through to modelling of the entire body as a mass and spring (Owen et al., 2005). Given the variety of ways to measure stiffness there are also a variety of techniques and mathematical models that can be utilised. For example, lower extremity stiffness can be calculated as vertical and torsional leg stiffness. Vertical stiffness is used to describe linear movements that occur in the vertical direction such as hopping and jumping (Butler et al., 2003; McMahon & Cheng, 1990; McMahon et al., 1987). This method involves peak vertical ground reaction force being divided by the maximal vertical displacement of the centre of mass during contact with the ground (Butler et al., 2003; McMahon & Cheng, 1990). Stiffness can be measured at a single joint using an isolated oscillation technique (McNair, Wood & Marshall, 1992; Murphy, Watsford, Coutts & Pine, 2003; Owen et al., 2005). The oscillation technique generally involves an applied external force perturbation to the joint complex which provides an excellent means for assessing joint stiffness during a static task. If dynamic joint motion is of interest during a task such as running or jumping, it has been suggested that torsional leg stiffness be evaluated (Butler et al., 2003). Angular or “torsional” stiffness is represented by the slope of the moment applied to the spring, plotted as a function of angular / rotational displacement of the joint (Davis & DeLuca, 1996; Farley et al., 1998). More simply it can be described as the change in joint moment divided by the change in joint angle (Farley & Gonzalez, 1996). Based on a variety of methods available to measure stiffness, the reliability of the test should be considered when choosing which test to utilise.

Reliability provides an indication of the degree of precision associated with a particular measure and is a vital element in the biomechanical assessment of athletes (Moir et al., 2004). A reliable test is characterized by small changes in the mean, small within-individual variation (Coefficient of Variation [CV], Standard Error of the Mean [SEM], or Typical Error [TE]) and a high test-retest correlation (intraclass correlation

coefficient [ICC]) (Atkinson & Nevill, 1998; Hausdorff et al., 1999; Hopkins, 2000). Therefore, the smaller the error, the better the measure (Hopkins, 2000).

Only a few studies have examined the reliability of stiffness assessment methods with results indicating either poor (Allison et al., 1998; Hunter & Spriggs, 2000) or very good repeatability (Murphy, Watsford, Coutts & Pine, 2003; Walshe, Wilson & Murphy, 1996) for lower body stiffness measures during isolated oscillation techniques. Whilst these findings offer support in the selection of oscillation methods to assess stiffness there are currently no reliability statistics available for the torsional leg/joint stiffness method. Outcomes from isolated oscillation methods may not be applicable / appropriate for explaining stiffness characteristics of sporting functional tasks given the dynamic nature of these activities. Investigation into the reliability of torsional leg/joint stiffness methods warrants investigation.

Aim

This study aimed to determine the reliability and variability of joint stiffness measures of dominant and non-dominant stance legs during unanticipated straight run and unanticipated 180° turning tasks performed by netballers.

Methods

Netball player characteristics

Ten elite (International = 6; National = 4) female netballers (mean \pm SD: age 22.2 \pm 4.2 yrs; height 1.79 \pm 0.08 m; mass 78.2 \pm 12.6 kg) volunteered to participate in the study. All had at least nine years experience playing netball (12.6 \pm 2.9 yrs). All netballers were in their pre-competition phase which consisted of four to seven (5.5 \pm 0.8) training sessions for a total of six to ten training hours (8.8 \pm 1.7 hrs) per week during data collection. The netballers had no history of significant lower extremity injury six months prior to testing and were injury free at the time of data collection. Each netballer gave informed consent in writing to participate in this study prior to testing. Ethical approval was obtained for all testing procedures from the Auckland University of Technology Ethics Committee. All netballers wore spandex shorts or pants and ASICS (Gel-Rocket) court shoes during the data collection.

Procedures

Study design

A test-retest between day protocol on two separate days was performed. There was a maximum of seven days between tests.

Netball player limb dominance

Limb dominance was determined via a series of questions and practical tests. The netballers were asked which leg was preferred for kicking a ball, and hopping on, with the preferred leg being considered the dominant leg (Maulder & Cronin, 2005). Furthermore, additional tests were used to identify which limb moved first; walking from a stationary position, and stepping off a 0.3 m high step from a stationary position. The limb that moved first was considered the dominant limb. This movement behaviour information in conjunction with the question data allowed for a comprehensive decision to be made on the netballer's limb dominance. The dominant limb was determined as the limb on the side of the body that was identified in the four assessments the majority of the time.

Unanticipated straight run task and unanticipated 180° turn tasks

The netballers performed three tasks from a 10 m approach that utilised a self selected start stance: a left leg plant and 180° turn; a straight ahead run (left or right foot placement); and a right leg plant and 180° turn. The tasks were presented as options in order to obtain an unanticipated / decision made movement response. Unanticipated movements have been demonstrated to elicit up to two times greater knee varus/valgus and internal/external rotation joint moments than anticipated movements (Besier et al., 2001). Movements during game situations are generally not always anticipated due to an external stimulus (Besier et al., 2001), thus unanticipated movements may offer a better reflection of the loads experienced around lower extremity joints during a sporting scenario. Therefore, a visual cue was displayed on a 19" computer screen which was triggered manually when the netballer was approximately 1 m away from the force platform. The screen was placed 0.5 m to the right side of the force platform. Testing tasks were assigned a colour consisting of green, yellow, and red which represented the 180° left leg plant and turn, straight ahead, and 180° right leg plant and turn respectively. Visual cues were created and presented using PowerPoint (Microsoft, Office, version 2003, California) slides.

Several pre-planned and unanticipated trials of each task were performed before data collection started in order to provide the netballers with the opportunity to familiarise themselves with the testing tasks. Each netballer completed all four tasks randomly, as cued by the computer monitor. This included foot placement of the left foot and right foot during the unanticipated straight run task, and pivoting on the left foot and right foot during the unanticipated 180° turn tasks. Bates et al. (1992) suggested that a minimum of five trials are needed to achieve 90% power for sample sizes of at least ten participants. To enable the five trials needed for data analysis to be collected for each task, a total of 20 successful trials were needed (Dierks & Davis,

2007). A maximum of 30 trials were completed by the participants to achieve the required data set. No feedback on trials performed previously in the testing session was provided to the participants as to avoid the possibility of the trials becoming planned. A 180° left (or right) leg plant and turn trial was deemed successful if: (a) the approach speed fell between 3.5 and 5 m.s⁻¹; (b) the left (or right) foot came in contact with the force platform; and (c) the exit speed was between 2.5 and 3.5 m.s⁻¹. A straight-ahead trial was deemed successful if (a) the approach speed was between 3.5 and 5 m.s⁻¹; (b) the left (or right) foot came into contact with the force platform; and (c) the netballer continued along the straight-ahead path and did not decelerate until at least 1 m after the centre of the force platform. The turning tasks were utilised in this study due to the use of the movement in field test assessment for the sport of netball. Specifically the 505 assessment (180° turn) is utilised to assess an individual's change of direction ability. Furthermore, anecdotally this type of turn is frequently utilised in netball. The approach and exit speeds were based on unpublished field testing scores typical in sprint and agility assessment in New Zealand netballers. Each netballer was given approximately 45 - 90 s of rest between trials to reduce the potential effects of fatigue.

Kinematic and kinetic data collection

Following the practice trials, four moulded thermoplastic shells were securely placed on the lateral surface of both the netballer's thighs and shanks. Each thermoplastic shell had four retro-reflective tracking markers attached. Additional tracking markers were placed on both anterior superior iliac spines, both iliac crests, and the mid-point of both posterior superior iliac spines to define the pelvis. Tracking markers were also placed on the heels of both feet, and the first and fifth metatarsal heads in order to define the foot. Calibration markers were placed on both greater trochanters (bilateral), both medial and lateral femoral condyles, and both medial and lateral malleoli to locate the segment origins. The marker placement protocol was based on those used by others previously (Dierks & Davis, 2007; Ferber et al., 2005; Pollard et al., 2004; Pollard et al., 2005). For a depiction of the marker set see Appendix 6. Once the markers were placed, a standing calibration trial was recorded to establish anatomical neutral. The netballers stood in a neutral position on the force plate at the centre of the camera capture space for approximately 1 minute. The calibration markers were removed after the standing trial, while the tracking markers remained on the netballer throughout the data collection session. The same individual placed the markers for all netballers and testing sessions.

A nine-camera motion capture system (Qualisys, Sweden) was used to record three dimensional (3-D) kinematic data at a sampling rate of 240 Hz (Pollard et al.,

2005). The cameras were positioned so that each marker was visible in multiple cameras throughout the stance phase (heel strike to toe off). The cameras encircled a force platform (~0.48m x ~0.51m) embedded within the floor (Advanced Mechanical Technology Inc., USA). The force platform, sampling at a rate of 1200 Hz, recorded the magnitude of three-dimensional ground reaction forces and was only used to identify the stance phase and foot strike region for the various tasks. The cameras and force platform were interfaced to a personal computer that allowed for synchronization of kinematic and kinetic data using the motion analysis software (Qualisys Track Manager, Sweden, version 1.10.283). Prior to testing, the nine-camera motion capture system was calibrated as per the manufacturer's protocol (Qualisys, Sweden), with a right-handed lab coordinate system being defined using a rigid L-frame containing four markers of known locations. A two-marker wand of known length was used within the calibration frame to scale the individual camera views of the measurement volume. The average movement residue for the retro-reflective markers during system calibration was minimal (less than 2 mm). The AMTI force platform was zeroed and calibrated for laboratory position and axis orientation. A two gate SWIFT® timing light system (SWIFT, Australia) was used to measure and monitor approach, performance and exit velocities. One timing light gate consisted of a dual beam modulated visible RED light sensor / reflector set up collecting at 4 MHz \pm 80 Hz. The timing lights were set at a height of 1.1 m (approximately hip height) and placed parallel to the approach runway with one gate located 3 m prior to the force platform and the other located 1 m prior (2 m apart). To view a schematic of the experimental set up see Appendix 7.

Kinematic and kinetic data processing & analyses

The following data reduction procedures were performed on the data for all five trials for each of the four unanticipated tasks. Q-Trac software (Qualisys, Sweden) was used to digitize the marker coordinates. Digitized coordinate data were then exported to Visual 3D™ software (C-Motion, Inc., Rockville, MD, USA) where it was low-pass filtered using a fourth-order Butterworth filter with an 8 Hz cut-off frequency (Pollard et al., 2005). Ground reaction force data were low-pass filtered using a fourth-order Butterworth filter with a 50 Hz cut-off frequency (Dierks & Davis, 2007; Pollard et al., 2004; Pollard et al., 2005). Three-dimensional kinematics and kinetics, namely angles, and net muscle moments (i.e., internal moments) were processed for the knee in the sagittal and transverse planes, and for the ankle in the sagittal and frontal planes from the coordinate data. All kinetic data were normalized to body mass, and net joint moments were calculated with standard inverse dynamics equations. Kinematic and ground reaction force data were exported to customised LabVIEW software (National Instruments, Austin, Texas, USA, version 6). The average joint stiffness values of the

ankle in the sagittal and frontal planes, and the knee in the sagittal and transverse planes were determined from the ratio of the change in net muscle moment (ΔM_{joint}) to change in joint angular displacement ($\Delta \theta_{\text{joint}}$) from touch-down to the instant when the joints were maximally flexed, pronated or internally rotated dependent on joint axis of interest (Farley et al., 1998) using the following equation.

$$k_{\text{joint}} = \Delta M_{\text{joint}} / \Delta \theta_{\text{joint}}$$

where k_{joint} is the average joint stiffness, ΔM_{joint} is the change in net muscle moment, and $\Delta \theta_{\text{joint}}$ the change in joint angular displacement. All stiffness measures were normalised to the netballer's body weight.

Statistical analyses

Descriptive statistics including overall group mean and standard deviations were calculated for all variables of interest. The reliability (performance consistency) and variability (performance flexibility) of the average joint stiffness for the four joint inclinations of interest during four unanticipated movement tasks was assessed using similar methods to that of Bradshaw, Hume, Calton and Aisbett (2010). The data were log transformed in order for reliability and variability measures to be presented as percentage changes where appropriate (Hopkins, 2000).

Reliability measures included the difference in the mean (MDiff) between the two days as a percentage, and Cohen's effect sizes (ES). Effect sizes were interpreted as 0 – 0.2 trivial, 0.2 – 0.6 small, 0.6 – 1.2 moderate, 1.2 – 2.0 large, and 2.0 – 4.0 very large (Hopkins, 2007b). An overall interpretation of the average reliability of the joint stiffness measures was based on the methods of Bradshaw et al. (2010). Average reliability was interpreted as 'good' when the difference in the mean was less than 5% and the effect size was trivial to small. Average reliability was interpreted as 'moderate' when the aforementioned criteria for 'good' was breached for either the difference in the mean or the effect size (MDiff > 5% or ES = moderate to large). Average reliability was categorised as 'poor' when both the difference in the mean and the effect size criteria were breached (MDiff > 5% and ES = moderate to large).

Variability measures included intraclass correlation coefficients (ICC) (Bradshaw et al., 2010), and the typical error of the measurement expressed as a coefficient of variation percentage (Hopkins, 2000). Based on 10 participants an ICC close to 1.00 indicates 'perfect' agreement with minimal variation (Atkinson & Nevill, 1998) whereas an ICC less than 0.70 is indicative of 'poor' agreement and high variability, $0.7 \leq \text{ICC} \leq 0.80$ represents a questionable outcome, and $\text{ICC} > 0.8$ represents an excellent outcome (Hopkins & Manly, 1989; Morrow & Jackson, 1993;

Shrout & Fleiss, 1979). A typical error (CV) of less than 10% is considered small variation (Cormack et al., 2008). An overall interpretation of the average variability of the joint stiffness measures was based on the methods of Bradshaw et al. (2010). Average variability was interpreted as 'small' when the ICC was > 0.70 and the CV was $< 10\%$. Average variability was interpreted as 'moderate' when ICC was < 0.70 or CV was $> 10\%$, and 'large' when ICC < 0.70 and CV $> 10\%$.

The use of a variety of reliability and variability measures which exceeds the recommendations of Atkinson and Neville (1998), allows for a robust decision to be made on the appropriateness to utilise a test measure of interest. In order for a joint coupling variability measure to be considered acceptable for future use the average reliability and average variability qualitative interpretations had to indicate 'good' to 'moderate' reliability and 'small' to 'moderate' variability respectively. In any instances where the average reliability outcome was 'poor' or the average variability was 'large' the measure was considered inappropriate for future use.

Results

The reliability and variability measures are reported for each joint stiffness measure and associated movement task in Table 16. Overall there were five (~31%) instances where the joint stiffness measures assessed during the four different movement tasks were identified as being acceptable (average reliability and average variability qualitative interpretations indicated 'good' to 'moderate' reliability and 'small' to 'moderate' variability respectively) for future use.

Moderate average reliability and moderate average variability was demonstrated for the ankle frontal plane joint stiffness measures of the dominant and non-dominant leg ground contacts during the unanticipated straight tasks, and also during the unanticipated 180° turn task performed on the dominant leg. Moderate average reliability and small average variability was demonstrated for the ankle frontal plane joint stiffness measure during the unanticipated 180° turn task performed on the non-dominant leg. Knee sagittal plane torsional stiffness during the unanticipated 180° turn on the dominant leg demonstrated moderate average reliability and moderate average variability.

Table 16: Reliability of torsional stiffness measures

					Reliability Statistics			Variability Statistics			Utilise	
	Day 1 (BW.m/°)		Day 2 (BW.m/°)		MDiff (%)	ES	Rating	ICC	Typical error as a CV (%)	Rating		
	mean	±SD	mean	±SD								
Straight dominant leg												
Ankle frontal plane	0.055	±0.032	0.081	±0.058	65.7	-0.56	Moderate	0.93	143.3	Moderate	Yes	
Ankle sagittal plane	0.096	±0.051	0.091	±0.044	0.9	0.12	Good	-0.13	117.8	Large	No	
Knee sagittal plane	0.947	±0.905	0.308	±0.199	-56.0	0.98	Poor	-0.54	141.5	Large	No	
Knee longitudinal	0.012	±0.059	0.016	±0.033	-46.8	0.09	Moderate	0.02	190.7	Large	No	
Straight non-dominant leg												
Ankle frontal plane	0.033	±0.044	0.027	±0.223	-41.5	0.37	Moderate	0.81	289.2	Moderate	Yes	
Ankle sagittal plane	0.104	±0.053	0.078	±0.048	-46.3	0.51	Moderate	0.35	269.7	Large	No	
Knee sagittal plane	0.488	±1.450	1.145	±2.481	9.4	-0.32	Good	-0.33	248.6	Large	No	
Knee longitudinal	0.062	±0.104	0.028	±0.041	-32.3	-0.44	Moderate	0.19	152.6	Large	No	
Turn dominant leg												
Ankle frontal plane	0.134	±0.269	0.086	±0.050	40.8	0.25	Moderate	0.42	5.8	Moderate	Yes	
Ankle sagittal plane	0.048	±0.011	0.054	±0.011	14.0	-0.61	Poor	0.87	13.8	Moderate	No	
Knee sagittal plane	0.077	±0.033	0.089	±0.046	10.7	-0.30	Moderate	0.86	26.8	Moderate	Yes	
Knee longitudinal	0.290	±1.143	0.065	±0.280	48.6	-0.43	Moderate	-0.72	379.7	Large	No	
Turn non-dominant leg												
Ankle frontal plane	0.079	±0.079	0.085	±0.048	-14.8	-0.10	Moderate	0.70	8.4	Small	Yes	
Ankle sagittal plane	0.048	±0.009	0.052	±0.012	7.3	-0.37	Moderate	0.47	18.7	Large	No	
Knee sagittal plane	0.041	±0.084	0.151	±0.237	35.7	-0.62	Poor	0.88	38.7	Moderate	No	
Knee longitudinal	0.066	±0.281	0.179	±0.356	-16.5	-0.76	Poor	0.31	433.3	Large	No	

Notes: SD, standard deviation; MDiff, inter-day difference in mean scores as a percentage; ES, Cohen's inter-day effect size; ICC, intraclass correlation coefficient; CV, typical error of measurement as a coefficient of variation; Use, indicates acceptable for future use.

Discussion

The non-existence of joint stiffness reliability research prompted this examination of the reliability and variability of lower extremity joint stiffness. Specifically, this study attempted to provide a reliable criterion of measuring lower extremity joint stiffness of the stance leg during unanticipated straight and unanticipated 180° turn tasks to aid in the development of future assessment methodologies. The results of the present study indicate five out of the 16 (~31%) measures investigated exhibited an acceptable level of reliability and variability for joint stiffness between testing sessions conducted on two days seven days apart.

Reliability and variability of joint stiffness measures

As with any new procedure it is necessary to determine the reliability and variability of testing results. Traditionally, a reliable test is considered to be one with a low standard error of measurement (SEM) and a high test-retest correlation between repeated trials (Hopkins, 2000). The findings of the present study indicated that only one torsional leg stiffness value met these criteria. Specifically, the ankle torsional stiffness in the frontal plane during an unanticipated 180° turn on the non-dominant leg was identified to have marginally acceptable reliability for both within day and between day situations. Marginally in the sense of the guidelines for levels of acceptable reliability provided in the literature for an ICC (Hopkins & Manly, 1989; Morrow & Jackson, 1993; Shrout & Fleiss, 1979) and a CV (Cormack et al., 2008). Acceptable criteria for an ICC begins at 0.70 (Hopkins & Manly, 1989; Morrow & Jackson, 1993; Shrout & Fleiss, 1979) whereas a CV of less than or equal to 10% declared the variable to be reliable (Cormack et al., 2008). The ankle torsional stiffness in the frontal plane during an unanticipated turn on the non-dominant leg was identified as having an ICC of 0.70 and a CV of 10%. These outcomes certainly ride the threshold of questionability for being utilised as measures in future research but are deemed reliable. Ultimately, it is up to the researcher to judge whether a measurement is reliable enough for its intended use (Atkinson & Nevill, 1998). Based on the aforementioned criteria for accepting a measure for future use it would render only one measure of this study adequate. It is plausible that a larger battery of statistical indicators of reliability would offer greater insight into the consistency of a measure. It was for this reason that the methods of Bradshaw et al. (2010), a more robust strategy for determining reliability and variability of a measure, was utilised in this study. Such a strategy allowed for a greater number (four) of possibilities of joint stiffness measures to be useable in future research. Specifically, the ankle frontal plane joint stiffness measure was found to have both acceptable levels of reliability and variability during

unanticipated straight sprints and 180° turning tasks performed on both the dominant and non-dominant legs. Additionally acceptable reliability and variability was demonstrated for the knee sagittal plane torsional stiffness measure during a 180° turn performed on the non-dominant leg.

Ankle frontal plane torsional stiffness measures during both the unanticipated 180° turn tasks performed on both the dominant leg and non-dominant leg exhibited acceptable coefficient of variation (CV) values of 5.8% and 8.4% respectively. These findings indicate that ankle frontal plane torsional stiffness during unanticipated 180° turn activities generally appears to have greater reliability than the unanticipated straight tasks. The presence of a reliable outcome may be attributed to the netballer's consistently using similar changes in ankle moments for given changes in ankle motions in the frontal plane whilst performing the 180° turn tasks.

The majority of torsional stiffness measures demonstrated very poor (>10%) consistency with coefficients of variation ranging from ~14 to 433%. Additionally the typical error (or standard error of measurement (SEM)) was excessively large for these measures when considering the magnitudes of the mean and standard deviations. The large CVs for most of the torsional stiffness measures examined suggest that they would be inadequate to detect important changes or differences in torsional stiffness during unanticipated tasks. The inclusion of an unanticipated stimulus that the netballers had to perform may somewhat explain the occurrence of such poor reliability outcomes.

Traditionally, retest variability is assessed via the intra correlation coefficient (ICC) statistic. In the present study acceptable retest variability ($ICC > 0.8$) was achieved for the torsional stiffness measures of the ankle frontal plane during the straight dominant leg ($ICC = 0.93$), and straight non-dominant leg ($ICC = 0.81$) conditions. An ICC of 0.87 was calculated for ankle sagittal plane during the turn on the non-dominant leg condition. Knee sagittal plane torsional stiffness during the turn on the dominant leg and turn on the non-dominant leg conditions achieved acceptable retest variability with calculated ICC's of 0.86 and 0.88 respectively. Questionable ($0.7 \leq ICC \leq 0.80$) retest variability was achieved for ankle frontal plane torsional stiffness during the turn on the non-dominant leg condition ($ICC = 0.70$). Interestingly the joint stiffness of the knee in the longitudinal plane during all unanticipated tasks revealed unacceptable variability outcomes to promote its use in future research. To this author's knowledge no data has been reported on the ICC statistics of joint stiffness measures therefore comparison of the results of the present study with reference to findings from previous research is not possible.

Unreliable and highly variable joint stiffness measures

The combined reliability and variability of a measure determines whether or not that particular measure may be of use in biomechanical research. Unfortunately, many (11; ~69%) of the joint stiffness measures investigated in the current study demonstrated both unacceptable reliability and variability during unanticipated straight run and unanticipated 180° turning tasks. Of the four joint stiffness measures ankle sagittal plane and knee longitudinal plane measures exhibited both unacceptable reliability and variability for all unanticipated tasks. The inclusion of an unanticipated stimulus that the netballers had to perform may somewhat explain the occurrence of such poor reliability outcomes. It is up to the researcher to judge whether a measurement is appropriate enough for its intended use (Atkinson & Nevill, 1998). It is acknowledged that the researcher ultimately decides whether or not to use such variables. and It is recommended that joint stiffness measures with low reliability and high variability found in the present study be considered cautiously as these variables are probably too unreliable and variable to monitor small changes in an athlete's joint stiffness during athletic performance following a period of training intervention.

Recommendations for future research

For joint stiffness measures identified as both acceptably reliable and variable in this study, future research should investigate the associations these measures may have with lower extremity injuries. Furthermore, the use of these measures in comparison investigations between genders, athletic populations, and athletic performance level would broaden the knowledge base of the joint stiffness paradigm.

Conclusion

Measures of ankle frontal plane joint stiffness had both acceptable levels of reliability and variability during unanticipated straight sprints and turning tasks performed on both the dominant and non-dominant legs. Acceptable reliability and variability was also demonstrated for the knee sagittal plane torsional stiffness measure during a 180° turn performed on the non-dominant leg. The use of these measures to quantify joint stiffness in the lower extremity across testing sessions during unanticipated straight run and unanticipated 180° turning tasks appears to be justified. Therefore it would be appropriate for these measures to be recommended for future use.

CHAPTER 8: DOES JOINT STIFFNESS DIFFER BETWEEN LEVELS OF PLAY IN FEMALE NETBALLERS, GENDER AND LOWER LIMBS?

Overview

The purpose of this study was to examine the effect of limb dominance, gender and netball playing ability on lower extremity joint stiffness during unanticipated straight run and unanticipated 180° turning tasks. Twelve elite female, 12 non-elite female, and 12 male netball players performed 20 to 30 trials of the unanticipated sprinting tasks (straight sprints and sprints with a 180° turn) on their dominant and non-dominant legs in the motion analysis laboratory from a 10 m approach.

When considering athletic ability discrepancies in JS differences appear to be movement specific as non-elite female netballers demonstrated 32.9% less ankle frontal plane torsional joint stiffness during the unanticipated 180° turn task performed on the dominant leg than elite level female netballers. On the other hand during the unanticipated straight task non-elite female netballers demonstrated greater ankle frontal plane torsional joint stiffness in both the dominant (306.5%) and non-dominant (255.0%) leg ground contacts compared to the elite female netballers. Research is required that further investigates athletic ability differences of other female sport populations joint stiffness measures utilising unanticipated motor patterns.

Gender differences exist for JS during unanticipated tasks. For instance non-elite female netballers demonstrated less ankle frontal plane stiffness during the unanticipated 180° turning tasks whilst elite female netballers demonstrated less ankle frontal plane stiffness during the unanticipated straight task than male netballers. These findings further confirm the concept of males possessing greater stiffness compared to females.

Comparisons between limb JS measures suggested differences in JS to be both population and movement specific. Specifically, elite female netballers demonstrated 39.5% greater ankle frontal plane joint stiffness in the dominant pivot leg during the unanticipated 180° turn compared to the 180° turn task performed on the non-dominant leg. All sub-categories (male netballers, elite female netballers and non-elite female netballers) presented with similar or symmetrical joint stiffness for the unanticipated straight task in this study.

Introduction

In Australasia netball is considered the primary team sport played both recreationally and competitively by females (McManus et al., 2006), and is also growing in interest and participation rate for males as well (Tagg, 2008). Some men's netball teams in New Zealand and Australia treat the game very seriously, training and competing with some of the best women's teams in the world (Tagg, 2008). Netball is a high-strategy sport requiring many explosive sprints, abrupt stops, change of direction and landing movements (Bock-Jonathan et al., 2007; McManus et al., 2006). Given the physical demands of netball there is a large exposure for risk of injury (Hume & Steele, 2000).

The incidence of injuries in court sports (e.g., netball, basketball, volleyball) has been well documented with the ankle and knee joints being identified as the primary anatomical locations injured (Hopper et al., 1995; Hume, 1993; Hume & Steele, 2000). Of these acute injuries, most occur as a result of play involving combinations of movements such as a change of direction whilst sprinting (Hume & Steele, 2000). Female athletes reportedly are four to six times more likely to sustain a serious knee injury than male athletes participating in the same sports that require explosive change of direction maneuvers whilst sprinting (Griffin et al., 2000; Hutchinson & Ireland, 1995; Ireland, 1999). Research into the mechanisms that cause injury is ongoing with attention currently focused upon the paradigm of joint stiffness (Mahieu et al., 2006; Milner et al., 2006; Milner et al., 2007; Pollard et al., 2005).

Joint stiffness is represented by the slope of the moment applied to the spring plotted as a function of angular / rotational displacement of the joint (Davis & DeLuca, 1996; Farley et al., 1998), or more simply the change in joint moment divided by the change in joint angle (Farley & Gonzalez, 1996). The importance of lower extremity joint stiffness in movement is in the storage and re-utilisation of the required spring energy to perform and continue movement (Latash & Zatsiorsky, 1993), and it's essential role in the maintenance of joint stability (Wagner & Blickhan, 1999). A stiffer joint resists sudden joint displacements quicker and more effectively, serving as a protective mechanism against acute injury (Riemann & Lephart, 2002). Joint stiffness has also been recently identified as a possible marker of lower extremity injury risk (Bradshaw, Le Rossignol, Williams & Lorenzen, 2006; Williams et al., 2004; Williams et al., 2001). Due to the infancy of the joint stiffness paradigm, information pertaining to joint stiffness is scarce with empirical evidence in the form of normative data being limited or nonexistent presently for athletes of various athletic ability, genders or limbs (e.g. legs).

Athletic ability comparisons of joint stiffness

Lower extremity stiffness is considered to be a critical factor in musculoskeletal performance (Butler et al., 2003) and has been suggested to be very important in movements that involve the stretch shortening cycle muscle activity (Komi, 1986). A “stiff” runner has been shown to spend less time in contact with the ground (Farley & Gonzalez, 1996) and attenuate less shock (McMahon et al., 1987), both of which are important to sprint performance (Mero et al., 1983; A. J. Murphy, R. G. Lockie et al., 2003). Furthermore, increased stiffness has been reported to be associated with land based sprint performance (Bret et al., 2002; Chelly & Denis, 2001) and increasing running speed in studies investigating actual participants (Arampatzis et al., 1999; Kuitunen et al., 2002) and from simulations (Seyfarth et al., 2002). Additionally, stiffness has been reported to be significantly higher in sprinters compared with endurance runners (Harrison et al., 2004), suggesting that it is possible that different types of athletes do differ in level of stiffness. Whilst information is prevalent for associations between stiffness and straight running / sprinting performance to this researcher’s knowledge no study has examined athletic ability differences in joint stiffness measures when performing tasks such as unanticipated straight sprints and unanticipated agility tasks.

Gender comparisons of joint stiffness

Males have been reported to possess greater stiffness compared to females (Blackburn et al., 2006; Rozzi et al., 1999), specifically in knee flexor (Blackburn, Riemann et al., 2004; Granata et al., 2004) and total leg comparisons (Granata et al., 2004). For example, Padua et al. (2005) reported females to demonstrate ~18% less stiffness during hopping in comparison with that of male. Whereas during landing from a volleyball spike block jump stiffness was ~46% less in females compared to males (Hughes & Watkins, 2008). These findings seem to support the notion that male musculature is more effective at resisting changes in its length (Blackburn et al., 2006). Consequently, knee joint stiffness may be an important factor in preventing lower extremity injury. The reduced joint stiffness in females compared with males may indicate reduced dynamic stability of the knee during functional tasks such as hopping and landing, which may contribute, at least in part, to the greater incidence of noncontact knee injury in females compared with males (Hughes & Watkins, 2008). Whilst information is prevalent for associations between stiffness and hopping and landing performance to this researcher’s knowledge no study has examined gender differences in joint stiffness measures when performing tasks such as unanticipated straight sprints and unanticipated agility tasks.

Limb comparisons of joint stiffness

Literature pertaining to the differences in joint stiffness between limbs is scarce. To this researcher's knowledge there is only one study that has made such an attempt. Joseph and colleagues (2007) investigated the influence of laterality on lower extremity stiffness in healthy soccer players and track runners. Eight male soccer players and male track runners performed single and double legged continuous straight and bent-legged jumping, and running tests to determine lower extremity musculoskeletal stiffness. Findings revealed the soccer players to exhibit symmetrical lower extremity musculoskeletal stiffness during the jumping and running tasks, whilst the track runners displayed significant asymmetry when running. These findings suggest differences in stiffness to be population specific and or movement specific. In this case, the asymmetry observed by Joseph et al. (2007) is likely due to long term training, in one direction, on a curved athletic track. To date no information exists on the differences in joint stiffness measures between limbs when performing tasks such as unanticipated straight sprints and unanticipated agility tasks.

Aim

The aim of this study was to examine the effect of limb dominance, gender and netball playing ability on lower extremity joint stiffness during unanticipated straight run and unanticipated 180° turning tasks.

Methods

Netball player characteristics

Thirty six netball players, consisting of three sub-groups of elite females ($N = 12$), non-elite females ($N = 12$) and males ($N = 12$), volunteered to participate in the study (see Table 17). Using data from Pollard et al. (2005) 12 participants per group were deemed adequate for the sample size based on a minimal statistical power of 80% ($p = 0.05$). Sample size and power calculations were completed using G*Power Software (Erdfelder et al., 1996).

Elite female netballers were classified as players who had represented their region or country at a senior level, whereas non-elite were classified as players who had participated in senior club level netball teams. Male netballers consisted mostly of regional representative level players and some high level competitive indoor netball players. All netballers had no history of significant lower extremity injury six months prior to testing and were injury free at the time of data collection. Each netballer gave informed consent in writing to participate in this study prior to testing. Ethical approval

was obtained for all testing procedures from the Auckland University of Technology Ethics Committee. All netballers wore spandex shorts or pants and ASICS (Gel-Rocket) court shoes during the data collection.

Table 17: Netball player characteristics.

	Elite females (<i>N</i> = 12) Mean \pm SD	Non-elite females (<i>N</i> = 12) Mean \pm SD	Males (<i>N</i> = 12) Mean \pm SD	All netballers (<i>N</i> = 36) Mean \pm SD
Age (yrs)	22.3 \pm 3.8	20.9 \pm 2.3	23.7 \pm 4.2	22.3 \pm 3.6
Height (m)	1.79 \pm 0.08	1.72 \pm 0.05	1.78 \pm 0.07	1.76 \pm 0.07
Mass (kg)	79.2 \pm 11.6	69.5 \pm 9.8	88.8 \pm 23.2	79.2 \pm 17.5
Playing history (yrs)	13.0 \pm 2.8	13.2 \pm 2.4	4.9 \pm 5.2	10.4 \pm 5.3
Training load (hours/week)	8.8 \pm 1.6	8.8 \pm 2.9	5.7 \pm 3.4	7.8 \pm 3.1
Training load (sessions/week)	5.5 \pm 0.8	5.3 \pm 2.0	3.5 \pm 2.3	4.8 \pm 2.0

Procedures

Netball player limb dominance

Limb dominance was determined via verbal questions and practical tests. The netballers were asked which leg was preferred for kicking a ball, and hopping on, with the preferred leg being considered the dominant leg (Maulder & Cronin, 2005). Furthermore, additional tests were used to identify which limb moved first; walking from a stationary position and stepping off a 0.3 m high step from a stationary position. The limb that moved first was considered the dominant limb. This information in conjunction with the question data allowed for a comprehensive decision to be made on limb dominance. The dominant limb was determined as the limb on the side of the body that was identified in the four assessments the majority of the time.

Unanticipated straight run task and unanticipated 180° turn tasks

The netballers performed three tasks from a 10 m approach that utilised a self selected start stance: a left leg plant and 180° turn; a straight ahead run (left or right foot placement); and a right leg plant and 180° turn. The tasks were presented as options in order to obtain an unanticipated / decision made movement response. Unanticipated movements have been demonstrated to elicit up to two times greater knee varus/valgus and internal/external rotation joint moments than anticipated movements (Besier et al., 2001). Movements during game situations are generally not

always anticipated due to an external stimulus (Besier et al., 2001), thus unanticipated movements may offer a better reflection of the loads experienced around lower extremity joints during a sporting scenario. Therefore, a visual cue was displayed on a 19" computer screen which was triggered manually when the netballer was approximately 1 m away from the force platform. The screen was placed 0.5 m to the right side of the force platform. Testing tasks were assigned a colour consisting of green, yellow, and red which represented the 180° left leg plant and turn, straight ahead, and 180° right leg plant and turn respectively. Visual cues were created and presented using PowerPoint (Microsoft, Office, version 2003, California) slides.

Several pre-planned and unanticipated trials of each task were performed before data collection started in order to provide the netballers with the opportunity to familiarise themselves with the testing tasks. Each netballer completed all four tasks randomly, as cued by the computer monitor. This included foot placement of the left foot and right foot during the unanticipated straight run task, and pivoting on the left foot and right foot during the unanticipated 180° turn tasks. Bates et al. (1992) suggested that a minimum of five trials are needed to achieve 90% power for sample sizes of at least ten participants. To enable the five trials needed for data analysis to be collected for each task, a total of 20 successful trials were needed (Dierks & Davis, 2007). A maximum of 30 trials were completed by the participants to achieve the required data set. No feedback on trials performed previously in the testing session was provided to the participants as to avoid the possibility of the trials becoming planned. A 180° left (or right) leg plant and turn trial was deemed successful if: (a) the approach speed fell between 3.5 and 5 m.s⁻¹; (b) the left (or right) foot came in contact with the force platform; and (c) the exit speed was between 2.5 and 3.5 m.s⁻¹. A straight-ahead trial was deemed successful if (a) the approach speed was between 3.5 and 5 m.s⁻¹; (b) the left (or right) foot came into contact with the force platform; and (c) the netballer continued along the straight-ahead path and did not decelerate until at least 1 m after the centre of the force platform. The turning tasks were utilised in this study due to the use of the movement in field test assessment for the sport of netball. Specifically the 505 assessment (180° turn) is utilised to assess an individual's change of direction ability. Furthermore, anecdotally this type of turn is frequently utilised in netball. The approach and exit speeds were based on unpublished field testing scores typical in sprint and agility assessment in New Zealand netballers. Each netballer was given approximately 45 - 90 s of rest between trials to reduce the potential effects of fatigue.

Kinematic and kinetic data collection

Following the practice trials, four moulded thermoplastic shells each with four retro-reflective tracking markers attached were securely placed on the lateral surface of both the netballer's thighs and shanks. Additional tracking markers were placed on both anterior superior iliac spines, both iliac crests, and the mid-point of both posterior superior iliac spines to define the pelvis. Tracking markers were also placed on both heels, first and fifth metatarsal heads to define the foot. Calibration markers were placed on both greater trochanters (bilateral), both medial and lateral femoral condyles, both medial and lateral malleoli, to locate the segment origins. All markers were based on those used by others previously (Dierks & Davis, 2007; Ferber et al., 2005; Pollard et al., 2004; Pollard et al., 2005). For a depiction of the marker set see Appendix 6. Once the markers were placed, a standing calibration trial was recorded to establish anatomical neutral. Netballers stood in a neutral position on the force plate at the centre of the camera set-up. The calibration markers were removed after the standing trial, while the tracking markers remained on the netballer throughout the data collection session. The same individual placed the markers for all netballers.

A nine-camera motion capture system (Qualisys, Sweden) was used to record 3-D kinematic data at a sampling rate of 240 Hz as used by Pollard et al. (2005). The cameras were positioned so that each marker was visible in multiple cameras throughout the stance phase (heel strike to toe off). The cameras encircled a force platform (~0.48m x ~0.51m) embedded within the floor (Advanced Mechanical Technology Inc., USA). The force platform, sampling at a rate of 1200 Hz, recorded the magnitude of three-dimensional ground reaction forces and was only used to identify the stance phase and foot strike region for the various tasks. The cameras and force platform were interfaced to a personal computer that allowed for synchronization of kinematic and kinetic data using the motion analysis software (Qualisys Track Manager, Sweden, version 1.10.283). Prior to testing the nine-camera motion capture system was calibrated as per the manufacturer's protocol (Qualisys, Sweden), with a right-handed lab coordinate system being defined using a rigid L-frame containing four markers of known locations. A two-marker wand of known length was used within the calibration frame to scale the individual camera views of the measurement volume. The average movement residue for the retro-reflective markers during system calibration was minimal (less than 2 mm). The AMTI force platform was zeroed and calibrated for laboratory position and axis orientation. A two gate SWIFT® timing light system (SWIFT, Australia) was used to measure / monitor approach, performance and exit velocities. One timing light gate consisted of a dual beam modulated visible RED light sensor / reflector set up collecting at 4 MHz \pm 80 Hz. The timing lights were set at a

height of 1.1 m and placed parallel to the approach runway with one gate located 3 m prior to the force platform and the other located 1 m prior. To view a schematic of the experimental set up see Appendix 7.

Kinematic and kinetic data processing & analyses

The following data reduction procedures were performed on data for all five trials for each of the four unanticipated tasks. Q-Trac software (Qualisys, Sweden) was used to digitize the marker coordinates. Digitized coordinate data were then exported to Visual 3D™ software (C-Motion, Inc., Rockville, MD, USA) where they were low-pass filtered using a fourth-order Butterworth filter with an 8 Hz cut-off frequency. Ground reaction force data were low-pass filtered using a fourth-order Butterworth filter with a 50 Hz cut-off frequency (Dierks & Davis, 2007; Pollard et al., 2004; Pollard et al., 2005).

Joint stiffness

Three-dimensional kinematics and kinetics, namely angles, and net muscle moments (i.e. internal moments) were processed for the knee in the sagittal and transverse planes, and ankle in the sagittal and frontal planes from the coordinate data. All kinetic data were normalized to body mass, and net joint moments were calculated with standard inverse dynamics equations (Johnson & Buckley, 2001). Kinematic and ground reaction force data were exported to customised LabVIEW software (National Instruments, Austin, Texas, USA, version 6). The JS measures of interest in this study can be viewed in Table 18. Reliability was established for these measures in earlier work reported in Chapter 7. The average JS of the ankle in the frontal plane, and the knee in the sagittal were determined from the ratio of the change in net muscle moment (ΔM_{joint}) to change in joint angular displacement ($\Delta \theta_{\text{joint}}$) from touch-down to the instant when the joints were maximally flexed, pronated or internally rotated dependent on joint axis of interest (Farley et al., 1998) using the following equation.

$$k_{\text{joint}} = \Delta M_{\text{joint}} / \Delta \theta_{\text{joint}}$$

where k_{joint} is the average torsional joint stiffness, ΔM_{joint} is the change in net muscle moment, and $\Delta \theta_{\text{joint}}$ the change in joint angular displacement. All stiffness measures were normalised to the netballer's body weight.

Table 18: Torsional joint stiffness measures of interest.

Movement task	Joint stiffness
Unanticipated straight run: dominant leg contact	Ankle frontal plane stiffness
Unanticipated straight run: non-dominant leg contact	Ankle frontal plane stiffness
Unanticipated 180° turn on the dominant leg	Ankle frontal plane stiffness Knee sagittal plane stiffness
Unanticipated 180° turn on the non-dominant leg	Ankle frontal plane stiffness

Statistical analyses

Comparisons were made between all JS measures (see Table 18) exhibited by the elite female, non-elite female and male netballers using the methods of Hopkins (2007b). Comparisons between limbs for the ankle frontal plane JS measures were made during the unanticipated straight and unanticipated 180° turning tasks. Comparisons were conducted using the methods of Hopkins (2006). All of Hopkins' (2006 & 2007) analyses allowed for Cohen effect sizes, 90% confidence intervals, and qualitative inferences to be presented, which is currently considered best practice for statistical use in sports medicine and the exercise sciences (Hopkins et al., 2009).

Differences between groups and differences between dominant and non-dominant limbs were expressed as a percentage via analysis of log-transformed values using natural logarithms. Logarithmic transformation allowed for uniformity of error and was used to reduce bias arising from non-uniformity of error raw values (differences) of the variables of interest. Inferential statistics were based on interpretation of magnitude of effects (differences), as described by Batterham & Hopkins (2006). The likelihood of differences (effect unit) was interpreted using the Cohen scale of magnitudes for the standardized differences in the mean. The Cohen scale is divided into different effect sizes (ES) which are used to quantify the differences between conditions (Hopkins et al., 2009). To make inferences about the true values of the percentage differences and effect sizes between the groups of netballers, and the limbs, the uncertainty in the percentage differences and ES were expressed as 90% confidence intervals and as likelihoods that the true value of the difference is substantial (Batterham & Hopkins, 2006). A difference was deemed unclear if its confidence interval of the effect statistic overlapped substantially positive and negative values and the threshold for the smallest worthwhile effect, otherwise, when a result was above the threshold for the smallest worthwhile effect the results could be given as: 0 – 0.2 trivial; 0.2 – 0.6 small; 0.6 – 1.2 moderate; 1.2 – 2.0 large; 2.0 – 4.0 very large. An effect size of 0.2 was chosen to be the smallest worthwhile difference in the means in standardized (Cohen) units as it gave likelihoods that the true effect would at least be small (Cohen, 1990).

Results

Comparisons between joint stiffness of elite female and non-elite female netballers

Non-elite female netballers demonstrated significantly greater ($p < 0.05$) ankle frontal plane torsional joint stiffness in both the dominant and non-dominant leg ground contacts of the unanticipated straight task (see Table 19). Specifically, ankle frontal plane torsional joint stiffness was 306.5% (123.6 to 638.9%) greater during the dominant leg ground contact and 255.0% (120.2 to 472.4%) greater during the non-dominant leg ground contact of the unanticipated straight task. Unclear statistical outcomes were computed for all torsional joint stiffness measures taken during the unanticipated 180° turn task performed on the dominant leg. During the unanticipated 180° turn task performed on the dominant leg non-elite female netballers demonstrated 32.9% (-48.3 to -12.9%) less ankle frontal plane torsional joint stiffness compared to the elite level female netballers.

Comparisons between joint stiffness of male and non-elite female netballers

Compared to male netballers non-elite female netballers demonstrated substantial large to trivial negative difference outcomes in ankle frontal plane torsional joint stiffness in both the dominant and non-dominant leg ground pivots of the unanticipated 180° turning task (see Table 20). Specifically, ankle frontal plane torsional joint stiffness was 15.4% (-32.1 to 5.3%) less during the dominant leg ground pivot and 18.2% (-33.0 to -0.1%) less during the non-dominant leg ground pivot of the unanticipated 180° turn task. Unclear statistical outcomes were computed for all torsional joint stiffness measures taken during unanticipated straight tasks, and the knee sagittal plane torsional joint stiffness measure during the unanticipated 180° turn on the dominant leg task.

Table 19: Differences in torsional joint stiffness[#] for various joints during unanticipated tasks between elite female ($N = 12$) and non-elite female ($N = 12$) netballers and the qualitative inferences about the effect of the differences.

	Elite Females Mean \pm SD	Non-elite Females Mean \pm SD	p value	Diff. in means as Percentage (%)	Diff. in means as % 90% Confidence levels		Cohen ES	Qualitative inference of ES
					lower	upper		
<i>Straight run: dominant leg contact</i>								
Ankle frontal plane	0.066 \pm 0.042	0.202 \pm 0.062	0.001*	306.5	123.6	638.9	1.60	moder.-v.large +ive
<i>Straight run: non-dominant leg contact</i>								
Ankle frontal plane	0.072 \pm 0.058	0.227 \pm 0.157	0.002*	255.0	120.2	472.4	1.80	moder.-v.large +ive
<i>180° turn on the dominant leg task</i>								
Ankle frontal plane	0.143 \pm 0.251	0.060 \pm 0.013	0.837	-7.2	-50.9	75.4	-0.08	unclear
Knee sagittal plane	0.068 \pm 0.037	0.137 \pm 0.202	0.613	20.4	-35.7	125.6	0.20	unclear
<i>180° turn on the non-dominant leg task</i>								
Ankle frontal plane	0.097 \pm 0.048	0.060 \pm 0.014	0.017*	-32.9	-48.3	-12.9	-1.04	large-small -ive

Key: [#] = Torsional joint stiffness normalised to body weight (BW.m/°); SD = standard deviation; Diff. = difference; ES = effect size; * = $p < 0.05$; moder. = moderate; v.large = very large; -ive = negative; +ive = positive.

Table 20: Differences in torsional joint stiffness[#] for various joints during unanticipated tasks between male (*N* = 12) and non-elite female (*N* = 12) netballers and the qualitative inferences about the effect of the differences.

	Males	Non-elite		Diff. in				
	Mean \pm SD	Females		means as	Diff. in means as %		Cohen	Qualitative
		Mean \pm SD	<i>p</i> value	Percentage	90% Confidence levels		ES	inference of ES
				(%)	lower	upper		
<i>Straight run: dominant leg contact</i>								
Ankle frontal plane	0.266 \pm 0.373	0.202 \pm 0.062	0.740	8.7	-29.4	67.3	0.13	unclear
<i>Straight run: non-dominant leg contact</i>								
Ankle frontal plane	0.183 \pm 0.106	0.227 \pm 0.157	0.439	17.4	-17.2	66.5	0.31	unclear
<i>180° turn on the dominant leg task</i>								
Ankle frontal plane	0.074 \pm 0.027	0.060 \pm 0.013	0.202	-15.4	-32.1	5.3	-0.52	moder.-trivial -ive
Knee sagittal plane	0.238 \pm 0.276	0.137 \pm 0.202	0.544	-29.1	-72.9	85.6	-0.24	unclear
<i>180° turn on the non-dominant leg task</i>								
Ankle frontal plane	0.076 \pm 0.028	0.060 \pm 0.014	0.099	-18.2	-33.0	-0.10	-0.68	large-trivial -ive

Key: [#] = Torsional joint stiffness normalised to body weight (BW.m/°); SD = standard deviation; Diff. = difference; ES = effect size; moder. = moderate; -ive = negative.

Comparisons between joint stiffness of male and elite female netballers

Elite female netballers demonstrated significantly less ($p < 0.05$) ankle frontal plane torsional joint stiffness in both the dominant and non-dominant leg ground contacts of the unanticipated straight task (see Table 21). Specifically, ankle frontal plane torsional joint stiffness was 73.3% (-86.5 to -47.1%) less during the dominant leg ground contact and 66.9% (-79.0 to -48.0%) less during the non-dominant leg ground contact of the unanticipated straight task. Unclear statistical outcomes were computed for all torsional joint stiffness measures taken during both unanticipated 180° tasks.

Comparisons between joint stiffness of dominant and non-dominant limbs

No clear differences were computed between dominant and non-dominant legs for ankle frontal plane torsional joint stiffness during unanticipated straight runs for the sub-categories of male netballers, elite female netballers and non-elite female netballers (see Table 22). During the unanticipated 180° turn task compared to the non-dominant pivot leg the dominant pivot leg demonstrated slightly greater ankle frontal plane torsional joint stiffness for the elite female netballers (>39.5%) and the larger combined female netball group (>18.6%) (see Table 23).

Table 21: Differences in torsional joint stiffness[#] for various joints during unanticipated tasks between male ($N = 12$) and elite female ($N = 12$) netballers and the qualitative inferences about the effect of the differences.

	Males Mean \pm SD	Elite Females Mean \pm SD	p value	Diff. in means as Percentage (%)	Diff. in means as % 90% Confidence levels		Cohen ES	Qualitative inference of ES
					lower	upper		
<i>Straight run: dominant leg contact</i>								
Ankle frontal plane	0.266 \pm 0.373	0.066 \pm 0.042	0.003*	-73.3	-86.5	-47.1	-1.31	large-moder. -ive
<i>Straight run: non-dominant leg contact</i>								
Ankle frontal plane	0.183 \pm 0.106	0.072 \pm 0.058	0.005*	-66.9	-79.0	-48.0	-1.66	v.large-moder. -ive
<i>180° turn on the dominant leg task</i>								
Ankle frontal plane	0.074 \pm 0.027	0.143 \pm 0.251	0.804	-8.9	-52.3	74.1	-0.10	unclear
Knee sagittal plane	0.238 \pm 0.276	0.068 \pm 0.037	0.297	-41.1	-75.1	39.2	-0.42	unclear
<i>180° turn on the non-dominant leg task</i>								
Ankle frontal plane	0.076 \pm 0.028	0.097 \pm 0.048	0.244	22.0	-8.3	62.2	0.47	unclear

Key: [#] = Torsional joint stiffness normalised to body weight (BW.m/°); SD = standard deviation; Diff. = difference; ES = effect size; * = $p < 0.05$; moder. = moderate; v.large = very large; -ive = negative.

Table 22: Differences in ankle frontal plane torsional joint stiffness[#] between dominant and non-dominant legs during unanticipated straight runs and the qualitative inferences about the effect of the differences.

						Diff. in	Diff. in means as a %		Cohen ES	Qualitative inference of ES
	Dominant		Non-dominant		means as	90% Confidence levels				
	Mean	±SD	Mean	±SD	p value	Percentage (%)	lower	upper		
Male (N = 12)	0.266	±0.373	0.183	±0.106	0.769	-7.2	-40.5	44.8	-0.09	unclear
Elite females (N = 12)	0.066	±0.042	0.072	±0.058	0.740	14.8	-44.6	138.0	0.11	unclear
Non-elite females (N = 12)	0.202	±0.062	0.227	±0.157	0.983	0.3	-20.3	26.2	0.01	unclear
Females (N = 24)	0.134	±0.086	0.149	±0.140	0.738	7.3	-24.9	53.4	0.06	unclear

Key: [#] = Torsional joint stiffness normalised to body weight (BW.m/°); Females represent the combination of all female netballers that participated in the study; SD = standard deviation; Diff. = difference; ES = effect size.

Table 23: Differences in ankle frontal plane torsional joint stiffness[#] between dominant and non-dominant legs during unanticipated 180° turning sprints and the qualitative inferences about the effect of the differences.

	Dominant		Non-dominant		p value	Diff. in	Diff. in means as a %		Cohen ES	Qualitative inference of ES
	Mean	±SD	Mean	±SD		means as Percentage (%)	90% Confidence levels	lower upper		
Male (N = 12)	0.074	±0.027	0.076	±0.028	0.638	4.2	-10.6	21.5	0.10	unclear
Elite females (N = 12)	0.143	±0.251	0.097	±0.048	0.306	39.5	-20.1	143.3	0.26	trivial-moder. +ive
Non-elite females (N = 12)	0.060	±0.013	0.060	±0.014	0.903	0.8	-10.0	12.8	0.03	unclear
Females (N = 24)	0.101	±0.179	0.079	±0.039	0.293	18.6	-9.6	55.5	0.19	trivial-small +ive

Key: [#] = Torsional joint stiffness normalised to body weight (BW.m/°); Females represent the combination of all female netballers that participated in the study; SD = standard deviation; Diff. = difference; ES = effect size; moder. = moderate; +ive = positive.

Discussion

Comparisons between joint stiffness of elite female and non-elite female netballers

Information is prevalent for associations between stiffness and straight running / sprinting performance; however no study has examined athletic ability differences in joint stiffness measures when performing tasks such as unanticipated straight sprints and unanticipated agility tasks. At the outset of this study it was expected that non-elite female netballers would demonstrate less joint stiffness in all unanticipated tasks compared to elite female netballers. This premise was only supported during the unanticipated 180° turn task performed on the non-dominant leg. Specifically, compared to the elite level female netballers non-elite female netballers demonstrated ~33% less ankle frontal plane torsional joint stiffness during the unanticipated 180° turn task performed on the dominant leg. Lower extremity stiffness is considered to be a critical factor in musculoskeletal performance (Butler et al., 2003) and has been suggested to be very important in stretch shorten cycle exercises (Komi, 1986). Intuitively, elite netball is played at a more physically and mentally intense level than non-elite netball. It is possible that elite players are in better condition than non-elites and are more capable of performing unanticipated turns at a better aptitude with more force and less contact time in the pivot. A “stiff” runner has been shown to spend less time in contact with the ground (Farley & Gonzalez, 1996) and attenuate less shock (McMahon et al., 1987) during running. It is possible that the stiffer ankle exhibited by the elite netballers during the pivot allows them to attenuate the shock of the pivot foot action thus maintaining sufficient stability to successfully execute the turn.

During the unanticipated straight task, non-elite female netballers demonstrated greater ankle frontal plane torsional joint stiffness in both the dominant and non-dominant leg ground contacts compared to the elite female netballers. Specifically, ankle frontal plane torsional joint stiffness was ~307% greater during the dominant leg ground contact and 255.0% greater during the non-dominant leg ground contact of the unanticipated straight task. These results were not expected by the researcher and are difficult to explain due to the paucity of research demonstrating athletes of lesser ability demonstrating more stiffness than their better counterparts. Research that has revealed strong associations between performance aptitude and high stiffness have typically demonstrated so with male participants in a planned straight task (Bret et al., 2002; Chelly & Denis, 2001). Perhaps females or even unanticipated tasks are atypical with respect to male and planned activities. Research is required that further investigates athletic ability differences of other female sport populations joint stiffness

measures utilising unanticipated motor patterns. This would further aid in the understanding of the function joint stiffness plays in discriminating athletic ability especially for females.

Another reason for the irregular outcome of the present study could be the possibility of the way the netballers were categorised (elite, non-elite) based on generalised sport / skill aptitude (netball levels) and not physical capacity aptitude. This may explain why non-elites were stiffer than the elites. It may be that the non-elites performed the straight task faster than the elites, however intuitively this would be unlikely. Unfortunately the straight performance outcomes were not measured in this study to confirm such a premise.

Comparisons between joint stiffness of male and female netballers

This study intended to identify whether or not differences exist between male and female (elite and non-elite) netballer's joint stiffness (JS) magnitudes during unanticipated turning performance and unanticipated straight sprint performance. It was expected that females would demonstrate lower JS compared to male netballers. The results of this study supported this expectation with non-elite female netballers demonstrating substantially less ankle frontal plane stiffness during the unanticipated 180° turning tasks and elite female netballers demonstrating substantially less ankle frontal plane stiffness during the unanticipated straight task. These findings further confirm the concept of males possessing greater stiffness compared to females (Blackburn et al., 2006; Hughes & Watkins, 2008; Padua et al., 2005; Rozzi et al., 1999). The magnitudes of the differences (~15 – 18%) between the males and females joint stiffness measures during the unanticipated turning tasks of the present study are similar to those reported by Padua et al. (2005). Their study reported females to demonstrate ~18% less stiffness during hopping in comparison with that of males. Furthermore, the present study's magnitudes of the differences (~67 – 73%) between the males and females joint stiffness measures during the unanticipated straight tasks were slightly larger than those of Hughes and Watkins (2008). These researchers reported knee joint stiffness during landing from a volleyball spike block jump stiffness to be ~46% less in females compared to males (Hughes & Watkins, 2008). All these findings including the present study's seem to support the notion that male musculature is more effective at resisting changes in its length (Blackburn et al., 2006). The differences identified between males and females in regards to JS may be due to anatomical and neuromuscular differences between the sexes (Hewett, 2000; D. F. Murphy et al., 2003).

Butler et al. (2003) proposed that too little stiffness may lead to soft tissue injuries and knee pathology. The greater the ability of the muscles to oppose rotation of

the joint (i.e. greater joint stiffness), the greater the dynamic stability of the joint is likely to be (Wagner & Blickhan, 1999) and therefore the less likely the passive structures of the joint will induce strain (Hughes & Watkins, 2008). Given that females present with less joint stiffness than males in various unanticipated locomotive tasks it is plausible that insufficient stiffness during the pivot phase of the 180° turn or stance phase of a straight sprint (as used in the present study) could result in an unwanted collapsing of lower limbs causing injury to soft tissue. Research has revealed that female athletes who participate in jumping and running sports reportedly are four to six times more likely to sustain a serious knee injury than male athletes participating in the same sports (Griffin et al., 2000; Hutchinson & Ireland, 1995; Ireland, 1999). Therefore, the torsional joint stiffness of the knee might be an important contributing factor for differences in ACL injury rates between genders (Hsu et al., 2006). Wojtys et al. (2003) showed that female athletes are less capable of increasing the torsional joint stiffness of the knee compared with size and sport matched male athletes using muscular contraction. This was also the case under passive conditions (Hsu et al., 2006). Utilising cadaveric knees Hsu et al. (2006) reported the torsional joint stiffness of female knees to be 25% lower than that of male knees at 15° of knee flexion. Whilst these findings do not present a definitive association between low stiffness and injury occurrence they do allow for the assumption that low stiffness may play a role in the occurrence of an injury. Only prospective research will validate whether or not there is an association between JS and injury occurrence, additionally further research is needed to compare gender differences in JS for other forms of sporting movements such as abrupt stops and cutting manoeuvres. Other sporting population samples (e.g. hockey players) may offer more insight into gender discrepancies in JS.

Comparisons between joint stiffness of dominant and non-dominant limbs

This study aimed to identify whether there were any substantial differences in lower extremity joint stiffness between dominant or non-dominant limbs during an unanticipated straight run and unanticipated 180° turn tasks. The expectation was that the dominant leg would exhibit more joint stiffness than the non-dominant leg which was supported by the findings in this study for the unanticipated 180° turn task but not the unanticipated straight task. Specifically, elite female netballers demonstrated greater ankle frontal plane joint stiffness in the dominant pivot leg during the unanticipated 180° turn compared to the 180° turn task performed on the non-dominant leg. All sub-categories (male netballers, elite female netballers and non-elite female netballers) presented with similar or symmetrical joint stiffness for the unanticipated straight task in this study. These findings suggest differences in stiffness to be population specific and movement specific. This concept is somewhat supported by the

findings of Joseph et al (2007) who revealed that soccer players exhibited symmetrical lower extremity musculoskeletal stiffness during jumping and running tasks, whilst track runners displayed significant asymmetry when running.

Given the present study reveals the dominant limb of elite female netballers to be stiffer is not surprising due to the link between leg dominance and functional performance (Itoh et al., 1998), and the link between functional performance and stiffness (Bret et al., 2002; Chelly & Denis, 2001). Furthermore the preferred / dominant leg controls propulsion during gait tasks whereas support is maintained more by the non-preferred / dominant leg (Sadeghi et al., 2000). As overreliance on the dominant limb is considered a risk factor for lower extremity injury (Beynnon et al., 2002), with links between limb dominance and injury existing (Chomiak et al., 2000; Ekstrand & Gillquist, 1983; Orchard, 2001). Excessive or too much stiffness may result in disproportionate loading rates about the joint resulting in injury to the bony structures. In fact it has been reported that too much stiffness may lead to bony injuries and ankle pathology whereas too little stiffness may lead to soft tissue injuries and knee pathology (Williams et al., 2004; Williams et al., 2001). A greater demand to use the dominant limb during athletic tasks in conjunction with high joint stiffness may lead to a greater likelihood of injury for an individual. The only way to validate such assumptions is through a study utilising a prospective design that identifies an association between high joint stiffness and injury occurrence. Such studies are warranted based on the findings of the present study and those of others (Bradshaw et al., 2006; Williams et al., 2004; Williams et al., 2001).

Conclusion

When considering athletic ability discrepancies in JS differences appear to be movement specific as non-elite female netballers demonstrated less ankle frontal plane torsional joint stiffness during the unanticipated 180° turn task performed on the dominant leg than elite level female netballers. On the other hand during the unanticipated straight task non-elite female netballers demonstrated greater ankle frontal plane torsional joint stiffness in both the dominant and non-dominant leg ground contacts compared to the elite female netballers. Research is required that further investigates athletic ability differences of other female sport populations joint stiffness measures utilising unanticipated motor patterns.

Gender differences exist for JS during unanticipated tasks. For instance non-elite female netballers demonstrated less ankle frontal plane stiffness during the unanticipated 180° turning tasks whilst elite female netballers demonstrated less ankle frontal plane stiffness during the unanticipated straight task than male netballers.

These findings further confirm the concept of males possessing greater stiffness compared to females.

Comparisons between limb JS measures suggest differences in JS to be both population and movement specific. Specifically, elite female netballers demonstrated greater ankle frontal plane joint stiffness in the dominant pivot leg during the unanticipated 180° turn compared to the 180° turn task performed on the non-dominant leg. All sub-categories (male netballers, elite female netballers and non-elite female netballers) presented with similar or symmetrical joint stiffness for the unanticipated straight task in this study.

CHAPTER 9: THE ASSOCIATION BETWEEN INJURY OCCURRENCE AND JOINT STIFFNESS DURING UNANTICIPATED 180° TURN AND RUN TASKS PERFORMED BY NETBALLERS

Overview

This study aimed to determine whether during unanticipated movements performed by netballers, lower extremity joint stiffness measures were associated with prospective lower limb injury in netball players. Twelve elite female, 12 non-elite female, and 12 male injury-free netballers performed 20 to 30 trials of unanticipated sprinting tasks in the motion analysis laboratory from a 10 m approach. The tasks included straight sprints and sprints with a 180° turn on their dominant and non-dominant legs. All netballers were monitored prospectively for a period of six months (one competitive season) for the occurrence of lower limb injury. Joint stiffness measures of the lower extremity were calculated for all movement tasks, and then compared between the 13 (36%) injured and 23 (64%) non-injured netball players. The majority of lower limb injuries (~92.3%; $N = 12/13$) occurred in the dominant leg. Low ankle frontal plane joint stiffness was associated with injury occurrence in elite female netballers ($r = 0.33$). High knee sagittal plane joint stiffness during the unanticipated 180° turn task was associated with lower extremity injury occurrence in elite ($r = -0.37$) and non-elite ($r = -0.51$) female netballers. Male netballers demonstrated an association between injury occurrence and high ankle frontal plane joint stiffness during the unanticipated straight task ($r = -0.55$). Ideal ranges of joint stiffness for particular movements that allow players to minimize the risk for injury may exist. This 'safe zone' may be independent of gender, joint or movement task.

Introduction

In New Zealand and Australia, netball is considered the primary team sport played both recreationally and competitively by females (McManus et al., 2006) and is also experiencing an increased participation rate for males (Tagg, 2008). Netball is a high-strategy sport requiring many explosive sprints, abrupt stops, changes of direction and landing movements (Bock-Jonathan et al., 2007; McManus et al., 2006). Given the physical demands of netball there is a heightened risk of injury (Hume & Steele, 2000). A potential injury mechanism of interest to researchers is the concept of joint stiffness (Mahieu et al., 2006; Milner et al., 2006; Milner et al., 2007; Pollard et al., 2005).

Joint stiffness (JS) is represented by the slope of the moment applied to the spring plotted as a function of angular / rotational displacement of the joint (Davis & DeLuca, 1996; Farley et al., 1998), or more simply the change in joint moment divided by the change in joint angle (Farley & Gonzalez, 1996). The importance of lower extremity JS in movement is in the storage and re-utilisation of the required spring energy to perform and continue movement (Latash & Zatsiorsky, 1993), and it's essential role in the maintenance of joint stability (Wagner & Blickhan, 1999). A stiffer joint resists sudden joint displacements quicker and more effectively, serving as a protective mechanism against acute injury (Riemann & Lephart, 2002). TJS has also been recently identified as a possible marker of lower extremity injury risk (Bradshaw et al., 2006; Williams et al., 2004; Williams et al., 2001).

Recently studies interested in the association between stiffness and injuries have begun to emerge (Mahieu et al., 2006; Milner et al., 2006; Milner et al., 2007) however information is still scarce to derive any formative conclusions. Initially the association between stiffness and injuries was assumed somewhat indirectly through a body of knowledge surrounding foot structure (Williams et al., 2004; Williams et al., 2001). Distinctively, foot structure is associated with different injury patterns when comparing injured high-arched runners with injured low-arched runners (Williams et al., 2001). Specifically, high-arched runners appear more likely to develop bony type injuries such as tibial stress fractures and injuries to the lateral portion of the lower extremity such as lateral ankle sprains. Low-arched runners were reported to be more likely to develop soft tissue injuries on the medial side of the lower extremity particularly around the knee joint (Williams et al., 2001). Uninjured high-arched runners have been reported to demonstrate both higher sagittal leg stiffness (10%) and knee stiffness (14%) compared to uninjured low-arched runners (Williams et al., 2004). In light of the findings of Williams et al. (2001) and Williams et al. (2004) it seems that too much stiffness may lead to bony injuries and ankle pathology whereas too little stiffness may lead to soft tissue injuries and knee pathology. Studies have reported the inability of

stiffness to discriminate between injured and uninjured individuals (Mahieu et al., 2006; Milner et al., 2006). Information pertaining to whether or not high or low stiffness is directly associated to any lower extremity injury warrants further investigation. Studies with a prospective design assessing lower extremity stiffness may offer a better insight into the causation of lower extremity injury occurrence.

Aim

This study aimed to determine whether during unanticipated movements performed by netballers, lower extremity joint stiffness measures were associated with prospective lower limb injury in netball players. It was expected that netballers who exhibited low joint stiffness would likely incur an injury to the lower extremity.

Methods

Netball player characteristics

Using data from pilot work (ten netballers monitored during six months of a competitive netball season) it was considered that 36 netballers were adequate for the sample size based on a minimal statistical power of 80% ($p = 0.05$). Sample size and power calculations were completed using G*Power Software (Erdfelder et al., 1996).

Thirty six netball players, consisting of three sub-groups of elite females ($N = 12$), non-elite females ($N = 12$) and males ($N = 12$), volunteered to participate in the study (see Table 24). Elite female netballers were classified as players who were representing their region or country at a senior level, whereas non-elite were classified as players who were participating in senior club level netball teams. Male netballers consisted mostly of regional representative level players and some high level competitive indoor netball players. All netballers had no history of significant lower extremity injury six months prior to testing and were injury free at the time of data collection. Each netballer gave informed consent in writing to participate in this study prior to testing. Ethical approval was obtained for all testing procedures from the Auckland University of Technology Ethics Committee. All netballers wore spandex shorts or pants and ASICS (Gel-Rocket) court shoes during the data collection.

Table 24: Netball player characteristics.

	Elite females (<i>N</i> = 12) mean \pm SD	Non-elite females (<i>N</i> = 12) mean \pm SD	Males (<i>N</i> = 12) mean \pm SD	All netballers (<i>N</i> = 36) mean \pm SD
Age (yrs)	22.3 \pm 3.8	20.9 \pm 2.3	23.7 \pm 4.2	22.3 \pm 3.6
Height (m)	1.79 \pm 0.08	1.72 \pm 0.05	1.78 \pm 0.07	1.76 \pm 0.07
Mass (kg)	79.2 \pm 11.6	69.5 \pm 9.8	88.8 \pm 23.2	79.2 \pm 17.5
Playing history (yrs)	13.0 \pm 2.8	13.2 \pm 2.4	4.9 \pm 5.2	10.4 \pm 5.3
Training load (hours/week)	8.8 \pm 1.6	8.8 \pm 2.9	5.7 \pm 3.4	7.8 \pm 3.1
Training load (sessions/week)	5.5 \pm 0.8	5.3 \pm 2.0	3.5 \pm 2.3	4.8 \pm 2.0

Procedures

Netball player limb dominance

Limb dominance was determined via questions and practical tests. The netballers were asked which leg was preferred for kicking a ball, and hopping on, with the preferred leg being considered the dominant leg (Maulder & Cronin, 2005). Furthermore, additional tests were used to identify which limb moved first; walking from a stationary position and stepping off a 0.3 m high step from a stationary position. The limb that moved first was considered the dominant limb. This information in conjunction with the question data allowed for a comprehensive decision to be made on limb dominance. The dominant limb was determined as the limb on the side of the body that was identified in the four assessments the majority of the time.

Unanticipated 180° turn and straight run task

The netballers performed three tasks from a 10 m approach that utilised a self selected start stance: a left leg plant and 180° turn; a straight ahead run (left or right foot placement); and a right leg plant and 180° turn. The tasks were presented as options in order to obtain an unanticipated / decision made movement response. Unanticipated movements have been demonstrated to elicit up to two times greater knee varus/valgus and internal/external rotation joint moments than anticipated movements (Besier et al., 2001). Movements during game situations are generally not always anticipated due to an external stimulus (Besier et al., 2001), thus unanticipated movements may offer a better reflection of the loads experienced around lower extremity joints during a sporting scenario. Therefore, a visual cue was displayed on a 19" computer screen which was triggered manually when the netballer was

approximately 1 m away from the force platform. The screen was placed 0.5 m to the right side of the force platform. Testing tasks were assigned a colour consisting of green, yellow, and red which represented the 180° left leg plant and turn, straight ahead, and 180° right leg plant and turn respectively. Visual cues were created and presented using PowerPoint (Microsoft, Office, version 2003, California) slides.

Several pre-planned and unanticipated trials of each task were performed before data collection started in order to provide the netballers with the opportunity to familiarise themselves with the testing tasks. Each netballer completed all four tasks randomly, as cued by the computer monitor. This included foot placement of the left foot and right foot during the unanticipated straight run task, and pivoting on the left foot and right foot during the unanticipated 180° turn tasks. Bates et al. (1992) suggested that a minimum of five trials are needed to achieve 90% power for sample sizes of at least ten participants. To enable the five trials needed for data analysis to be collected for each task, a total of 20 successful trials were needed (Dierks & Davis, 2007). A maximum of 30 trials were completed by the participants to achieve the required data set. No feedback on trials performed previously in the testing session was provided to the participants as to avoid the possibility of the trials becoming planned. A 180° left (or right) leg plant and turn trial was deemed successful if: (a) the approach speed fell between 3.5 and 5 m.s⁻¹; (b) the left (or right) foot came in contact with the force platform; and (c) the exit speed was between 2.5 and 3.5 m.s⁻¹. A straight-ahead trial was deemed successful if (a) the approach speed was between 3.5 and 5 m.s⁻¹; (b) the left (or right) foot came into contact with the force platform; and (c) the netballer continued along the straight-ahead path and did not decelerate until at least 1 m after the centre of the force platform. The turning tasks were utilised in this study due to the use of the movement in field test assessment for the sport of netball. Specifically the 505 assessment (180° turn) is utilised to assess an individual's change of direction ability. Furthermore, anecdotally this type of turn is frequently utilised in netball. The approach and exit speeds were based on unpublished field testing scores typical in sprint and agility assessment in New Zealand netballers. Each netballer was given approximately 45 - 90 s of rest between trials to reduce the potential effects of fatigue.

Injury data collection & analyses

The prospective nature of the study involved all netballers being monitored for six months (one competitive season) for the occurrence of lower limb injury. Prospective study designs are considered powerful for determining the risk factors of injury (Hagglund et al., 2005). Injury was defined as that which interfered with performance and required professional treatment, causing the player to miss training

and/or game time (McKay et al., 2001). A training session was defined as any coach directed scheduled physical activity carried out with the team, whereas a game was considered friendly or competitive (Hagglund et al., 2006).

Netball players were contacted regularly (fortnightly) via email and telephone to enquire if a lower limb injury had occurred. If an injury had occurred, information about the injury type and location (Hagglund et al., 2005) was recorded by the principal researcher, as communicated by the netballer. Injury was diagnosed by clinicians that were outside the research party. For reasons such as clinician client confidentiality, verification of the injury from the clinician was unable to be obtained by the principal researcher. It was presumed that the information that the netballers were communicating were accurate.

For analyses purposes, injured player data were grouped into an injured group with all remaining participant data being grouped into the non-injured group category. Data classification allowed comparisons in mechanical concepts to be made of which the procedures are outlined in subsequent sections.

Kinematic and kinetic data collection

Following the practice trials of unanticipated 180° turn and straight run tasks, four moulded shells each with four retro-reflective tracking markers attached were securely placed on the lateral surface of both the netballer's thighs and shanks. Additional tracking markers were placed on both anterior superior iliac spines, both iliac crests, and the mid-point of both posterior superior iliac spines to define the pelvis. Tracking markers were also placed on both heels, and first and fifth metatarsal heads to define the foot. Calibration markers were placed on both (bilateral) greater trochanters, both medial and lateral femoral condyles, and both medial and lateral malleoli in order to locate the segment origins. All markers were based on those used by others previously (Dierks & Davis, 2007; Ferber et al., 2005; Pollard et al., 2004; Pollard et al., 2005). For a depiction of the marker set see Appendix 6. Once the markers were placed, a standing calibration trial was recorded to establish anatomical neutral. Netballers stood in a neutral position on the force plate at the centre of the camera set-up. The calibration markers were removed after the standing trial, while the tracking markers remained on the netballer throughout the data collection session. The same individual placed the markers for all netballers.

A nine-camera motion capture system (Qualisys, Sweden) was used to record three dimensional (3-D) kinematic data at a sampling rate of 240 Hz as used by Pollard et al. (2005). The cameras were positioned so that each marker was visible in multiple cameras throughout the stance phase (heel strike to toe off). The cameras encircled a force platform (~0.48m x ~0.51m) embedded within the floor (Advanced Mechanical

Technology Inc., USA, 1200 Hz). The force platform recorded the magnitude of the three-dimensional ground reaction forces and was only used to identify the stance phase and foot strike region for the various sprint tasks. The cameras and force platform were interfaced to a personal computer that allowed for synchronization of the kinematic and kinetic data using the motion analysis software (Qualisys Track Manager, Version 1.10.283). Prior to testing, the nine-camera motion capture system was calibrated as per the manufacturer's protocol (Qualisys, Sweden), with a right-handed lab coordinate system being defined using a rigid L-frame containing four markers of known locations. A two-marker wand of known length was used within the calibration frame to scale the individual camera views of the measurement volume. The average movement residue for the retro-reflective markers during system calibration was minimal (less than 2 mm). The AMTI force platform was zeroed and calibrated for laboratory position and axis orientation. A two gate SWIFT® timing light system (SWIFT, Australia) was used to measure / monitor approach, performance and exit velocities. One timing light gate consisted of a dual beam modulated Visible RED Light sensor / reflector set up collecting at 4 MHz \pm 80 Hz. The timing lights were set at a height of 1.1 m and placed parallel to the approach runway with one gate located 3 m prior to the force platform and the other located 1 m prior. To view a schematic of the experimental set up see Appendix 7.

Kinematic and kinetic data processing & analyses

The following data reduction procedures were performed on data for all five trials for each of the four tasks. Q-Trac software (Qualisys, Sweden) was used to digitize the marker coordinates. Digitized coordinate data were then exported to Visual 3D™ software (C-Motion, Inc., Rockville, MD, USA) where they were low-pass filtered using a fourth-order Butterworth filter with an 8 Hz cut-off frequency. Ground reaction force data were low-pass filtered using a fourth-order Butterworth filter with a 50 Hz cut-off frequency (Dierks & Davis, 2007; Pollard et al., 2004; Pollard et al., 2005).

Joint stiffness

Three-dimensional kinematics and kinetics, namely angles, and net muscle moments (i.e., internal moments) were processed for the knee in the sagittal and transverse planes and ankle in the sagittal and frontal planes from the coordinate data. All kinetic data were normalized to body mass, and net joint moments were calculated with standard inverse dynamics equations. Kinematic and ground reaction force data were exported to customised LabVIEW software (National Instruments, Austin, Texas, USA, version 6). The JS measures of interest in this study can be viewed in Table 25. Reliability was established for these measures in work reported in Chapter 7). The

average JS of the ankle in the frontal plane, and the knee in the sagittal were determined from the ratio of the change in net muscle moment (ΔM_{joint}) to change in joint angular displacement ($\Delta \theta_{\text{joint}}$) from touch-down to the instant when the joints were maximally flexed, pronated or internally rotated dependent on joint axis of interest (Farley et al., 1998) using the following equation.

$$k_{\text{joint}} = \Delta M_{\text{joint}} / \Delta \theta_{\text{joint}}$$

where k_{joint} is the average joint stiffness, ΔM_{joint} is the change in net muscle moment, and $\Delta \theta_{\text{joint}}$ the change in joint angular displacement. All stiffness measures were normalised to the netballer's body weight.

Table 25: Joint stiffness measures of interest.

Movement task	Joint stiffness
Unanticipated straight run: dominant leg contact	Ankle frontal plane stiffness
Unanticipated straight run: non-dominant leg contact	Ankle frontal plane stiffness
Unanticipated 180° turn on the dominant leg	Ankle frontal plane stiffness
	Knee sagittal plane stiffness
Unanticipated 180° turn on the non-dominant leg	Ankle frontal plane stiffness

Statistical analyses

Comparisons were made between physical characteristics, stance based parameters, joint stiffness measures exhibited by the injured and non-injured netballers using the methods of Hopkins (2007b). These analyses allowed for Cohen effect sizes, 90% confidence intervals, and qualitative inferences to be presented, which is currently considered best practice for statistical use in sports medicine and the exercise sciences (Hopkins et al., 2009). Differences between injured and non-injured netballers were expressed as a percentage via analysis of log-transformed values using natural logarithms. Logarithmic transformation allowed for uniformity of error and was used to reduce bias arising from non-uniformity of error raw values (differences) of the variables of interest. Inferential statistics were based on interpretation of magnitude of effects (differences) as described by Batterham & Hopkins (Batterham & Hopkins, 2006). The likelihood of the differences (effect unit) was interpreted using the Cohen scale of magnitudes for the standardized differences in the mean. The Cohen scale is divided into different effect sizes which are used to quantify the differences between conditions (Hopkins et al., 2009). To make inferences about the true values of the percentage differences and effect sizes between injured and non-injured netballers the

uncertainty in the percentage differences and effect sizes were expressed as 90% confidence intervals and as likelihoods that the true value of the difference is substantial (Batterham & Hopkins, 2006). A difference was deemed unclear if its confidence interval of the effect statistic overlapped substantially positive and negative values and the threshold for the smallest worthwhile effect, otherwise, when a result was above the threshold for the smallest worthwhile effect the results could be given as: 0 – 0.2 trivial; 0.2 – 0.6 small; 0.6 – 1.2 moderate; 1.2 – 2.0 large; 2.0 – 4.0 very large. An effect size of 0.2 was chosen to be the smallest worthwhile difference in the means in standardized (Cohen) units as it gave likelihoods that the true effect would at least be small (Cohen, 1990).

SPSS version 18 was used to calculate Pearson correlation coefficients to identify associations between joint stiffness measures and injury occurrence. The magnitude of the associations was qualitatively interpreted utilising the following criteria: 0.0 – 0.1 poor; 0.1 – 0.3 small; 0.3 – 0.5 moderate; >0.5 large (Cohen, 1990). Confidence intervals (90% CI) were processed for these correlations to show the likely range of the true correlation using the methods of Hopkins (2007a). Furthermore, clinical inferences were also provided on the likelihood these relationships were clinically substantial.

Results

Player characteristics

The non-injured group were substantially shorter (MDiff: -2.4% [90% Confidence limit: -4.6 to -0.2%], ES=-0.65 [moderate]) than the injured group. There were no other notable differences for the other physical and training characteristics (see Table 26).

Lower limb injuries

Lower limb injury occurred in ~36% (N = 13/36) of the netballers which required them to miss either training and/or game time. The injuries included five ankle sprains, two cases of patellar tendonitis, two calf strains, an Achilles strain, an adductor strain, and two cases of shin splints. The majority of injuries (~92.3%; N = 12/13) occurred on the netballer's dominant leg (see Table 27).

Comparisons between kinematic and kinetic measures of injured and non-injured netballers

Non-injured netballers demonstrated substantially smaller temporal variables during the straight non-dominant leg condition compared with the injured netballer's. Specifically ground contact time was less (MDiff = -7.6% [-14.8 to 0.1%], ES = -0.59 [small]), time to peak active vertical ground reaction force (VGRF) was less (MDiff = -14.0% [-24.1 to -2.6%], ES = -0.72 [moderate]), and time to peak active VGRF as a percentage of ground contact (stance) was less (MDiff = -6.0% [-12.3 to 0.6%], ES = -0.51 [small]). The statistical outcomes were unclear for these temporal variables during the straight dominant leg and turn on the non-dominant leg tasks (see Table 28).

Table 26: Player characteristics between injured ($N = 13$) and non-injured ($N = 23$) netballers.

	Injured		Non-injured			MDiff	90% Confidence levels		Cohen	Clinical inference
	Mean	\pm SD	Mean	\pm SD	p value	(%)	lower	upper	ES	
Age (years)	21.6	± 2.2	22.7	± 4.2	0.587	2.7	-5.5	11.6	0.18	unclear
Height (m)	1.79	± 0.07	1.75	± 0.07	0.075	-2.4	-4.6	-0.2	-0.65	large-trivial -ive
Mass (kg)	79.9	± 14.6	78.8	± 19.2	0.469	-4.9	-15.3	6.8	-0.25	unclear
Playing history (years)	10.8	± 4.8	10.1	± 5.6	0.618	-14.8	-50.3	46.1	-0.17	unclear
Training per week (hours)	7.8	± 3.1	7.7	± 3.2	0.352	-13.8	-34.0	12.6	-0.30	unclear

Key: SD = standard deviation; MDiff. = difference in the group means; ES = effect size; -ve = negative.

Table 27: Injured player characteristics ($N = 13$; ~36%).

Player	Gender	Sub-group	Age (yr)	Height (m)	Mass (kg)	Dominant limb	Injured limb	Injury type
1	F	Elite	25	1.94	85.0	R	D	Ankle sprain
2	F	Elite	18	1.72	75.0	R	D	Patella tendonosis
3	F	Elite	21	1.80	77.0	R	D	Ankle sprain
4	F	Elite	22	1.79	66.0	L	D	Calf strain
5	F	Elite	21	1.87	111.0	R	D	Patella tendonosis
6	F	Non-elite	23	1.71	82.4	R	D	Achilles strain
7	F	Non-elite	24	1.78	83.0	R	D	Calf strain
8	F	Non-elite	18	1.80	71.0	R	D	Adductor strain
9	F	Non-elite	21	1.68	70.0	R	D	Shin splints
10	M	Male	21	1.84	107.7	R	D	Shin splints
11	M	Male	24	1.77	69.8	R	D	Ankle sprain
12	M	Male	23	1.77	77.0	R	ND	Ankle sprain
13	M	Male	20	1.80	64.0	R	D	Ankle sprain

Key: F = female; M = male; R = right leg; L = left leg; D = dominant leg; ND = non-dominant leg

Table 28: Differences in stance based parameters during unanticipated tasks between injured (N = 13) and non-injured (N = 23) netballers and the qualitative inferences about the effect of the differences.

	Injured		Non-injured			MDiff	90% Confidence levels		Cohen	Clinical inference
	Mean	±SD	Mean	±SD	p value	(%)	lower	upper	ES	
<i>Straight dominant leg</i>										
Contact time (s)	0.203	±0.028	0.197	±0.028	0.593	-2.7	-10.9	6.2	-0.19	unclear
Time to Peak active VGRF (s)	0.092	±0.020	0.092	±0.020	0.926	0.7	-11.7	14.9	0.03	unclear
Time to Peak active VGRF (%)	45.7	±3.1	46.3	±4.9	0.744	1.0	-4.1	6.4	0.11	unclear
<i>Straight non-dominant leg</i>										
Contact time (s)	0.211	±0.029	0.194	±0.023	0.105	-7.6	-14.8	0.1	-0.59	moderate-trivial -ive
Time to Peak active VGRF (s)	0.098	±0.020	0.085	±0.016	0.048*	-14.0	-24.1	-2.6	-0.72	large-trivial -ive
Time to Peak active VGRF (%)	46.2	±4.0	44.0	±5.6	0.134	-6.0	-12.3	0.6	-0.51	moderate-trivial -ive
<i>Turn non-dominant leg</i>										
Performance time (s)	0.872	±0.114	0.893	±0.087	0.608	2.2	-4.9	9.9	0.18	unclear
Contact time (s)	0.464	±0.088	0.460	±0.092	0.822	-1.5	-12.3	10.6	-0.08	unclear
Time to Peak active VGRF (s)	0.315	±0.088	0.340	±0.245	0.862	-2.3	-22.4	22.9	-0.06	unclear
Time to Peak active VGRF (%)	63.6	±8.2	62.8	±10.9	0.318	-5.5	-14.1	3.9	-0.34	unclear

Key: SD = standard deviation; MDiff. = difference in the group means; ES = effect size; * = $p < 0.05$; -ive = negative.

Comparisons between joint stiffness measures of injured and non-injured netballers

Two of the five joint stiffness measures demonstrated trivial to moderate positive differences (see Table 29). Specifically, compared to the injured netballers non-injured netballers demonstrated 40.8% (-10.6 to 121.7%) and 32.9% (-9.6 to 95.4%) greater ankle frontal plane joint stiffness measures during the non-dominant leg ground contact of an unanticipated straight run and the dominant pivot leg during an unanticipated 180° turning sprint. Non-injured netballers demonstrated 36.4% (-67.7 to 25.4%) less knee sagittal plane joint stiffness than injured netballers which was a moderate to trivial negative statistical outcome. Unclear outcomes were calculated for the ankle frontal plane joint stiffness measures during the dominant leg ground contact of an unanticipated straight run and the non-dominant pivot leg during an unanticipated 180° turning sprint.

Associations between joint stiffness measures and the occurrence of injury in netballers

The associations between joint stiffness measures during the unanticipated dominant leg tasks (straight and turning) and dominant leg injury occurrences are presented in Table 30. Poor correlations existed between injury occurrence and various coupling variability measures when considering all netballers that participated in this study. A moderate ($r = 0.33$) likely probable positive association and moderate ($r = -0.37$) likely probable negative association were identified between injury occurrence and ankle frontal plane joint stiffness and knee sagittal plane joint stiffness respectively during the unanticipated 180° turn task performed by elite netballers. Non-elite female netballers demonstrated a large ($r = -0.51$) likely probable negative association between injury occurrence and knee sagittal plane joint stiffness during the unanticipated 180° turn task. Male netballers demonstrated a large ($r = -0.55$) likely probable negative association between injury occurrence and ankle frontal plane joint stiffness during the unanticipated straight task.

Table 29: Differences in joint stiffness[#] for various joints during unanticipated tasks between injured (*N* = 13) and non-injured (*N* = 23) netballers and the qualitative inferences about the effect of the differences.

	Injured Mean ±SD	Non-injured Mean ±SD	<i>p</i> value	Diff. in means as Percentage (%)	Diff. in means as % 90% Confidence levels		Cohen ES	Qualitative inference of ES
					lower	upper		
<i>Straight run: dominant leg contact</i>								
Ankle frontal plane	0.231 ±0.369	0.148 ±0.081	0.656	-14.6	-53.1	55.4	-0.15	unclear
<i>Straight run: non-dominant leg contact</i>								
Ankle frontal plane	0.118 ±0.071	0.185 ±0.149	0.211	40.8	-10.6	121.7	0.42	trivial-moder. +ive
<i>180° turn on the dominant leg task</i>								
Ankle frontal plane	0.060 ±0.026	0.111 ±0.181	0.220	32.9	-9.6	95.4	0.40	trivial-moder. +ive
Knee sagittal plane	0.179 ±0.208	0.130 ±0.206	0.266	-36.4	-67.7	25.4	-0.39	moder.-trivial -ive
<i>180° turn on the non-dominant leg task</i>								
Ankle frontal plane	0.079 ±0.036	0.077 ±0.036	0.685	-5.1	-23.7	18.0	-0.14	unclear

Key: [#] = Torsional joint stiffness normalised to body weight (BW.m/°); SD = standard deviation; MDiff. = difference in the group means; ES = effect size; moder. = moderate; +ive = positive; -ive = negative.

Table 30: Correlations between dominant leg joint stiffness measures and dominant leg injury occurrences.

	Straight run: dominant leg contact	180° turn on the dominant leg task	
	Ankle frontal plane	Ankle frontal plane	Knee sagittal plane
Group (N=35*)			
r (90%CL upper – lower)	-0.17 (-0.43 to 0.12)	0.17 (-0.12 to 0.43)	-0.12 (-0.39 to 0.17)
Clinical inference	Possibly may not be associated	Possibly may not be associated	Association is unlikely
Elite (N=12)			
r (90%CL upper – lower)	0.29 (-0.24 to 0.69)	0.33 (-0.20 to 0.71)	-0.37 (-0.73 to 0.16)
Clinical inference	Possibly may not be associated	Association is likely probable	Association is likely probable
Non-Elite (N=12)			
r (90%CL upper – lower)	0.24 (-0.29 to 0.66)	-0.23 (-0.65 to 0.30)	-0.51 (-0.80 to -0.01)
Clinical inference	Possibly may not be associated	Possibly may not be associated	Association is likely probable
Male (N=11*)			
r (90%CL upper – lower)	-0.55 (-0.83 to -0.04)	0.11 (-0.44 to 0.60)	0.07 (-0.47 to 0.57)
Clinical inference	Association is likely probable	Possibly may not be associated	Possibly may not be associated

Key: r = correlation coefficient; CL = confidence limits; * = only 35 from 36 and 11 from 12 due to one netballer attaining injury on the non-dominant leg.

Discussion

Sports injuries result in pain, loss of playing or working time, as well as medical expenditure (Fong et al., 2007). Research attempting to understand the mechanisms behind injuries is warranted as the identification of risk factors for injury is critical for the effective prevention of injury (DeLeo et al., 2004; Dierks & Davis, 2007; Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 1999; Pollard et al., 2005). A prospective study, which follows participants going forward in time, is generally viewed as more meaningful compared to a retrospective study (Hamill & Davis, 2006), thus the inclusion of a prospective design in the present study. The purpose of this study was to identify whether or not there was an association between lower limb injury occurrence measured prospectively and joint stiffness measures during unanticipated movements performed by netballers.

Injury occurrence

Lower limb injury, as defined by McKay et al. (2001), occurred in ~36% of the netballers tested in the present study which required them to miss either training or game time. The ~39% of ankle sprains in our netballers were consistent with the frequency of ankle ligament sprains reported in the literature (Handoll et al., 2001; Hopper et al., 1995; Hume, 1993). Additionally, Hume and Steele (2000) identified muscle strains within the lower extremity to be common in netball which is in agreement with the 8% adductor strains for the players in our study. Netball is a high-strategy sport requiring many explosive sprints, abrupt stops, change of direction and landing movements (Bock-Jonathan et al., 2007; McManus et al., 2006). Therefore, it is no surprise that the ankle complex would be the most commonly injured site due to amount of stress it would encounter as a major pivot point in the kinetic link system during such movement tasks.

Limb dominance is considered a risk factor for lower extremity injury because most athletes place a greater demand on their dominant limb (Beynnon et al., 2002). In certain sports, the dominant leg is preferentially used for kicking, pushing off, changing direction, jumping, or landing (D. F. Murphy et al., 2003). This can lead to an increased frequency and magnitude of moments about the knee and ankle, particularly during high-demand activities that place the ankle and knee at risk (Beynnon et al., 2002). In the present study the majority of injuries (~92.3%) occurred in the netballer's dominant leg which is consistent with the findings of others (Chomiak et al., 2000; Ekstrand & Gillquist, 1983; Orchard, 2001). It must be acknowledged that the association between limb dominance and injury is controversial due to equivocal findings in the literature (Beynnon et al., 2001; Matava et al., 2002; Negrete et al., 2007; Seil et al., 1998; Surve

et al., 1994). The contrasting findings may have been the result study designs, participant type and numbers, injury location or the methods used for data analysis.

Associations between joint stiffness measures and the occurrence of injury in netballers

Due to the majority of injury occurrences occurring on the dominant leg in the present study, the following discussion will focus on the joint stiffness measures during the unanticipated straight dominant leg task and the unanticipated 180° turn performed on the dominant leg. An expectation of this study was that low joint stiffness would be associated with lower extremity injury occurrence in netballers. Data from the present study was contradictory to this expectation when the netballers were categorised as one group. All associations computed were small and possibly unlikely to be substantially meaningful. When categorised into sub groups (i.e. elite females), the correlations increased in magnitude for the sub-category of elite female netballers, which then offered support for our expectation. Specifically, a moderate correlation was observed between ankle frontal plane joint stiffness and injury occurrence for elite female netballers. This finding was indicative of an association between low joint stiffness and injury occurrence and offers support to the affirmative side in a somewhat equivocal view point (Mahieu et al., 2006; Milner et al., 2006). It is plausible that if elite female netballers demonstrate insufficient stiffness during the pivot phase of the 180° turn resulting in an unwanted collapsing of lower limbs causing injury to the soft tissue. It would be more beneficial for these netballers to have a stiffer joint so that it resists sudden joint displacements quicker and more effectively, serving as a protective mechanism against acute injury (Riemann & Lephart, 2002). The greater the ability of the muscles to oppose rotation of the joint (i.e. greater joint stiffness), the greater the dynamic stability of the joint is likely to be (Wagner & Blickhan, 1999) and therefore the less likely the passive structures of the joint will induce strain (Hughes & Watkins, 2008).

Too little stiffness may lead to soft tissue injuries and knee pathology whereas too much stiffness may lead to bony injuries and ankle pathology (Williams et al., 2004; Williams et al., 2001). Therefore too much or too little stiffness seems detrimental to an individual. This proposition was supported by further findings of the present study. For example, elite and non-elite female netballers demonstrated negative associations between injury occurrence and knee sagittal plane joint stiffness during the unanticipated 180° turn task whereas male netballers demonstrated negative association between injury occurrence and ankle frontal plane joint stiffness during the unanticipated straight task. Such outcomes can be interpreted as high amounts of joint stiffness being associated with injury occurrence. Excessive or too much stiffness may

result in disproportionate loading rates resulting in injury to the bony structures (Hughes & Watkins, 2008). In fact high joint stiffness has been linked to injury retrospectively (Bradshaw et al., 2006; Milner et al., 2007). Bradshaw and colleagues (2006) measured leg stiffness in a group of female gymnasts using continuous jump (straight & bent legged) tests, and rebound jumps. Findings revealed links between retrospective injury observations and ankle extensor stiffness. Specifically four gymnasts with high stiffness had histories of take-off ankle injuries. Further work of Milner et al. (2007) identified knee stiffness during the initial loading of stance to be significantly greater in female runners with a history of tibial stress fractures compared with the age and training mileage matched uninjured females. To this researcher's knowledge only one study has investigated the association between joint stiffness and injury occurrence prospectively. Mahieu et al. (2006) prospectively examined the relationship between stiffness of the Achilles tendon and the rate of Achilles tendon overuse injuries in male military cadets during six weeks of basic military training. Stiffness of the Achilles tendon was defined as the relationship between the supplied muscle force from an isometric maximal voluntary contraction and the elongation of the Achilles tendon. Ten of the 69 male participants (14.5%) sustained an Achilles tendon overuse injury during this study. Stiffness was not reported to be an intrinsic factor associated with this type of injury. The findings of the present study may differ to those of Milner et al. (2007) due to the participant and movement pattern characteristics utilised. Female netballers demonstrated more frequent associations between joint stiffness and injury occurrence in the present study which may be in part to the well accepted notion that males possess greater stiffness compared to females (Blackburn et al., 2006; Hughes & Watkins, 2008; Padua et al., 2005; Rozzi et al., 1999).

This study has provided insights into stiffness being directly related with injury. More information pertaining to whether or not high or low stiffness is directly associated to any lower extremity injury warrants further investigation. Studies with a prospective design assessing lower extremity stiffness during other functional tasks may offer more insight into the causation of lower extremity injury occurrence whilst identifying an optimal range in which risk of injury is reduced.

Additional findings

Height has been implicated as a risk factor for injury and in particularly ankle injury (Beynnon et al., 2002) in netballers. In the present study the non-injured group were substantially shorter (-2.4% (90% Confidence limit: -4.6 to -0.2%)) which was confirmed by a moderate effect size (ES = -0.65). This finding is consistent with those of Milgrom et al.(1991) and Watson et al. (1999). Specifically, Milgrom et al (1991) reported that during basic training, taller military recruits were at increased risk of

suffering an ankle injury. Watson et al. (1999) reported taller soccer athletes more likely attain ankle sprains than those who were shorter. A taller athlete may be at more of an at-risk position for inversion ankle injury during dynamic tasks, as the increase in height may proportionally increase the magnitude of inversion torque that must be resisted by the ligaments and muscles that span the ankle complex.

Recommendations for future research

Future research investigating training interventions aimed at adapting JS are needed. The gender differences observed in this group of netballers suggests that an intervention program designed for women should be focused more on developing a greater repertoire of coupling strategies whereas for males the intervention should focus on minimising coupling variability. More prospective research is needed identifying an optimal range of JS in which risk of injury is reduced. Research that monitors changes in JS post injury, then following treatment and rehabilitation would be of great worth to the JS body of knowledge.

Conclusion

An association between low ankle frontal plane joint stiffness and injury occurrence existed for elite female netballers. High knee sagittal plane joint stiffness during the unanticipated 180° turn task was associated with lower extremity injury occurrence in elite and non-elite female netballers. Male netballers demonstrated an association between injury occurrence and high ankle frontal plane joint stiffness during the unanticipated straight task. It is plausible that an optimal range of stiffness is required for enhancing performance whilst preventing injury. More prospective studies are required to identify such an optimal range.

CHAPTER 10: DISCUSSION / CONCLUSIONS

Netball requires a multitude of direction changes whilst sprinting (McManus et al., 2006), predisposing netballers to a high risk of injury (Hume & Steele, 2000). Injury prevention researchers have indicated a need for a better understanding of biomechanical mechanisms of injury. Thus further research is required to identify mechanisms and strategies that may reduce the risk of injuries. Mechanistic measures of movement control such as joint coupling variability (JCV) and joint stiffness (JS) have been recently identified as possible markers of lower extremity injury risk. While there have been a number of new papers on the topics of JCV and JS during the period in which the research comprising this thesis was conducted, to date no published study has examined these biomechanical paradigms with respect to unanticipated sprint tasks performed by netballers. Furthermore, the association between injury occurrence and JCV and JS has not yet been investigated. Nonetheless, the main question this thesis addressed was “What is the role of joint coupling variability and joint stiffness in lower limb injury?”. Specifically the series of studies in this doctoral thesis addressed the measurement reliability of joint coupling variability and joint stiffness in an athletic population of netball players, and the effect of player level (elite vs. non-elites), gender, limb dominance, and injury occurrence on these measures. The following discussion summarises the results and inferences of these studies for the two main paradigms of interest: joint coupling variability and joint stiffness.

Joint coupling variability

The first specific aim of this thesis was to determine the measurement reliability of various lower extremity JCV measures of the dominant and non-dominant stance leg during unanticipated straight run and unanticipated 180° turning tasks performed by netballers (see Chapter 3). Such an analysis has previously not been performed at least for the reliability of JCV measures during any athletic manoeuvres calculated using the vector coding method. A recently proposed robust battery of measurement reliability and measurement variability tests were utilised in this study (Bradshaw et al., 2010). Specifically, the percentage difference in the mean and Cohen's effect sizes were calculated for reliability assessment and intra-class correlation coefficients, and the coefficient of variation percentages were calculated for variability assessment. The results revealed acceptable levels of measurement reliability and measurement variability (average measurement reliability and average measurement variability qualitative interpretations indicated 'good' to 'moderate' reliability and 'small' to 'moderate' variability respectively) for a variety of lower extremity JCV measures during

unanticipated straight run and unanticipated 180° turning tasks. Specifically, rearfoot_(eversion/inversion)–knee_(flexion/extension), rearfoot_(eversion/inversion)–knee_(rotation) and tibial_(rotation)–knee_(flexion/extension) JCV of the dominant leg during an unanticipated straight run task, the rearfoot_(eversion/inversion)–tibial_(rotation) and rearfoot_(eversion/inversion)–knee_(rotation) JCV of the non-dominant leg during unanticipated straight run task, and the rearfoot_(eversion/inversion)–tibial_(rotation), rearfoot_(eversion/inversion)–knee_(rotation) and tibial_(rotation)–knee_(rotation) JCV of the non-dominant leg during an unanticipated 180° turning task were deemed to have acceptable levels of measurement reliability and measurement variability. As a result of Chapter 3, only the JCV measures that were deemed acceptable were used as the primary JCV measures of interest throughout chapters 6 and 7 of this thesis.

The effect of limb dominance, gender and netball playing ability on lower extremity JCV (aforementioned measures) was investigated in Chapter 4, whereas Chapter 5 prospectively investigated the associations between JCV and injury occurrence. With respect to athletic ability the findings of Chapter 4 suggested JCV is context-specific and likely related to the nature of the movement. For example, non-elite female netballers demonstrated less JCV during the stance phase of the dominant leg during a straight sprint when compared with elite female netballers. During stance of the unanticipated turn performed on the non-dominant leg, non-elite netballers demonstrated greater JCV than the elite netballers. Originally, the literature demonstrated greater JCV to only be associated with superior performance (Arutyunyan et al., 1968; Bartlett et al., 2007; Bradshaw et al., 2007). More recently novice cyclists have been reported to exhibit significantly greater JCV than expert cyclists (Chapman et al., 2009). The findings of Chapman et al. (2009) in conjunction with those of this thesis support the premise that JCV is context specific. High amounts of JCV regardless of playing level may be beneficial for avoiding injury as low coupling variability has been linked to injury retrospectively (Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005). As a high-strategy sport, netball requires the precise execution of technical motor skills as well as the application of tactical knowledge when making decisions (Bock-Jonathan et al., 2007). Decisions about where and when to change position or direction on the court are made continuously by players “off the ball” when either team-mates or opponents are in possession of the ball (Smith, 1985). Intuitively, elite female netball is played at a more physically and mentally intense level than non-elite female netball, thus it is possible that greater demands experienced physically by the elites may make them even more susceptible to injury than the non-elites. This speculation in conjunction with the aforementioned findings of Chapter 4 for the turning task highlights elite netballers as

possibly being more at risk to the likelihood of injury compared to non-elite netballers. Given the lower JCV demonstrated during turning by the elite netballers in Chapter 4 utilising similar rearfoot frontal plane-tibial rotation strategies may lead to repetitive torsional stress of the tissues surrounding the knee joint thus predisposing these elite netballers to injury. This was not the case as Chapter 5 identified similar frequencies and types of injury occurrences between elite and non-elite female netballers (N = 5 vs. 4). When considering rearfoot_(eversion/inversion)—knee_(rotation) JCV the fact that elite female netballers presented with a stronger association between low variability and injury occurrence compared to the non-elites is interesting. The stronger association found in this study for the elite group suggests that having low coupling variability and playing netball at an elite level may increase the likelihood of injury compared to playing at a non-elite club competition level. The speculated theories of researchers (Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005) that advocate low JCV being an aetiological factor of lower extremity injury is supported by the findings of Chapter 5, at least for female netballers.

In Chapter 4 gender differences in JCV were identified but were movement context specific. For example during unanticipated turning tasks male netballers demonstrated greater JCV than female netballers which is in accordance with existing research investigating JCV during 45° cutting movements (Pollard et al., 2005). These findings suggest that during an unanticipated 180° turn females may lack the flexibility of joint movements required to adapt to challenges potentially experienced during netball. Due to the nature of netball being a high-strategy sport requiring many explosive sprints, abrupt stops, change of direction and landing movements (Bock-Jonathan et al., 2007; McManus et al., 2006) this can predispose the athlete to increased risk of injury (Hume & Steele, 2000). The elevated likelihood of female athletes sustaining a serious lower extremity injury compared with male athletes participating in the same sports that require explosive change of direction maneuvers whilst sprinting (Griffin et al., 2000; Hutchinson & Ireland, 1995; Ireland, 1999) and the presence of low JCV in a movement pattern being linked to injury retrospectively (Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005). The present study further highlighted the potential of minimal JCV being a mechanism in lower extremity aetiology during agility movements for females. Such an investigation to validate such an assumption was not possible in this thesis research as no JCV measures of the turn performed on the dominant leg were identified as reliable in Chapter 3. This in conjunction with the majority (~92.3%; N = 12/13) of injury occurrences reported in Chapter 5 being present in the dominant leg prevented such an investigation.

As mentioned previously differences in JCV were identified but were movement context specific. Female netballers tended to demonstrate greater JCV during the leg ground contacts during the unanticipated straight task than the male netballers. This finding was a surprising outcome as this was contrary to literature norms (Pollard et al., 2005). This researcher proposed that a high amount of variability in ankle and knee motion in a movement task such as unanticipated straight sprinting may perhaps be detrimental to performance and the health of male netballers. Such a claim was supported by the findings of Chapter 5 by where an association between high JCV and injury occurrence for the male netballers during an unanticipated straight task was identified. This finding was contrary to the theories proposed in earlier literature (Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005). If males potentially utilise an inappropriate coupling movement (e.g. excessive or insufficient internal rotation of the shank in conjunction with excessive rearfoot pronation or external tibial rotation, which is a risk factor for injury (Heiderscheit et al., 1999)) that is not suitable for unanticipated straight run performance it could likely be detrimental to their health.

The differences identified between males and females in regards to an association between JCV and injury occurrence may be due to anatomical and neuromuscular differences between genders (Hewett, 2000; D. F. Murphy et al., 2003). Based on the findings of this thesis it is possible that there may be optimal levels of coupling variability for both females and males.

Chapter 4 further intended to identify whether there were any substantial differences in lower extremity JCV between dominant or non-dominant limbs during an unanticipated straight run. Only one JCV measure ($\text{rearfoot}_{(\text{eversion/inversion})} - \text{knee}_{(\text{rotation})}$) was used for comparing the two limbs due to the reliability outcomes of Chapter 3. Findings of Chapter 6 revealed the non-dominant leg to be more variable than the dominant leg especially for female netballers. From an information processing theoretical perspective, the findings of Chapter 4 (i.e. the dominant limb demonstrating less variability or more stability) may support the premise that motor learning is characterised by the development towards invariance in motor output (Schmidt, 1985). It is generally believed that participants can learn tasks better with their dominant limb than with their non-dominant limb (Davidson & Wolpert, 2003). The dominant limb therefore may have more stable invariant regions within the motor pattern leading to greater functional stability compared to the non-dominant limb. When considering motor learning from a dynamical systems theoretical perspective, consistent high-level performance across a variety of situations and conditions can only be achieved with a variable coupling pattern that can be adapted to suit the demands of the task at hand (Hamill et al., 1999), or the search for stable and functional states of coordination

(Davids et al., 2008). The non-dominant limb had more JCV than the dominant limb which may reflect a more explorative nature within a movement task in order to optimize future performance via enhanced learning (Chapman et al., 2009). A lack of JCV demonstrated by the dominant limb in the Chapter 4 may lead to less flexible movement strategies that can adapt adequately to meet the needs of an environment change or perturbation, thus increasing the risk for the individual attaining injury (Hamill et al., 1999). If movement patterns are invariant (performed identically) the same tissues would be maximally loaded each time (Bartlett, 2004). The greater bandwidth of JCV strategies the non-dominant leg has access to, may allow a more explorative nature within a movement task in order to optimize performance and reduce the risk of injury. It was speculated by this researcher that the reduced lower extremity JCV demonstrated by the dominant limb may possibly explain the higher likelihood of injury to that particular limb. Such a speculation was due to limb dominance being proposed as a risk factor for lower extremity injury because most athletes place a greater demand on their dominant limb (Beynnon et al., 2002), and the links between low JCV and injury occurrence (Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005). The findings of Chapter 5 supported such a premise as the majority of injuries (~92.3%) occurred in the netballer's dominant leg which is consistent with the findings of others (Chomiak et al., 2000; Ekstrand & Gillquist, 1983; Orchard, 2001). Furthermore, female netballers that demonstrated low JCV strategies in their dominant leg were linked to the occurrence of injury. Demonstrating greater amounts of JCV appears to be beneficial for female netballers avoiding injury, a finding confirmed prospectively in Chapter 5 of this thesis.

Joint stiffness

The reliability and variability of joint stiffness (JS) measures of the dominant and non-dominant stance leg during unanticipated straight run and unanticipated 180° turning tasks performed by netballers was examined in Chapter 7. Such an analysis had previously not been performed at least for the reliability of JS measures during any unanticipated athletic manoeuvres calculated using the torsional joint stiffness method. Similar to Chapter 3 a robust battery of reliability and variability tests were utilised in this study (Bradshaw et al., 2010). Specifically, the percentage difference in the mean and Cohen's effect sizes were calculated for reliability assessment and intra-class correlation coefficients, and the coefficient of variation percentages were calculated for variability assessment. The results showed acceptable levels of reliability and variability (average reliability and average variability qualitative interpretations indicated 'good' to 'moderate' reliability and 'small' to 'moderate' variability respectively) for a variety of lower extremity JS measures during unanticipated straight run and unanticipated 180°

turning tasks. Specifically, the ankle frontal plane joint stiffness measure was found to have both acceptable levels of reliability and variability during unanticipated straight sprints and 180° turning tasks performed on both the dominant and non-dominant legs. Additionally, acceptable reliability and variability was demonstrated for the knee sagittal plane torsional stiffness measure during a 180° turn performed on the non-dominant leg. As a result of Chapter 7, the JS measures were used as the primary JS measures of interest throughout chapters 8 and 9 of this thesis.

The effect of limb dominance, gender and netball playing ability on lower extremity JS (aforementioned measures) was investigated in Chapter 8, whereas Chapter 9 prospectively investigated the associations between JS and injury occurrence. When considering athletic ability discrepancies in JS differences appeared to be movement specific. For example, non-elite female netballers demonstrated less ankle frontal plane torsional joint stiffness during the unanticipated 180° turn task performed on the dominant leg than elite level female netballers. Such an outcome was expected given lower extremity stiffness is considered to be a critical factor in musculoskeletal performance (Butler et al., 2003) and has been suggested to be very important in stretch shorten cycle exercises (Komi, 1986). Additionally, this researcher thought that intuitively elite netball is played at a more physically and mentally intense level than non-elite netball thus it is possible that the elite players are in better condition than the non-elites and are more capable of performing unanticipated turns at a better aptitude with more force and less contact time in the pivot. It is possible that the stiffer ankle exhibited by elite netballers during the pivot allowed them to attenuate the shock of the pivot foot's action thus maintaining sufficient stability to successfully execute the turn and prevent injury. Interestingly, such a premise was supported by the findings of Chapter 9, at least for elite female netballers. Specifically a moderate positive correlation was observed between ankle frontal plane joint stiffness and injury occurrence for elite female netballers. This finding was indicative of an association between low joint stiffness and injury occurrence and those elite female netballers that demonstrated high stiffness were likely to not be hindered by the occurrence of injury.

On the other hand Chapter 8 revealed that during the unanticipated straight task non-elite female netballers demonstrated greater ankle frontal plane torsional joint stiffness in both the dominant and non-dominant leg ground contacts compared to the elite female netballers. This was not expected by the researcher thus these results are difficult to explain due to the paucity of research demonstrating athletes of lesser ability demonstrating more stiffness than their better counterparts. Such findings may be due to differing mythological approaches utilised previously (Bret et al., 2002; Chelly & Denis, 2001), and perhaps the idea that females or even unanticipated tasks JS

outcomes are atypical with respect to male and planned activities. Another reason for the irregular outcome of the present study could be the possibility of the way the netballers were categorised (elite, non-elite) based on generalised sport / skill aptitude (netball levels) and not physical capacity aptitude. This may explain why non-elites were stiffer than the elites. It may be that the non-elites performed the straight task faster than the elites, however intuitively this would be unlikely. Unfortunately the straight performance outcomes were not measured in this study to confirm such a premise.

Whilst it was thought that non-elite female netballers may present with more individual injury occurrences this was not the case as Chapter 9 identified similar frequencies and types of injury occurrences between elite and non-elite female netballers (N = 5 vs. 4 respectively). Furthermore, there were no clear associations between injury occurrence and ankle frontal plane JS in the dominant leg ground contact of an unanticipated straight task for both elite and non-elite netballers. Research is required that further investigates athletic ability differences of other female sport population's joint stiffness measures utilising unanticipated motor patterns and the likely hood these measure are associated with injury occurrence.

Prior to this thesis there was a substantial body of research reporting that males possess greater stiffness compared to females (Blackburn et al., 2006; Rozzi et al., 1999), specifically in knee flexor (Blackburn, Riemann et al., 2004; Granata et al., 2004) and total leg comparisons (Granata et al., 2004). The findings of Chapter 8 of this thesis provided further support to such claims by demonstrating that gender differences exist for JS during unanticipated tasks. For instance non-elite female netballers demonstrated less ankle frontal plane stiffness during the unanticipated 180° turning tasks whilst elite female netballers demonstrated less ankle frontal plane stiffness during the unanticipated straight task than male netballers. These findings including the present study's seem to support the notion that male musculature is more effective at resisting changes in its length (Blackburn et al., 2006), which may be due to anatomical and neuromuscular differences between the sexes (Hewett, 2000; D. F. Murphy et al., 2003). Consequently, JS may be an important factor in preventing lower extremity injury. The reduced joint stiffness in females compared with males may indicate reduced dynamic stability of the knee during functional tasks which may contribute, at least in part, to the greater incidence of lower extremity injury in females compared with males (Hughes & Watkins, 2008). Butler et al. (2003) proposed that too little stiffness may lead to soft tissue injuries and knee pathology. The greater the ability of the muscles to oppose rotation of the joint (i.e. greater joint stiffness), the greater the dynamic stability of the joint is likely to be (Wagner & Blickhan, 1999) and therefore the

less likely the passive structures of the joint will induce strain (Hughes & Watkins, 2008). Given that females present with less joint stiffness than males in various unanticipated locomotive tasks it is plausible that insufficient stiffness during the pivot phase of the 180° turn or stance phase of a straight sprint could result in an unwanted collapsing of lower limbs causing injury to soft tissue. It was proposed by this researcher that female netballers with low stiffness of the ankle during an unanticipated 180° turn pivot would be more susceptible to injury. Chapter 9 investigated such a premise with findings revealing an association between low ankle frontal plane joint stiffness and injury occurrence for elite female netballers. Interestingly, though it seemed beneficial for males to exhibit greater ankle JS during the straight tasks than female netballers (Chapter 8) it was inherently detrimental in regards to obtaining an injury (Chapter 9). Specifically, male netballers demonstrated a negative association between injury occurrence and ankle frontal plane joint stiffness during the unanticipated straight task. Such an outcome can be interpreted as high amounts of joint stiffness being associated with injury occurrence. Excessive or too much stiffness may have resulted in disproportionate loading rates resulting in injury to the bony structures of the lower extremity (Hughes & Watkins, 2008). In fact high joint stiffness has been linked to injury retrospectively (Bradshaw et al., 2006; Milner et al., 2007) and now prospectively (Chapter 9). Additional findings of Chapter 9 revealed the knee joint JS association with injury occurrence to be opposite to that of the ankle for female netballers. For example high knee sagittal plane joint stiffness during the unanticipated 180° turn task was associated with lower extremity injury occurrence in elite and non-elite female netballers. Whilst Chapters 8 and 9 provide insights into the characteristics of JS it is plausible that ideal ranges of joint stiffness for particular movements that allow players to minimize the risk for injury may exist. This 'safe zone' may be independent of gender, joint or movement task.

Chapter 8 further intended to identify whether there were any substantial differences in lower extremity JS between dominant or non-dominant limbs during an unanticipated straight run or unanticipated 180° turn. Ankle frontal plane stiffness was the measure of interest during the unanticipated tasks based on the reliability outcomes of Chapter 7. Findings of Chapter 8 revealed differences in JS to be both population and movement specific. Specifically, elite female netballers demonstrated greater ankle frontal plane joint stiffness in the dominant pivot leg during the unanticipated 180° turn compared to the 180° turn task performed on the non-dominant leg. All sub-categories (male netballers, elite female netballers and non-elite female netballers) presented with similar or symmetrical joint stiffness for the unanticipated straight task. These population specific and movement specific findings are similar to those of Joseph and

colleagues (2007). The fact that Chapter 8 reveals the dominant limb of elite female netballers to be stiffer is not surprising due to the link between leg dominance and functional performance (Itoh et al., 1998), and the link between functional performance and stiffness (Bret et al., 2002; Chelly & Denis, 2001). Furthermore the preferred / dominant leg controls propulsion during gait tasks whereas support is maintained more by the non-preferred / dominant leg (Sadeghi et al., 2000). Overreliance on the dominant limb is considered a risk factor for lower extremity injury (Beynon et al., 2002), with links between limb dominance and injury existing (Chomiak et al., 2000; Ekstrand & Gillquist, 1983; Orchard, 2001). Excessive or too much stiffness may result in disproportionate loading rates about the joint resulting in injury to the bony structures. In fact it has been reported that too much stiffness may lead to bony injuries and ankle pathology whereas too little stiffness may lead to soft tissue injuries and knee pathology (Williams et al., 2004; Williams et al., 2001). High joint stiffness has been linked to injury retrospectively (Bradshaw et al., 2006; Milner et al., 2007). It is possible that a greater demand to use of the dominant limb during athletic tasks in conjunction with high joint stiffness may lead to a greater likelihood of injury for an individual. Such a premise was not supported by the findings of Chapter 9 as female netballers that demonstrated low ankle JS strategies in their dominant leg during an unanticipated turn were linked to the occurrence of injury. Demonstrating large amounts of ankle JS to be beneficial for female netballers avoiding injury, a finding confirmed prospectively in Chapter 9 of this thesis.

Thesis limitations

Methodological limitations were present in this thesis. These limitations mainly surrounded the delivery of the unanticipated stimulus and collection of injury statistics.

- Throughout the research unanticipated sprint stimulus were simulated via computer software on a digital screen in a controlled laboratory environment. It is possible that JCV and JS observations may be different in a competitive field setting. The addition of competitors and other possible environmental perturbations may lead to further alterations in lower extremity JCV and JS measures which may lead to more or less JCV or JS displayed by the athlete.
- The unanticipated stimulus that the netballers had to respond to was provided as a visual cue which was displayed on a 19" screen placed ahead of the netballer's line of forward motion. This stimulus was triggered manually by the lead researcher when the netballer was approximately 1 m away from the force platform. It is accepted that this method did not allow for consistency in

response start point and perhaps was subjected to human error. A trigger device via photocells where the individual broke a beam which triggered the screen to display the stimulus would have allowed greater consistency to respond among participants in this thesis.

- In chapters 5 and 9 injury occurrence was diagnosed by clinicians that were outside the research party of this thesis. For reasons such as clinician client confidentiality, verification of the injury from the clinician was unable to be obtained by the principal researcher. It was presumed that the information that the netballers were communicating were accurate. Having a qualified clinician designated to the study in which all injured netballers could have been assessed by would have strengthened the validity of the injury occurrence data.
- It would have been beneficial to monitor the training and playing loads of the netballers throughout the monitored netball season period of the prospective study. This was not considered until after the completion of the study as this thesis was only interested in establishing whether or not high or low levels of JCV or JS would lead to injury in a given period. Such loading information may have added to the demonstrated associations between injury occurrence and the JCV and JS measures.
- It is possible that the injury history of the participants prior the 6 months before testing may have lead to non normal movement strategies. For example if one of the participants had a broken femur as a child or an ACL reconstruction a year before the study, they may have performed quite differently than some who does not have a history of injury. Such information was not sourced as part of this thesis as it was thought that a 6 month injury free period prior to testing would provide a sufficient baseline measure of the participant's movement patterns. Avoidance of such an occurrence would be to recruit participant's with a history of no injury in the netball population would prove difficult as the potential sample participants (netballers) is not large and would prove logistically difficult.
- The reliability studies conducted as part of this thesis utilised elite netballers to identify acceptable JCV and JS measures for future study. It is possible that these identified measures may not be applicable to non elite and male cohorts or in fact display differing reliability outcomes for these populations. Given this

proposition it is possible that the outcomes found for non elite and male netballers in this thesis may not be valid and thus should be interpreted with caution.

While this thesis has demonstrated substantial outcomes that further broaden the body of knowledge surrounding the JCV and JS paradigms, the results need to be interpreted with caution given the aforementioned thesis limitations.

Recommendations for future research

The findings of this thesis have lead to the following recommendations for future research:

- JCV and JS measures derived primarily from the distal aspect of the thigh to the foot were investigated with a number of measures displaying acceptable levels of measurement reliability and measurement variability. There were instances where unacceptable outcomes were exhibited in particularly for the unanticipated 180° turn task on the dominant leg for JCV measures and knee based JS measures for most unanticipated tasks. Given the discrepancies and inability of acceptable outcomes for JCV and JS measures assessed in this thesis it is recommended more research be conducted that investigates the measurement reliability and measurement variability of other lower extremity coupling (e.g. hip – thigh based coupling) relationships and other JS measures (e.g. hip joint stiffness) during the unanticipated tasks utilised in this thesis. Furthermore, the measures identified as having acceptable measurement reliability and measurement variability (e.g. rearfoot_(eversion/inversion)–knee_(flexion/extension), ankle frontal plane stiffness) in this thesis should be investigated in other unanticipated tasks (e.g. landing) performed by other types of athletes (e.g. volleyball players).
- Chapter 4 identified a greater repertoire of coupling strategies demonstrated by the non-elite female netballers which may lead to them potentially utilising an inappropriate coupling movement that is not suitable for turning performance e.g. excessive internal rotation of the shank leading to an increase in pivot time with a substantial loss in momentum and propulsive impulse. It is unknown what mechanical movement strategies are important for 180° turning. Future analysis into the biomechanical determinants of unanticipated 180° turning performance is required to provide insight as to what movement strategies may lead to superior performance.

- There were differences in JCV and JS measures during unanticipated sprint tasks between netballers of differing ability, netballers of different gender and netballer's lower limbs. Additional research is needed to better appreciate the context-specificity of JCV (for couplings not measured in this study) in athletes of varying ability from different sporting pursuits. Further research is needed to compare gender differences and lower limb differences in JCV and JS for other forms of sporting movements such as abrupt stops, landings and lateral side step cutting. Other sporting population samples (e.g. hockey players) may offer more insight into gender and limb discrepancies in JCV and JS.
- There were associations between injury occurrence and low JCV, low JS and high JS exhibited during unanticipated sprint tasks. Future research investigating training interventions aimed at adapting JCV or JS during unanticipated tasks are needed. Gender differences in JCV characteristics with respect to injury occurrence observed in this group of netballers suggests that an intervention program designed for women should be focused more on developing a greater repertoire of coupling strategies whereas for males the intervention should focus on minimising coupling variability. Training interventions that increase JS of the ankle and decrease stiffness of the knee during unanticipated turning tasks would be advantageous for female netballers. Male netballers would benefit from training that decreases ankle stiffness during unanticipated straight tasks. Stiffness can be increased via three strategies that enhance force production: Increasing the number of contractile elements in the muscle via hypertrophy / strength training; Inhibition of the golgi tendon organs through maximal strength training; excitation of the muscle spindles through plyometric training. To decrease stiffness one must become more compliant / increase extensibility / flexibility. Flexibility interventions that aim to change the ROM of a joint in this case the ankle for males and knee for females could potentially increase ROM thus decreasing joint stiffness. However it is plausible that a trade off between high and low stiffness is necessary and thus the presence of an optimal stiffness region advantageous for both enhanced performance and injury prevention would exist. Nonetheless, training interventions that expose netballers to various unanticipated conditions so that they will be able to adapt their JCV or JS strategies to circumstances they encounter during competition would be advantageous, and therefore requires attention.

- Even though associations between injury occurrence and low JS and high JS exhibited during unanticipated sprint tasks were identified, more prospective research is needed to identify an optimal range of JS in which risk of injury is reduced.
- Research that monitors changes in JCV or JS post injury, then following treatment and rehabilitation would be of great worth to the JCV and JS bodies of knowledge. Ideally, the investigation would involve a prospective study design where injury free individual's JCV or JS data are measured, followed by a period of monitoring until the occurrence of injury, then identifying the rate of change of the JCV or JS measure back to pre injury state.
- Future research should attempt to address whether reading a tactical situation typical of the athlete's sport in a competitive field setting can better discriminate JCV between elite and non-elite players, males and females, or dominant and non-dominant limbs.

Conclusions

This thesis demonstrated substantial outcomes that further broaden the body of knowledge surrounding joint coupling variability and joint stiffness paradigms. The main question this thesis addressed was "What is the role of joint coupling variability and joint stiffness during change of direction sprints and the association with lower limb injury?". In regards to joint coupling variability it appears that female netballers in particular at the elite level that demonstrate low levels of lower extremity joint coupling variability in their dominant leg during unanticipated sprint tasks are susceptible to injury. Male netballers on the other hand that demonstrate high joint coupling variability in their dominant leg during unanticipated sprint tasks are likely to acquire injury. When considering joint stiffness the associations with injury occurrence were not as prevalent and strong as those found with joint coupling variability. Nonetheless, elite level female netballers with low levels of ankle joint stiffness during an unanticipated turn are likely to get injured. On the other hand if female netballers demonstrate high levels of knee joint stiffness this can also predispose them to the likelihood of injury. Male netballers that exhibit high levels of ankle joint stiffness during ground contact of an unanticipated straight sprint are likely to be injured.

The findings of this thesis have further supported theories proposed in the literature, and provided justification for speculated theories especially in regards to

associations between injury occurrence and joint coupling variability and joint stiffness. Nonetheless there is still a need for further investigations into some of the other factors identified in this research as being related to context specificity of joint coupling variability or joint stiffness between genders, limbs and athletic populations. Additionally research involving training interventions may yield additional avenues for improving the welfare of netballers.

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APPENDICES

APPENDIX 1: CAN JOINT COUPLING VARIABILITY PROVIDE INSIGHT TO LOWER EXTREMITY INJURY ETIOLOGY? SMESNZ 2007.

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Aim: The purpose of this study was to review movement variability from a dynamical systems perspective, and to determine its potential role in injury prevention strategies specifically related to lower extremity joint and segment couplings during dynamic sporting tasks.

Findings: Minimal variability of a performance measure (e.g., 100m sprint time) from competition to competition or trial to trial is a key factor to success for the sporting individual, especially when matched to athletes of similar ability (Hopkins & Hewson, 2001). However, dynamical systems theory suggests that consistent high-level performance across a variety of situations and conditions can only be achieved with a variable joint coupling pattern that can be adapted to suit the demands of the task at hand (Hamill et al., 1999). Thus, a variable control strategy could be favourable over a traditional approach of absolute invariance in the movement execution pattern through repetition (Knight, 2004). The relationship between joint/segment coupling variability and injury during running has been of growing interest to researchers (Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005). Such studies have used a dynamical systems approach, considered possibly more appropriate in determining the aetiology of an injury compared to commonly used time-discrete measures (i.e., Q-angle) (Hamill et al., 1999; Heiderscheit et al., 1999). Though information is presently scarce, studies using the dynamical systems approach have identified a variety of lower extremity intra-limb couplings (all involving either a transverse (rotational) or frontal (medial-lateral) plane component of motion) during the stance phase of running to be a marker of current lower extremity injury (Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005). Though these studies indicate that low intra-limb joint coupling variability was related to the presence of injury, they do not determine the cause of injury due to the case-cohort study designs incorporated. For example, information pertaining to whether or not the reduced variability identified in the injured individuals system was observed as a result of pain or possibly existed prior to the onset of pain placing them at greater risk of injury is not known. Studies with a prospective design assessing lower extremity coupling variability patterns may offer a better insight into the causation/aetiology of lower extremity injury occurrence.

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APPENDIX 2: CAN JOINT COUPLING VARIABILITY PROVIDE INSIGHT TO LOWER EXTREMITY INJURY ETIOLOGY? AAESS 2008.

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Introduction

Minimal variability of a performance measure (e.g., 100m sprint time) from competition to competition or trial to trial is a key factor to success for the sporting individual, especially when matched to athletes of similar ability. However, dynamical systems theory suggests that consistent high-level performance across a variety of situations and conditions can only be achieved with a variable joint coupling pattern that can be adapted to suit the demands of the task at hand (1). Thus, a variable control strategy could be favourable over a traditional approach of absolute invariance in the movement execution pattern through repetition. The relationship between joint/segment coupling variability and injury during running has been of growing interest to researchers (1-3). Such studies have used a dynamical systems approach, considered possibly more appropriate in determining the aetiology of an injury compared to commonly used time-discrete measures (i.e., Q-angle) (1-3).

Purpose

The purpose of this study was to review joint coupling variability from a dynamical systems perspective, and to determine its potential role in injury prevention strategies specifically related to lower extremity joint and segment couplings during dynamic sporting tasks.

Methods

The methods used for retrieving articles in this review involved searching four electronic databases including Ovid MEDLINE, Cochrane database for systematic and complete reviews, SportDiscus and Science Direct through the years 1960 – 2007. Relevant studies were identified using a combination of medical subject headings (MeSH) and text words such as coupling, variability, injury, knee, and ankle.

Findings

Though information is presently scarce, studies using the dynamical systems approach have identified a variety of lower extremity intra-limb couplings (all involving either a transverse (rotational) or frontal (medial-lateral) plane component of motion) during the stance phase of running to be a marker of current lower extremity injury (1-3). Though these studies indicate that low intra-limb joint coupling variability was related to the presence of injury, they do not determine the cause of injury due to the case-cohort study designs incorporated. For example, information pertaining to whether or not the reduced variability identified in the injured individuals system was observed as a result of pain or possibly existed prior to the onset of pain placing them at greater risk of injury is not known. Studies with a prospective design assessing lower extremity coupling variability patterns may offer a better insight into the causation/aetiology of lower extremity injury occurrence.

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APPENDIX 3: JOINT COUPLING VARIABILITY CAN LIKELY INDICATE LOWER EXTREMITY INJURY OCCURENCE. SMESNZ 2008.

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Background: The relationship between joint/segment coupling variability and injury during running tasks has been of growing interest to researchers (Ferber et al., 2005; Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005). Though information is presently scarce, studies using a dynamical systems approach have identified a variety of lower extremity intra-limb couplings (all involving either a transverse (rotational) or frontal (medial-lateral) plane component of motion) during the stance phase of running to be a marker of current lower extremity injury (Hamill et al., 1999; Heiderscheit et al., 2002; Kurz et al., 2005). To date there have been no studies with a prospective design assessing joint/segment coupling variability that can offer some insight into the causation/aetiology of lower extremity injury occurrence.

Aim: The purpose of this study was to identify the association between low joint/segment coupling variability and injury occurrence.

Methods: Ten injury free elite Netballers performed unanticipated straight sprints, and 180° turns on both dominant and non-dominant legs. It was the straight trials that were of interest for this study. Five trials of each task with approximately 60–90 s of rest between trials were randomly performed with all testing completed in one session. Kinematic data were collected at 240 Hz using a Qualisys, nine-camera, 3-D motion analysis system synchronised with a force platform embedded within the floor. Q-Trac software was used to digitize the kinematic data. Coordinate data were low-pass filtered using a fourth-order Butterworth filter with an 8Hz cutoff frequency. Using Visual 3D software 3-D joint angles were calculated for the knee and segment angles for the rearfoot, tibia and thigh for each trial. The angle data were linearly interpolated to 101 data points, with each point representing 1% of the stance phase (0–100%). Joint coupling angles were then quantified using vector coding calculations in a customised LabVIEW software package. The standard deviation of the coupling angles across the five trials were calculated for each percent of stance, providing a measure of between-trial, within-subject variability. This procedure was repeated for six intralimb couplings. The variability was averaged from the impact peak to the maximum vertical ground reaction force as this was the phase of interest. Participants were contacted regularly throughout a six month period for verification of any lower extremity injury experienced during their netball season.

Preliminary Findings: Four participants experienced an injury in their dominant leg that required them to miss both training and game time. Types of injuries were 2 ankle sprains and 2 cases of patellar tendonitis. Preliminary analysis identifies small to large associations between low coupling variability for most of the couplings measured in this study and injury occurrence. Chances that the true value of the effect statistic is substantially positive appear likely for the Pearson correlation coefficients as demonstrated by the 90% confidence intervals.

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APPENDIX 4: DOES SUCCESSFUL UNANTICIPATED TURNING ABILITY LEAD TO SUCCESSFUL UNANTICIPATED STRAIGHT SPRINT ABILITY IN NETBALLERS? SMESNZ 2009.

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Background: During court sports such as netball the ability to change direction explosively whilst reacting to an environmental stimulus, such as a defending player, is of great importance to an attacking player when attempting to find space in which to receive the ball. It is accepted that planned agility performance and straight sprint running performance are not associated with each other (1 & 2). However, it is unknown if this is the case in unanticipated turning events. Additionally it is unknown whether or not foot ground contact time is associated with unanticipated turning performance and whether or not leg dominance may play a role.

Aim: The purpose of this study was to investigate any association between unanticipated turning performance and unanticipated straight sprint performance and the effects of leg dominance and foot ground contact time.

Methods: Thirty-six netballers performed unanticipated straight sprints and unanticipated agility sprints (180° turns) on both dominant and non-dominant legs. Five trials of each task with approximately 60–90 s of rest between trials were randomly performed, with all testing completed in one session in a Motion Analysis Lab. Turn performance time was measured using Swift timing lights. An AMTI force platform (1200 Hz) measured ground contact time during all trials. Pearson correlation coefficients with 90% confidence intervals were used to identify any associations between leg dominance, ground contact time, unanticipated straight and unanticipated agility performance. Clinical inferences were also calculated to investigate the likelihood these associations were clinically substantial.

Findings: Netballers who performed unanticipated agility sprints on their dominant leg with a short contact time were also usually faster on their non-dominant leg ($r = 0.66$, 90% CI 0.47 to 0.79). A similar trend occurred during the unanticipated straight sprints ($r = 0.81$, 90% CI 0.69 to 0.89). However, those netballers who performed unanticipated agility sprints with faster contact times did not necessarily perform unanticipated straight runs with fast contact times when performing on the dominant leg ($r = 0.26$, 90% CI -0.02 to 0.50). This finding illustrates the need for specificity in training as there was not necessarily transference in straight speed ability to agility ability which is in accordance with past research (1, 2, & 3). There were moderate associations between contact time and unanticipated agility performance of $r = 0.43$ (90% CI 0.18 to 0.64) and $r = 0.50$ (90% CI 0.26 to 0.68) for the dominant and non-dominant legs respectively. This suggests a substantial link between turning contact time and turning performance. More research is required to understand the best determinants of unanticipated turning performance.

Conclusion: The sports science practitioner is urged to consider unanticipated movement patterns in the conditioning of their athletes with emphasis being placed on varying straight, turning, and multiple changes of direction movement tasks to ensure that athletes can better combat the demands of their sport. Providing cues to athletes to minimise their foot ground contact times during such activities may also be beneficial.

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APPENDIX 5: DOMINANT LIMB ASYMMETRY GREATER THAN 10% DURING AN UNANTICIPATED AGILITY SPRINT WITH 180° TURN IS ASSOCIATED WITH PROSPECTIVE LOWER LIMB INJURY OCCURRENCE. SMESNZ 2010.

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Background: The dominant leg is considered to encounter greater stress at the joints (1) because it is preferentially used for jumping, landing, or pushing off tasks (2). This heightened stress results in an increased risk of injury (1). Epidemiological studies have speculated that side-to-side (e.g. dominant to non-dominant) functional asymmetries greater than 10% may further heighten this injury risk (3 & 4). Therefore, the analysis of limb asymmetries within an athlete's motor behaviour appears important for injury prevention.

Purpose: To identify associations between lower limb asymmetry in unanticipated agility performance and prospective injury occurrence.

Methods: Twenty-four female netballers performed unanticipated 180° turn agility sprints on both the dominant and non-dominant legs interspersed with an additional straight running (no turn) task (5 trials per task). All tasks involved a 7 m near maximal running approach to a "cue zone" where the tasks were cued randomly using a visual monitor in the gait laboratory. Turn performance time over 2 m was measured using Swift timing lights (4 MHz). Netballers were contacted regularly throughout the following six month period for verification of any lower extremity injury experienced during their netball season. Pearson correlation coefficients with 90% confidence intervals were used to identify any associations between dominant limb asymmetry of greater than 10% for unanticipated agility performance and injury occurrence. Clinical inferences were also calculated to investigate the likelihood these associations were clinically substantial.

Findings: Lower limb injury occurred in 37.5% (N = 9/24) of the netballers. All injuries (100%) occurred in the netballer's dominant leg. Notably, 78% (7/9) of the injured netballers and 47% (7/15) of the non-injured netballers performed faster unanticipated turns on their dominant leg compared to the non-dominant leg. A dominant limb asymmetry of greater than 10% in performance was identified for 57% (4/7) of the injured netballers and 14% (1/7) of the non-injured netballers. A moderate association of $r = 0.45$ (90% CI: -0.01 to 0.75) was identified between dominant limb asymmetry of greater than 10% and injury occurrence.

Conclusion: There is a substantial likely probable link between dominant limb asymmetry of greater than 10% and lower limb injury occurrence. Favouring a lower limb during performance may be detrimental to an athlete's health prospectively.

References:

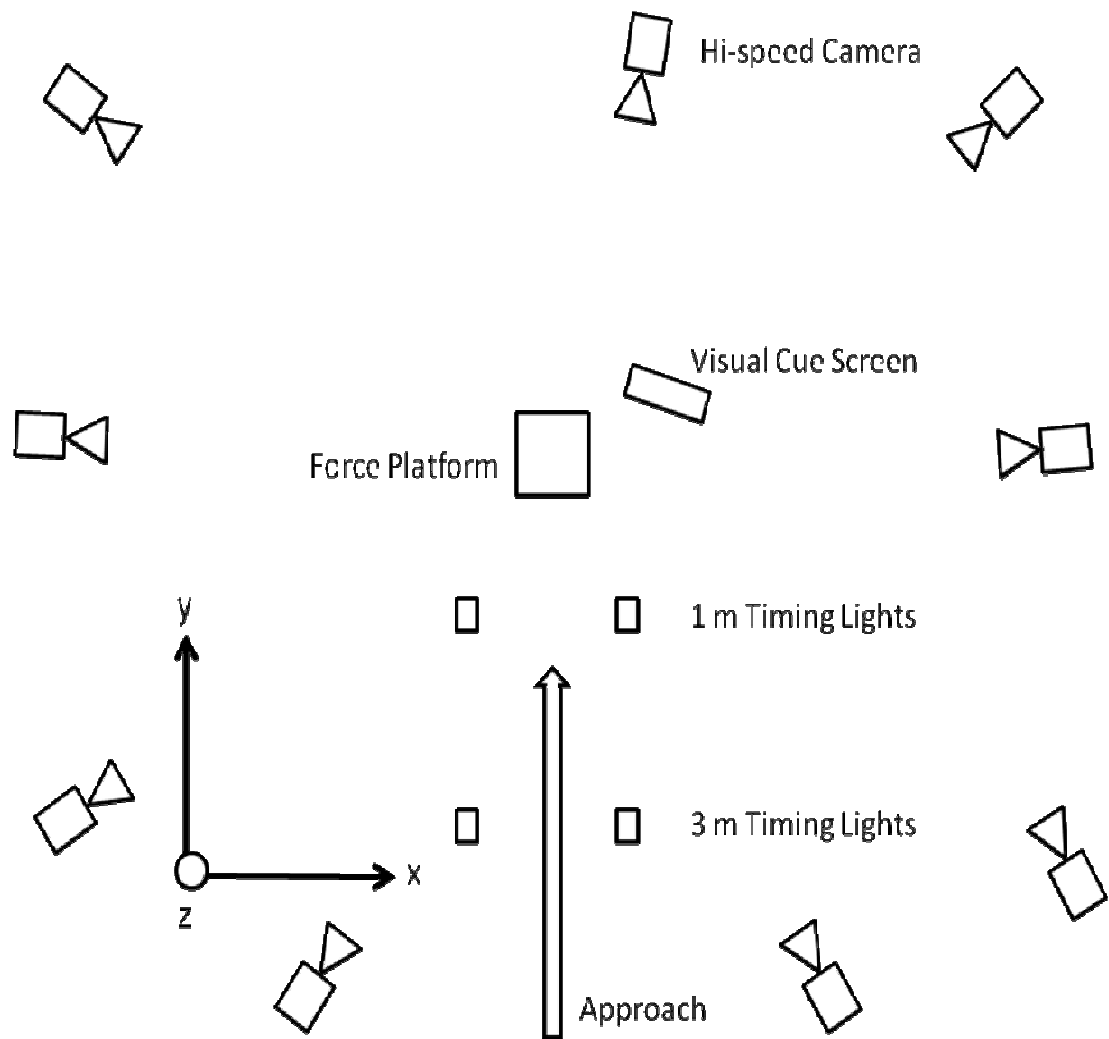
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APPENDIX 6: MARKER SET UTILISED THROUGHOUT THESIS



- A) Right side of participant
- B) Anterior aspect of the participant
- C) Posterior Aspect of the participant
- D) Left side of the participant

APPENDIX 7: SCHEMATIC OF EXPERIMENTAL SETUP



APPENDIX 8: SUBJECT INFORMATION PACK

Participant Information Sheet

Date Information Sheet Produced: 13th October 2006

Project title

The role of movement variability and muscle stiffness in lower limb injury prevention.



Invitation to participate

You are invited to take part in the above mentioned research project. Your participation in this testing is voluntary. You are free to withdraw consent and discontinue participation at anytime without influencing any present and/or future involvement with the Auckland University of Technology.

Your consent to participate in this research will be indicated by your signing and dating the consent form. Signing the consent form indicates that you have freely given your consent to participate, and that there has been no coercion or inducement to participate by the researchers from AUT.

What is the purpose of the study?

The purpose of the study is to identify the role of movement variability and muscle stiffness for lower limb injury prevention, particularly for running and jumping movement tasks.

This study is being conducted as part of a PhD degree. The results of this study will be presented at national / international conferences and submitted to peer-reviewed journals.

How was I chosen to be asked to participate in the study?

Those people aged 18 - 35 years who compete in sports requiring running and jumping tasks. You must be injury free within the last six months of testing.

What happens in the study?

Those participating in the study will be asked to attend one testing session.

Prior to testing you will be asked to complete your competition based warm-up.

You will be familiarised with straight ahead running overground at velocities ranging between ~5.5 m/s and 6.5 m/s (measured using timing lights) and combined run/jump technique.

Seven trials each of straight ahead run and run/jump will be randomly performed.

You will be given approximately 60–90 s of rest between trials so as to reduce the potential effects of fatigue.

Retroflective markers will be placed on your hip, knee, ankle, heel, and big toe of your right leg. You will be videoed performing the running and jumping tasks over a force plate.

The testing will be conducted at the Auckland University of Technology (AUT) or at the Millennium of Institute of Sport and Health (MISH).

Following the testing you will be monitored for a period of 6 months for the occurrence of lower limb injury using a web based injury data collection system.

What are the discomforts and risks?

There is a possible injury risk however this is equivalent to what you normally experience during physical training or competition.

What are the benefits?

Information gained from this research has potential to help shape training strategies, and develop prognostic and diagnostic indicators of value to athletes, clinicians, physical conditioners and coaches.

What compensation is available for injury or negligence?

Compensation is available through the Accident Compensation Corporation within its normal limitations.

How is my privacy protected?

The data from the project (both text and image) will be coded and held anonymously in secure storage under the responsibility of the principal investigator of the study in accordance with the requirements of the New Zealand Privacy Act (1993).

All reference to participants will be by code number only in terms of the research thesis and publications. Identification information will be stored on a separate file and computer from that containing the actual data. In the case of any video footage, subject's faces will be obscured / blanked out.

Only the investigators will have access to computerised data.

What are the costs of participating?

Participating in this research project will not cost you apart from your time.

You will be required to give 1 to 1.5 hours for the testing session and anywhere between 0 and 3 hours during the 12 month injury monitoring phase dependent on how often you acquire an injury during your individual sporting pursuits.

A moderate contribution to travel shall be provided.

Opportunity to consider invitation

Please take the necessary time you need to consider the invitation to participate in this research.

It is reiterated that your participation in this research is completely voluntary.

If you require further information about the research topic please feel free to contact Peter Maulder (details are at the bottom of this information sheet).

You may withdraw from the study at any time without there being any adverse consequences of any kind

You may ask for a copy of you results at any time and you have the option of requesting a report of the research outcomes at the completion of the study.

How do I join the study?

If you are interested in participating in this research please feel free to contact Peter Maulder (details are at the bottom of this information sheet).

Participant concerns

If you have any questions please feel free to contact Peter Maulder or Associate Professor Patria Hume. Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor – Patria Hume. Concerns regarding the conduct of the research should be notified to the Executive Secretary, AUTECH, Madeline Banda, madeline.banda@aut.ac.nz , 917 9999 ext 8044.

Researcher contact details: Peter Maulder, Institute of Sport and Recreation Research New Zealand, Division of Sport and Recreation, Auckland University of Technology. Email: peter.maulder@aut.ac.nz or phone +64 9 921 9999 ext 7855 or 027 677 4270.

Project supervisor contact details: Associate Professor Patria Hume, Institute of Sport and Recreation Research New Zealand, Division of Sport and Recreation, Auckland University of Technology. Email: patria.hume@aut.ac.nz or phone +64 9 921 9999 ext 7306.

Approved by the Auckland University of Technology Ethics Committee on 2nd March 2007 AUTECH Reference number 06 / 202.

APPENDIX 9: SUBJECT CONSENT FORM



Consent to Participation in Research

Title of Project: **The Role of Movement Variability and Muscle Stiffness in Lower Limb Injury Prevention**

Project Supervisor: **Associate Professor Patria Hume**

Researcher: **Peter Maulder**

-
- I have read and understood the information provided about this research project (Information Sheet dated 13th October 2006).
 - I have had an opportunity to ask questions and to have them answered.
 - I am not suffering from any injury that impairs my physical performance.
 - I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.
 - If I withdraw, I understand that all relevant information will be destroyed.
 - I agree to take part in this research.
 - I wish to receive a copy of the report from the research: tick one: Yes ☐ No ☐

Participant signature:

Participant name:

Date:

Participants contact details:

.....
.....

Project Supervisor Contact Details:

Associate Professor Patria Hume
Institute of Sport & Recreation Research New Zealand
Division of Sport and Recreation
Auckland University of Technology
Private Bag 92006
Auckland 1020
Ph 917 9999 ext. 7306
patria.hume@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee on 2 March 2007
AUTEC Reference number 06/202

APPENDIX 10: ETHICS APPROVAL



MEMORANDUM

Auckland University of Technology Ethics Committee (AUTEC)

To: Patria Hume
From: **Madeline Banda** Executive Secretary, AUTEC
Date: 2 March 2007
Subject: Ethics Application Number 06/202 **The role of movement variability and muscle stiffness in lower limb injury prevention.**

Dear Patria

Thank you for providing written evidence as requested. I am pleased to advise that it satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC) at their meeting on 13 November 2006 and that as the Executive Secretary of AUTEC I have approved your ethics application. This delegated approval is made in accordance with section 5.3.2.3 of AUTEC's *Applying for Ethics Approval: Guidelines and Procedures* and is subject to endorsement at AUTEC's meeting on 12 March 2006. Your ethics application is approved for a period of three years until 2 March 2010.

I advise that as part of the ethics approval process, you are required to submit to AUTEC the following:

A brief annual progress report indicating compliance with the ethical approval given using form EA2, which is available online through <http://www.aut.ac.nz/research/ethics>, including when necessary a request for extension of the approval one month prior to its expiry on 2 March 2010;

A brief report on the status of the project using form EA3, which is available online through <http://www.aut.ac.nz/research/ethics>. This report is to be submitted either when the approval expires on 2 March 2010 or on completion of the project, whichever comes sooner; It is also a condition of approval that AUTEC is notified of any adverse events or if the research does not commence and that AUTEC approval is sought for any alteration to the research, including any alteration of or addition to the participant documents involved.

You are reminded that, as applicant, you are responsible for ensuring that any research undertaken under this approval is carried out within the parameters approved for your application. Any change to the research outside the parameters of this approval must be submitted to AUTEC for approval before that change is implemented.

Please note that AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to make the arrangements necessary to obtain this.

To enable us to provide you with efficient service, we ask that you use the application number and study title in all written and verbal correspondence with us. Should you have any further enquiries regarding this matter, you are welcome to contact Charles Grinter, Ethics Coordinator, by email at charles.grinter@aut.ac.nz or by telephone on 921 9999 at extension 8860.

On behalf of the Committee and myself, I wish you success with your research and look forward to reading about it in your reports.

Yours sincerely

Madeline Banda

Executive Secretary

Auckland University of Technology Ethics Committee

Cc: Peter Maulder Peter.maulder@aut.ac.nz, Dr Elizabeth Bradshaw