HIP FUNCTION AND RUNNING MECHANICS IN YOUTH ATHLETES

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A thesis submitted to the Auckland University of Technology in fulfilment of the degree of Master of Health Science

June 2011

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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 nor material which to a substantial extent has been accepted for the award of any other degree or diploma of a university or other institution of higher learning, except where due acknowledgement is made in the acknowledgements.

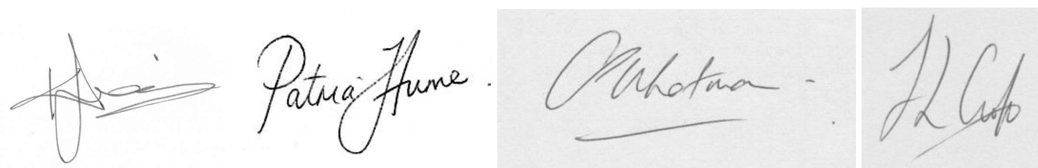
Chapters 2 to 5 of this thesis represent four separate papers that have either been published, have been submitted, or will be submitted to peer-reviewed journals for consideration for publication. My contribution and the contribution by the various co-authors to each of these papers are outlined at the beginning of each chapter. All co-authors have approved the inclusion of the joint work in this Masters' thesis.

Kelly Sheerin

June 2011

CANDIDATE CONTRIBUTIONS TO CO-AUTHORED PAPERS

Chapter 2. Sheerin, K.R., Hume, P.A., Whatman, C. Hip strength and lower limb alignment as risk factors and intervention strategies for running related lower limb injuries in young athletes. To be submitted to *Sports Medicine*	Sheerin 80%, Hume 10%, Whatman 10%.
Chapter 3 – reference A. Sheerin, K.R, Hume, P.A., Whatman, C. Reliability and variability of within-day and between-day hip isometric strength measures for youth athletes. To be submitted to *Journal of Science, Medicine and Sport.*	Sheerin 80%, Hume 10%, Whatman 10%.
Chapter 3 – reference B. Sheerin, K.R., Whatman, C., Hume, P.A., Croft, J. The reliability of lower limb isometric strength and hip flexibility measures for young athletes. Oral presentation and published in the *Proceedings of the III International Conference of Physical Education and Sports Science, Singapore, 2010*	Sheerin 80%, Hume 10%, Whatman 8%, Croft 2%.
Chapter 3 – reference C. Sheerin, K.R., Hume, P.A., Whatman, C. Reliability of lower limb strength, flexibility and 3D gait measures during running in young athletes. Oral presentation and published in *Proceedings of the New Zealand Medicine and Science Conference, Wellington, New Zealand, 2010*	Sheerin 80%, Hume 10%, Whatman 10%.
Chapter 4. Sheerin, K.R, Hume, P.A., Whatman, C., Croft, J. Reliability of 3D frontal plane knee ab/adduction range of motion during running in young athletes. Oral presentation and published in *Proceedings of the 28th Conference of the International Society of Biomechanics in Sports*, Michigan, USA, 2010	Sheerin 80%, Hume 10%, Whatman 8%, Croft 2%.
Chapter 5. Sheerin, K.R, Hume, P.A., Whatman, C. Effects of a lower limb functional exercise programme aimed at minimising knee valgus angle on running kinematics in youth athletes. Published in *Physical Therapy in Sport.*	Sheerin 80%, Hume 10%, Whatman 10%.



Kelly Sheerin   Professor Patria Hume   Chris Whatman   Dr James Croft

ACKNOWLEDGEMENTS

This thesis has come about not only through a great deal of personal dedication and sacrifice, but through the encouragement and assistance of many others. There are far too many to list you all, but thank you all very much. I wouldn't have got to this point on my own.

Firstly I would like to thank Patria, my primary supervisor. This has been a long and at times challenging journey, but your constant support has kept me on the right track. You have gone over and above the call of duty on numerous occasions, and I am very thankful to have you as my supervisor, mentor and friend.

Chris, thanks for being the yang to Patria's yin! You've provided a level-headed approach to this thesis, which has helped no end. You have stepped up to the plate on more than one occasion when the boss has been out of action, and I can't thank you enough for this.

I look forward to continuing to work closely with both of you as part of the strong team that we have established.

Thank you to my colleagues and friends within the School of Sport and Recreation, in particular Henry Duncan and Gaye Bryham for their parts in providing an encouraging and supportive environment throughout this process. Thanks also to Professor Will Hopkins for his statistical advice at various stages along the road, and his endlessly useful spreadsheets.

Thanks to Rodrigo Bini for the countless hours spent assisting with the processing of the 3D data. Thanks to all the young athletes and their parents for their participation in this study and also to Cesar Meylan, the Millennium Institute of Sport and Health LTAD programme leader, for his cooperation in making this project a success.

I would like to acknowledge Sport and Recreation New Zealand (SPARC) for providing financial support for this project, as well as the Auckland branch of Sports Medicine New Zealand (SMNZ) for assisting in the costs of my travel so that I could present my work at the International Society for Biomechanics in Sport (ISBS) and SMNZ conferences.

To my family Helen, Peter and Megan: Thank you for the support you've provided in various shapes and forms throughout my entire educational journey. I would never have got this far without you all.

And finally to my wife Imelda: Thanks for your love, patience and constant encouragement. The completion of this thesis has required considerable sacrifice on your part. Thanks for always standing at my side, and also for giving me a nudge along when required. We make a great team, and I look forward to a few more fun times now that this is completed.

ETHICAL APPROVAL

Ethical approval for this research was granted by the Auckland University of Technology Ethics Committee (AUTEC). The AUTEC reference was 08/258, with approval granted originally on the 10 December 2008.

ABSTRACT

The identification and development of youth sporting talent is becoming increasingly important. However, injuries can disrupt training and hence the development of youth athletes. Although only a small proportion of youth athletes participate in pure running sports, many sports they do compete in involve a large proportion of running. During assessments of gait, clinicians typically evaluate dynamic lower extremity alignment. Poor frontal plane knee control during running is considered a risk factor for the development of injuries such as patellofemoral dysfunction in adults, however, there is minimal knowledge for youth athletes risk factors. This thesis has sought to gain knowledge of hip function and running mechanics in youth athletes; specifically, whether a lower limb functional exercise programme can reduce hip and knee frontal plane motion in this cohort. On the basis of the literature review on gait, strength and lower limb injuries in youth athletes, it was established that runners with lower limb overuse injuries were weaker on measures of hip abduction, extension and internal rotation muscle strength. In addition, these runners demonstrated increased hip internal rotation and hip adduction angles. No published studies focused on youth athletes and running mechanics. The discrepancy in literature regarding the relationship between hip muscle function and lower limb kinematics makes it difficult to assign absolute cause-effect relationships. There was some support for hip strengthening as prevention or rehabilitation for overuse injuries. Training studies with defined parameters, specific to appropriate age and development levels, are needed to optimise intervention strategies. The reliability and variability of within-day and between-day hip isometric strength measures and 3D frontal plane hip and knee range of motion during running was established in youth athletes as it has not been previously reported. Hip abductor, hip flexor, and hip internal and external rotator strength measures demonstrated sufficient within-day reliability to be used as a baseline classification tool for youth athletes. However, the between-day reliability of these measures was poor, and therefore it is not recommended that our technique be used to measure the change overtime in hip strength for youth athletes. Within-day and between-day reliability of hip and knee ab/adduction range of motion during the stance phase of running in a youth athlete population demonstrated average to good reliability. Hip and knee frontal plane range of motion could be useful as clinical screening tools. An intervention including lower limb functional exercises aimed at minimising knee valgus angle could potentially mediate the strength and alignment issues that lead to the development of lower limb overuse injuries in youth athletes. Although our 8-week lower limb functional exercise programme employed for this thesis study was minimal in changing frontal plane hip and knee motion when running, this study was the first to describe effects of such an intervention on running mechanics of youth athletes. Practical implications for future research as a result of this thesis include increasing volume for the lower limb functional exercise intervention to increase the likelihood of a effect on running mechanics, determining a series of lower limb functional exercises suitable for use with youth athletes, and determining more sensitive assessment measures to help classify youth athletes with variable movement patterns.

CHAPTER 1

INTRODUCTION AND RATIONALE (PREFACE)

Background

In New Zealand, as in many countries, the identification and development of youth sporting talent is becoming increasingly important. Sports specific development academies and generalised athletic training programmes are being established in many areas to focus specifically on athletes aged between 7 and 12 years of age. Although there is theoretical background to long-term athletic development (Balyi & Hamilton, 2004), much of the detail still remains undefined and therefore improvised by coaches.

Athletic success in any sport requires years of dedicated training and development. To achieve proficiency and ultimately reach an elite level of performance, training must begin at an early age. As a result more athletes are undertaking intense training at younger ages, participating in multiple sports in one season, and continuing training throughout the entire year. Despite the many positive attributes of sports participation, all too often injuries can disrupt training and hence the development of sporting talent. Not only can such injuries have a flow-on effect to the elite level in terms of youth athletes not achieving the success they are potentially capable of, they can also lead to youth athletes dropping out of sports participation altogether, as well as chronic disability in adulthood, such as chronic pain or arthritis (Adirim & Cheng, 2003).

Injuries are often considered an inevitable part of sports. However, like other injuries, sports injuries are potentially avoidable. The incidence and distribution of sport-related injuries vary based on sport affiliation, participation level (e.g. grade level, age and skill level) and gender. The incidence of injury in youth sports is difficult to determine. Published studies vary considerably in terms of populations studied, methodology used and types and severity of injuries reported. In addition, because of the different criteria used to define an injury, comparisons between reports are difficult, and any such comparisons should be interpreted with caution (Shanmugam & Maffulli, 2008).

Not only is it essential to ensure that our youth sporting talent progresses to the elite level, preventing sports injuries in this age group is important to reduce the short- and long-term social and health consequences. Although it is impossible to avoid all injuries, many are preventable and therefore improving the understanding of the incidence and contributing factors of such injuries is desirable, so that we can develop tools and strategies to enhance injury prevention (Adirim & Cheng, 2003; Shanmugam & Maffulli, 2008; Stein & Micheli, 2010). Although guidelines exist to help limit injuries in youth athletes (Micheli, Glassman, & Klein, 2000), most of these simply parallel adult sporting recommendations. It is important to remember that there are important factors that are specific to youth athletes and therefore these must be reflected in any injury prevention guidelines and recommendations (Adirim & Cheng, 2003; Shanmugam & Maffulli, 2008).

During an assessment of gait, clinicians typically evaluate dynamic lower extremity alignment. Poor frontal plane hip and knee control observed during activities such as running, squatting and landing, is considered a key risk factor for the development of common injuries such as patellofemoral dysfunction (Powers, 2003). Hip strength has been identified as a key contributor to lower limb alignment during running in various adult populations (Cichanowski, Schmitt, Johnson, & Niemuth, 2007; Fredericson et al., 2000), and has also been associated with some of the same injuries in young runners (Fredericson et al., 2000; Robinson & Nee, 2007). Impaired hip muscle strength can render the hip joint susceptible to dysfunctional kinematics in all planes (Powers, 2010). Excessive hip adduction and internal rotation during stance has the potential to affect the kinematics of the entire lower limb, such as causing the knee joint center to move medially relative to the foot. When the foot is fixed to the ground, the inward movement of the knee joint causes the tibia to abduct and the foot to pronate, with the result being dynamic knee valgus (Powers, 2010).

For a performance test to be valuable it must be specific enough to measure the performance variable of interest and reliable enough to detect the relatively small differences in performances that are beneficial to elite athletes (Schabort, Hawley, Hopkins, & Blum, 1999). Using a reliable assessment tool helps ensure that variations between measurements are attributed to changes in the variable being measured (L. A. Bolgla, 1997; Clark, 2001). Reliability refers to whether a specific measurement tool produces consistent outcomes during repeated measures of the same variable (Clark, 2001). Highly sensitive sports science measurements are characterised by little variation in consecutive measures of performance (W.G. Hopkins, 2000b). A change in performance due to an intervention has to be greater than the normal day-to-day variation before it can be concluded that the intervention has had a meaningful impact on the athlete's performance (Soper & Hume, 2004). The reliability of tests needs to be established if they are to be used in longitudinal studies evaluating injury risk or the effect of rehabilitation interventions. A few studies have investigated the reliability of 3D frontal plane kinematics during running (Diss, 2001; Ferber, Davis, Williams, & Laughton, 2002; Queen, Gross, & Liu, 2006), but none have assessed children. However, it is crucial to know if kinematics are consistent enough from day to day for making clinical decisions in populations other than adults.

It is postulated that if running mechanics can be improved so that youth athletes are less prone to suffering injuries and more able to sustain training, a higher level of long term athletic development will likely ensue. This lead to the formulation of the central theme of this thesis, which was to increase understanding of hip function and running mechanics in youth athletes.

Structure of the thesis

This thesis consists of six chapters (see Figure 1) that culminate in an overall discussion. Some of the study chapters have been submitted for publication in journals or for conference presentations, which has allowed the author to gain international peer reviewed feedback on the content, which has improved the chapters. Each chapter is presented in the wording of the journal or the proceedings for which they were written. Consequently, there is some repetition in the introduction and methods between the review and experimental chapters. References are not included at the end of each chapter, rather as required by AUT for thesis submission an overall reference list from the entire thesis has been collated at the end of the final chapter.

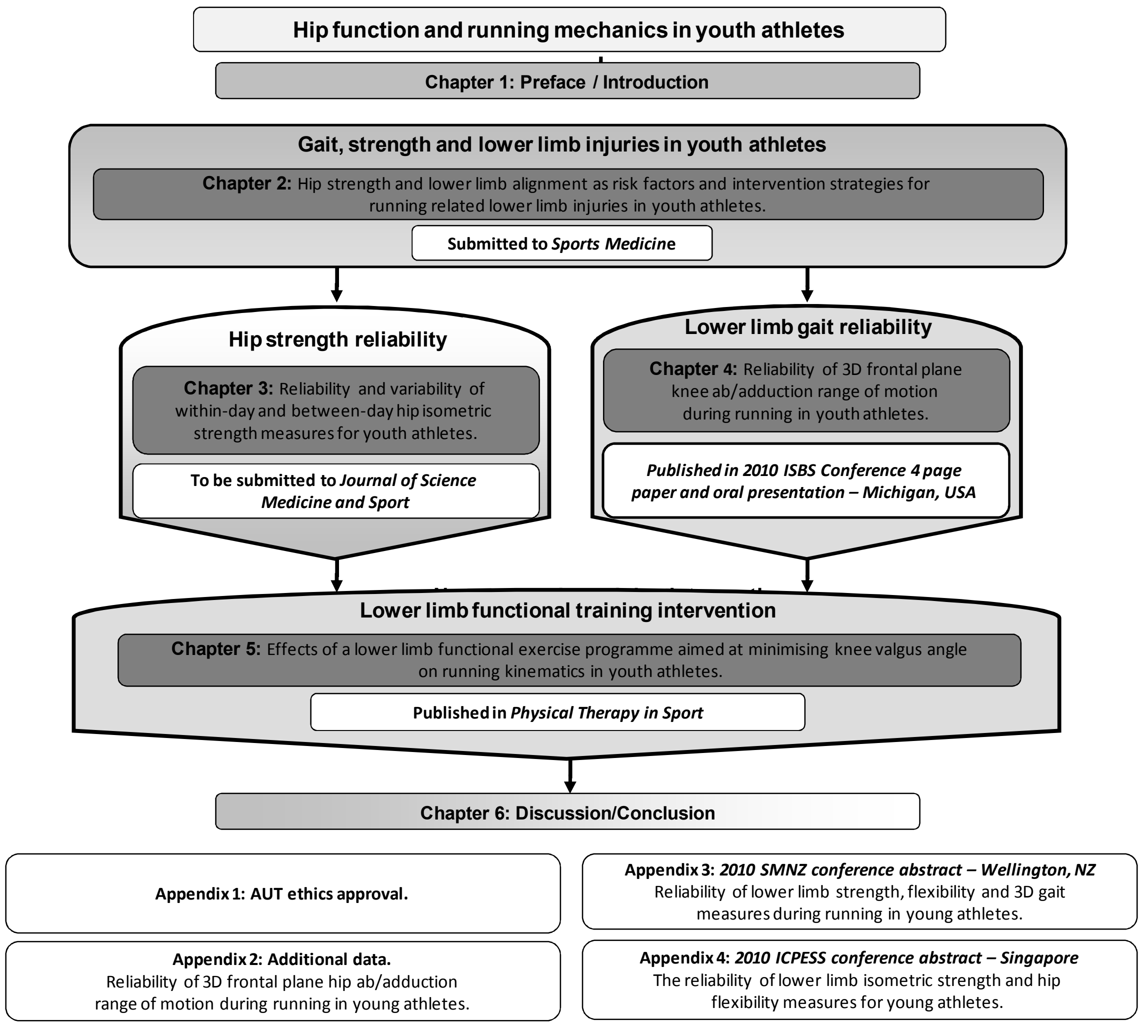


Figure 1: Overview of masters thesis chapter flow.

Chapter 2 contains a review of the literature relating to hip strength and lower limb alignment as risk factors and intervention strategies for running related lower limb injuries in children. The review is divided into four parts. The first two parts assess the evidence for reduced hip muscle strength and altered lower limb alignment as risk factors for running related lower limb injuries in children. The third part focuses on the evidence for a relationship between hip muscle strength and lower limb alignment during running in children, and the fourth part reviews the evidence for hip strengthening and lower limb alignment as intervention strategies to reduce the risk of running related lower limb injuries in children. The key findings from this chapter were that no studies have been published focusing on youth athletes and running mechanics. Investigations linking faulty running mechanics and injuries have focused on adult females. The discrepancy in literature regarding the relationship between hip muscle function and lower limb kinematics makes it difficult to assign absolute cause-effect relationships. There is some support for hip strengthening as prevention or rehabilitation for overuse injuries. Training studies with defined parameters, specific to appropriate age and development levels, are needed to optimise intervention strategies.

Given chapter 2 showed a lack of information on hip strength measures for youth athletes, the third chapter of the thesis focused on the reliability and variability of within-day and between-day hip isometric strength measures for youth athletes. It was established that hip abductor, hip flexor, and hip internal and external rotator strength measures demonstrated sufficient within-day reliability to be used as a baseline classification tool for youth athletes. However, the between-day reliability of these measures was poor, and therefore it is not recommended that our technique be used to measure the change overtime in hip strength for youth athletes.

Since chapter 2 also showed a lack of information on lower limb gait measures for youth athletes, the fourth chapter of this thesis examined the reliability of 3D frontal plane hip and knee range of motion during running in youth athletes. The main body of chapter 4 includes the published paper from the proceedings of the *2010 International Society of Biomechanics in Sports Conference*, however, this only details the reliability results for the knee. Additional data for the hip are therefore presented in Appendix 2. The key findings from the analysis of the reliability of lower limb gait measures in youth athletes were that within-session and between-session reliability of hip and knee frontal plane range of motion during the stance phase of running in a youth athlete population demonstrated average to good reliability. Hip and knee frontal plane range of motion could be useful as clinical screening tools.

As a result of the findings from chapters 3 and 4 regarding reliability of hip strength and lower limb gait measures in youth athletes, chapter 5 used only hip and knee frontal plane measures to examine the effects of a lower limb functional exercise programme aimed at minimising knee valgus angle on running kinematics in youth athletes. It was established that although the youth athletes who underwent the 8-week lower limb functional exercise programme qualitatively showed improvements in their exercise technique and lower limb alignment, this was not reflected in a reduction in their hip and knee frontal plane angles during running.

Chapter 6 consists of a general discussion of findings from the presented research projects, comments on limitations to the research studies, provides areas for future research, and provides some concluding statements on the key findings from the thesis.

CHAPTER 2

HIP STRENGTH AND LOWER LIMB ALIGNMENT AS RISK FACTORS AND INTERVENTION STRATEGIES FOR RUNNING RELATED LOWER LIMB INJURIES IN YOUNG ATHLETES.

This chapter comprises the following paper to be submitted to *Sports Medicine*.

Sheerin, K.R., Hume, P.A., Whatman, C. Hip strength and lower limb alignment as risk factors and intervention strategies for running related lower limb injuries in young athletes. To be submitted to *Sports Medicine.*

(Author contribution percentages: KS 80%, PH 10%, CW 10%).

Overview

Background: Lower limb running-related injuries in youth athletes are usually overuse or microtraumatic in nature. Impaired hip muscle strength can render the hip joint susceptible to dysfunction, which may influence knee loading and contribute to injury. *Aim:* To outline evidence for hip strength and lower limb alignment as risk factors and intervention strategies for running related lower limb overuse injuries in youth athletes. *Methods:* An electronic search of databases including Medline, SportsDiscus, and Google Scholar for articles from 1975 to 2011 used key words including youth/young, child/ren, athlete, injury/ies, gait, running, dysfunction and mechanics. Forty of the 78 published studies sourced were retained for review. *Findings:* No studies were published focusing on youth athletes and running mechanics, therefore studies including adults and other related activities were included in the analysis. There was strong evidence for reduced hip abductor and extensor muscle strength, and moderate evidence for reduced hip external rotator muscle strength, as risk factors for the development of overuse injuries in adults. There was substantial moderate evidence for injured adult athletes exhibiting greater hip adduction motion during dynamic tasks, and a small amount of moderate evidence for increased hip internal rotation. There was weak evidence that a relationship exists between reduced hip muscle strength and abnormal lower limb alignment during running in adults. There was weak evidence for hip strengthening and lower limb alignment as effective interventions to reduce the risk of running related lower limb injuries in adults. The discrepancy in literature regarding the relationship between hip muscle function and lower limb kinematics in adults makes it difficult to assign absolute cause-effect relationships. There is some support for hip strengthening for prevention or rehabilitation of overuse injuries. Training studies with defined parameters, specific to appropriate age and development levels, are needed to optimise intervention strategies. *Conclusion:* Evidence for hip strength and lower limb alignment as risk factors and intervention strategies for running related lower limb overuse injuries in youth athletes was minimal given findings in adult populations have yet to be applied to youth athletes. Studies in youth athletes should focus on hip abductor, extensor and external rotator muscle strength given the strength of the evidence for these as risk factors for overuse injuries in adults.

Introduction

Benefits and risks of participation in sport by children

Sports participation provides benefits for children such as improved health, weight management, enhanced physical fitness, and opportunities for social interaction, team building, goal setting, motor skill development and enjoyment (Stein & Micheli, 2010). To achieve proficiency and ultimately reach an elite level of performance, athletes are undertaking intense training at younger ages, participating in multiple sports in one season, and continuing training throughout the entire year. However, with these increases in volume and intensity of training, there has also been an increase in athletic injuries in the youth athletic population (Seto, Statuta, & Solari, 2010). The majority of injuries sustained by youth athletes are mild, causing only minor discomfort. However, moderate injuries can result in significant pain and time out of sports, while the most serious injuries can lead to drop out of sports participation altogether. Sporting injuries at a youth age can also have a flow-on effect to the elite level, whereby youth athletes may not achieve the success they are capable of, as well as the potential to develop disability, such as chronic pain or arthritis later in adulthood (Adirim & Cheng, 2003).

Over one third of youth athletes seek medical attention for injuries that occur during physical activity or sport (Adirim & Cheng, 2003; Hawkins & Metheny, 2001). Many more likely go unreported and untreated. With a growing musculoskeletal system, skeletally immature athletes can be at a high risk for sustaining injuries (Seto et al., 2010). Growth spurts result in sporadic changes in mass, height, muscle strength and flexibility which may cause increased strain on cartilage, bone and soft tissue structures (Hawkins & Metheny, 2001). As bones elongate, the attached soft tissue structures are stretched, creating a relative reduction in flexibility. While bones are growing rapidly, mineralisation may lag behind bone growth, leaving new bone temporarily more vulnerable to injury (Stein & Micheli, 2010). Until the apophyses (tendon insertion sites) fuse at skeletal maturity, the connection between the apophysis and the underlying bone can be weaker than the associated tendon or muscle. As a result, youth athletes can injure or inflame the apophysis rather than the tendon or muscle (Seto et al., 2010). In addition, the immature articular cartilage in youth athletes' joints is more susceptible to injury caused by shear forces than it is in adults (Seto et al., 2010). Injuries can either occur acutely from an associated macrotraumatic event, as with fractures and sprains, or can arise gradually due to repetitive microtraumatic events, such as with stress fractures or tendinopathies (Shanmugam & Maffulli, 2008).

Running related injuries in youth athletes

Although only a small proportion of youth athletes participate in pure running sports, many sports they compete in do involve a large proportion of running. Running-related injuries in youth athletes are usually overuse or microtraumatic in nature and most frequently include patello-femoral pain syndrome (PFPS), ilio-tibial band friction syndrome (ITBFS), Osgood-Schlatter disease, stress reactions and fractures, medial tibial stress syndrome, calcaneal apophysitis and chronic tendonosis (Adirim & Cheng, 2003; Seto et al., 2010; Stein & Micheli, 2010). Although many factors can contribute to the development of running related injuries (Stein & Micheli, 2010), several lower limb injuries have been linked to faulty running mechanics (L. Bolgla, Malone, Umberger, & Uhl, 2008). Despite the increasing number of injuries in youth runners, there are few epidemiologic studies focused on youth athletes, and none specifically addressing running injuries in this population (Seto et al., 2010).

Hip function and lower limb mechanics during running

The hip as the most proximal link in the lower extremity kinematic chain shares a common segment (the femur) with the knee. Through its proximal articulation with the acetabulum, it is also closely associated with the pelvis. Although the ball-and-socket configuration of the hip provides a high degree of bony stability, the joint is dependent on a complex set of muscles to create motion and provide dynamic stability (Powers, 2010). During loading (first 10% of the gait cycle after initial contact) in the stance phase of running, the hip flexes, adducts, and internally rotates. This tri-planar motion is caused by the external moments acting at the joint and is resisted by actions of the hip extensors, abductors, and external rotators, respectively (Powers, 2010).

Sagittal plane hip motion is essentially sinusoidal in nature, with maximum hip extension at toe off. Maximum hip flexion increases with increasing velocity, leading to a longer step length (Novacheck, 1998). As the lower limb is loaded, the pelvis remains relatively stationary and the hip adducts in the frontal plane relative to the pelvis. Throughout the remainder of stance the pelvis drops with respect to the stance leg until the start of double float (both feet off the ground) where the pelvis is at its greatest lateral tilt. This motion is reversed during lower limb swing to assist with foot clearance. The hip is at maximal external rotation at initial lower limb ground contact and it progressively internally rotates through the subsequent stance phase (Novacheck, 1998). Motion in the transverse and frontal planes is small in magnitude compared to the sagittal plane. Despite the smaller magnitudes, it is non-sagittal plane motion at the hip that has been linked to various running-related injuries (Fredericson et al., 2000; Leetun, Ireland, Willson, Ballantyne, & Davis, 2004; Niemuth, Johnson, Myers, & Thieman, 2005; Noehren, Davis, & Hamill, 2007). Mid-stance is the period of the gait cycle when ground reaction forces are highest on the body, with peak internal joint moments generating peak mechanical strain on tissues (Dicharry, 2010). The ability of runners to accommodate these forces is essential to remaining injury free (Craik & Oatis, 1995; Dicharry, 2010).

Hip strength has been identified as a key contributor to lower limb alignment during running in various adult populations (Cichanowski et al., 2007; Fredericson et al., 2000), and has also been associated with some of the same injuries in young runners (Fredericson et al., 2000; Robinson & Nee, 2007). Impaired hip muscle strength can render the hip joint susceptible to dysfunctional kinematics in all planes (Powers, 2010). Excessive hip adduction and internal rotation during stance has the potential to affect the kinematics of the entire lower limb, such as causing the knee joint center to move medially relative to the foot. When the foot is fixed to the ground, the inward movement of the knee joint causes the tibia to abduct and the foot to pronate, with the result being dynamic knee valgus (Powers, 2010). Hip adduction is a primary contributor to excessive dynamic knee valgus (Hollman et al., 2009; J. D. Willson & I. Davis, 2008) and would be expected to strain the soft tissue restraints that limit knee valgus. As a transverse plane motion, hip internal rotation plays less of a role in the medial collapse of the lower limb. However, excessive internal rotation of the femur on a relatively fixed tibia would also strain the structures that limit this motion (i.e. the medial and lateral collateral ligaments) (Powers, 2010). These excessive motions over time are thought to lead to the development of subsequent lower limb overuse injuries, such as PFPS and ITBFS (Powers, 2010).

Although the costs and long-term health ramifications of running related injuries in youth athletes are difficult to determine, enhanced understanding of the contributing factors is desirable, in order to develop tools and strategies to enhance injury prevention (Adirim & Cheng, 2003; Shanmugam & Maffulli, 2008; Stein & Micheli, 2010). Although guidelines exist (Micheli et al., 2000) to help youth athletes reduce the risk of injury, they are largely non-specific and there is a call for more research to help minimise the risk for youth athletes participating in organised sport. It is also important to remember that children are not just scaled down versions of adults, and that factors specific to youth athletes must be reflected in injury prevention recommendations (Adirim & Cheng, 2003; Shanmugam & Maffulli, 2008). This paper examines the evidence for hip strength and lower limb alignment as risk factors and intervention strategies for running related lower limb overuse injuries in youth athletes.

Methods

Cochrane Collaboration (*Cochrane Handbook for Systematic Reviews of Interventions 5.0.2* 2008) review methodology (Literature search; Assessment of study quality; Data collection of study characteristics including participants, sport, outcome measures and results; Analysis and interpretation of results; Recommendations for injury prevention strategies and further research) was used to evaluate the evidence for hip strength and lower limb alignment as risk factors and intervention strategies for running related lower limb overuse injuries in youth athletes. For the purposes of this review, we defined youth athletes as children between the ages of 7 and 12 who participated in competitive sport. Teenagers were defined as individuals aged between 13 and 19 years of age, and adults aged 19 years and over.

Literature search

An electronic search was conducted of the Medline, SportsDiscus, ProQuest Direct, Google Scholar, and Cinahl databases for articles from 1975 to March 2011 using the initial key words youth/young, child/ren, adolescent, athlete, injury/ies, gait, running, dysfunction, rehabilitation, treatment, strength, exercise, neuromuscular, prevention, training, biomechanics/cal, hip, kinematics, kinetics, mechanics. These keywords were used separately and in combination. Reference lists of all retrieved articles were manually checked for additional studies. Exclusion criteria included: (1) unavailable in English and in full text; (2) article was not in a peer reviewed journal or full conference proceeding; (3) review papers and current concept papers; (4) intervention studies that did not include a component of hip strengthening or lower limb alignment assessment. Due to the shortage of studies with the target age group, the search was expanded to include relevant studies with adults. Only eleven studies exclusively targeted runners in their cohort, and therefore the search criteria for this review was expanded to include other studies with similar movement patterns, such as jumping, landing, squats and stair ascent/descent.

Assessment of study quality

The quality of the papers that met our inclusion/exclusion criteria was assessed based on key components of their methodological quality using an adapted scale described by Juni et al. (2001). Study quality was ranked zero to four, where the larger number indicates better quality: (4) Controlled study, with randomisation of subject allocation, plus blinding of subjects and assessors; (3) Controlled study, with randomisation of subject allocation, and blinding of subjects or assessors, but not both; (2) Controlled study, with randomisation of subject allocation, but no blinding of subjects or assessors; (1) Controlled study that lacked randomisation of subject allocation and blinding of subjects and assessors; (0) A study with no control condition, randomisation of subjects, or blinding of subjects or assessors.

Methodological limitations were associated with many of the studies reviewed; namely, a failure to clearly describe the specific type of injury assessed, the characteristics of the cohort, the specifics of strength or lower limb gait assessment methods used, or the p-value associated with the outcome measure. Many studies in the literature had made inferences about injury risks based only on the p-value derived from a null hypothesis test. This can result in misleading conclusions being made, depending on the magnitude of the effect statistic, the sample size and the error of measurement (Batterham & Hopkins, 2006).

Data extraction

After applying the exclusion criteria, of the 78 articles sourced, 40 published studies were retained for review. No studies were specifically conducted with youth athletes, while eight studies targeted their investigation on teenagers (approximate mean age of 15 years). The nature of the studies that provided data that could be assessed using magnitude based inferences for effects of hip strength or lower limb gait on injury is summarised in Tables 1 to 4. In each table the studies are ordered according to the power of the study.

Of the twelve studies that evaluated the relationship between hip muscle strength and lower limb overuse injuries, ten specifically investigated PFPS; one investigated ITBFS; and one investigated running related overuse injuries. Of the ten studies that evaluated the relationship between lower limb alignment and overuse injuries, seven specifically investigated PFPS, two investigated ITBFS and one investigated tibial stress fractures. Each of these studies assessed biomechanics during at least one set task. Five studies investigated running, four investigated a jump-landing task, three assessed stair ascent/descent and one study investigated squatting. Of the eleven studies that evaluated the relationship between hip strength and lower limb mechanics, two specifically investigated individuals with PFPS and nine investigated non-injured individuals. Of the twelve studies that evaluated the effect of hip strengthening interventions on lower limb injuries, six specifically investigated individuals with PFPS, one investigated ITBFS, one investigated piriformis syndrome, one investigated general injuries and three investigated lower limb injuries. Twenty-nine studies had a female only sample, two studies had a male sample only and the nine remaining studies included both genders.

Analysis and interpretation of results

Where possible Cohen's effect sizes (ES) were calculated (if not already reported) to enable interpretation of the evidence. The magnitudes of these effects were described as trivial (0.0-0.1), small (0.11-0.3), moderate (0.31-0.5), large (0.51-0.7), very large (0.71-0.9), or extremely large (0.91-1.0) (W.G. Hopkins, 2007).

Findings

Evidence for reduced hip muscle strength as a risk factor for lower limb overuse injuries

There is a growing awareness of the lower limb kinetic chain and how hip muscle weakness may contribute to youth athletes' lower limb running related injuries. In a 2009 review of the literature, Reiman et al. (2009) cited 51 articles that provided epidemiological, neuromuscular, or biomechanical evidence to support the concept that proximal factors may influence knee loading and therefore contribute to injury. The purpose of this section is to assess the evidence for reduced hip muscle strength as a risk factor for running related lower limb overuse injuries in children.

Characteristics and quality of the studies

Twelve cross-sectional or case control studies investigated the association between hip muscle strength and running related lower limb overuse injuries via comparisons between individuals' injured limb and their non-injured limb, and/or to the limb of non-injured controls (see Table 1).

No studies investigating the association between hip muscle strength and running related lower limb overuse injuries specifically assessed youth athletes. One study focused their sample on teenagers (Ireland, Willson, Ballantyne, & Davis, 2003), while the remainder included only adults (Baldon et al., 2009; L. Bolgla et al., 2008; Cichanowski et al., 2007; Fredericson et al., 2000; Magalhães et al., 2010; Niemuth et al., 2005; Robinson & Nee, 2007; Souza & Powers, 2009a; Willson & I., 2009). Ten studies focused specifically on PFPS (Baldon et al., 2009; L. Bolgla et al., 2008; Boling, Padua, & Creighton, 2009; Cichanowski et al., 2007; Ireland et al., 2003; Magalhães et al., 2010; S. Piva, Goodnite, & Childs, 2005; Robinson & Nee, 2007; Souza & Powers, 2009a; Willson & I., 2009), one on ITBFS (Fredericson et al., 2000), and one on general running related overuse injuries (Niemuth et al., 2005). All twelve studies assessed the strength of the hip abductor muscles, while ten measured the external rotators (Baldon et al., 2009; L. Bolgla et al., 2008; Boling, Padua, & Creighton, 2009; Cichanowski et al., 2007; Ireland et al., 2003; Magalhães et al., 2010; Niemuth et al., 2005; S. Piva et al., 2005; Robinson & Nee, 2007; Willson & I., 2009), six measured the extensors (Boling, Padua, & Creighton, 2009; Cichanowski et al., 2007; Magalhães et al., 2010; Niemuth et al., 2005; Robinson & Nee, 2007), four measured the adductors and internal rotators (Baldon et al., 2009; Cichanowski et al., 2007; Magalhães et al., 2010; Niemuth et al., 2005), while only three measured the flexors (Cichanowski et al., 2007; Magalhães et al., 2010; Niemuth et al., 2005). Seven studies did not report the athletic participation of their participants, while two studies included college or recreational level athletes, one study included sedentary participants and only two studies specifically assessed runners (Fredericson et al., 2000; Niemuth et al., 2005). Four studies included both males and females in their sample (Boling, Padua, & Creighton, 2009; Fredericson et al., 2000; Niemuth et al., 2005; S. Piva et al., 2005), while the remaining eight studies only included females (Baldon et al., 2009; L. Bolgla et al., 2008; Cichanowski et al., 2007; Ireland et al., 2003; Magalhães et al., 2010; Robinson & Nee, 2007; Souza & Powers, 2009a; Willson & I., 2009).

All studies assessing hip muscle strength and injuries were cross-sectional or case control design. Bolgla et al.'s (2008) study did not provide sufficient data to enable the calculation of ES. Ten studies scored a quality rating score of 1 (Baldon et al., 2009; L. Bolgla et al., 2008; Boling, Padua, & Creighton, 2009; Cichanowski et al., 2007; Ireland et al., 2003; Magalhães et al., 2010; S. Piva et al., 2005; Robinson & Nee, 2007; Souza & Powers, 2009a; Willson & I., 2009), indicating they included a control group. One study achieved a quality rating of 2 (Fredericson et al., 2000), by including random allocation of subjects, and one study blinded the assessors and therefore scored a rating of 3 (Niemuth et al., 2005).

Strength of the evidence and key results from the studies

Based on the effect size calculations there was strong evidence for reduced hip abductor and extensor muscle strength, and moderate evidence for reduced hip external rotator muscle strength, as risk factors for the development of running related overuse injuries in adults.

However, there was no direct evidence to support or refute similar risk factors within a youth athlete population. Evidence for the involvement of the hip flexors and internal rotators was poor to weak at best. There was no evidence that these same risk factors would not be consistent with youth athletes, however there was no literature that allowed conclusions to be drawn relating to age or maturation. Given the retrospective nature of the studies, a casual relationship between hip strength and lower limb injury cannot be assumed. It was not possible to determine whether diminished hip strength was a cause or the result of the injuries. In addition, it is not known whether strength deficiencies were the result of injury-related muscle weakness, altered muscle-firing patterns, central inhibition, or unknown compensatory strategies.

Studies which investigated individuals with PFPS reported hip abductor muscle weakness between 11% to 20% compared to the non-injured side and 14% to 28% compared to non-injured controls (Baldon et al., 2009; L. Bolgla et al., 2008; Boling, Padua, & Creighton, 2009; Cichanowski et al., 2007; Ireland et al., 2003; Magalhães et al., 2010; Robinson & Nee, 2007; Willson & I., 2009). Magnitudes of effects for differences in hip abductor strength ranged from small (0.2) (Boling, Bolgla, Mattacola, Uhl, & Hosey, 2006) to extremely large (1.2) (Ireland et al., 2003). Only one study (S. Piva et al., 2005) reported no significant difference ($p = 0.016$) in hip abductor strength between PFPS and non-injured controls, however the calculated magnitude of the effect was large (ES = 0.5). Boling et al. (2009) reported a small (ES = 0.2) reduction in peak quadriceps and hamstrings concentric strength and a large (ES = 0.8) reduction in peak eccentric hip abductor strength for participants sustaining PFPS.

Studies which included measures of hip external rotator strength reported weaknesses of 7% (Cichanowski et al., 2007) compared to the non-injured side, and 15% (Willson & I., 2009) to 36% (Ireland et al., 2003) compared to non-injured controls. Magnitudes of the effects ranged from trivial (0.02) (Baldon et al., 2009) to extremely large (1.4) (Robinson & Nee, 2007). Both studies, which had trivial ES also detailed no significant differences in hip external rotator strength between individuals with PFPS and non-injured controls (Baldon et al., 2009).

Despite employing similar methodology to other studies, Piva et al. (2005) did not report significant differences in hip strength between those experiencing PFPS and age-matched, non-injured controls. The corresponding ES calculated for hip flexor strength was small (0.2). However, a moderate to large magnitude ES (0.5) was calculated for hip abductor strength.

Table 1: Studies evaluating the relationship between hip muscle strength and lower limb overuse injuries.

Study	Type and quality rating of study	Number, gender and mean age of subjects*	Athletic participation / competition	Type of injuries	Strength measured	Relevant results	Relevant effect sizes and strength of the evidence
Robinson et al.[(2007)]	Cross-sectional; Quality rating: 1	Injured: 10 F 21.0 y Control: 10 F 26.6 y	Not reported	PFPS	HA, HER, HExt	PFPS limbs had ↓ 52% HExt (p<001), 27% ↓ HA (p=0.007), and ↓ 30% HER strength (p=0.004) when compared to weakest limbs of controls.	HExt: 2.2, HA: 1.0, HER: 1.4 Strong evidence
Ireland et al.[(2003)]	Cross-sectional Quality rating: 1	Injured: 15 F 15.7 ±2.7 y Control: 15 F 15.7 ±2.7 y	Recreational level sport participation	PFPS	HA, HER	PFPS had ↓ 26% HA (23.3 ±6.9 vs 31.4 ±6.2 %BW; p<0.01) and ↓ 36% HER strength (10.8 ±4.0 vs 16.8 ±5.5 %BW; p<0.001) than controls.	HA: 1.2, HER: 1.2 Strong evidence
Cichanowski et al.[(2007)]	Cross-sectional Quality rating: 1	Injured: 13 F 19.3 ±1.1 y Control: 13 F 19.5 ±1.3 y	College female athletes	PFPS	HA, HAdd, HF, HExt, HIR, HER	PFPS had ↓14% HA (0.29 ±0.08 vs 0.33 ±0.07 Nm/kg; p=0.003) and ↓ 7% HER (0.17 ±0.04 vs 0.18 ±0.04 Nm/kg; p=0.049) strength than non-affected side. No differences between sides for HF, HExt, HAdd or HIR muscles. PFPS had ↓ 20% HF (0.27 ±0.07 vs 0.33 ±0.05 Nm/kg; p=0.033), ↓ 19% HExt (0.30 ±0.08 vs 0.36 ±0.05 Nm/kg; p=0.029), ↓ 27% HA (0.29 ±0.08 vs 0.37 ±0.06 Nm/kg; p=0.010) and ↓ 18% HIR (0.18 ±0.04 vs 0.21 ±0.03 Nm/kg; p=0.049) and ↓ 18% HER (0.17 ±0.04 vs 0.20 ±0.03 Nm/kg; p=0.033) strength than controls.	Injured side vs non-injured side - HA: 1.1, HER: 0.3, HF: 0.1 Injured vs control: HF, HExt, HIR & HER: 0.9, HA 1.1 Strong evidence
Bolgla et al.[(2008)]	Cross-sectional Quality rating: 1	Injured: 18 F 24.5 ±3.2 y Control: 18 F 23.9 ±2.8 y	Not reported	PFPS	HA, HER	PFPS had ↓ 24% HER (p=0.002) and ↓ 26% HA (p=0.006) strength than controls.	Calculation not possible
Willson et al.[(2009)]	Cross-sectional Quality rating: 1	Injured: 20 F 23.7 ±3.6 y Control: 20 F 23.3 ±3.1 y	Not reported	PFPS	HA, HER, KExt, KF Trunk Lat-Flex	PFPS had ↓ 15% HER (9.1 vs 10.8 %BW; p=0.04), ↓ 15% HA (21.1 vs 24.9 %BW; p=0.05) and ↓ 29% Trunk Lat Flex (16.1 vs 22.6 %BW; p=0.02) strength than controls.	HER: 0.7, HA: 0.6, KExt: 0.4, Trunk Lat-Flex: 0.8 Strong evidence
Magalhães et al.[(2010)]	Cross-sectional Quality rating: 1	Injured: 50 F 24.6 ±6.4 y Control: 50 F 24.1 ±6.3 y	Sedentary	PFPS	HIR, HER, HExt., HF, HA, HAdd	PFPS had ↓ 20% HA (11.7 ±4.2 vs 14.8±4.1 %BW; p<0.05) and ↓ 19% HF (16.3 ±6.0 vs 18.5±5.5 %BW; p<0.05) and ↓ 8% HER (12.7 ±4.1 vs 13.8±3.9 %BW; p<0.05) strength compared to the non-injured side (11.7 ±4.2 vs 14.5 %BW; p<0.05). PFPS had ↓ 12-36% strength for all muscles measured than controls (p<0.05).	Compared to non-injured side – HA: 0.7, HF: 0.4, HER: 0.3 Compared to controls: HIR: 0.2, HER: 0.5, HExt: 0.3, HF: 0.6, HA: 0.8, HAdd: 0.2 Strong evidence
Souza et al.[(2009a)]	Cross-sectional Quality rating: 1	Injured: 21 F 27 ±6 y Control: 21 F 27 ±6 y	Not reported	PFPS	HA, HExt	PFPS had ↓ 14% HA (1.39 ±0.41 vs 1.62 ±0.26 Nm/kg; p=0.02) and ↓ 17% HExt (1.98 ±0.50 vs 2.35 ±0.38 Nm/kg; p=0.005) strength compared to controls.	HA: 0.7, HExt: 0.8 Strong evidence

Table 1 cont: Studies evaluating the relationship between hip muscle strength and lower limb overuse injuries.

Study	Type and quality rating of study	Number, gender and mean age of subjects*	Athletic participation / competition	Type of injuries	Strength measured	Relevant results	Relevant effect sizes and strength of the evidence
Baldon et al.[2009]	Cross-sectional Quality rating: 1	Injured:10 F 22.9 ±5.2 y Control:10 F 23.9 ±2.3 y	Not reported	PFPS	HA, HAdd, HER, HIR	PFPS had ↓ 28% Ecc HA (88.9 ±10.3 vs 123.4 ±5.9 Nm/kg; p= 0.008) and ↓ 14% HAdd (171.0 ±13.4 vs 197.4 ±12.1 Nm/kg; p=0.009) torque compared to controls. No differences in Ecc HER (51.7 ±3.0 vs 51.5 ±3.8 Nm/kg; p=0.96) or HIR (113.3 ±8.3 vs 124.5 ±9.2 Nm/kg; p=0.47) rotation peak torque values between PFPS and control.	Ecc HA: 1.1, HAdd: 0.7, Ecc HER: 0.02, HIR: 0.4 Strong evidence
Piva et al.[2005]	Case control Quality rating: 1	Injured: 13 M & 17 F 25.8 ±6.0 y Control group: 13 M & 17 F 25.8 ±6.0 y	Not reported	PFPS	HA, HER	No significant differences in HER (22.0 ±4.3 vs 23.0 ±4.7 %BW; p=0.218) or HA strength (18.0 ±7.3 vs 21.0 ±4.0 %BW; p=0.016) between PFPS and uninjured controls .	HA: 0.5, HER: 0.2 Moderate evidence
Boling et al.[2009]	Case control Quality rating: 1	Injured: 7 M & 13 F 25.6 ±2.8 y Control: 7 M & 13 F 25.6 ±2.8 y	Not reported	PFPS	Conc peak - HA, HExt, HER; Ecc peak- HA, HExt, HER	PFPS had ↓ 27% peak Ecc HA torque (0.048 ±0.018 vs 0.061 ±0.015 Nm/kg; p=0.014) and ↓ 22% Conc (0.027 ±0.010 vs 0.033 ±0.013 Nm/kg; p=0.048) and ↓ 14% Ecc (0.035 ±0.012 vs 0.040 ±0.015 Nm/kg; p=0.032) HER torque compared to controls.	Conc peak – HA: 0.2, HER: 0.5; Ecc peak – HA: 0.8, HER: 0.4 Moderate evidence
Fredericson et al.[2000]	Case series Quality rating: 2	Injured: 14 M, 27.1 ±4.0 y & 10 F, 27.6 ±3.7 y Control: 16 M, 20.6 ±0.7 y & 14 F, 19.7 ±0.7 y	College or club distance runners	ITBFS	HA	Female runners with ITBFS had ↓ 25% HA torque in their injured leg (7.8 ±1.9 %BWh) vs their non-injured leg (9.8 ±3.0 %BWh) and ↓ 31% vs non-injured controls (10.2 ±1.1 %BWh). Male runners with ITBFS had ↓ 25% HA torque in their injured leg (6.9 ±1.2 %BWh) vs their non-injured leg (8.6 ±1.2 %BWh) and ↓ 31% vs non-injured controls (9.7 ±1.3 %BWh) (p<0.05).	Calculation not possible
Niemuth et al.[2005]	Cross-sectional Quality rating: 3	Injured: 13 M 40.6 y & 17 F 32.2 y; Control: 14 M 38.2 y & 16 F 38.6 y	Recreational runners	Running-related overuse	HA, HAdd, HF, HExt, HIR, HER	Non-injured runners hip muscle strength was similar to the non-injured leg of the injured runners. No side-to-side differences in hip muscle strength in control runners (p=0.62–0.93). For injured runners, the injured side had ↓ 11% HA (11.48 ±2.34 vs 12.83 ±2.31 Nm/Kg; p=0.0003) and ↓ 5% HF (10.80 ±2.06 vs 11.40 ±2.28 Nm/Kg; p=0.026) strength compared to non-injured side.	Injured side vs non-injured side - HA: 0.6, HF: 0.3 Moderate evidence

Abbreviations: ACL=anterior cruciate ligament; ADL=activities of daily living; Conc=concentric; Ecc=eccentric; EMG=electromyography; F=female; HA=hip abduction; HAdd=hip adduction; HExt=hip extension; HER=hip external rotation; HF=hip flexion; HIR=hip internal rotation; IKPD=Isokinetic pelvic drop; IMPD=isometric pelvic drop; ITB=iliotibial band; ITBFS=iliotibial band friction syndrome; ITEPD=isotonic endurance pelvic drop; KA=knee abduction; KExt=knee extension; KF=knee flexion; LL=lower limb; M=male; NMT=neuromuscular training; PFPS=patellofemoral pain syndrome; RCT=randomised controlled trial; ROM=range of motion; SLHA=side lying hip abduction Trunk Ext=trunk extension; Trunk Lat-Flex=trunk lateral flexion; vGRF=vertical ground reaction force; y=years; %BWh=percent body weight times height; ↓=reduced/decreased; ↑=increased/higher ***Study quality rating:*** (4) Controlled study, randomised subject allocation, subject and assessor blinding; (3) Controlled study, randomised subject allocation, subject or assessor blinding; (2) Controlled study, randomised subject allocation; (1) Controlled study; (0) Uncontrolled study. ***Note:*** SD are reported where studies provided this information. Some studies did not provide sufficient information to enable ESs to be calculated.

Only two studies measured hip flexor strength (Cichanowski et al., 2007; Magalhães et al., 2010). When hip flexor strength measures for individuals with PFPS were compared with non-injured controls, both groups of researchers returned similar strength deficits of 19% (ES = 0.6) (Magalhães et al., 2010) and 20% (ES = 0.9) (Cichanowski et al., 2007). When the same measures were compared to the non-injured side, Cichanowski et al. (2007) reported no strength differences (ES = 0.1), while Magalhães et al. (2010) reported a 19% deficit (ES = 0.4).

Two studies compared hip abductor muscle strength of runners suffering ITBFS (Fredericson et al., 2000) and running related overuse injuries (Niemuth et al., 2005) to that of non-injured runners. Fredericson et al.'s (2000) male and female runners with ITBFS had 25% less hip abductor strength on their injured side compared to their non-injured. Female runners exhibited a 31% hip abductor strength deficit compared to non-injured runners, where as males had a 40% deficit (Fredericson et al., 2000). Niemuth, et al. (2005) compared the differences in strength of all six muscle groups of the hip between injured and non-injured runners. Injured runners were diagnosed with either PFPS or ITBFS, but were also included if they had medial tibial stress syndrome, Achilles tendinopathy, plantar fasciitis, or lower leg stress fractures. Hip muscle strength for non-injured runners was similar to the non-injured leg of the injured runners, and there were no side-to-side differences in muscle strength for the control group. Compared with their non-injured counterparts, injured runners showed significant side-to-side weaknesses in muscle strength in two hip muscle groups, injured side hip abductors were 11% weaker and hip flexors 5% weaker than their non-injured side. Despite these differences being presented as statistically significant ($p=0.0003$ and 0.026 respectively), the magnitude of effect for the hip flexors was small (0.3) compared to the large effect for the hip abductors (0.6). No direct strength comparisons were made of specific muscle groups between injured and non-injured runners (Niemuth et al., 2005).

Evidence for altered lower limb alignment as a risk factor for lower limb overuse injuries

Excessive hip adduction and internal rotation during running has the potential to affect the kinematics of the entire lower limb, specifically to cause the knee joint centre to move medially relative to the foot. When the foot is fixed to the ground the inward movement of the knee joint causes the tibia to abduct and the foot to pronate with the end result being dynamic knee valgus. It is theorised that this altered alignment during running is a contributing factor to the development of numerous lower limb overuse injuries (Powers, 2010). The purpose of this section is to assess the evidence for altered lower limb alignment as a risk factor for lower limb injuries.

Characteristics and quality of the studies

Ten kinematic experimental studies were published that provide evidence for altered lower limb alignment being a risk factor for the development of lower limb overuse injuries, but only adult age participants were included in these studies (see Table 2) (L. Bolgla et al., 2008; Boling, Padua, Marshall, et al., 2009; Ferber, Noehren, Hamill, & Davis, 2010; McKenzie, Galea, Wessel, & M., 2010; Milner, Hamill, & Davis, 2010; Noehren et al., 2007; Souza & Powers, 2009a; Stefanyshyn, Stergiou, Lun, Meeuwisse, & Worobets, 2006; J. D. Willson & I. S. Davis, 2008; Willson & I., 2009). Only five studies examined either over-ground (Souza & Powers, 2009a, 2009b; Stefanyshyn et al., 2006; J. D. Willson & I. S. Davis, 2008) or treadmill (Dierks, Manal, Hamill, & Davis, 2008) running. Additional studies that examined lower limb three-dimensional (3D) kinematics and joint load kinetics during related tasks such as stair ascent/descent (L. Bolgla et al., 2008; McKenzie et al., 2010; Souza & Powers, 2009a), vertical drop jumps/landings (Souza & Powers, 2009a), and single leg jumps (J. D. Willson & I. S. Davis, 2008; Willson & I., 2009) were also included.

Similar to the research conducted on hip strength and overuse lower limb injuries, most studies which assessed lower limb alignment included participants with PFPS (L. Bolgla et al., 2008; Boling, Padua, Marshall, et al., 2009; McKenzie et al., 2010; Souza & Powers, 2009a; Stefanyshyn et al., 2006; J. D. Willson & I. S. Davis, 2008; Willson & I., 2009). A further three studies included participants with ITBFS (Ferber et al., 2010; Noehren et al., 2007) and tibial stress fractures (Milner et al., 2010). Four studies did not report the athletic participation of their participants (L. Bolgla et al., 2008; Souza & Powers, 2009a; J. D. Willson & I. S. Davis, 2008; Willson & I., 2009), while one study included recreational level athletes (McKenzie et al., 2010), one included military recruits (Boling, Padua, Marshall, et al., 2009), and four studies specifically assessed runners (Ferber et al., 2010; Milner et al., 2010; Noehren et al., 2007; Stefanyshyn et al., 2006). Two studies included both males and females in their sample (Boling, Padua, Marshall, et al., 2009; Stefanyshyn et al., 2006), while the remaining eight studies only included females (L. Bolgla et al., 2008; Ferber et al., 2010; McKenzie et al., 2010; Milner et al., 2010; Noehren et al., 2007; Souza & Powers, 2009a; J. D. Willson & I. S. Davis, 2008; Willson & I., 2009).

The majority of studies assessing lower limb alignment and overuse injuries were cross-sectional or case control studies. Three studies did not provide sufficient data to enable the calculation of ES (L. Bolgla et al., 2008; McKenzie et al., 2010; J. D. Willson & I. S. Davis, 2008). One study did not include control subjects, and therefore achieved a 0 quality rating (Boling, Padua, Marshall, et al., 2009). Eight studies scored a quality rating score of 1 (L. Bolgla et al., 2008; Ferber et al., 2010; McKenzie et al., 2010; Milner et al., 2010; Noehren et al., 2007; Souza & Powers, 2009a; J. D. Willson & I. S. Davis, 2008; Willson & I., 2009). One study included blinding of assessors, a control group and randomisation of participants, scoring a quality rating of 3 (Stefanyshyn et al., 2006).

Strength of the evidence and key results from the studies

There were a substantial number of studies with moderate ES supporting the suggestion that injured athletes exhibit greater hip adduction motion during dynamic tasks. Although six studies specifically analysed kinematics during running, many used other dynamic tasks. No study directly compared running with tasks similar in demands to running (e.g. stair climbing), therefore the results from these studies must be interpreted with caution.

There were a small number of studies (Boling, Padua, Marshall, et al., 2009; Souza & Powers, 2009a) with moderate ES supporting increased hip adduction and hip internal rotation in injured athletes. Some studies reported that injured athletes demonstrate altered kinetics, such as abduction impulse (Stefanyshyn et al., 2006) and hip external rotation moment (Boling, Padua, Marshall, et al., 2009) which could lead to altered kinematics during demanding tasks. However, there has not been sufficient research to make any firm conclusions. There was no evidence that these same risk factors would not be consistent with youth athletes, however there was no literature that allowed conclusions to be drawn relating to age or maturation.

In one of the few prospective epidemiologic studies of runners, Stefanyshyn et al. (2006) quantified the type and severity of injuries sustained over a six-month period. Kinematic and kinetic data were collected on 145 runners at the beginning of the summer running season and on 83 runners six months later. Six runners who developed PFPS over this period had knee abduction impulses that were on average 19% higher than those in the remaining runners who did not develop PFPS (ES = 0.4). These differences were not significantly different, however, they were confounded by various factors such as runners developing other running-related injuries (e.g. ITBFS and tibial stress syndrome). When the PFPS runners were matched with non-injured controls they exhibited a 97% higher knee abduction impulse before injury than the controls (ES = 1.2).

Using a cross-sectional case control design, McKenzie et al. (2010) assessed female athletes with and without PFPS performing continuous stair ascent and descent for three minutes at two speeds. PFPS patients had greater knee flexion during slow-speed stair stepping and greater hip adduction and internal rotation during stair descent than age-matched healthy controls. Sufficient data were not provided to enable calculation of effect sizes.

A further two cross-sectional studies analysed hip strength measures and hip and knee kinematics during jump/landing (Willson & I., 2009) and stair stepping movements (L. Bolgla et al., 2008) for females with and without PFPS. Despite both groups reporting significantly reduced hip muscle strength in participants with PFPS than without PFPS, only Willson et al. (2009) reported greater hip adduction excursion (ES = 0.7) and hip abduction impulses (ES = 0.5) for PFPS subjects. However, the association between the strength measurements and lower limb mechanics was low (*r* = 0.02-0.13). Bolgla et al. (2008) reported no differences in average hip and knee transverse and frontal plane angles during stair descent between 18 females diagnosed with PFPS and 18 matched controls. However, the selected task might not have been challenging enough for differences in kinematics to arise.

Two studies examined hip and knee kinematics in subjects with and without PFPS during progressively challenging tasks (step-down, single-leg squat, drop jump, running, and repeated single-leg jumping) (Souza & Powers, 2009a; J. D. Willson & I. S. Davis, 2008). Willson et al. (2008) reported that irrespective of the activity, PFPS participants exhibited greater hip adduction and hip external rotation range of motion (ROM) than controls. Sufficient data to enable the calculation of ES were not published.

Souza et al. (2009a) reported participants with PFPS demonstrated on average 6.4° greater peak hip internal rotation ROM than non-injured controls for running, as well as drop jump and step-down manoeuvres (ES = 1.1). The largest difference in peak hip internal rotation occurred during running (ES = 1.4). Despite a 15% deficit in hip abductor strength there was no subsequent increase in hip adduction motion during the tasks evaluated. Increases in hip internal rotation ROM, but no significant change in hip abduction, were in contrast to the results of Willson et al. (2008), but in partial agreement with those presented by Bolgla et al. (2008) However, the task evaluated by Bolgla et al. (2008) may not have been of sufficient demand to elicit differences in hip kinematics.

Noehren et al. (2007) conducted a prospective study of 400 female runners to establish the evidence for altered lower limb alignment at the development of ITBFS. Bilateral 3D lower limb kinematics and kinetics were collected during running, and running related injuries for two years. Eighteen runners developed ITBFS during this period, and these participants were matched with age and mileage equivalent non-injured runners as controls. The injured leg of the ITBFS group was compared to the right leg of the control group. Strongest predictors of individuals who developed ITBFS were excessive stance phase knee internal rotation (ES = 0.9) and hip adduction ROM (ES = 0.3). However, the calculated magnitude of the effect for hip adduction ROM was only small to moderate (Noehren et al., 2007). Ferber et al. (2010) also reported in a cross-sectional study that female runners with a history of ITBFS exhibited, on average, a 2.5° greater stance phase peak hip adduction ROM (ES = 0.5), and a 2.9° greater peak knee internal rotation ROM (ES = 0.5), compared to those with no injury history. Greater peak hip internal rotation and adduction during the stance phase of running were thought to be associated risk factors for the development of ITBFS.

Table 2: Studies evaluating the relationship between lower limb alignment and overuse injuries.

Study	Type of study	Number, gender and age (years) of subjects	Athletic participation / competition	Type of injuries	Task or activity	Relevant results	Relevant effect sizes and strength of the evidence
Stefanyshyn et al.[2006]	Prospective case control Quality rating: 3	Prospective: 41 M 39.8 ±8.9 y; 39 F 35.9 ±8.0 y. PFPS: 3 M; 3 F.	Experienced recreational runners	PFPS	Overground running	PFPS had ↑ KA impulses than matched controls (9.2 ±3.7 vs 4.7 ±3.5 Nms; p=0.042).	KA impulse - PFPS to all uninjured: 0.4, Matched controls: 1.2 Strong evidence
McKenzie et al.[2010]	Cross-sectional Quality rating: 1	Injured: 10 F 23.5 ±3.4 y Control: 10 F 22.3 ±2.4 y	Recreational athletes	PFPS	Stair ascent and descent	PFPS had ↑ HAdd ROM across both tasks and ↑ HIR ROM during stair descent compared to controls (p<0.05).	Calculation not possible
Bolgla et al.[2008]	Cross-sectional Quality rating: 1	Injured: 18 F 24.5 ±3.2 y Control: 18 F 23.9 ±2.8 y	Not reported	PFPS	Stair descent	No between-group differences for average hip and knee transverse and frontal plane angles during stair descent (p>0.5). PFPS had similar HIR (2.1° vs 1.0°, p=0.67) and HA (1.0° vs 2.6°; p=0.15) to controls during stair descent.	Calculation not possible
Willson et al.[2009]	Case control Quality rating: 1	Injured: 20 F 23.7 ±3.6 y Control: 20 F 23.3 ±3.1 y	Not reported	PFPS	Single leg jumps	PFPS had ↑ 2.3^{o} HAdd excursion than control (p=0.05). No correlations between strength and joint excursion (r = -0.12 to 0.13), or strength and angular impulses (r = -0.27 to 0.31).	HAdd ROM: 0.7 Strong evidence
Willson et al.[2008]	Cross-sectional Quality rating: 1	Injured: 20 F 23.7 ± 3.6 y Control: 20 F 23.3 ± 3.1 y	Not reported	PFPS	Single leg squats, running, and repetitive single leg jumps	PFPS performed all three activities with ↑ 4.3^{o} knee external rotation (p=0.06), ↑ 3.5^{o} HAdd (p=0.012), and ↓ 3.9^{o} HIR (p=0.01) compared to controls.	Calculation not possible
Souza et al.[2009a]	Cross-sectional Quality rating: 1	Injured: 21 F 27 ±6 y Control: 21 F 27 ±6 y	Not reported	PFPS	Drop jump, step-down and running	Averaged across all three activities, females with PFPS had ↑ peak HIR ROM compared to control (7.6 ±7.0^{o} vs 1.2 ±3.8^{o}; p<0.001).	Peak HIR (average all 3 activities): 1.1 Peak HIR (running): 1.4 Strong evidence
Noehren et al.[2007]	Prospective Quality rating: 1	Injured: 18 F 26.8 y Control: 18 F 28.5 y	Recreational runners	ITBFS	Treadmill running	ITBFS had ↑ peak HAdd (14.1 ±25° vs 10.6 ±5.1°; p=0.01) and knee internal rotation (3.9 ±3.7° vs 0.02 ±4.6°;p=0.01) ROM. No differences in rearfoot eversion, knee flexion or moments between groups.	Peak HAdd ROM: 0.3; Peak KIR ROM: 0.9 Moderate evidence
Ferber et al.[2010]	Cross-sectional Quality rating: 1	Injured: 35 F 35.5 ±10.4 y Control: 35 F 31.2 ±11.1 y	Competitive female runners	ITBFS	Overground running	ITBFS had ↑ 2.89^{o} peak knee internal rotation angle (1.75 ±5.94^{o} vs 2.89 ±0.98^{o}; p=0.03), and ↑ 2.47^{o} HAdd angle (10.39 ±4.36^{o} vs 7.92 ±5.84^{o}; p=0.05) compared to controls.	KIR ROM:0.5. HAdd ROM: 0.5 Moderate evidence

Table 2 cont: Studies evaluating the relationship between lower limb alignment and overuse injuries.

Study	Type of study	Number, gender and age (years) of subjects	Athletic participation / competition	Type of injuries	Task or activity	Relevant results	Relevant effect sizes and strength of the evidence
Milner et al.(2010)	Cross-sectional Quality rating: 1	Injured: 30 F 28 ±10 y Control: 30 F 26 ±9 y	Distance runners	Tibial stress fracture	Overground running	Stress fracture group had ↑ 2.7° peak rearfoot eversion compared to control (11.7 ±4.2° vs 9.0. ±3.9°; p=0.015). ↑ peak HAdd (11.5 ±5.0° vs 8.1 ±6.1°; p=0.004) in tibial stress fracture group.	Peak angles – Rearfoot eversion: 0.7, HAdd: 0.8 Strong evidence
Boling et al.(2009)	Prospective cohort Quality rating: 0	606 F & 919 M (age not stated)	US Military recruits	PFPS	Jump-landing task	40 participants developed PFPS during the study. PFPS risk factors included ↓ KFlex torgue (p=0.02), ↓ vGRF (p=0.02), and ↑ HIR angle (p=0.04).	Moments – HA: 0.1, HER: 0.5, KExt 0.4, KA: 0.0, vGRF: 0.4 Kinematics: HF: 0.2 HAdd: 0.1, HIR: 0.04, KF: 0.3, KA: 0.06, KIR: 0.3 Moderate evidence

Abbreviations: ACL=anterior cruciate ligament; ADL=activities of daily living; Conc=concentric; Ecc=eccentric; EMG=electromyography; F=female; HA=hip abduction; HAdd=hip adduction; HExt=hip extension; HER=hip external rotation; HF=hip flexion; HIR=hip internal rotation; IKPD=Isokinetic pelvic drop; IMPD=isometric pelvic drop; ITB=iliotibial band; ITBFS=iliotibial band friction syndrome; ITEPD=isotonic endurance pelvic drop; KA=knee abduction; KExt=knee extension; KF=knee flexion; LL=lower limb; M=male; NMT=neuromuscular training; PFPS=patellofemoral pain syndrome; RCT=randomised controlled trial; ROM=range of motion; SLHA=side lying hip abduction Trunk Ext=trunk extension; Trunk Lat-Flex=trunk lateral flexion; vGRF=vertical ground reaction force; y=years; %BWh=percent body weight times height; ↓=reduced/decreased; ↑=increased/higher ***Study quality rating:*** (4) Controlled study, randomised subject allocation, subject and assessor blinding; (3) Controlled study, randomised subject allocation, subject or assessor blinding; (2) Controlled study, randomised subject allocation; (1) Controlled study; (0) Uncontrolled study. ***Note:*** SD are reported where studies provided this information. Some studies did not provide sufficient information to enable ESs to be calculated.

A single cross-sectional study by Milner et al. (2010) investigated the kinematics of the hip, knee and rearfoot in female distance runners with a history of tibial stress fracture. While peak values during stance were similar at the knee and tibia between the groups, runners with a previous tibial stress fracture exhibited on average a 3° greater peak hip adduction (ES = 0.8) and 2.7° greater rearfoot eversion angles (ES = 0.7) during the stance phase of running, compared to healthy controls. A consequence of these mechanics may be an alteration in the relationship between torsional and axial loading of the tibia resulting in increasing susceptibility to stress fracture (Milner et al., 2010).

In the first large-scale prospective investigation to assess potential biomechanical risk factors for PFPS, Boling et al. (2009) measured lower limb strength and kinematics during a jump-landing task from 1,597 military recruits and followed them for two and a half years. Forty participants developed PFPS during the study and through regression analysis the authors were able to determine that the risk factors included decreased knee flexion and hip internal rotation angle, and decreased vertical ground-reaction force during the jump-landing task. This was in addition to decreased quadriceps and hamstring strength, and increased hip external rotator strength for the participants that developed PFPS. While some of these variables appear different to those presented in many other studies, the authors developed a conceptual model for how the described risk factors could potentially interact to lead to PFPS as part of their research (Boling, Padua, Marshall, et al., 2009). Two multivariate models were developed, based on findings from domain-specific Poisson regression models. Each model significantly predicted the development of PFPS ($p < 0.05$). The kinematics/kinetics/posture model included hip internal rotation angle, knee flexion angle, vertical ground-reaction force, navicular drop, and gender. The muscle strength/posture model included knee flexion peak torque, knee extension peak torque, hip external rotation peak torque, navicular drop, and gender. Navicular drop was the one of the most predictive variables. The authors provided the following interpretation of the models: "Based on model 1, the rate of development of PFPS was 3.4 times greater for the subjects with navicular drop at the 90th percentile (10.7 mm) relative to those at 10th percentile (4.0 mm) when adjusting for all other variables in the model. Additionally, the rate of development of PFPS was 3.1 (RR: 0.32-1) times greater for the people with knee flexion angle at the 10th percentile (63.2°) relative to those at the 90th percentile (99.5°) when adjusting for all other variables in the model (2009)." The finding of decreased vertical ground-reaction force is somewhat counter-intuitive and not in agreement with theorised risk factors, However, despite additional analysis specifically to address this, the authors did not establish an explanation.

Evidence for a relationship between hip muscle strength and lower limb alignment

Electromyography has shown that the gluteus medius muscle and also the tensor fascia lata, are active during the stance phase of running, corresponding to a hip abduction moment (R. A.

Mann, G. T. Moran, & S. E. Dougherty, 1986). It is possible that when weakness exists in the hip muscles of runners, the lower limbs may not be optimally aligned, leading to increased hip adduction, hip internal rotation and pelvic drop. The purpose of this section is to assess the evidence for a relationship between hip muscle strength and lower limb alignment during running in youth athletes.

Characteristics and quality of the studies

Eleven studies investigated the evidence for a relationship between hip muscle strength and lower limb alignment (see Table 3) (Carcia, Eggen, & Shultz, 2005; Dierks et al., 2008; Geiser, O'Connor, & Earl, 2010; Heinert, Kernozek, Greany, & Fater, 2008; Herman et al., 2008; Lawrence, Kernozek, Miller, Torry, & Reuteman, 2008; Myer, Ford, Palumbo, & Hewett, 2005; Pollard, Sigward, Ota, Langford, & Powers, 2006; Sigward, Ota, & Powers, 2008; Snyder, Earl, O'Connor, & Ebersole, 2009; Souza & Powers, 2009b). No studies specifically assessed youth athletes. Three studies focused their sample on teenagers (Myer et al., 2005; Pollard et al., 2006; Sigward et al., 2008; Snyder et al., 2009), while the remainder included only adults (Carcia et al., 2005; Dierks et al., 2008; Geiser et al., 2010; Heinert et al., 2008; Herman et al., 2008; Lawrence et al., 2008; Myer et al., 2005; Snyder et al., 2009; Souza & Powers, 2009b). Only five studies assessed lower limb kinematics during running (Dierks et al., 2008; Geiser et al., 2010; Heinert et al., 2008; Snyder et al., 2009; Souza & Powers, 2009b), seven included a jump-landing task (Carcia et al., 2005; Geiser et al., 2010; Herman et al., 2008; Lawrence et al., 2008; Myer et al., 2005; Pollard et al., 2006; Sigward et al., 2008), while one assessed cutting (Geiser et al., 2010). Seven of these studies measured hip abductor strength (Carcia et al., 2005; Dierks et al., 2008; Geiser et al., 2010; Heinert et al., 2008; Lawrence et al., 2008; Sigward et al., 2008; Souza & Powers, 2009b), four measured the hip external rotators (Dierks et al., 2008; Lawrence et al., 2008; Sigward et al., 2008; Souza & Powers, 2009b), and two the hip extensors (Sigward et al., 2008; Souza & Powers, 2009b). The additional four studies assessed the kinematics of non-injured participants before and after they took part in 6 to 9 week-long neuromuscular training programme which included a hip strengthening component (Herman et al., 2008; Myer et al., 2005; Pollard et al., 2006; Snyder et al., 2009).

Ten studies included recreationally active, college or high school athletes (Carcia et al., 2005; Geiser et al., 2010; Heinert et al., 2008; Herman et al., 2008; Lawrence et al., 2008; Myer et al., 2005; Pollard et al., 2006; Sigward et al., 2008; Snyder et al., 2009; Souza & Powers, 2009b), while one study specifically assessed runners (Dierks et al., 2008). One study included both males and females in their sample (Dierks et al., 2008), while the remaining ten studies only included females (Carcia et al., 2005; Geiser et al., 2010; Heinert et al., 2008; Herman et al., 2008; Lawrence et al., 2008; Pollard et al., 2006; Sigward et al., 2008; Souza & Powers, 2009b). Two studies did not provide sufficient data to enable the calculation of ES (Dierks et al., 2008; Sigward et al., 2008). Four studies received a rating score of 1 (Dierks et al., 2008;

Heinert et al., 2008; Myer et al., 2005; Souza & Powers, 2009b), while one study scored 2 (Herman et al., 2008) and another 3 (Lawrence et al., 2008).

Strength of the evidence and key results from the studies

Based on the effect size calculations there was some weak evidence that a relationship exists between reduced hip muscle strength and abnormal lower limb alignment during running. However, the results of these studies were varied, and it was therefore not possible to make any firm conclusions about this relationship, or whether there was a stronger relationship between specific hip muscle groups and abnormal lower limb motion. There was no evidence that a similar relationship would not exist with youth athletes, however there was no literature that allowed conclusions to be drawn relating to age or maturation.

Excessive hip internal rotation motion may contribute to patellofemoral joint misalignment and increased patellofemoral joint stress (Powers, 2003), with this dysfunction possibly linked with reduced hip muscle strength (Ireland et al., 2003; Powers, 2003). However, greater degrees of femoral inclination and femoral valgus, as well as hip muscle moment arms, are also thought to influence lower limb alignment (Arnold, Komattu, & Delp, 1997; Powers, 2003). Using 3D motion analysis and dynamic magnetic resonance imaging (MRI), Souza et al. (2009b) found that women with PFPS demonstrated decreased hip-muscle strength (ES = 0.7 to 1.1), increased average hip internal rotation during running (ES = 1.5), and differences in femoral structure (greater femoral inclination) (ES = 0.9) compared to non-injured participants during a running task. Regression analysis revealed that isotonic hip extension endurance was the best predictor of average hip internal rotation (r = –0.45) (Souza & Powers, 2009b).

Two groups of researchers assessed lower limb mechanics of non-injured female athletes completing either a single (Lawrence et al., 2008) or double leg (Sigward et al., 2008) drop landing. Based on hip external rotator strength values, Lawrence et al. (2008) ranked participants in order of ascending strength (top 22% = “stronger”; lower 22% = “weaker”). Stronger females exhibited lower vertical ground reaction forces (ES = 0.1) and generated lower external knee valgus moments (ES = 0.8) when landing. Despite reporting average knee frontal plane angles similar to other studies during the same drop landing task, (Ford, Myer, & Hewett, 2003) Sigward et al. (2008) did not replicate these positive findings. Of the six clinical measures evaluated, only hip external rotation and ankle dorsiflexion ROM were predictors of frontal plane knee excursion in 81 non-injured participants. These variables only accounted for 27% of the variance in frontal plane knee excursion. No relationships between hip strength and knee valgus angles or moments were revealed (Sigward et al., 2008). The relationship between hip muscle strength, abnormal kinematics and the development of injury may not be as simple as first thought. Noehren et al. (2007) and Ferber et al. (Ferber et al., 2010) also reported that females with a history of ITBFS demonstrated approximately 30% greater peak hip adduction motion during running despite having essentially identical hip abductor torque profiles as females without prior knee injury.

Two studies measured the effect of isolated hip abductor muscle fatigue on frontal plane lower limb mechanics (Carcia et al., 2005; Geiser et al., 2010). Carcia, et al. (2005) measured kinematics from 20 recreationally active college age students during a drop landing pre- and post-fatigue. Although students in this study landed with their knees in more of a valgus orientation bilaterally than in the non-fatigued condition, they did not significantly differ between conditions for maximum frontal plane angle (right ES = 0.05; left ES = 0.01) or total excursion (right ES = 0.2; left ES = 0.1).

Using a similar fatigue protocol to Carcia et al. (2005), Geiser et al. (2010) fatigued the hip abductor muscles of 20 active participants to assess the effect on frontal plane kinematics during tasks of increasing demand. Regardless of task the knee underwent greater abduction ROM (ES: cut = 0.8; jump = 0.9; run = 0.7) and there were greater internal knee adductor moments during the weight acceptance phase of stance after fatigue (ES: cut = 0.4; jump = 0.5; run = 0.7) (Geiser et al., 2010). Although there was a consistent increase in ROM with hip abductor fatigue, these results were not necessarily consistent with those reported by Carcia et al. (2005) or Stefanyshyn et al. (2006). It is possible that the different findings are potentially a result of the variation in equipment used, tasks assessed and participant characteristics.

In a cross-sectional study, Dierks et al. (2008) investigated the relationship between hip muscle strength and lower limb mechanics before and after a prolonged treadmill run in 20 runners with PFPS and 20 non-injured runners. The duration of the prolonged run was determined by an individual's perceived fatigue, actual fatigue or pain. For all runners, prior to the run, only a fair correlation (r = -0.34) between hip abductor strength and peak hip adduction ROM was reported. However, after prolonged running, runners with PFPS demonstrated a larger inverse correlation (r = -0.74) between hip abductor strength and peak hip adduction. No significant relationship between hip abductor strength and hip adduction angle was seen for the non-injured runners post-run (r = 0.051; p = 0.208). In addition, no association was established between hip external rotator weakness and peak hip internal rotation (r = 0.012). Therefore, participants with PFPS might not exhibit altered hip kinematics until their muscle strength falls below a certain threshold, suggesting that potentially muscle strength endurance and the ability to delay the onset of fatigue play more of a role that just maximal, non-fatigued muscle strength.

As the result of an observational prospective study, Heinert et al. (2008) indicated that hip abductor weakness may influence the knee abduction angle during stance. After an initial screening of hip abductor strength, recreational college athletes were divided into 'strong' and 'weak' hip abductor groups, before undergoing kinematic analysis during treadmill running. The weak hip abductor group had approximately 4° greater knee abduction at initial contact of the stance phase of running than the strong hip abductor group (ES = 0.8). The weak group also maintained a position of knee abduction throughout stance (ES = 0.8 to 0.9). These results support the notion that from initial contact through to early stance when tensor fascia lata is most active, the placement of the knee in relative abduction during running may produce increased tension on the ilio-tibial band (ITB). This could predispose runners to knee pain due to abnormal patella pressures (Heinert et al., 2008).

A further three studies investigated the effect of hip strengthening/neuromuscular control training programmes on frontal plane lower limb mechanics with non-injured participants undertaking jumping/landing tasks (Herman et al., 2008; Myer et al., 2005; Pollard et al., 2006). Pollard et al. (2006) revealed that after a season of injury prevention training, players demonstrated significantly less hip internal rotation excursion (ES = 0.7) and significantly greater hip abduction excursion (ES = 0.6), but no differences in knee valgus angles. Despite the lack of statistical significance reported by the authors, the calculated magnitude of effect for knee valgus ROM was very large (ES = 1.9).

Myer et al.'s (2005) 41 high-school age athletes did not demonstrate any changes in frontal plane kinematics when landing after participating in a 6-week neuromuscular training programme, but did show a 26% and 38% reductions in right knee valgus (ES = 3.7) and varus (ES = 3.3) frontal plane torques at the knee. Despite the differences on the right side, the left knee varus and valgus torques were not significantly different, and sufficient data to calculate ES for the left side were not published.

Using a slightly more robust research design, incorporating a randomly allocated control group, Herman et al. (2008) also reported no significant changes in either hip or knee kinematics after a 9-week strength training programme (ES = 0.1 to 0.2) in recreational athletes. This was despite participants in the intervention group demonstrating 35-48% strength improvements in target muscles. The researchers also reported no significant differences in knee or hip kinetics between groups, however a moderate magnitude of effect was calculated for the hip adduction moment (ES = 0.4).

Only one study investigated the impact of a 6-week hip strengthening/neuromuscular training programme on lower limb mechanics during over-ground running in 13 non-injured participants (Snyder et al., 2009). The researchers hypothesised that increased hip abductor and external rotator strength would decrease frontal and transverse plane lower limb motion during running. Snyder et al. (2009) reported a significant 9.5% reduction in knee abduction moment, which equated to a moderate effect size (ES = 0.5) after the intervention programme. The 29% reduction in hip internal rotation ROM equated to a moderate effect size (ES = 0.4), even though the authors reported a statistically insignificant trend. A 17% increase in hip adduction

ROM (ES = 0.3) for running was reported as an insignificant trend, which was contrary to the original hypothesis.

Table 3: Studies evaluating the relationship between hip strength and lower limb mechanics.

Study	Type of study	Number, gender and age (years) of subjects	Athletic participation / competition	Strength measured	Task or activity	Relevant results	Relevant effect sizes and strength of the evidence
Souza et al.(2009b)	Cross-sectional Quality rating: 1	Injured: 19 F 27 ±6 y Control: 19 F 26 ±4 y	Recreationally active	IMPD, HER, HExt, SLHA; IKPD (Conc & Ecc), HExt (Conc & Ecc); ITEPD, HExt	Over-ground running	PFPS had ↑ HIR ROM, (8.2 ±6.6° vs 0.3 ±3.6°; p<0.001), ↓ hip strength measurements (8 of 10), and ↑ femoral inclination (132.8 ±5.2° vs 128.4 ±5.0°; p=0.011) compared with controls.	HIR ROM: 1.5 Strength – 0.7 to 1.1 Femoral inclination: 0.9 Strong evidence
Lawrence et al.(2008)	Cross-sectional Quality rating: 3	Strong group: 16 F 22.9 ±2.6 y Weak group: 16 F 20.4 ±2.1 y	Recreational athletes from a range of sports	HER, HA, KFlex, KExt	Vertical drop landing (single leg)	Weak group had ↑ 78% vGRF (2.9 ±0.1 vs 1.6 ±1.2 Nm/kg % body mass, p=0.001) KA (-0.99 ±0.50 vs -0.55 ±0.61 Nm/kg of body mass, p=0.021), KF (0.99 ±0.94 vs 1.24 ±0.66 Nm/kg of body mass, p=0.021) and HAdd (1.42 ±0.80 vs 0.75 ±0.50 Nm/kg of body mass, p=0.003) moments. No differences in sagittal or frontal kinematics.	vGRF: 1.1 Moments – KF: 0.3, HA: 1.0, KA: 0.8, Kinematics - HAdd: 0.5 Strong evidence
Sigward et al.(2008)	Cross-sectional Quality rating: 0	39 F 15.5 ±1.0 y	High school soccer players	HA, HER HExt	Vertical drop landing (double leg)	HER ROM (r = –0.40, p=0.005) and ankle dorsi-flexion ROM (r = –0.27, p=0.05) were negatively correlated with frontal plane knee excursion. HER ROM and ankle dorsi-flexion ROM accounted for 27% of frontal plane knee excursion variance (p =0.03). No relationships between hip strength and frontal plane knee excursion.	Calculation not possible
Carcia et al.(2005)	Pre-post-test experimental Quality rating: 0	10 M &10 F 24.0 ±2.8 y	Active college students	HA	Vertical drop jump (double leg)	No differences in frontal-plane knee excursion (0.65° right & 0.07° left, p=0.286 & 0.996) or vGRF (3.64 ±0.77 vs 3.71 ±0.76 x body weight, p=0.549) pre and post fatigue.	Knee angles- Max frontal plane – R: 0.05, L: 0.01, Frontal plane excursion – R: 0.2, L: 0.1. vGRF – 0.1 No evidence
Geiser et al.(2010)	Pre-post-test experimental Quality rating: 0	20 F 20.7 ±1.7 y	Recreationally active	HA	Cutting, jumping and running	Regardless of task, ↑ KAdd angle at initial contact (pre =0.7° vs post =1.2°; p=0.032) and ↑ KAbd ROM (pre =0.7° post =2.1°; p< 0.001) post fatigue.	KAdd angle at initial contact: 0.2, KAbd ROM: 0.9 Moderate evidence
Dierks et al.(2008)	Cross-sectional Quality rating: 1	Injured: 5 M & 15 F 24.1 ±7.4 y Control: 5 M & 15 F 22.7 ±5.6 y	Recreational runners	HA, HER	Treadmill running (prolonged)	PFPS had ↓ HA strength compared to controls both before and after the prolonged run (p=0.045). Control peak HAdd angle was 11.8 ±3.9° pre- and 12.0 ±4.3° post-run. PFPS had 8.7 ±5.2° pre- and 8.8 ±5.7°. A significant main effect for group (p= 0.044). HA strength was related to peak HAdd angle (r = –0.74), but only post-run for PFPS (p=0.05).	Calculation not possible
Heinert et al.(2008)	Observational prospective Quality rating: 1	Strong group: 15 F 25.8 ±6.7 y Weak group: 15 F 23.4 ±2.8 y	Recreational college athletes	HA	Treadmill running	Weak group had ↑ 4° KA angle compared to strong group at initial contact (p=0.008) and maintained this difference through stance. No significant differences in KFlex (p=0.83), HF (p=0.10), HA (p =0.13) ROM, or pelvic tilt (p= .055) between weak and strong groups.	KA angle – IC: 0.8, Minimum: 0.8, Toe-off: 0.9 Weak evidence

Table 3 cont: Studies evaluating the relationship between hip strength and lower limb mechanics.

Study	Type of study	Number, gender and age (years) of subjects	Athletic participation / competition	Programme details	Task or activity	Relevant results	Relevant effect sizes and strength of the evidence
Pollard et al.[(2006)]	Longitudinal pre-post intervention study Quality rating: 0	18 F 14.9 y	Football	A season long (duration not defined) structured warm-up programme including flexibility, strengthening, plyometric and agility exercises.	Jump landing	Post-intervention ↓ HIR ROM (7.1 ±6.8° vs -1.9 ±7.8°; p=0.01) and ↑ HA ROM (-4.9 ±4.0° vs -7.7 ±4.7°;p=0.02) than pre-intervention.	Kinematics: HA: 0.6, HIR: 0.7, KA: 1.9 Strong evidence
Myer et al.[(2005)]	Non-randomised controlled repeated-measures Quality rating: 1	Intervention: 41 F 15.3 ±0.9 y Control: 41 F 16.5 ±1.0 y	Basketball, soccer and volleyball	6-week NMT programme including plyometrics and movement training, core strengthening, balance and interval speed training. Controls did no training.	Jump landing	Intervention ↓ 28% right knee valgus (60.4 ±5.5 Nm vs 43.4 ±3.3 Nm; p<0.001) and ↓ 38% varus torque (34.0 ±2.8 Nm vs 21.1 ±1.7 Nm; p<0.001) than control during box drop landing. Left knee varus and valgus torques were not different (p= 0.08 & p= 0.09).	Right side knee torque – Internal valgus: 3.7, Internal varus: 5.5. Calculation of left side ES not possible Strong evidence
Herman et al.[(2008)]	RCT Quality rating: 2	Intervention: 33 F 22.5 ±2.3 y Control: 33 F 22.5 ±3.8 y	Recreational athletes	9-week strength training programme targeting quadriceps, hamstrings, HA and gluteus maximus. Controls did no training.	Stop-jump task	Intervention group ↑ strength in all muscles (35% to 48%) (p>0.001). No differences in knee and hip kinematics or kinetics between groups pre- post-intervention (p>0.05).	Kinematics - KF: 0.1, KA: 0.2, HF: 0.2 Moments: KExt: 0.2, KA: 0.2, HAdd: 0.4, HIR: 0.1 No evidence
Snyder et al.[(2009)]	Within subject, repeated measures Quality rating: 0	15 F 21.9 ±1.2 y	Moderately active	6-week strengthening programme incorporating closed-chain hip rotation exercises.	Over-ground running	Post-intervention had ↑ HAdd ROM (8.1 ±4.1° vs 9.5 ±4.8°; p=0.05), ↓ HIR ROM (5.5 ±3.7° vs 4.2 ±2.9°; p=0.08) and ↓ KAbd moment (82.8 ±17.4 Nm vs 74.9 ±16.1 Nm; p=0.05) than pre-intervention.	HAdd ROM: 0.33, HIR ROM: 0.43 KAbd moment: 0.48 Weak evidence

Abbreviations: ACL=anterior cruciate ligament; ADL=activities of daily living; Conc=concentric; Ecc=eccentric; EMG=electromyography; F=female; HA=hip abduction; HAdd=hip adduction; HExt=hip extension; HER=hip external rotation; HF=hip flexion; HIR=hip internal rotation; IKPD=Isokinetic pelvic drop; IMPD=isometric pelvic drop; ITB=iliotibial band; ITBFS=iliotibial band friction syndrome; ITEPD=isotonic endurance pelvic drop; KA=knee abduction; KExt=knee extension; KF=knee flexion; LL=lower limb; M=male; NMT=neuromuscular training; PFPS=patellofemoral pain syndrome; RCT=randomised controlled trial; ROM=range of motion; SLHA=side lying hip abduction Trunk Ext=trunk extension; Trunk Lat-Flex=trunk lateral flexion; vGRF=vertical ground reaction force; y=years; %BWh=percent body weight times height; ↓=reduced/decreased; ↑=increased/higher. ***Study quality rating:*** (4) Controlled study, randomised subject allocation, subject and assessor blinding; (3) Controlled study, randomised subject allocation, subject or assessor blinding; (2) Controlled study, randomised subject allocation; (1) Controlled study; (0) Uncontrolled study. ***Note:*** SD are reported where studies provided this information. Some studies did not provide sufficient information to enable ESs to be calculated.

Evidence for hip strengthening and lower limb alignment as intervention strategies to reduce the risk of lower limb overuse injuries

There was some evidence that faulty lower limb kinematics during running were contributing factors in the etiology of overuse injuries in adults. A programme designed to address these factors has the potential to alter lower limb mechanics and reduce or prevent lower limb injuries.

Given the growing body of clinical and biomechanical literature devoted to the role of the hip musculature in controlling the lower limb and evidence of an association between hip function and injury, sports trainers and clinicians have begun to employ hip strengthening interventions for individuals experiencing chronic injury. A number of studies have been conducted to evaluate the effectiveness of such interventions. Although many researchers have employed hip strengthening in isolation, many have embedded hip strengthening within neuromuscular training programmes which also incorporate other components. The purpose of this section is to assess the evidence for hip strengthening and lower limb alignment as intervention strategies to reduce the risk of running related lower limb overuse injuries in youth athletes.

Characteristics and quality of the studies

Twelve studies investigated the evidence for hip strengthening and lower limb alignment correction as intervention strategies to reduce the risk of running related lower limb overuse injuries (see Table 4) (Cibulka & Threlkeld-Watkins, 2005; J. Earl & Hoch, 2011; Fredericson et al., 2000; Fukuda et al., 2010; Heidt, Sweeterman, Carlonas, Traub, & Tekulve, 2000; Junge, Rösch, Peterson, Graf-Baumann, & Jiri Dvorak, 2002; Mascal, Landel, & Powers, 2003; Nakagawa et al., 2008; Pasanen et al., 2008; Steffen, Myklebust, Olsen, Holme, & Bahr, 2008; Tonley et al., 2010; Tyler, Nicholas, Mullaney, & McHugh, 2006). Three studies focused their sample on teenagers (Cibulka & Threlkeld-Watkins, 2005; Junge et al., 2002; Steffen et al., 2008), while the remainder included only adults (J. Earl & Hoch, 2011; Fredericson et al., 2000; Fukuda et al., 2010; Heidt et al., 2000; Mascal et al., 2003; Nakagawa et al., 2008; Pasanen et al., 2008; Tonley et al., 2010; Tyler et al., 2006). No study investigated the relationship between hip muscle strength and lower limb alignment during running in children. Six studies focused specifically on PFPS (Cibulka & Threlkeld-Watkins, 2005; J. Earl & Hoch, 2011; Fukuda et al., 2010; Mascal et al., 2003; Nakagawa et al., 2008; Tyler et al., 2006), general or lower limb injuries (Heidt et al., 2000; Junge et al., 2002; Pasanen et al., 2008; Steffen et al., 2008), one on ITBFS (Fredericson et al., 2000) and one on piriformis syndrome (Tonley et al., 2010). One study included only males in their sample (Tonley et al., 2010), three studies included both males and females (Fredericson et al., 2000; Nakagawa et al., 2008; Tyler et al., 2006), while all others included only females (Cibulka & Threlkeld-Watkins, 2005; J. Earl & Hoch, 2011; Fukuda et al., 2010; Heidt et al., 2000; Mascal et al., 2003; Pasanen et al., 2008; Steffen et al., 2008; Tyler et al., 2006).

Seven studies did not provide sufficient data to enable the calculation of ES (Cibulka & Threlkeld-Watkins, 2005; Fredericson et al., 2000; Heidt et al., 2000; Mascal et al., 2003; Pasanen et al., 2008; Steffen et al., 2008; Tonley et al., 2010). Five studies did not utilise control subjects, randomisation or blinding, scoring a 0 rating score (Cibulka & Threlkeld-Watkins, 2005; J. Earl & Hoch, 2011; Mascal et al., 2003; Tonley et al., 2010; Tyler et al., 2006), two studies received a rating score of 1 (Fredericson et al., 2000; Junge et al., 2002), and five studies scored a rating of 3 (Fukuda et al., 2010; Heidt et al., 2000; Nakagawa et al., 2008; Pasanen et al., 2008; Steffen et al., 2008).

Strength of the evidence and key results from the studies

Based on the effect size calculations there was some weak evidence for hip strengthening and lower limb alignment as intervention strategies to reduce the risk of running related lower limb overuse injuries. Despite the improvements in hip muscle strength, there were no consistent lower limb kinematic changes across all studies. There were positive decreases in knee abduction moments which could be viewed as positive in terms of a potential protective mechanism for lower limb injuries. Increasing lower limb strength on its own is not always sufficient to alter lower limb alignment in recreational athletes, and appropriate muscle activation strategies may have an important role to play. There was no evidence that hip strengthening and lower limb alignment as intervention strategies would not be effective with youth athletes, however there was no literature that allowed conclusions to be drawn relating to age or maturation.

Several research groups have attempted to prospectively measure the effect of hip strengthening and neuromuscular training interventions (such as structured warm-up programmes) on the incidence of overuse lower limb injuries for high-risk sports over the course of a competitive season (Heidt et al., 2000; Junge et al., 2002; Pasanen et al., 2008; Steffen et al., 2008). Of the two prospective intervention studies, Junge et al. (2002) prescribed a considerably longer training programme intervention period of 12 months compared to Heidt et al. (2000) who prescribed seven weeks. However, both groups reported similar reductions in the incidence of lower limb injuries for participants who undertook the interventions incorporating hip strengthening, compared to controls. Junge et al. (2002) reported that male teenage football players who participated in the intervention sustained 21% fewer injuries per 1,000 hours of training and matches than those who did no specialised training (ES = 1.0). Heidt et al. (2000) reported a 19% lower incidence of injuries across the season for female teenage football players in the intervention group. However, these researchers did not present this statistic as injuries per 1,000 hours of exposure and did not provide sufficient data for the calculation of effect statistics.

A further two randomised control trials were published using similar methodology. Two hundred and fifty six floor-ball players who participated in a 6-month neuromuscular training programme sustained 20 lower limb injuries during their season, compared to 52 lower limb injuries sustained by 201 control participants. This equated to a 66% reduction in the risk of non-contact lower limb injuries as a result of the injury prevention programme (Pasanen et al., 2008). In contrast to the previous three studies, Steffen et al. (2008) reported no difference between female football players in the intervention (n=1073, 181 injured) and control (n=947, 173 injured) groups for the overall injury rate, in the distribution of type, location or severity of injuries or injury rate ratio.

Together these four studies (Heidt et al., 2000; Junge et al., 2002; Pasanen et al., 2008; Steffen et al., 2008) provide a substantial sample of data, encompassing hundreds of athletes who underwent interventions incorporating an element of hip muscle strengthening or neuromuscular control training. However, despite the largely positive results, there were a number of potential limitations. Potentially the largest factor that limits the ability to directly compare between studies was the length of the intervention, and the differences in the structure of the programmes. While all studies included a hip-strengthening component, exactly which muscles were targeted, along with how the exercises were carried out were often different. Elements such as injury education, plyometrics, running or landing drills, and balance and proprioception exercises were included in some studies, but not all.

Several randomised control trials, cohort, case-series and case studies reported the effects of 4-8 week hip strengthening programmes on individuals with PFPS (Cibulka & Threlkeld-Watkins, 2005; J. Earl & Hoch, 2011; Fukuda et al., 2010; Mascal et al., 2003; Nakagawa et al., 2008; Tyler et al., 2006), with outcomes measuring changes in strength, pain and functional ability. Nakagawa et al. (2008) and Fukuda el al. (2010) provided robust research designs by including injured control subjects and blinded assessors. Both groups of researchers compared non-athletes who undertook either four (Fukuda et al., 2010) or six (Nakagawa et al., 2008) weeks of hip abductor, hip external rotator and quadriceps strengthening, with those who undertook quadriceps strengthening only. In both studies the participants who included hip strengthening in their rehabilitation experienced significantly less pain during subsequent functional activities compared to participants who did not include hip strengthening (Fukuda et al., 2010; Nakagawa et al., 2008). The magnitude of effect calculated for squatting pain was very large (ES = 1.0) (Nakagawa et al., 2008) and while the effect for ascending stairs was small (ES = 0.2) (Fukuda et al., 2010), the effect for descending stairs was large (ES = 0.6) (Fukuda et al., 2010).

Tyler et al. (2006) prescribed a 6-week strengthening and flexibility programme targeting the hip flexors, abductors and adductors for 35 individuals with PFPS. Treatment success was defined as a clinically significant reduction in PFPS pain (1.5 cm decrease in visual analog scale) associated with activities of daily living and with exercise. Based on these criteria 66% of the PFPS symptomatic participants exhibited an improvement in functionally related pain. However, there was only a significant increase in hip flexor muscles strength with improvement of 35% in

26 lower extremities treated successfully, compared with -1.8% in 17 lower extremities with an unsuccessful outcome. Increased strength of the hip adductors and abductors may not be essential for pain resolution in this condition.

Earl et al. (2011) were the only researchers to measure kinematic and kinetic variables from 19 participants with PFPS as they ran over-ground, both before and after undertaking an 8-week hip muscle and abdominal strengthening programme. Participants demonstrated improvements in PFPS pain (ES = 2.7) as well as a reduction in the knee abduction moments (ES = 0.4) during running after completing the strengthening programme. However, knee abduction (ES = 0.1), hip adduction (ES = 0.2) and internal rotation (ES = 0.4) kinematics did not change substantially. The effect size for hip internal rotation was reported incorrectly as 0.7, however the corresponding statements were correct. As a result of the lack of asymptomatic control subjects in either of these studies (J. Earl & Hoch, 2011; Tyler et al., 2006) the strength of the evidence they provided was limited.

Several case studies were also published where individuals with running related injuries participated in hip strengthening rehabilitation programmes. Two case studies of individuals with PFPS (Cibulka & Threlkeld-Watkins, 2005; Mascal et al., 2003) and a case of piriformis syndrome (Tonley et al., 2010) were reported where individuals experienced complete resolution of symptoms and demonstrated improved hip and knee strength following targeted intervention programmes. One case study also reported reduced peak hip abduction and internal rotation ROM during a step down task post intervention (Tonley et al., 2010). However, these case studies provided only weak evidence for the effectiveness of hip strengthening rehabilitation programmes.

One case series (Fredericson et al., 2000) compared hip abductor strength of the involved limb of 24 long-distance runners with ITBFS to their non-involved side, as well as to an asymptomatic control group. Following a 6-week hip abductor strengthening rehabilitation programme the increases in hip abductor torque were 10.6% for females and 10.4% for males. In addition, 92% of those with ITBFS were able to return to pain-free running after six weeks. At 6-months follow-up all athletes had returned to full participation. Sufficient data to enable the calculation of effect statistics was not published.

With clear guidelines it would be possible to alter current methods for preparing youth athletes for participation in high-level sports. Such training, if effectively used on a widespread basis, might help to decrease the number of youth athletes injured each year, helping these individuals stay active and focus on healthy competition.

Table 4: Studies evaluating the effect of hip strengthening interventions on lower limb injuries.

Study	Type of study	Number, gender and age (years) of subjects	Athletic participation / competition	Type of injuries	Programme details	Relevant results	Relevant effect sizes and strength of the evidence
Junge et al.(2002)	Prospective intervention Quality rating: 1	Intervention: 101 M 16.7 y Control: 93 M 16.3 y	Football	General injuries	A season long (12 month) structured programme to improve ankle and knee stability, and trunk and hip flexibility, strength and coordination.	188 injuries occurred during the season, 77 in intervention group and 111 in control. Intervention had 21% fewer injuries per 1,000 hours of training and matches than control (p<0.001).	Injuries per player per year: 1.0 Moderate evidence
Heidt et al.(2000)	Prospective intervention Quality rating: 3	203 females age range 14-18	Football	LL injuries	7-week preseason programme incorporating sport-specific cardiovascular conditioning, plyometrics, strengthening and flexibility exercises.	Intervention group had significantly lower (p= 0.0085) incidence of LL injuries across the season than the control group (14.3% compared to 33.7%).	Calculation not possible
Pasanen et al.(2008)	RCT Quality rating: 3	Intervention: 256 F 24 y from 14 teams Control: 201 F 24 y from 14 teams	Floor-ball	Non-contact LL injuries	A season long (6 month) structured warm-up NMT programme to enhance players' motor skills and body control (including running, balance, strength, plyometrics and stretching exercises).	72 LL injuries occurred during the season, 20 in intervention group and 52 in control. Risk of non-contact LL injury was ↓ 66% in intervention compared control (p<0.001).	Calculation not possible
Steffen et al.(2008)	RCT Quality rating: 3	Intervention: 1073 F 15.4 ± 0.8 y from 58 teams Control - 947 F 15.4 ± 0.8 y from 51 teams	Football	LL injuries	A season long (8 month) structured warm-up NMT programme focusing on core stability, balance, dynamic stabilisation and Ecc hamstrings strength.	354 LL injuries during the season, 181 in intervention group and 173 in control. No differences in overall injury rate (p=0.94), nor incidence for any type of injury between intervention and control.	Calculation not possible
Nakagawa et al.(2008)	RCT Quality rating: 3	10 F & 4 M 23.6 ±5.9 y (all injured and randomly assigned intervention / control)	Not reported	PFPS	Intervention = quadriceps, HA and HER strengthening; Control = quadriceps strengthening (6-weeks).	Both groups ↑ ecc knee extensor torque (p=0.04 & p=0.02). Only intervention group had ↑ HA EMG during maximal contraction (p=0.03) and improved pain symptoms during functional activities (p=0.02–0.04).	Squatting pain: 1.1 Moderate evidence

Table 4 cont: Studies evaluating the effect of hip strengthening interventions on lower limb injuries.

Study	Type of study	Number, gender and age (years) of subjects	Athletic participation / competition	Type of injuries	Programme details	Relevant results	Relevant effect sizes and strength of the evidence
Fukuda et al.[(2010)]	RCT Quality rating: 3	Knee: 20 F 25.0 ±6.0 y Knee & hip: 21 F 25.0 ±7.0 y Control :23 F 24.0 ±7.0 y (all injured and randomly assigned intervention / control)	Sedentary	PFPS	Knee and hip group = HA, HER and knee strengthening; Knee group = knee strengthening only; Control group = no strengthening (4-weeks).	Both hip and knee ($p<0.001$) and hip ($p<0.05$) groups improved in pain scores compared to control. Only hip and knee group showed clinically meaningful improvements in pain scores.	Pain descending stairs: 0.6, Pain ascending stairs: 0.2 Moderate evidence
Tyler et al.[(2006)]	Cohort study Quality rating: 0	Injured: 6 M & 29 F 33.0 ±16.0 y	Not reported	PFPS	6-week HF, HA, HAdd and HExt strengthening and ITB and HF stretching programme.	HF strength ↑ 35% in 26 lower extremities treated successfully ($p=0.001$), compared to 1.8% ↓ in HF strength in 17 lower extremities treated unsuccessfully ($p=0.001$). HA and HAdd strength were unrelated to outcome ($p>0.3$). HF strength ↑ >20% (and normalised ITB and HF ROM) was associated with 89% of successful outcomes. A significant ($p<0.01$) ↓ in exercise pain (squatting and stair ascending).	Daily activity pain: 0.7, Exercise pain: 7.0 Strong evidence
Earl et al.[(2011)]	Case series Quality rating: 0	Injured: 19 F 22.7 ±7.2 y	Recreational or college athletes	PFPS	8-week programme to strengthen hip and core muscles and improve dynamic malalignment.	Improvements in pain ($p<0.0005$) and functional ability ($p<0.0005$), ↓ KAbd moment (-70.2 ±51.4 Nm vs -54.0 ±22.6 Nm; $p=0.05$) during running. No changes in hip or knee kinematics.	Pain: 2.7, Function: 1.7, KAbd moment: 0.4, HIR ROM: 0.7 Weak evidence
Mascal et al.[(2003)]	Case report Quality rating: 0	2 females ages 20 and 37	Non-athletes	PFPS	14-week NMT programme to targeting the hip, pelvis, and trunk musculature.	During a step-down task, patient A demonstrated an average improvement in HIR (decrease from 1.4° of HIR to 2.6° of HER) HAdd (decrease from 8.7° to 2.3°), and contralateral pelvic drop (decrease from 3.9° to 1.1°). Both patients experienced a reduction in symptoms. Kinematics were only measured from patient A.	Calculation not possible

Table 4 cont. Studies evaluating the effect of hip strengthening interventions on lower limb injuries.

Study	Type of study	Number, gender and age (years) of subjects	Athletic participation / competition	Type of injuries	Programme details	Relevant results	Relevant effect sizes and strength of the evidence
Cibulka et al.(Cibulka & Threlkeld-Watkins, 2005)	Case study Quality rating: 0	1 female age 15	Basketball	PFPS	Strengthening and flexibility intervention designed to increase hip internal rotation ROM and HA and HIR muscle strength.	This patient demonstrated a 25° improvement in HIR ROM. HA and HIR muscle strength improved to a grading of 'good' after two weeks and 'normal' muscle strength grade was achieved at six months. Knee pain resolved.	Calculation not possible
Tonley et al.(Tonley et al., 2010)	Case report Quality rating: 0	1 male age 30	Recreational tennis and basketball	Piriformis syndrome	12-week strengthening intervention of the HA, HExt and HER, as well as movement reeducation.	This patient demonstrated a reduction in peak HA (15.9 to 5.8°) and HIR (12.8 to 5.9°) ROM during a step-down task, and also experienced a total resolution of symptoms.	Calculation not possible
Fredericson et al.(2000)	Case series Quality rating: 1	Injured: 14 M 27.1 ±4.0 y & 10 F 27.6 ±3.7 y Control: 16 M 20.6 ±0.7 y & 14 F 19.7 ±0.7 y	College / club level distance runners	ITBFS	6-week HA strengthening programme. Uninjured controls did no training.	Female pre- rehab HA torque was 7.8 ±1.9% BWh vs 9.8 ±3.0% BWh for the non-injured limb and 10.2 ±1.1 %BWh for controls. Post-rehab ↑ 10.6% BWh (34.9%). Male average pre- rehab HA torque was 6.9 ±2.0% BWh vs 8.6 ±1.2% BWh for the non-injured limb and 9.7 ±1.3% BWh for controls. Post-rehab ↑ 10.4% BWh (51.4%). All comparisons were statistically significant ($p < 0.05$). After 6 weeks strengthening 92% runners were pain free.	Calculation not possible

Abbreviations: ACL=anterior cruciate ligament; ADL=activities of daily living; Conc=concentric; Ecc=eccentric; EMG=electromyography; F=female; HA=hip abduction; HAdd=hip adduction; HExt=hip extension; HER=hip external rotation; HF=hip flexion; HIR=hip internal rotation; IKPD=Isokinetic pelvic drop; IMPD=isometric pelvic drop; ITB=iliotibial band; ITBFS=iliotibial band friction syndrome; ITEPD=isotonic endurance pelvic drop; KA=knee abduction; KExt=knee extension; KF=knee flexion; LL=lower limb; M=male; NMT=neuromuscular training; PFPS=patellofemoral pain syndrome; RCT=randomised controlled trial; ROM=range of motion; SLHA=side lying hip abduction Trunk Ext=trunk extension; Trunk Lat-Flex=trunk lateral flexion; vGRF=vertical ground reaction force; y=years; %BWh=percent body weight times height; ↓=reduced/decreased; ↑=increased/higher. ***Study quality rating:*** (4) Controlled study, randomised subject allocation, subject and assessor blinding; (3) Controlled study, randomised subject allocation, subject or assessor blinding; (2) Controlled study, randomised subject allocation; (1) Controlled study; (0) Uncontrolled study. ***Note:*** SD are reported where studies provided this information. Some studies did not provide sufficient information to enable ESs to be calculated.

Conclusion

The overriding conclusion from this literature review was that there was the lack of studies incorporating youth athletes. Evidence for hip strength and lower limb alignment as risk factors and intervention strategies for running related lower limb overuse injuries in youth athletes is minimal. Poor hip abductor, extensor and external rotator muscle strength and lower limb alignment (hip adduction and internal rotation) exhibits close links with development of overuse injuries, at least with adults. However, there is discrepancy across the literature with regard to the exacting relationship between hip muscle function and lower limb kinematics during sporting movements, making absolute cause-effect relationships difficult to assign.

There is the need for more research targeting youth athletes, specifically assessing running technique in an athletic population. Despite strong theoretical propositions for a relationship between hip muscle strength and lower limb alignment during running, the results from the few studies that have been carried out is varied. Additional well-controlled trials are needed to better understand the association between hip dysfunction and kinematics specifically with running, and to delineate the relative contribution of key muscles. There is also the need to investigate the relationships between hip strength, lower extremity kinematics (and kinetics) and prospective injury risk in youth athletes.

There is some support, at least in the short-term, for incorporating hip strengthening as either an injury rehabilitation or prevention intervention for lower limb overuse injuries in adults. However, there are varied results from studies, largely due to the wide range of intervention parameters used. Training studies with defined parameters, specific to appropriate age and development levels, are needed to better target treatment strategies for optimal prevention and rehabilitation programmes.

CHAPTER 3

RELIABILITY OF STRENGTH MEASURES IN YOUNG ATHLETES.

This chapter comprises the following paper that is to be submitted to *Journal of Science, Medicine and Sport.*

Sheerin, K.R, Hume, P.A., Whatman, C. Reliability and variability of within-day and between-day hip isometric strength measures for youth athletes. To be submitted to *Journal of Science, Medicine and Sport.*

(Author contribution percentages: KS 80%, PH 10%, CW 10%).

Overview

Objectives: To quantify within-day and between-trial reliability and variability of lower limb isometric strength measures for youth athletes. *Design:* Quantitative repeated measures experimental. *Methods:* Eleven male and 12 female youth athletes (11.4 ±1.3 years) were recruited from a long-term athletic development programme. Isometric hip flexor, hip abductor, hip internal and external rotator strength were measured using a dynamometer. All 23 participants were assessed at baseline (day 1) and ten returned for repeat testing 8 to 10 weeks later (day 2). Within-day (between trials) and between-day reliability was assessed using differences in the means and Cohen's effect sizes (ES), while variability was assessed using intraclass correlation coefficients and the coefficient of variation percentage. *Results:* The within-day reliability of hip strength measures in youth athletes was acceptable, however, the between-day reliability was poor. There was little difference in reliability across limbs within a day, and trials 1 to 2 were the most reliable. *Conclusions:* Isometric hip flexor, hip abductor, hip internal and external rotator strength were acceptable for future use within a single day. Future research should continue to examine how hip strength can be measured more reliably between days.

Introduction

Sports participation provides youth athletes with improved health, weight management, enhanced physical fitness, opportunities for social interaction, team building, goal setting, motor skill development and enjoyment (Stein & Micheli, 2010). To achieve proficiency and elite performance, athletes are undertaking intense training at younger ages, participating in multiple sports in one season, and continuing training throughout the entire year. However, with increases in volume and intensity of training there have also been increases in athletic injuries in the youth athletic population (Seto et al., 2010).

Over one third of youth athletes seek medical attention for injuries that occur during physical activity or sport (Adirim & Cheng, 2003; Hawkins & Metheny, 2001). Many more injuries likely go unreported and untreated. Many sports youth athletes participate in involve a large proportion of running. Running-related injuries in youth athletes are usually overuse or microtraumatic in nature and most frequently include patello-femoral pain syndrome (PFPS), ilio-tibial band friction syndrome (ITBFS), Osgood-Schlatter disease, stress reactions and fractures (Adirim & Cheng, 2003; Seto et al., 2010; Stein & Micheli, 2010). Although many factors can contribute to the development of running related injuries (Stein & Micheli, 2010), many lower limb injuries have been linked to faulty running mechanics (L. Bolgla et al., 2008). Despite the increasing number of injuries in youth runners, there are few epidemiologic studies focused on youth athletes, and none specifically addressing running injuries (Seto et al., 2010).

Hip strength has been identified as a key contributor to lower limb alignment during running in various adult populations (Cichanowski et al., 2007; Fredericson et al., 2000), and has also been associated with some of the same injuries in youth runners (Fredericson et al., 2000; Robinson & Nee, 2007). Impaired hip muscle strength can render the hip joint susceptible to dysfunction in all planes (Powers, 2010). Excessive hip adduction and internal rotation during stance has the potential to affect the kinematics of the entire lower limb, such as causing the knee joint center to move medially relative to the foot. Although guidelines exist to help youth athletes reduce the risk of injury (Micheli et al., 2000), they are largely non-specific and there is a call for more research to help minimise the risk for youth athletes participating in organised sport. It is also important to remember that children are not just scaled down versions of adults, and that factors specific to youth athletes must be reflected in injury prevention recommendations (Adirim & Cheng, 2003; Shanmugam & Maffulli, 2008).

Some studies have investigated the reliability of hip strength (Fredericson et al., 2000; S. R. Piva et al., 2006; Willson & I., 2009), but few have assessed youth athletes (Stuberg & Metcalf, 1988). Measurement consistency from day to day is needed for making clinical decisions for youth athletes. The reliability of tests needs to be established if they are to be used in longitudinal studies evaluating the effects of interventions designed to improve strength. With this in mind there is also the need for reliability studies that are consistent with the time course of intervention studies. Four hip muscle groups (hip abductors [HA], hip flexors [HF], hip internal [HIR] and external rotators [HER]) were chosen for reliability and variability of isometric strength evaluation due to their action over the major hip movement planes, ease of testing and the proposed links with lower limb injuries (Fredericson et al., 2000; Powers, 2010).

Methods

A quantitative repeated measures experimental design was used to collect data at the running mechanics laboratory. Twenty-three youth athletes (11 males and 12 females, age 11.4 ±1.3 years, height 1.53 ±0.12 m, weight 44.1 ±7.9 kg) were recruited from an existing long-term athletic development programme designed to develop all-round sporting ability. The youth athletes also participated in a range of competitive sports. In accordance with institutional requirements ethics consent was granted for this study. The youth athletes and their guardians provided written consent and completed a self-report injury questionnaire. No youth athletes had an injury that would impact on test performance at the time of data collection.

Age, height and mass were recorded, then the youth athletes were given an explanation of the hip muscle strength tests. Isometric strength was measured by the same physiotherapist for the HF, HA, HIR and HER using a load cell force-detecting dynamometer (Lafayette Instruments, Lafayette, IN) secured via a strap against the youth athlete's leg. Hip muscle strength testing using dynamometers has been reported as reliable in healthy, physically active adults (Fenter, Bellew, Pitts, & Kay, 2003; Fulcher, Hanna, & E.C., 2010; Kawaguchi & Babcock, 2010; Kelln, McKeon, Gontkof, & Hertel, 2008). The specific testing positions were as described by Ireland et al. (2003) and Kendall et al. (1993). The youth athlete was instructed to push with maximal effort for five seconds and this was repeated three times on each leg with a 15 second rest between trials. All strength measures were normalised to the athletes' body mass (%BM) (Fredericson et al., 2000). All twenty-three participants were assessed at baseline (day 1) and ten youth athletes returned for repeat testing 8 to 10 weeks later on "day 2". The 8 to 10 weeks timeframe was designed to evaluate reliability and variability over the duration of a typical intervention used during the long-term athlete development programme.

Descriptive statistics including overall group mean and standard deviations were calculated for the four hip strength variables for all 23 youth athletes at day 1 and for ten youth athletes at day 2. Using the spreadsheet by Hopkins (W.G. Hopkins, 2000b) for repeated measures analysis data were log transformed in order for measurement reliability and measurement variability outcomes to be presented as percentage changes where appropriate (W.G. Hopkins, 2000a) and to reduce bias arising from non-uniformity of error. Measurement reliability (performance consistency) and measurement variability of the strength variables was assessed using similar methods to that of Bradshaw, Hume, Carlton and Aisbett (2010).

Between trials (within-day) or between days (between-day) reliability measures included differences in the means (MDiff) as a percentage, and Cohen's effect sizes (ES). Effect sizes were interpreted as trivial (0.0-0.1), small (0.11-0.3), moderate (0.31-0.5), large (0.51-0.7), very large (0.71-0.9), or extremely large (0.91-1.0) (W. Hopkins, Marshall, Batterham, & Hanin, 2009). An overall interpretation of the average measurement reliability was based on the methods of Bradshaw et al. (2010) where average reliability was interpreted as 'good' when the difference in the mean was less than 5% and the ES 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 ES (MDiff > 5% or ES = moderate to large). Average reliability was categorised as 'poor' when both the difference in the mean and the ES criteria were breached (MDiff > 5% and ES = moderate to large).

Measurement variability outcomes included intraclass correlation coefficients (ICC) and the typical error of the measurement expressed as a coefficient of variation percentage (CV%) (W.G. Hopkins, 2000a). An ICC close to 1.00 indicates 'perfect' agreement with minimal variation (Atkinson & Nevill, 1998) whereas an ICC < 0.70 is indicative of 'poor' agreement and high measurement variability, 0.7 ≤ ICC ≤ 0.80 represents a questionable outcome, and ICC > 0.8 represents an excellent outcome (W.G. Hopkins & Manly, 1989; Morrow & Jackson, 1993; Shrout & Fleiss, 1979). A typical error (CV) of < 10% is considered small variation (Cormack, Newton, McGuigan, & Doyle, 2008). An overall interpretation of the average measurement variability of the strength measures was based on the methods of Bradshaw et al. (2010) where 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 ICC < 0.70 and CV > 10%.

As outlined by Bradshaw et al. (2010) 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 hip strength 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. Where the average reliability outcome was 'poor' or the average measurement variability was 'large' the measure was considered inappropriate for future use.

Results

Group means, standard deviations, differences between trials within a day (or differences between averaged trials between days) and reliability and variability statistics for isometric hip strength for internal rotators, external rotators, flexors and abductors for 23 youth athletes at day 1 (see Table 5) and for ten youth athletes at day 2 (see Table 6) are reported. Overall there were 16 from 24 instances where the hip strength measures 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. The within-day reliability of hip strength measures in youth athletes was acceptable, however, the between-day reliability was poor. There was little difference in reliability across limbs within a day, and trials 2 to 3 were the most reliable.

When the differences between trials within a day for each limb were compared for trials 1 to 2, the mostly trivial ESs and small percentage change in means indicate good reliability. Seven of the eight hip strength measures achieved an acceptable level of measurement reliability, with only left-side HER not achieving this grade. Overall the slightly lower ESs and percentage change in means from trials 2 to 3 indicated greater reliability for these measures, with all eight measures reaching an acceptable reliability grading for trials 2 to 3.

When the differences between days were compared, only one (left side HIR) of the eight hip strength measures achieved an acceptable level of measurement reliability and measurement variability.

Table 5: **Within-day differences between trials and reliability and variability statistics for isometric hip strength for internal rotators, external rotators, flexors and abductors for 23 youth athletes.**

	HIR		HER		HF		HA	
	right limb	left limb	right limb	left limb	right limb	left limb	right limb	left limb
Trial 1 M ±SD (%BM)	26.8 ±8.0	25.0 ±6.2	19.2 ±4.1	18.1 ±3.9	34.6 ±9.6	29.4 ±9.3	25.6 ±7.3	25.0 ±6.8
Trial 2 M ±SD (%BM)	26.3 ±8.1	25.3 ±7.4	19.5 ±4.6	19.7 ±4.0	33.4 ±10.1	30.3 ±9.8	25.8 ±8.9	24.9 ±7.4
Trial 3 M ±SD (%BM)	28.6 ±8.8	25.5 ±7.2	19.5 ±4.3	19.8 ±4.3	35.0 ±11.1	30.4 ±10.7	28.3 ±7.9	26.3 ±6.8
Trial 2-1 comparison								
MDiff (%BM)	-0.5	0.2	0.3	1.6	-1.1	0.8	0.2	-0.2
ES	-0.06	0.04	0.08	0.40	-0.12	0.09	0.03	-0.02
MDiff% (90%CL)	-2.2 (-6.4 to 2.2)	0.1 (-4.6 to 5.1)	1.6 (-4.0 to 7.4)	9.1 (3.8 to 14.8)	-3.6 (10.0 to 3.2)	2.5 (-3.2 to 8.4)	-1.2 (-6.3 to 4.1)	-1.6 (-6.5 to 3.6)
Reliability rating	Good	Good	Good	Moderate	Good	Good	Good	Good
CV% (90%CL)	9.0 (7.2 to 12.2)	10.0 (8.0 to 13.6)	11.6 (9.3 to 15.8)	10.5 (8.3 to 14.2)	14.4 (11.4 to 20.0)	11.8 (9.4 to 16.0)	11.0 (8.7 to 14.9)	10.7 (-8.5 to 14.5)
ICC (90%CL)	0.92 (0.84 to 0.96)	0.89 (0.77 to 0.94)	0.82 (0.66 to 0.91)	0.79 (0.61 to 0.89)	0.80 (0.63 to 0.90)	0.91 (0.81 to 0.95)	0.90 (0.81 to0.95)	0.87 (0.75 to 0.94)
Variability rating	Small	Moderate	Moderate	Large	Moderate	Moderate	Moderate	Moderate
Use	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Trial 3-2 comparisons								
MDiff (%BM)	2.3	0.2	-0.1	0.1	1.6	0.1	2.5	1.4
ES	0.29	0.03	-0.01	0.02	0.16	0.01	0.29	0.19
MDiff % (90%CL)	8.8 (3.9 to 14.0)	0.9 (-4.53 to 6.63)	0.1 (-3.7 to 4.1)	0.0 (-2.9 to 3.0)	4.2 (-1.2 to 9.9)	0.22 (-5.4 to 6.2)	12.31 (5.5 to 19.6)	6.8 (2.0 to12.0)
Reliability rating	Moderate	Good	Good	Good	Good	Good	Moderate	Moderate
CV% (90%CL)	9.6 (7.7 to 13.0)	11.5 (9.19 to 15.7)	8.0 (6.4 to 10.8)	5.9 (4.7 to 8.0)	11.0 (8.8 to 15.0)	12.1 (9.6 to 16.4)	13.2 (10.5 to18.0)	9.6 (7.67 to 13.0)
ICC (90%CL)	0.91 (0.83 to 0.96)	0.86 (0.73 to 0.93)	0.90 (0.81 to 0.95)	0.93 (0.86 to 0.97)	0.89 (0.78 to 0.95)	0.90 (0.81 to 0.95)	0.86 (0.73 to 0.93)	0.90 (0.79 to 0.95)
Variability rating	Moderate	Moderate	Small	Small	Moderate	Moderate	Moderate	Small
Use	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: HIR, hip internal rotators; HER, hip external rotators; HF, hip flexors; HA, hip abductors; M, mean; SD, standard deviation; CL, confidence limits; MDiff, inter-trial difference in mean scores normalized and expressed as a percentage of body mass (BM). Reliability statistics are Cohen's effect size (ES) and inter-trial difference in mean scores as a percentage (MDiff%). Variability statistics are typical error of measurement as a coefficient of variation expressed as a percentage (CV%), and intraclass correlation coefficient (ICC).

Table 6: Differences between days for the average of three trials per day and reliability and variability statistics for isometric hip strength for internal rotators, external rotators, flexors and abductors for 10 youth athletes.

	HIR		HER		HF		HA	
	right limb	**left limb**	**right limb**	**left limb**	**right limb**	**left limb**	**right limb**	**left limb**
Day 1 M ±SD (%BM)	29.7 ±7.0	26.4 ±5.6	22.4 ±3.6	22.6 ±4.4	37.1 ±9.2	33.3 ±10.1	27.7 ±8.0	25.8 ±5.9
Day 2 M ±SD (%BM)	26.3 ±5.7	25.7 ±6.8	18.7 ±4.2	19.0 ±4.4	45.1 ±11.3	40.9 ±10.1	36.3 ±7.8	33.2 ±4.8
MDiff (%BM)	-3.4	-0.7	-3.7	-3.6	8	7.5	8.6	7.4
MDiff% (90%CL)	-10.6 (-19.7 to -0.5)	-3.4 (-12.7 to 6.9)	-17.6 (-29.7 to -3.3)	-17.1 (-24.6 to -8.8)	21.0 (10.9 to 32.1)	24.6 (10.5 to 40.5)	33.7 (15.4 to 54.7)	30.5 (15.3 to 47.7)
ES	0.53	0.11	0.95	0.82	0.78	0.75	1.09	1.38
Reliability rating	Poor	Good	Poor	Poor	Poor	Poor	Poor	Poor
CV% (90%CL)	14.0 (10.0 to 24.0)	13.1 (9.4 to 22.5)	21.6 (15.3 to 33.9)	12.3 (8.8 to 21.05)	11.3 (8.1 to 19.2)	15.8 (11.3 to 27.2)	19.6 (13.9 to 31.2)	16.3 (11.7 to 28.3)
ICC (90%CL)	0.76 (0.40 to 0.92)	0.81 (0.51 to 0.94)	0.06 (-0.047 to 0.57)	0.82 (0.51 to 0.94)	0.88 (0.67 to 0.96)	0.80 (0.4 to 0.9)	0.55 (0.05 to 0.83)	0.37 (-0.18 to 0.75)
Variability rating	Moderate	Moderate	Large	Moderate	Moderate	Moderate	Large	Large
Use	No	Yes	No	No	No	No	No	No

Note: HIR, hip internal rotators; HER, hip external rotators; HF, hip flexors; HA, hip abductors; M, mean; SD, standard deviation; CL, confidence limits; MDiff, inter-day difference in mean scores normalized and expressed as a percentage of body mass. Reliability statistics are Cohen’s effect size (ES) and inter-day difference in mean scores as a percentage (MDiff%). Variability statistics are typical error of measurement as a coefficient of variation expressed as a percentage (CV%), and intraclass correlation coefficient (ICC).

Discussion

Reports of the measurement reliability and measurement variability of hip strength measures in youth athletes are scarce. The purpose of this study was to determine the measurement reliability and measurement variability of four hip strength measures of both right and left limbs for youth athletes across a time interval realistic of an intervention study.

The mostly trivial ESs and small percentage change in means indicated acceptable within-day reliability for hip abductor, hip flexor and hip internal and external rotator strength measures. These measures would be useful for classifying athletes, or assigning athletes to groups according to their baseline strength characteristics. The finding that differences between trials 1 to 2 were less than differences between trials 2 to 3 was in contrast to what is typically reported (W.G. Hopkins, 2000a). Due to a learning effect, it is more common to find the reverse relationship with trial 1 being more variable. It is possible that this result came about due to these tests assessing muscular strength, and therefore fatigue may have been a factor in less reliability for the third measurement. Although 15 s rest was provided between trials this may not have been sufficient to eliminate fatigue effects in the third trial.

Only the right side HER, of the eight hip strength measures, achieved an acceptable level of measurement reliability and measurement variability for differences between days. This indicates that hip strength can not accurately be measured in youth athletes over an eight to ten week timeframe.

There are several reasons that could somewhat explain these results. During the eight to ten weeks between testing days, the youth athletes were active in their normal sporting pursuits. It is evident that over this time, even without any form of intervention, this normal activity resulted in a natural increase in the variability of hip strength measured between test days. In addition, it is inherent with youth athletes that their skeletons are changing, including bone growth and increased muscle stiffness. Alongside these anatomical changes it is not uncommon to see reductions in neuromuscular control during dynamic tasks and subsequent increased natural variability of movement. Further longitudinal studies with repeated measures are required to determine the natural variance in running gait and the nature of change in youth athletes.

Several studies have examined intra- and inter-rater reliability of hip muscle strength testing using force dynamometry in adults. Two studies report intra-tester reliability of hip muscle strength assessment over a single day. Bohannon et al. (1986) tested hip flexion, hip abduction, hip extension and hip adduction across 30 participants, with three strength tests per limb. Intra-rater reliability was greater than or equal to 0.87 in the all correlations. Willson et al. (2009) reported excellent reliability for hip abductors and hip external rotators across three trials, with ICCs between 0.93 and 0.97. Three studies assessed the inter-tester reliability of specific hip muscles. Fredericson, et al. (2000) assessed hip abductor strength from both legs of 10 non-injured adults. Three trials were averaged per subject, per tester and the reported

ICC was 0.96. Piva et al. (2006) reported moderate reliability (ICC = 0.85) for HER and substantial reliability for HA (ICC = 0.79) for individuals with PFPS. A third study by Bohannon et al. (2005) reported an inter-rater reliability correlation (Pearson r) of 0.84 for hip flexors in 30 subjects using two examiners. Our results for within-day reliability of hip strength measures with youth athletes were in line with the research presented for adults. The small differences in these results could be due to the strength differences between youth athletes and adults, although we did not assess this, or the specific tests assessed. Different test positions have been used in studies report in the literature, in addition to use or non-use of dynamometer stabilisation straps. We did not conduct inter-rater reliability, and no previous studies presented between-day reliability, precluding any comparisons.

Recommendations for future research

Although the hip strength measures assessed in this study achieved both acceptable reliability and variability within a day, future research should investigate the length of recovery time between trials to reduce the effect of fatigue and possibly improve reliability. Furthermore, the use of these measures in comparison investigations between youth athletes of other ages (i.e. younger and older than our youths' mean age of 11.4 years), genders, athletic populations, and athletic performance level would broaden the knowledge base of the use of hip strength measures. Given our hip strength measures were all isometric, further research on the reliability of strength during functional movements would also be warranted. There is also the need for further research to establish reliable protocols for the measurement of hip strength over the course of intervention studies. Isometric hip flexor, hip abductor, hip internal and external rotator strength measures could be useful as part of a clinical screening tool, however, future research should continue to examine how isometric hip strength can be measured more reliably between days and used for monitoring youth athletic development.

Conclusion

Isometric hip flexor, hip abductor, hip internal and external rotator strength were acceptable for future use within a single day for youth athletes based on reliability and variability results.

Practical implications

- Isometric hip flexor, hip abductor, hip internal and external rotator strength measures in youth athletes can be used repeatedly during a single day with confidence by clinicians.
- Monitoring hip strength in youth athletes over time needs to be interpreted with caution due to concerns around adequate hip strength reliability between measurement days.
- Clinicians should measure two trials for each hip strength variable and use the magnitude of the difference between trials 1 and 2 as an indication of reliability.
- With increased variability between days spread 8 to 10 weeks apart, a control group should be included in intervention studies with youth athletes.

CHAPTER 4

RELIABILITY OF 3D FRONTAL PLANE HIP AND KNEE RANGE OF MOTION DURING RUNNING IN YOUNG ATHLETES.

This chapter comprises the following paper that has been published in the *Proceedings of the 28th Conference of the International Society of Biomechanics in Sports.*

Sheerin, K.R, Hume, P.A., Whatman, C., Croft, J. Reliability of 3D frontal plane knee ab/adduction range of motion during running in young athletes. Oral presentation and published in *Proceedings of the 28th Conference of the International Society of Biomechanics in Sports*, Michigan, USA, 2010.

(Author contribution percentages: KS 80%, PH 10%, CW 8%, JC 2%).

Overview

This study quantified within-session and between-session reliability of 3D frontal plane knee ab/adduction range of motion during the stance phase of running gait calculated for 18 long-term athlete development programme participants (10 males and 8 females, 11.5 ±1.4 years) during two testing sessions (spaced 10 weeks apart). All 18 participants were assessed at baseline (session 1) and 10 young athletes returned for repeat testing 8 to 10 weeks later. Average mean differences in frontal plane knee ab/adduction between running trials (for the right or left side) within a session (week 1 or week 10) ranged from 0.2 to 7.2% (ES 0.01–0.26), which were acceptable differences. However, average mean differences between sessions for running trials (for the right or left side) ranged from 0.1 to 20% (ES 0.01–0.6). The mixed model resulted in estimates of knee ab/adduction range of motion for effects of limb side (3.6°), session (2.8°), run trial (0.2°) and subjects (4.5°). Within-session ICCs ranged from 0.80 to 0.92 and between-session ICCs ranged from 0.51 to 0.73. Based on these ICCs, within-session reliability of frontal plane knee ab/adduction is good and between-session reliability is average to good.

Introduction

Screening of individuals for risk of lower limb injury and as a means of optimising performance has become common, particularly in professional sport, but also at other competitive and recreational levels (Mottram & Comerford, 2008). When assessing the lower extremity, the use of functional gait screening to evaluate movement quality is becoming commonplace. During assessments of gait, clinicians typically evaluate dynamic lower extremity alignment. Poor dynamic alignment has been described as a combination of excessive pelvic drop, hip adduction, internal rotation and knee valgus (J. E. Earl, Monteiro, & Snyder, 2007; Powers, 2003; Sahrmann, 2002; Willson & I., 2009). Poor frontal plane knee control observed during activities such as running, squatting and landing, is considered a key risk factor for the development of common injuries such as patellofemoral dysfunction. Clinically this is often observed as increased stance phase valgus angle at the knee (Powers, 2003).

Few studies have investigated the reliability of frontal plane kinematics during gait, and none have assessed youth athletes. However, it is crucial to know if kinematics are consistent enough from day to day for making clinical decisions. Reliability refers to whether a specific measurement tool produces consistent outcomes during repeated measures of the same variable (Clark, 2001). Highly sensitive sports science measurements are characterised by little variation in consecutive measures of performance (W.G. Hopkins, 2000a). A change in performance due to an intervention has to be greater than the normal day-to-day training variation before coaches can conclude that the intervention has had a meaningful impact on the athlete's performance (Soper & Hume, 2004). For a performance test to be valuable it must be specific enough to measure the performance variable of interest and reliable enough to detect the relatively small differences in performances that are beneficial to elite athletes (Schabort et al., 1999). Utilisation of a reliable assessment tool helps ensure that variations between measurements are attributed to changes in the variable being measured (L. A. Bolgla, 1997; Clark, 2001). Furthermore, the reliability of tests needs to be established if they are to be used in longitudinal studies evaluating injury risk or the effect of rehabilitation interventions.

The purpose of this study was to investigate within-session and between-session reliability of 3D frontal plane knee ab/adduction range of motion during the stance phase of treadmill running in healthy young athletes.

Methods

Eighteen young athletes (10 male and 8 female, 11.5 ±1.4 years, 1.5 ±0.1 m, 44.0 ±7.9 kg) were recruited from an existing long-term athletic development (LTAD) programme designed to develop all-round sporting ability. All athletes were injury-free at the time of testing. Data were collected during two sessions 10 weeks apart. All 18 participants were assessed at baseline (session 1) and 10 young athletes returned for repeat testing 8 to 10 weeks later on "session 2". During each session participants underwent a treadmill-based assessment of running kinematics. A nine-camera motion analysis system (Qualysis Medical AB, Sweden) recorded lower body 3D kinematics. Twenty-one retro-reflective markers were secured to specific lower extremity anatomical locations. Two cluster marker sets (four markers attached to a plastic shell) were also attached to the thigh and shank of each leg. Children ran for five minutes at a self-selected speed (2.19 ±0.22 m/s) and kinematic data were collected in two 30-second increments at two-minute intervals. The same running speed that was used in the first session was repeated in the second session. Anatomical markers were tracked using the Qualysis motion capture software and exported to Visual 3D (C-Motion Inc, USA) for calculation of relevant kinematic data. Kinematic data 'text' files were imported into Labview (National Instruments, USA) for calculation of range of motion via maximum and minimum joint angles during the stance phase of ten running strides. To summarise, each athlete completed two running trials at session 1 and session 2. Ten continuous steps for each limb were extracted from each trial for sequential analyses.

Statistical Analysis System (SAS) (SAS Institute Incorporated, USA) was used to calculate descriptive statistics including means and standard deviations (spread of results among participants) and within-session and between-session reliability of 3D frontal plane knee ab/adduction range of motion. Data were log transformed to provide measures of reliability (performance consistency) using a repeated measures analysis of variance. Reliability measures included the difference in the mean as a percentage, and Cohen's effect sizes (ES). Effect sizes are interpreted as <0.2 as trivial, <0.41 as small, 0.41-0.7 as moderate, and >0.7 as large (W.G. Hopkins, 2002). Variability measures included intra-class correlation coefficients (ICC), and typical error of measurement as a coefficient of variation percentage (W.G. Hopkins, 2000a) estimated from the knee ab/adduction range of motion (discrete value). The ICC classifications of Fleiss (1999) were used to describe the magnitude of ICC values (<0.4 as poor, 0.40-0.75 as fair to good and 0.75 as excellent). A mixed modelling approach using SAS allowed quantification of both fixed effects (e.g. trial number, week of testing) and random effects (e.g. individual identity) and included variances and co-variances caused by both between- and within-subject factors (W.G. Hopkins, 2002). ICCs were calculated for a variety of steps (1 to 25).

Results and discussion

Kinematics in all three planes were measured, however, given the proposed links between poor frontal plane knee control and the development of lower extremity injuries (Powers, 2003), the focus was placed on the assessment of knee ab/adduction range of motion. Within-session descriptive and reliability statistics, including 90% confidence limits (90%CL), for knee ab/adduction range of motion for all participants are presented in Table 7. Between-session, within trial statistics for each limb are presented in Table 8. Within-session average mean differences between running trials for each limb ranged from 0.2 to 7.2%, which were acceptable differences. However, average mean differences between sessions for running trials for a given limb side ranged from 0.1 to 20%.

A standard error of measurement of 10% or less is considered small in pure test-repeats of three or more trials (Bennell, Crossley, Wrigley, & Nitschke, 1999). Our typical errors expressed as CV% were 10-13% indicating moderate variability for knee ab/adduction between subjects. Although the CV%s were moderate, the magnitude of the angles was relatively small, usually less than a few degrees. Variability in 3D kinematics may be due to errors in measurement, marker replication and movement, and variability of human locomotion. It is difficult to separate these and therefore the variability reported in this study includes all contributions.

Table 7: **Within-session statistics, including 90%CL, for frontal plane knee ab/adduction range of motion during the stance phase of running for healthy young athletes (n=18).**

	Session 1		**Session 2**	
	Right	**Left**	**Right**	**Left**
Trial 1 mean ±SD (degrees)	6.8 ±2.0	6.8 ±2.9	8.1 ±2.2	6.8 ±2.4
Trial 2 mean ±SD (degrees)	7.4 ±2.5	6.8 ±2.7	8.4 ±2.6	7.2 ±2.4
ES (within-session, between-trials)	0.26	-0.01	0.10	0.15
Change in mean % (90%CL)	7.2 (0.5 to 14.4)	0.2 (-5.5 to 6.2)	2.1 (-5.1 to 9.9)	5.4 (-2.0 to 13.4)
Typical error as a CV% (90%CL)	11.8 (9.2 to 16.9)	10.5 (8.2 to 15.0)	13.5 (10.5 to 19.5)	13.4 (10.4 to 19.2)
Total error (%)	12.7	10.2	13.2	13.6
Intraclass r (90%CL)	0.87 (0.73 to 0.94)	0.92 (0.82 to 0.96)	0.80 (0.59 to 0.91)	0.90 (0.78 to 0.96)

Table 8: **Between-session statistics, including 90%CL, for frontal plane knee ab/adduction range of motion during the stance phase of running for healthy young athletes (n=10).**

	Right		**Left**	
	Trial 1	**Trial 2**	**Trial 1**	**Trial 2**
Session 1 mean ±SD (degrees)	6.8 ±2.0	7.4 ±2.5	6.8 ±2.9	6.8 ±2.7
Session 2 mean ±SD (degrees)	8.1 ±2.2	8.4 ±2.6	6.8 ±2.4	7.2 ±2.4
ES (for a trial, between-sessions)	0.63	0.40	0.01	0.16
Change in mean % (90%CL)	20.3 (9.4 to 32.2)	14.6 (0.7 to 30.3)	0.1 (-10.7 to 12.2)	5.4 (-7.8 to 20.4)
Typical error as a CV% (90%CL)	17.7 (13.7 to 25.6)	24.9 (19.1 to 36.5)	21.8 (16.8 to 31.8)	25.9 (19.8 to 38.1)
Total error (%)	22.8	26.7	21.1	25.5
Intraclass r (90%CL)	0.66 (0.35 to 0.84)	0.51 (0.13 to 0.76)	0.73 (0.46 to 0.87)	0.61 (0.28 to 0.81)

The mixed model resulted in knee ab/adduction estimates for effects of limb side (3.6°), session (2.8°), trial (0.2°) and subjects (4.5°). Analyses of ICCs and standard deviations (SD) expressed as degrees showed that for most variables at least 10 steps per running trial were needed. Knowledge of the variation in variables within a session and between sessions allows an estimation of the number of subjects and numbers of trials when designing experiments. For an experimental study with parallel groups (control and intervention), the number of subjects required can be determined by the equation 2*(1-ICC)*272 where the smallest worthwhile effect is 0.2 (W.G. Hopkins, 2000a). The number of subjects in each group varies depending on the number of steps analysed and the subsequent ICC of the variable to be measured. For example, if three steps were analysed for a variable giving an ICC of 0.71 then the equation 2*(1-0.71)*272 results in 158 subjects in each group. If ten steps were analysed for a variable giving an ICC of 0.78, then the equation 2*(1-0.78)*272 results in 119 subjects in each group. If ten steps were analysed for a variable giving an ICC of 0.96, then the equation 2*(1-0.96)*272 results in 22 subjects in each group.

A change and/or reduction in frontal plane knee motion when running is potentially important for designing injury prevention interventions. It is therefore essential that researchers and clinicians have a good appreciation of how reliably this can be measured. These results demonstrate that knee ab/adduction can be reliably measured within acceptable limits both within-sessions and between-sessions. However, it should be noted that to achieve this level of reliability at least 10 steps should be analysed.

Conclusion

Within-session and between-session reliability of knee ab/adduction range of motion during the stance phase of running in a young athlete population demonstrated average to good reliability. Knee ab/adduction range of motion could be a useful clinical screening tool.

CHAPTER 5

EFFECTS OF A LOWER LIMB FUNCTIONAL EXERCISE PROGRAMME AIMED AT MINIMISING KNEE VALGUS ANGLE ON RUNNING KINEMATICS IN YOUTH ATHLETES

This chapter comprises the following paper has been submitted to *Physical Therapy in Sport*:

Sheerin, K.R, Hume, P.A., Whatman, C. Effects of a lower limb functional exercise programme aimed at minimising knee valgus angle on running kinematics in youth athletes.

(Author contribution percentages: KS 80%, PH 10%, CW 10%).

Overview

Objectives: To investigate the effectiveness of 8-weeks of lower limb functional exercises on improving hip abduction and knee valgus kinematics during running in youth athletes. Design: Pre- and post-intervention quantitative experimental. Methods: Nineteen athletes (11 male, 8 female, 11.54 ±1.34 years) from a long-term athletic development programme had 3-dimensional running gait measured pre and post an 8-week exercise intervention. Youth athletes randomised to control (upper limb strengthening exercises) or experimental (lower limb functional exercises aimed at minimising knee valgus angle) interventions completed the exercises during the first 10 minutes of training, three mornings a week. Pre- and post-parallel groups' analysis provided estimates of intervention effects for control and experimental groups. Results: Differences in pre- to post-intervention changes in mean frontal plane angles between control and experimental groups were trivial for the left hip (0.1°) and right knee (-0.3°). There was a small beneficial decrease in right hip joint angle (0.4°) but a very large (ES = 0.77, CI 0.1 to 3.7) detrimental increase in left knee valgus angle (1.9°) between groups. Conclusion: The 8-week lower limb functional exercises had little beneficial effects on lower limb hip and knee mechanics in youth athletes aged 9 to 14 years.

Introduction

To achieve proficiency and elite performance, athletes are undertaking intense training at younger ages, participating in multiple sports in one season, and continuing training throughout the entire year. However, with increases in volume and intensity of training there have also been increases in athletic injuries in the youth athletic population (Seto et al., 2010). The majority of injuries sustained by youth athletes are mild, causing only minor discomfort. However, moderate injuries can result in significant pain and time out of sports, while serious injuries can lead to a complete drop out of participation. Sporting injuries in youth can also have a flow-on effect, whereby athletes may not achieve the success they are capable of, and they also have the potential to develop disability, such as chronic pain or arthritis later in adulthood (Adirim & Cheng, 2003).

Many sports involve an element of running, and overuse injuries common in youth athletes such as patello-femoral pain syndrome and iliotibial band friction syndrome, have been linked to faulty running mechanics (Powers, 2010). Lower limb alignment, as well as hip muscle dysfunction have been identified as potential contributing factors to such injuries (Powers, 2010). Although guidelines exist to help youth athletes reduce the risk of injury (Micheli et al., 2000), they are largely non-specific, and there is a call for more research to help minimise the risk for youth athletes. Improving the understanding of the factors contributing to the development of running related overuse injuries is desirable, so that ultimately clear injury prevention strategies can be developed (Adirim & Cheng, 2003; Shanmugam & Maffulli, 2008; Stein & Micheli, 2010).

Gluteus medius, and to some extent tensor fascia lata, are active during the stance phase of running, corresponding to a hip abduction moment (R. Mann, G. Moran, & S. Dougherty, 1986). At foot-strike, these muscles act eccentrically to control hip adduction, and then concentrically from the support phase into propulsion to create hip abduction (R. Mann et al., 1986). If proximal instability exists, the lower limb could move into more hip adduction, creating an increased valgus angle at the knee, which in turn could place the runner at an increased risk for lower limb injury (Ferber, Davis, Hamill, Pollard, & McKeown, 2002). Frontal plane hip and knee angles are therefore useful variables for screening youth athletes given the proposed links between excess lower limb frontal plane motion and the development of lower limb overuse injuries (Powers, 2010).

Altered or decreased lower limb control identified in runners with overuse injuries (Ferber et al., 2010; Milner et al., 2010) is also highlighted as a risk factor for anterior cruciate ligament (ACL) injury during dynamic sporting actions (Hewett et al., 2005). Lower limb functional training with a focus on correcting lower limb alignment and improving lower limb strength can not only reduce the levels of potential biomechanical risk factors for ACL injury, but also decreases knee and ACL injury incidence in female athletes (Hewett, Ford, & Myer, 2006). Programmes including exercises such as double and single leg squats, and lying and standing hip abductor muscle strengthening have been used with children to reduce risk of ACL injury as a result of jumping activities. Other studies reporting exercises such as broad jumps and jump squats could also be useful for lower limb functional training in children (Hewett, Lindenfeld, Riccobene, & Noyes, 1999; Myer, Chu, Brent, & Hewett, 2008; Presswood, Cronin, Keogh, & Whatman, 2008), but no studies have looked at the effects of this type of training on running mechanics.

It is postulated that if knee valgus can be reduced, and lower limb alignment can be improved during running, athletes will no longer be in a risk position for the development of overuse injuries. Therefore, the aim of this study was to investigate the effectiveness of an 8-week lower limb functional exercise programme on improving hip abduction and knee valgus kinematics during running in youth athletes.

Methods

The AUT University Ethics Committee gave approval for this study. Youth athletes and their guardians provided written consent and completed a self-report injury questionnaire. No youth athletes had an injury that would impact on running performance at the time of data collection.

Nineteen (11 male and 8 female) youth athletes, ranging in age from 9 to 14 years, recruited from an existing long-term athletic development (LTAD) programme designed to develop all-round sporting ability completed pre- and post-intervention testing and 8-weeks of exercise intervention. The youth athletes also participated in a range of competitive sports.

Data were collected pre- and post- an 8-week intervention. Height, body mass and strength measures were recorded, and then the youth athletes warmed up by running on the treadmill (PowerJog, Birmingham, UK) for five minutes reaching a self-selected comfortable pace at the end of this timeframe. Isometric strength was measured for the hip abductor muscles using a load cell force-detecting dynamometer (Lafayette Instruments, Lafayette, IN) secured via a strap against the youth athlete’s leg. The specific test positions were as described by Ireland et al. (2003). The youth athletes were instructed to push with maximal effort for five seconds, and this was repeated three times on each leg with a 15 s rest between trials. The strength tests were all conducted by a single physiotherapist, experienced in the use of the load cell force-detecting dynamometer. Within-session reliability for these tests using this device has been previously reported as moderate to good for all strength measures (K. R. Sheerin, Hume, Whatman, & Croft, 2010).

Descriptive statistics for demographic variables are represented as mean and standard deviations (SDs), and were calculated for control and experimental groups at pre- and post-intervention (see Table 9). Paired t-test statistics for the baseline variation between the experimental and control groups showed there were no significant differences ($p<0.05$) between groups for age, height, body mass, or hip abductor muscle strength. To achieve balanced control and experimental groups, a form of minimisation was employed for hip abductor strength and frontal plane knee control (maximum stance phase knee abduction angle) (Treasure & MacRae, 1998) based on subsequent pairs in rank order from pre-intervention (baseline) testing results.

Table 9: Participant characteristics.

	Combined (n=19)	Control (n=11)	Intervention (n=12)
Age (years)	11.5 ±1.4	11.3 ±1.7	11.6 ±0.6
Height (m)	1.54 ±0.10	1.53 ±0.11	1.55 ±0.10
Mass (kg)	43.7 ±7.9	42.2 ±9.0	45.0 ±6.8

The data collection session was completed with the youth athletes undergoing a treadmill-based assessment of running gait kinematics. A nine-camera motion analysis system (Qualysis Medical, AB, Sweden) recorded lower body 3-dimensional (3D) kinematics at a sampling rate of 240 Hz. Twenty-one individual retro-reflective markers were secured to specific anatomical locations by an experienced physiotherapist (see Figure 2). Two cluster marker sets were also attached to the thigh and shank of each leg (Whatman, Hing, & Hume, 2011). Youth athletes ran for five minutes at a self-selected speed (mean ±SD: 2.19 ±0.22 m/s). 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. Therefore the youth athletes completed 30 s of running to achieve the required data set of ten running strides. Kinematic data were collected in two 30 s increments at two-minute intervals. Motion data were combined with participants' height and weight in Visual 3D (C-Motion Inc, USA) to create geometric objects of appropriate shape and mass to represent the pelvis, thigh, shank and foot body segments. Joints in the model were defined as places where the distal end of one segment met the proximal end of another segment, and analyses of joint motion was based solely on the relative motion between segments. Data from running files were filtered with a second-order Butterworth bidirectional low-pass filter with a cut-off frequency of 12 Hz. Kinematic data were exported as 'text' files and imported into Labview (National Instruments, USA) for further analysis. A customised Labview programme processed the lower limb kinematic data and output maximum and minimum hip and knee frontal plane joint angles during the loading response of stance phase of ten running strides. A standard error of measurement of 10% or less is considered small in pure test-repeats of three or more trials (Bennell et al., 1999). Our typical errors expressed as coefficient of variation percentages (CV%) were 10-13% indicating moderate variability for hip and knee ab/adduction between subjects. Reliability assessment for the gait variables presented in this paper was previously determined with average to good between-session reliability achieved (K. Sheerin, Whatman, Hume, & Croft, 2010).

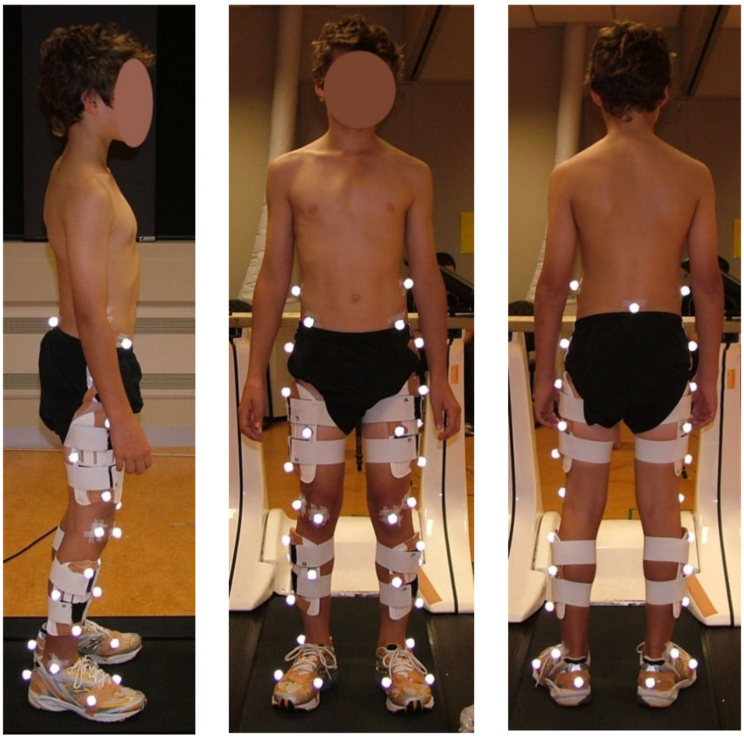


Figure 2: Marker placements for running lower limb kinematic analysis.

All youth athletes in the LTAD programme completed either control or experimental exercises during the first 10 minutes of their normal training session for three mornings a week for eight weeks. The experimental group completed functional weight bearing exercises aimed at minimising knee valgus angle and open and closed kinetic chain exercises to promote hip muscle activation. These exercises were sourced from other studies (Hewett et al., 1999; Myer, Chu, et al., 2008; Presswood et al., 2008). The exercises progressed in difficulty over the course of the intervention. A full description of each exercise is provided in Table 10. The control group completed a range of open and closed kinetic chain upper limb strengthening exercises including low pulley row and overhead pull-down with a resistance band, bicep curls, lying chest press, front and side shoulder raises, and overhead press with small hand-weights, in addition to tricep dips from a bench. Through the kinetic chain some upper limb exercises may have the potential to influence trunk stability and therefore lower limb control, however care was taken to choose exercises for the control group that would minimise this effect. Both the control and intervention exercises were supervised at all times by a qualified exercise professional. Individual technique correction was provided when required.

Table 10: Descriptions of the exercises included in the lower limb functional exercise programme.

Exercise and source	Description
Side lying hip abduction (Presswood et al., 2008)	Athlete side lying with a resistance band tied around their knees. The top leg is abducted upwards against the band resistance, and slowly lowered to the starting position (progressed to three sets of ten repetitions).
Double leg squats (Presswood et al., 2008)	From standing, the athlete bends at the knees and hips into a crouched position. Some forward inclination of the trunk is permitted, however, the knees should not go into a varus or valgus position (progressed to three sets of ten repetitions).
Crab walking (Presswood et al., 2008)	With a resistance band tied around the athletes' ankles, in a slow movement, the athlete abducts one leg laterally as far as possible and places it back on the ground. The athlete then lifts their second leg and slowly brings it to meet the first. This pattern is repeated (progressed to two sets of 20 s).
Standing hip abduction (Presswood et al., 2008)	A resistance band is tied around a fixed structure. The athlete stands side on to the band and loops it around both feet. While maintaining an erect posture the athlete slides their foot out and slowly abducts their leg. Their leg is then slowly returned to the starting position and the pattern repeated (progressed to three sets of ten repetitions).
Single leg squat (Myer, Paterno, Ford, & Hewett, 2008)	The athlete squats on a single leg, attempting to achieve approximately 90° knee flexion. When viewed anteriorly, the knee should remain above the ankle and below the hip at all times. This exercise was advanced by wrapping a resistance band around the knees of the athlete and having them hold it taut (progressed to three sets of ten repetitions).
Jump squats (Hewett et al., 1999)	As with 'double leg squats', however the athlete first jumps vertically, before landing into a squat position. The bottom position should be held for 5 s (progressed to five sets of three repetitions).
Jump squats with rotation (90^{o} or 180^{o}) (Hewett et al., 1999)	As with 'jump squats', however the athlete performs a 90° (180°) rotation in the air before landing in a squat position. The bottom position should be held for 5 s (progressed to five sets of three repetitions).
Broad jump (forward deep hold) (Myer, Paterno, et al., 2008)	The athlete begins in a semi-squat position and then jumps forward to achieve maximum distance. The athlete must stick the landing with their knees bent to approximately 90° and with no inwards collapse. This position should be held for 5 s and the knees should not go into a varus or valgus position (progressed to three sets of ten repetitions).
Broad jump (single leg) (Hewett et al., 1999)	The athlete begins in a semi-squat position and then jumps forward to achieve maximum distance and landing on one leg. The athlete must stick the landing with their knee bent to approximately 90° and with no inwards collapse. This position should be held for 5 s and the knees should not go into a varus or valgus position (progressed to three sets of ten repetitions).
Box drops (double leg landing) (Hewett et al., 1999)	The athlete drops down from a 30 cm high box, landing with both feet in the squat position (progressed to five sets of three repetitions).

Descriptive statistics for all variables are represented as mean and standard deviations. The Hopkins (2009) spreadsheet for pre- and post-parallel groups analysis was used to provide estimates of the effect of the intervention on the youth athletes in the control and experimental groups. Qualitative inferential outcomes based on interpretation of the span of the confidence interval relative to magnitude thresholds for effects were calculated. Effect sizes were interpreted as trivial (0.0-0.1), small (0.11-0.3), moderate (0.31-0.5), large (0.51-0.7), very large (0.71-0.9), or extremely large (0.91-1.0) (W. Hopkins et al., 2009).

Results

The pre-intervention angles (i.e. baseline) were small for both groups (see Table 11), however there were some small left to right limb differences within the groups such as for hip adduction where the mean pre-intervention angle was 9.5 ±1.4^{o} and 6.0 ±1.4^{o} for the right and left sides respectively for the control group and 9.4 ±2.0^{o} and 5.2 ±1.9^{o} for the experimental group (see Table 11). The mean post-intervention angle was 9.1 ±1.4^{o} and 5.6 ±1.4^{o} for the right and left sides respectively for the control group and 9.4 ±1.9^{o} and 5.6 ±1.5^{o} for the experimental group. These changes equated to a small beneficial effect (effect size = 0.22) for the right hip and a trivial effect (effect size = 0.09) on the left. For knee abduction the mean pre-intervention angle was 6.5 ±3.5^{o} and 6.6 ±4.0^{o} for the right and left sides respectively for the control group and 7.1 ±2.1^{o} and 7.0 ±1.4^{o} for the experimental group. The mean post-intervention angle was 8.8 ±3.1^{o} and 5.7 ±2.4^{o} for the right and left sides respectively for the control group and 9.1 ±3.0^{o} and 8.0 ±1.8^{o} for the experimental group. These changes equated to a trivial effect (effect size = -0.3) for the right knee and a negative (very large) effect (effect size = 0.77) for the left.

Table 11: Pre- and post-intervention means, standard deviations, change in means, differences in changes in means and effect size for control versus experimental groups for hip and knee frontal plane angles.

	Control	Experimental	Control	Experimental
	Right		Left	
Hip adduction				
Pre-intervention mean ±SD (degrees)	9.5 ±1.4	9.4 ±2.0	6.0 ±1.5	5.2 ±1.9
Post-intervention mean ±SD (degrees)	9.1 ±1.4	9.4 ±1.9	5.6 ±1.5	4.9 ±1.6
Change in means (degrees)	0.4	0	0.4	0.3
Difference in change in means (control - experimental) (degrees)	0.4		0.1	
Effect size control vs. experimental (90% CI)	0.22 (-1.1 to 2.0)		0.09 (-0.9 to 1.2)	
Inference control vs. experimental	small beneficial		trivial	
Knee abduction				
Pre-intervention mean ±SD (degrees)	6.5 ±3.5	7.1 ±2.1	6.6 ±4.0	7.0 ±1.4
Post-intervention mean ±SD (degrees)	8.8 ±3.1	9.1 ±3.0	5.7 ±2.4	8.0 ±1.8
Change in means (degrees)	-2.3	-2.0	0.9	-1.0
Difference in change in means (control - experimental) (degrees)	-0.3		1.9	
Effect size control vs. experimental (90% CI)	-0.08 (-3.4 to 2.9)		0.77 (0.1 to 3.7)	
Inference control vs. experimental	trivial		very large detrimental	

Discussion

The intervention programme employed with the experimental group consisted of a series of functional weight bearing exercises aimed at minimising knee valgus angle and open and closed kinetic chain exercises to promote hip muscle activation. However, there were minimal differences between pre- and post-intervention frontal plane hip and knee angles between the control and experimental groups, indicating that the intervention was not effective in improving the targeted gait measures in this cohort of youth athletes.

When the change in mean between the control and experimental groups was considered, no change, or a small change in either direction (to account for normal variation), was expected in the control group. The aim of the lower limb functional exercise programme was to reduce hip and knee frontal plane motion, and therefore it was expected that there would be a positive change in mean hip and knee frontal plane motion for the experimental group. The left hip was the only variable that demonstrated this change, but the magnitude of the effect was trivial. There was no consistent reduction in frontal plane angle for the right hip, or the knee on either side with the youth athletes who followed the functional lower limb exercise programme.

The left knee frontal plane angle demonstrated a very large negative effect. However, the difference in the change in means (1.9°) between the control and experimental group, pre- and post-intervention, was still within the variability demonstrated by the control group pre-intervention (6.6 ±4.0°), and the whole group at baseline (6.8 ±2.4°) (K. Sheerin et al., 2010). This result can partially be explained by the natural movement variability demonstrated within youth athletes. The slow running speed selected by the participants may also help explain the small angles measured. Although the participants were familiarised with treadmill running, they were not necessarily familiar with the laboratory environment and this could have lead them to select a slow running speed resulting in small joint angles. It is also possible that because of the small size the frontal plane angles of interest, that any possible changes could have been masked by the error introduced through equipment calibration, marker placement and movement artifacts.

There are several other potential reasons that could explain why no beneficial changes in frontal plane angles were measured during running. Firstly, some subjects may have exhibited normal angles at baseline, and therefore were not likely to have changed with intervention. Ideally subjects would have been compared with published norms at baseline, and those demonstrating normal angles would have been excluded from further intervention. However, no published normal values exist, and therefore this was not possible. The second potential reason for no demonstrated changes was the structure of the intervention programme. Although the duration of the intervention was considered appropriate based on other intervention studies with similar goals (Herman et al., 2008; Myer et al., 2005; Snyder et al., 2009), the overall volume may have been too low. It would have been preferable to have the youth athletes carrying out the exercises five to six days a week. However, with the LTAD group only gathering on three days per week, and the need for close supervision of the exercises to ensure correct technique, this was not possible. There was also the potential that there wasn't direct cross-over between the intervention exercises and frontal plane control during running.

The exercises selected for the intervention would typically be employed clinically (Myer, Paterno, et al., 2008), and are similar to those described in other studies (Presswood et al., 2008). Although the youth athletes who underwent the 8-week lower limb functional exercise intervention qualitatively showed improvements in their exercise technique and lower limb alignment (as observed by the researcher, but not assessed), there was no cross-over in terms of improvement in running mechanics.

This study was the first to describe the effects of a lower limb functional exercise intervention aimed at changing running mechanics in a cohort of youth athletes. No research has previously been conducted with youth athletes specifically assessing the change in running technique, and therefore it was not possible to compare the findings from this study with a comparable group. Largely positive effects of similar lower limb functional exercise programmes have been demonstrated on lower limb running mechanics (Snyder et al., 2009), and the incidence of lower limb injuries (Heidt et al., 2000; Junge et al., 2002; Pasanen et al., 2008; Steffen et al., 2008), in non-injured adult populations. However, there is no way of knowing if these findings are unique to adults, and whether children would respond in a similar manner.

Given the scarcity of research in this area, there is a need for further studies assessing the running mechanics of youth athletes. Gait measures could be a useful clinical screening tool, however, future research should continue to examine how these measures can be used for monitoring athletic movement development. There is also the need for appropriately designed, large-scale studies, to determine whether there are any sub-groups of youth athletes who would benefit more from lower limb functional training.

Future research should continue to define which exercises are best used with youth athletes, as well as to examine how assessment measures can be used for monitoring athletic movement development.

Conclusion

Although the effect of the 8-week lower limb functional exercise programme employed in this study was minimal in changing frontal plane hip and knee motion when running, this study was the first to describe the effects of such an intervention on the running mechanics of youth athletes.

Practical implications

- Include more volume for the lower limb functional exercise intervention to increase the likelihood of an effect on running mechanics.
- Determine a series of lower limb functional exercises that are suitable for use with youth athletes.
- Determine more sensitive assessment measures to help classify youth athletes with variable movement patterns.

CHAPTER 6

DISCUSSION AND CONCLUSIONS

The identification and development of youth sporting talent is becoming increasingly important. However, injuries can disrupt training and hence the development of this young talent. Although only a small proportion of youth athletes participate in pure running sports, many sports they do compete in involve a large proportion of running.

Many factors can contribute to the development of running related injuries, but several lower limb injuries have been linked to faulty running mechanics. During gait assessments clinicians typically evaluate dynamic lower extremity alignment. Poor frontal plane knee control observed during running is considered a key risk factor for the development of common injuries such as patellofemoral dysfunction. There is however minimal knowledge of how these risk factors relate to youth athletes. This Masters' thesis has sought to uncover a more detailed understanding of hip function and running mechanics in youth athletes. Specifically, whether a lower limb functional exercise programme can reduce hip and knee frontal plane motion in this cohort.

On the basis of the literature review on gait, strength and lower limb injuries in youth athletes, it was established that runners who develop lower limb overuse injuries were weaker on measures of hip abduction, extension and internal rotation muscle strength. In addition, these runners demonstrated increased hip internal rotation and hip adduction angles.

To understand how all of the risk factors described may interact with each other and lead to the development of lower limb overuse injuries in runners, we have developed a conceptual model (see Figure 3). When running, athletes who have decreased hip abductor or external rotator muscle strength may display increased hip adduction and hip internal rotation angles because running demands a large amount of force from these muscles which are weak. Increased hip adduction and hip internal rotation may lead to decreased dynamic control of the lower limb kinetic chain and potentially an increased dynamic knee valgus position and increased tibial or knee internal rotation. The combination of the increased lower limb kinematics will most likely lead to an increase in lower limb forces, and over time, repetitive action in this position may lead to the development of overuse injuries. Although there was no direct evidence to support or refute similar risk factors within a youth athlete population, there was also no evidence that these same risk factors would not be consistent with youth athletes.

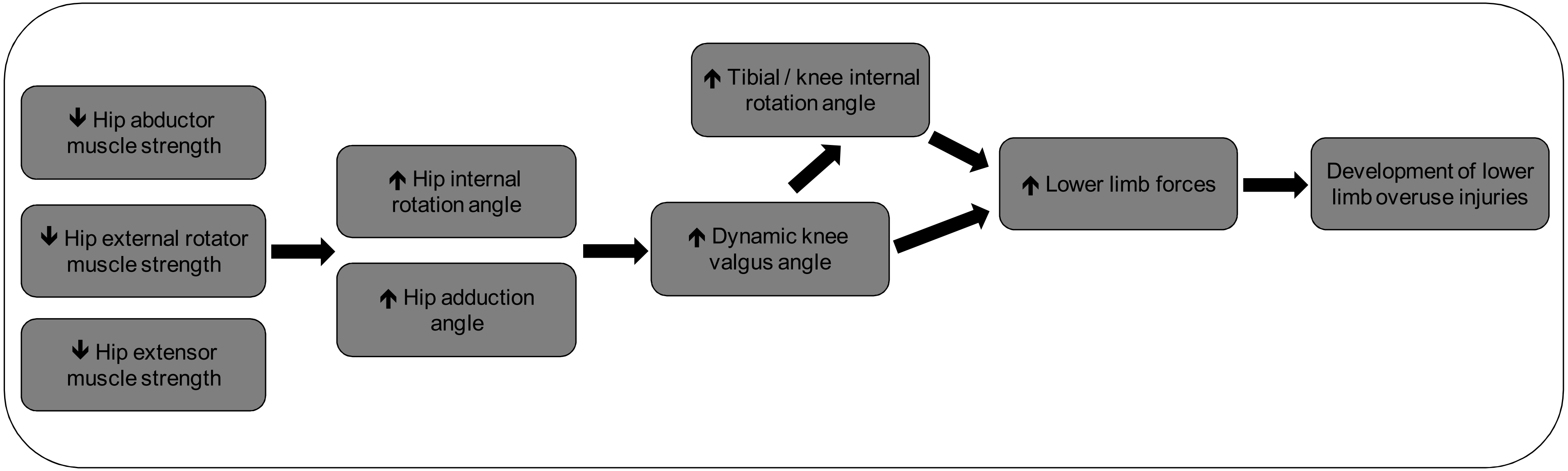


Figure 3: Conceptual model for the development of lower limb overuse injuries.

Given the lack of published information on hip strength measures, as well as 3D frontal plane hip and knee running gait measures for youth athletes, it was necessary to establish the within- and between-day reliability and variability of these variables. It was established that isometric hip abductor, hip flexor, and hip internal and external rotator strength measures demonstrated sufficient within-day reliability to be used as baseline classification tools for youth athletes. However, the between-day reliability of these measures was poor, and therefore these measures were not used to measure changes overtime.

The key findings from the analysis of the reliability of lower limb gait measures in youth athletes were that within-session and between-session reliability of hip and knee frontal plane range of motion during the stance phase of running demonstrated average to good reliability. As a result these measures could be used with confidence to assess changes over time, and potentially the effectiveness of an intervention with youth athletes.

The main aim of the intervention study (chapter 5) was to determine the effect of a lower limb functional exercise programme aimed at minimising knee valgus angle during running in youth athletes. It was proposed that this intervention could potentially mediate the strength and alignment issues outlined in Figure 3, and break the cascade of events leading to the development of lower limb overuse injuries.

Although the effect of the 8-week lower limb functional exercise programme employed on this occasion was minimal in changing frontal plane hip and knee motion when running, this study was the first to describe the effects of such an intervention on the running mechanics of youth athletes. Practical implications for future research as a result of this Masters thesis include increasing volume for the lower limb functional exercise intervention to increase the likelihood of a effect on running mechanics, determining a series of lower limb functional exercises that are suitable for use with youth athletes, and determining more sensitive assessment measures to help classify youth athletes with variable movement patterns.

Thesis limitations and delimitations

The studies presented in this thesis may have been limited by methodological constraints, and it is important to be cognizant of the following limitations when interpreting the results.

Four youth athletes did not complete the second testing session inside the 10-week period and therefore were unable to be included in the final results of the intervention study (chapter 5).

Participant numbers were generally lower than would be ideal, potentially compromising statistical power. It should be noted that the participants used in this study were all from the same long-term athletic training programme, and therefore there was a limited number of athletes within the target age range available for selection.

Throughout this research we used a treadmill installed in a gait laboratory for the analysis of running. Although this provided a realistic simulation of over-ground running, it must be acknowledged that there may be differences. Although treadmill running familiarisation was conducted with all participants, running on a treadmill would not have been as natural for these athletes as running over-ground.

Participants were required to wear reflective markers as part of the kinematic testing sessions. It was assumed that these markers would not alter the normal movement patterns, however this may not necessarily have been correct. In addition, there is the chance the marker placement in each of the testing sessions was different, introducing greater variability into the data, and making the test less sensitive to actual changes. To minimise this potential source of error, on both testing occasions, the markers were secured by the same experienced physiotherapist to known anatomical landmarks.

The nature of the exercises used in the lower limb functional exercise programme (chapter 5), were such that they needed to be conducted with attention to the correct technique. The young age, and subsequent immaturity, of some the athletes recruited for this study meant they were not always completely engaged in how they did these exercises. An experienced coach or physiotherapist was present at all times to supervise the intervention, however it is anticipated that this problem did lead to reducing the effect of the intervention.

There are limitations to strength measurement via dynamometry, which largely relate to the technique and experience of the tester. To minimise these limitations, the same tester, who was experienced in the use of the dynamometer, performed all of the muscle testing. In addition, a fixation strap was used to secure the dynamometer to eliminate the effect of the tester's own strength.

Future directions

This thesis reported reliability statistics for the measurement of hip strength, as well as hip and knee frontal plane motion during treadmill running in youth athletes. Based on these analyses a lower limb functional training programme designed to minimise knee valgus angle and promote hip muscle activation was implemented to reduce hip and knee frontal plane motion during running. In the process, several areas requiring further clarification have arisen.

Although the hip strength measures assessed in this thesis achieved both acceptable reliability and variability within a day, future research should investigate the length of recovery time between trials to reduce the effect of fatigue and possibly improve reliability. Furthermore, the use of these measures in comparison investigations between youth athletes of other ages (i.e. younger and older than our youths' mean age of 11.4 years), genders, athletic populations, and athletic performance level would broaden the knowledge base of the use of hip strength measures. Given our hip strength measures were all isometric, further research on the reliability of strength during functional movements would also be warranted. There is also the need for further research to establish reliable protocols for the measurement of hip strength over the course of intervention studies.

Isometric hip flexor, hip abductor, hip internal and external rotator strength measures could be useful as part of a clinical screening tool, however, future research should continue to examine how isometric hip strength can be measured more reliably between days and used for monitoring youth athletic development.

The key findings from the analysis of the reliability of lower limb gait measures in youth athletes were that within-day and between-day reliability of hip and knee frontal plane range of motion during the stance phase of running in a youth athlete population demonstrated average to good reliability. Further research should examine the within-day and between-day reliability of additional potentially important lower limb gait measures such as hip and knee rotation and lateral pelvic tilt.

Given the scarcity of research in this area, there is a need for further studies assessing the running mechanics of youth athletes. Gait measures could be a useful clinical screening tool, however, future research should continue to examine how these measures can be used for monitoring athletic movement development. There is also the need for appropriately designed, large-scale studies, to determine whether there are any sub-groups of youth athletes who would benefit more from lower limb functional training. Future research should continue to define which exercises are best used with youth athletes, as well as to examine how assessment measures can be used for monitoring athletic movement development.

Conclusion

This thesis consists of a series of studies evaluating the reliability and variability of hip strength and frontal plane hip and knee range of motion in youth athletes. It culminates in an intervention study assessing the effects of a lower limb functional exercise programme on reducing hip and knee frontal plane motion in this cohort. Although the effect of the 8-week lower limb functional exercise programme employed on this occasion was minimal in changing frontal plane hip and knee motion when running, this study was the first to describe the effects of such an intervention on the running mechanics of youth athletes.

REFERENCES

Adirim, T., & Cheng, T. (2003). Overview of injuries in the young athlete. *Sports Medicine, 33*(1), 75.

Arnold, A. S., Komattu, A. V., & Delp, S. L. (1997). Internal rotation gait: a compensatory mechanism to restore abduction capacity decreased by bone deformity. *Developmental Medicine and Child Neurology, 39*, 40-44.

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

Baldon, R., Nakagawa, T., Muniz, T., Amorim, C., Maciel, C., & Serra, V. (2009). Eccentric hip muscle function in females with and without patellofemoral pain syndrome. *Journal of Athletic Training, 44*(5), 490-496.

Balyi, I., & Hamilton, A. (2004). *Long-Term Athlete Development: Trainability in Childhood and Adolescence. Windows of Opportunity. Optimal Trainability.* Victoria: National Coaching Institute British Columbia & Advanced Training and Performance Ltd.

Bates, B., Dufek, J., & Davis, H. (1992). The effect of trial size on statistical power. *Medicine and Science in Sports and Exercise, 24*(9), 1059-1065.

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

Bennell, K., Crossley, K., Wrigley, T., & Nitschke, J. (1999). Test-retest reliability of selected ground reaction force parameters and their symmetry during running. *Journal of Applied Biomechanics, 15*, 330-336.

Bohannon, R. (1986). Test-retest reliability of hand-held dynamometry during a single session of strength assessment. *Physical Therapy, 66*(2), 206-209.

Bohannon, R. (2005). Manual muscle testing: does it meet the standards of an adequate screening test? *Clinical Rehabilitation, 19*, 662-667.

Bolgla, L., Malone, T., Umberger, B., & Uhl, T. (2008). Hip strength and hip and knee kinematics during stair descent in females with and without patellofemoral pain syndrome. *Journal of Orthopedics and Sports Physical Therapy, 38*(1), 12-18.

Bolgla, L. A. (1997). Reliability of lower extremity functional performance tests. *Journal of Orthopaedic & Sports Physical Therapy, 26*(3), 138-142.

Boling, M., Bolgla, L., Mattacola, C. G., Uhl, T., & Hosey, R. (2006). Outcomes of a weight-bearing rehabilitation program for patients diagnosed with patellofemoral pain syndrome. *Archieves of Phsical Medicine and Rehabilitation, 87*, 1428-1435.

Boling, M., Padua, D., & Creighton, R. A. (2009). Concentric and eccentric torque of the hip musculature in individuals with and without patellofemoral pain. *Journal of Athletic Training, 44*(1), 7-13.

Boling, M., Padua, D., Marshall, S., Guskiewicz, K. M., Pyne, S., & Beutler, A. (2009). A prospective investigation of biomechanical risk factors for patellofemoral pain syndrome: The joint undertaking to monitor and prevent ACL injury (JUMP-ACL) cohort. *American Journal of Sports Medicine, 37*(11), 2108-2011.

Bradshaw, E., Hume, P., Calton, M., & Aisbett, B. (2010). Reliability and variability of day-to-day vault training measures in artistic gymnastics. *Sports Biomechanics, 9*(2), 79-97. doi:10.1080/14763141.2010.488298

Carcia, C., Eggen, J., & Shultz, S. (2005). Hip-abductor fatigue, frontal-plane landing angle, and excursion during a drop jump. *Journal of Sport Rehabilitation, 14*(4), 321–331.

Cibulka, M., & Threlkeld-Watkins, J. (2005). Patellofemoral pain and asymmetrical hip rotation. *Physical Therapy, 85*(11), 1201-1207.

Cichanowski, H. R., Schmitt, J. S., Johnson, R. J., & Niemuth, P. E. (2007). Hip strength in collegiate female athletes with patellofemoral pain. *Medicine and Science in Sports and Exercise, 39*(8), 1227-1232.

Clark, N. (2001). Functional performance testing following knee ligament injury. *Physical Therapy in Sport, 2*(2), 91-105.

Cochrane Handbook for Systematic Reviews of Interventions 5.0.2 (2008). (3 ed.)

Cormack, S. J., Newton, R. U., McGuigan, M. R., & Doyle, T. L. A. (2008). Reliability of measures obtained during single and repeated countermovement jumps. *International Journal of Sports Physiology & Performance, 3*(2), 131-144.

Craik, R., & Oatis, C. (1995). *Gait Analysis. Theory and Application*. St. Louis: Mosby.

Dicharry, J. (2010). Kinematics and kinetics of gait: From lab to clinic. *Clinical Sports Medicine, 29*(3), 347-364.

Dierks, T. A., Manal, K. T., Hamill, J., & Davis, I. S. (2008). Proximal and distal influences on hip and knee kinematics in runners with patellofemoral pain during a prolonged run. *Journal of Orthopaedics and Sports Physical Therapy, 38*(8), 448–456.

Diss, C. (2001). The reliability of kinetic and kinematic variables used to analyse normal running gait. *Gait and Posture, 14*, 98-103.

Earl, J., & Hoch, A. (2011). A proximal strengthening program improves pain, function, and biomechanics in women with patellofemoral pain syndrome. *American Journal of Sports Medicine, 39*(1), 154-163.

Earl, J. E., Monteiro, S. K., & Snyder, K. R. (2007). Differences in lower extremity kinematics between a bilateral drop-vertical jump and a single-leg step-down. *Journal of Orthopaedic and Sports Physical Therapy, 5*(37), 245-252.

Fenter, P., Bellew, J., Pitts, T., & Kay, R. (2003). Reliability of stabilised commercial dynamometers for measuring hip abduction strength: A pilot study. *British Journal of Sports Medicine, 37*, 331-334.

Ferber, R., Davis, I., Hamill, J., Pollard, C., & McKeown, K. (2002). Kinetic variables in subjets with previous lower extremity stress fractures. *Medicine and Science in Sports and Exercise, 34*(5), S5.

Ferber, R., Davis, I. M., Williams, D., & Laughton, C. (2002). A comparison of within- and between-day reliability of discrete 3D lower extremity variables in runners. *Journal of Orthopaedic Research, 20*, 1139-1145.

Ferber, R., Noehren, B., Hamill, J., & Davis, I. (2010). Competitive female runners with a history of iliotibial band syndrome demonstrate atypical hip and knee kinematics. *Journal of Orthopaedic and Sports Physical Therapy, 40*(2), 52-58.

Ford, K. R., Myer, G. D., & Hewett, T. E. (2003). Valgus knee motion during landing in high school female and male basketball players. *Medicine and Science in Sport and Exercise, 35*(10), 1745-1750.

Fredericson, M., Cookingham, C., Chaudhari, A., Dowdell, B., Oestreicher, N., & Sahrmann, S. (2000). Hip abductor weakness in distance runners with Iliotibial band syndrome. *Clinical Journal of Sports Medicine, 10*, 169-175.

Fukuda, T., Rossetto, F., Magalhães, E., Bryk, F., Lucareli, R., & Carvalho, N. (2010). Short-term effects of hip abductors and lateral rotators strengthening in females with patellofemoral pain syndrome: A randomized controlled clinical trial. *Journal of Orthopaedic and Sports Physical Therapy, 40*(11), 736-742.

Fulcher, M. L., Hanna, C. M., & E.C., R. (2010). Reliability of handheld dynamometry in assessment of hip strength in adult male football players. *Journal of Science and Medicine in Sport, 13*(1), 80-84.

Geiser, C., O'Connor, K., & Earl, J. (2010). Effects of isolated hip abductor fatigue on frontal plane knee mechanics. *Medicine and Science in Sport and Exercise, 42*(3), 535–545.

Hawkins, D., & Metheny, J. (2001). Overuse injuries in youth sports: Biomechanical considerations. *Medicine and Science in Sports and Exercise, 33*(10), 1701-1707.

Heidt, R., Sweeterman, L., Carlonas, R., Traub, J., & Tekulve, F. (2000). Avoidance of soccer injuries with preseason conditioning. *The Amercian Journal of Sports Medicine, 28*, 659-662.

Heinert, B., Kernozek, T., Greany, J., & Fater, D. (2008). Hip abductor weakness and lower extremity kinematics during running. *Journal of Sport Rehabilitation, 17*(3), 243-256.

Herman, D., Weinhold, P., Guskiewicz, K., Garrett, W., Yu, B., & Padua, D. (2008). The effects of strength training on the lower extremity biomechanics of female recreational athletes during a stop-jump task. *The American Journal of Sports Medicine, 36*(4), 733-740.

Hewett, T., Ford, K., & Myer, G. (2006). Anterior cruciate ligament injuries in female athletes. Part 2, A meta-analysis of neuromuscular interventions aimed at injury prevention. *The Amercian Journal of Sports Medicine, 34*(3), 498.

Hewett, T., Lindenfeld, T., Riccobene, J., & Noyes, F. (1999). The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *The American Journal of Sports Medicine, 27*(6), 699-706.

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

Hollman, J. H., Ginos, B. E., Kozuchowski, J., Vaughn, A. S., Krause, D. A., & Youdas, J. W. (2009). Relationships between knee valgus, hip-muscle strength, and hip-muscle recruitment during a single-limb step-down. *Journal of Sport Rehabilitation, 18*(1), 104-117.

Hopkins, W. (2009). *Spreadsheet for the analysis of reliability (beta version)*. Retrieved2010, from http://www.sportsci.org/.

Hopkins, W., Marshall, S., Batterham, A., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sport and Exercise, 41*(1), 3-12.

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

Hopkins, W. G. (2000b). *Reliability from conecutive pairs of trials (Excel spreadsheet). In: A new viewof statistics.* Retrieved January 16th, 2009, from sportsci.org: Internet Society for Sport Science, sportsci.org/resource/stats/xrely.xls

Hopkins, W. G. (2002). *A scale of magnitudes for effect statistics*. Retrieved 23.04.09, 2009, from http://sportsci.org/resource/stats/effectmag.html

Hopkins, W. G. (2007). A spreadsheet to compare means of two groups. *Sportscience*(11), 22-23.

Hopkins, W. G., & Manly, B. F. J. (1989). Errors in assigning grades based on tests of finite validity. *Research Quarterly for Exercise and Sport, 60*(2), 180-182.

Ireland, M., Willson, J., Ballantyne, B., & Davis, I. (2003). Hip strength in females with and without patellofemoral pain. *The Journal of Orthopaedic and Sports Physical Therapy, 33*(11), 671-676.

Junge, A., Rösch, D., Peterson, L., Graf-Baumann, T., & Jiri Dvorak, J. (2002). Prevention of soccer injuries: a prospective intervention study in youth amateur player. *The Amercian Journal of Sports Medicine, 30*(5), 652-659.

Juni, P., Altman, D. G., & Egger, M. (2001). Systematic reviews in health care - Assessing the quality of controlled clinical trials. *British Medical Journal, 23*(7303), 42-46.

Kawaguchi, J. K., & Babcock, G. (2010). Validity and reliability of handheld dynametric strength assessment of hip extensor and abductor muscles. *Athletic Training and Sports Health Care, 2*(1), 11-17.

Kelln, B., McKeon, P., Gontkof, L., & Hertel, J. (2008). Hand-held dynamometry: Reliability of lower extremity muscle testing in healthy, physically active, young adults. *Journal of Sport Rehabilitation, 17*, 160-170.

Kendall, F., McCreary, E., & Provance, P. (1993). *Muscles: Testing and and Function* (4th ed.). Baltimore: Williams and Wilkins.

Lawrence, R. K., Kernozek, T. W., Miller, E. J., Torry, M. R., & Reuteman, P. (2008). Influences of hip external rotation strength on knee mechanics during single-leg drop landings in females. *Clinical Biomechanics, 23*(6), 806-813.

Leetun, D., Ireland, M., Willson, J., Ballantyne, B., & Davis, I. (2004). Core stability measures as risk factors for lower extremity injury in athletes. *Medicine and Science in Sports and Exercise, 36*(6), 926-934.

Magalhães, E., Fukuda, T., Sacrament, S., Forgas, A., Cohen, M., & Abdalla, R. (2010). A comparison of hip strength between sedentary females with and without patellofemoral pain syndrome. *Journal of Orthopaedic and Sports Physical Therapy, 40*(10), 641-647.

Mann, R., Moran, G., & Dougherty, S. (1986). Comparative electromyography of the lower extremity in jogging, running, and sprinting. *American Journal of Sports Medicine, 14*, 501-509.

Mann, R. A., Moran, G. T., & Dougherty, S. E. (1986). Comparative electromyography of the lower extremity in jogging, running, and sprinting. *American Journal of Sports Medicine, 14*, 501-509.

Mascal, C., Landel, R., & Powers, C. (2003). Management of patellofemoral pain targeting hip, pelvis, and trunk muscle function: 2 case reports. *Journal of Orthopaedic and Sports Physical Therapy, 33*(11), 647-660.

McKenzie, K., Galea, V., Wessel, J., & M., P. (2010). Lower extremity kinematics of females with patellofemoral pain syndrome while stair stepping. *Journal of Orthopaedic and Sports Physical Therapy, 40*(10), 625-632.

Micheli, L., Glassman, R., & Klein, M. (2000). The prevention of sports injuries in children. *Clinics in Sports Medicine, 19*(4), 821-834.

Milner, C., Hamill, J., & Davis, I. (2010). Distinct hip and rearfoot kinematics in female runners with a history of tibial stress fracture. *Journal of Orthopaedic and Sports Physical Therapy, 40*(2), 59-66.

Morrow, J. R., & Jackson, A. W. (1993). How 'significant' is your reliability? *Research Quarterly for Exercise and Sport, 64*(3), 352-355.

Mottram, S., & Comerford, M. (2008). A new perspective on risk assessment. *Physical Therapy in Sport, 9*(1), 40-51.

Myer, G., Chu, D., Brent, J., & Hewett, T. (2008). Trunk and hip control neuromuscular training for the prevention of knee joint injury. *Clinics in Sports Medicine, 27*, 428-448.

Myer, G., Ford, K., Palumbo, J., & Hewett, T. (2005). Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *Journal of Strength and Conditioning Research, 19*(1), 51-60.

Myer, G., Paterno, M., Ford, K., & Hewett, T. (2008). Neuromuscular training techniques to target deficits before return to sport after anterior cruciate ligament reconstruction. *Journal of Strength and Conditioning Research, 22*(3), 987-1014.

Nakagawa, T., Muniz, T., Baldon, R., Maciel, C., Reiff, R., & Serrao, F. (2008). The effect of additional strengthening of hip abductor and lateral rotator muscles in patellofemoral pain syndrome: A randomized controlled pilot study. *Clinical Rehabiitation, 22*(12), 1051-1060.

Niemuth, P. E., Johnson, R. J., Myers, M. J., & Thieman, T. J. (2005). Hip muscle weakness and overuse injuries in recreational runners. *Clinical Journal of Sport Medicine, 15*(1), 14-21.

Noehren, B., Davis, I., & Hamill, J. (2007). Prospective study of the biomechanical factors associated with iliotibial band syndrome. *Clinical Biomechanics, 22*, 951-956.

Novacheck, T. (1998). The biomechanics of running. *Gait and Posture, 7*, 77-95.

Pasanen, K., Parkkari, J., Pasanen, M., Hiilloskorpi, H., Makinen, T., Jarvinen, M., & Kannus, P. (2008). Neuromuscular training and the risk of leg injuries in female floorball players: Cluster randomised controlled study. *British Medical Journal, 337*(10), 802-805.

Piva, S., Goodnite, E., & Childs, J. (2005). Strength around the hip and flexibility of soft tissues in individuals with and without patellofemoral pain syndrome. *Journal of Orthopaedic and Sports Physical Therapy, 35*(12), 793-801.

Piva, S. R., Fitzgerald, K., Irrgang, J. J., Jones, S., Hando, B. R., Browder, D. A., & Childs, J. D. (2006). Reliability of measures of impairments associated with patellofemoral pain syndrome. *Biomedical Central - Musculoskeletal Disorders, 7*, 33.

Pollard, C. D., Sigward, S. M., Ota, S., Langford, K., & Powers, C. M. (2006). The influence of in-season injury prevention training on lower-extremity kinematics during landing in female soccer players. *Clinical Journal of Sport Medicine, 16*(3), 223-227.

Powers, C. (2003). The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: A theoretical perspective. *Journal of Orthopaedic and Sports Physical Therapy, 33*, 639.

Powers, C. (2010). The influence of abnormal hip mechanics on knee injury: A biomechanical perspective. *Journal of Orthopaedic and Sports Physical Therapy, 40*(2), 42-51.

Presswood, L., Cronin, J., Keogh, J., & Whatman, C. (2008). Gluteus medius: Applied anatomy, dysfunction, assessment, and progressive strengthening. *Strength and Conditioning Journal, 30*(5), 41-53.

Queen, R. M., Gross, M. T., & Liu, H. Y. (2006). Repeatability of lower extremity kinetics and kinematics for standardized and self-selected running speeds. *Gait and Posture, 23*(3), 282-287. doi:10.1016/j.gaitpost.2005.03.007

Reiman, M., Bolgla, L., & Lorenz, D. (2009). Hip function's influence on knee dysfunction: A proximal link to a distal problem. *Journal of Sport Rehabilitation, 18*(1), 33-46.

Robinson, R. L., & Nee, R. J. (2007). Analysis of hip strength in females seeking physical therapy treatment for unilateral patellofemoral pain syndrome. *The Journal of Orthopaedic and Sports Physical Therapy, 37*(5), 232-238.

Sahrmann, S. A. (2002). *Diagnosis and treatment of movement impairment syndromes*. London: Mosby.

Schabort, E. J., Hawley, J. A., Hopkins, W. G., & Blum, H. (1999). High reliability of performance of well-trained rowers on a rowing ergometer. *Journal of Sport Sciences, 17*, 627-632.

Seto, C., Statuta, S., & Solari, I. (2010). Pediatric running injuries. *Clinics in Sports Medicine, 29*, 499-511.

Shanmugam, C., & Maffulli, N. (2008). Sports injuries in children. *British Medical Bulletin, 86*(1), 33-57.

Sheerin, K., Whatman, C., Hume, P. A., & Croft, J. (2010 *Reliability of 3D gait kinematics in treadmill running in healthy young athletes*. presented at the meeting of the International Society of Biomechanics in Sports Congress, Michigan, USA.

Sheerin, K. R., Hume, P. A., Whatman, C., & Croft, J. (2010). Reliability of lower limb strength, flexibility and 3D gait measures during running in young athletes Symposium conducted at the meeting of the Sports Medicine New Zealand Conference, Wellington, New Zealand.

Shrout, P. E., & Fleiss, J. L. (1979). Intraclass correlations: Uses in assessing rater reliability. *Psychological Bulletin, 86*(2), 420-428.

Sigward, S. M., Ota, S., & Powers, C. (2008). Predictors of frontal plane knee excursion during a drop land in young female soccer players. *Journal of Orthopaedic and Sports Physical Therapy, 38*(11), 661-668.

Snyder, K., Earl, J., O'Connor, K., & Ebersole, K. (2009). Resistance training is accompanied by increases in hip strength and changes in lower extremity biomechanics during running. *Clinical Biomechanics, 24*, 26-34.

Soper, C., & Hume, P. A. (2004). Reliability of power output during rowing changes with ergometer type and race distance. *Sport Biomechanics, 3*, 237-247.

Souza, R., & Powers, C. (2009a). Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain. *Journal of Orthopaedic and Sports Physical Therapy, 39*(1), 12-19.

Souza, R., & Powers, C. (2009b). Predictors of hip internal rotation during running: an evaluation of hip strength and femoral structure in women with and without patellofemoral pain. *American Journal of Sports Medicine, 37*(3), 579-587.

Stefanyshyn, D., Stergiou, P., Lun, V., Meeuwisse, W., & Worobets, J. (2006). Knee angular impulse as a predictor of patellofemoral pain in runners. *The American Journal of Sports Medicine, 34*(11), 1844-1851.

Steffen, K., Myklebust, G., Olsen, O., Holme, I., & Bahr, R. (2008). Preventing injuries in female youth football – a cluster-randomized controlled trial. *Scandinavian Journal of Medicine and Science in Sports, 18*(5), 605-614.

Stein, C., & Micheli, L. (2010). Overuse injuries in youth sports. *The Physician and Sportsmedicine, 38*(2), 102-108.

Stuberg, W., & Metcalf, W. (1988). Reliability of quantitative muscle testing in healthy children and in children with duchenne muscular dystrophy using a hand-held dynamometer. *Physical Therapy, 68*(6), 977-982.

Tonley, J., Yun, S., Kochevar, R., Dye, J., Farrokhi, S., & Powers, C. (2010). Treatment of an individual with piriformis syndrome focusing on hip muscle strengthening and movement reeducation: A case report. *Journal of Orthopaedic and Sports Physical Therapy, 40*(2), 103-111.

Treasure, T., & MacRae, K. (1998). Minimisation: the platinum standard for trials? Randomisation doesn't guarantee similarity of groups; minimisation does. *British Medical Journal, 317*, 362-363.

Tyler, T. F., Nicholas, S. J., Mullaney, M. J., & McHugh, M. P. (2006). The role of hip muscle function in the treatment of patellofemoral pain syndrome. *American Journal of Sports Medicine, 34*(4), 630-636.

Whatman, C., Hing, W., & Hume, P. (2011). Kinematics during lower extremity functional screening testseAre they reliable and related to jogging? *Physical Therapy in Sport, 12*, 22-29.

Willson, J. D., & Davis, I. (2008). Utility of the frontal plane projection angle in females with patellofemoral pain. *Journal of Orthopaedic and Sports Physical Therapy, 38*(10), 606-615.

Willson, J. D., & Davis, I. S. (2008). Lower extremity mechanics of females with and without patellofemoral pain across activities with progressively greater task demands. *Clinical Biomechanics, 23*(2), 203-211.

Willson, J. D., & I., D. (2009). Lower extremity strength and mechanics during jumping in women with patellofemoral pain. *Journal of Sport Rehabilitation, 18*(1), 75-89.

APPENDIX 1

AUT ETHICS APPROVAL

Participant Information Sheet

Date Information Sheet Produced: 22nd October 2008

Project Title How does the strength of my hip affect my running?

An invitation
My name is Kelly Sheerin and I am inviting you to help with a project that looks at how children run. It will involve running on a treadmill and some basic measurements of muscle strength and flexibility. There is also a possibility of doing some simple new exercises as part of your existing Long Term Athlete Development programme. Together, you and your parents should decide whether or not you would like to be involved. You don't have to be involved, it won't affect your role in the programme, and you can stop being involved in the study at any time.

What will happen in this project?
You will come to the University two times on different days, for 1 hour at a time. During each session we will measure your muscle strength, flexibility of your legs and video you running on a treadmill. You will have to run on the treadmill for 5 minutes in total. It will be at your own speed, so you shouldn't be tired at the end of it. You will also do two exercises (a small hop and a small jump). A video recording of these exercises will be shown to some physiotherapists to assess your technique. We will record your height, weight and injury history. In addition, one group will undergo some basic strengthening exercises during their normal LTAD sessions.

What chance do I have to decide whether or not I would like to be involved in the study?
You may take the time you need to talk to your parents and decide whether or not you would like to be involved in the project. You can stop being involved in the project at any point. Your involvement in this study is voluntary and it will not affect what you would normally do as part of the programme.

How do I agree to become involved in this research?
If you and your parents decide that you would like to be involved in the study please ask your parents to contact Kelly Sheerin (contact details below).

Will I receive feedback on the results of this research?
Yes, a report will be provided to your parents with your results.

How will my privacy be protected?
All information related to you will coded in order to ensure that you cannot be identified. The information will remain in locked storage and will only be accessible to the people running the project. No-one at the Millennium Institute of Sport and Health will be able to identify you from any findings that they are given.

What happens if there are concerns about this research?
Any concerns regarding the nature of this project should be notified in the first instance to the Primary Researcher:

Primary Researcher Contact Details: Kelly Sheerin, Institute of Sport and Recreation Research New Zealand, School of Sport and Recreation, AUT University. Email: kelly.sheerin@aut.ac.nz or phone +64 9 917 9999 ext 7354.

Project Supervisor Contact Details: Associate Professor Patria Hume, Institute of Sport and Recreation Research New Zealand, School of Sport and Recreation, AUT University. Email: patria.hume@aut.ac.nz or phone +64 9 917 9999 ext 7306.

Concerns regarding the conduct of the research should be notified to the Executive Secretary, AUTEC, Madeline Banda, *madeline.banda@aut.ac.nz*, 921 9999 ext 8044.

Approved by the Auckland University of Technology Ethics Committee on 10/12/2008, AUTEC Reference number 08/258.

Parent / Guardian Information Sheet

Date Information Sheet Produced: 22nd October 2008

Project Title Relationship of hip strength to running mechanics in young athletes.

An Invitation
Your child has been invited to participate in this research study, which aims to determine the relationship of hip strength to running mechanics in children. Their participation in the study is voluntary and that they may withdraw at any time without any adverse consequences. Withdrawal from the study will not affect your's or their relationship with AUT or Millennium Institute of Sport and Health, or their participation in the Long Term Athlete Development programme.

What is the purpose of this research?
Athletic success in any sport requires years of dedicated training and one requirement of effective training is that athletes remain free of injury. However, over one third of young athletes seek medical attention for injuries that occur during physical activity or sport. Injuries sustained in youth have the potential to disturb growth and lead to chronic disability in adulthood, such as arthritis. The purpose of this research is to determine whether a programme designed to increase hip muscle strength can improve running mechanics and prevent the incidence of injuries in young athletes. The data gathered in this study may be presented and conferences and published in academic journals.

How was my child chosen for this study?
Your child has been selected for this study because they are a participant in the Millennium Institute of Sport - Long Term Athlete Development (LTAD) programme.

What will happen in this research?
Your child will be required to attend two testing sessions at The AUT University Running Mechanics Clinic, 90 Akoranga Drive, Northcote. During each session they will be taken through some basic tests of muscle strength and flexibility and will be videoed while they run on a treadmill for 5 minutes and while they perform two functional tests (a small knee bend and a small jump). The video recordings of the functional tests will be shown to 15 experienced physiotherapists for visual rating. In addition, one group will undergo some basic strengthening exercises during their normal LTAD sessions.

Outline of Testing Sessions

Station 1	*Station 2*	*Station 3*	*Station 4*
Study explanation, questions and informed consent (5 mins) Injury history questionnaire (5 mins) Baseline height and weight measures (5 mins)	Strength measures (10 mins) Flexibility measures (10 mins)	Mark-up with reflective markers (10 mins)	Functional screening tests (5 mins) Gait mechanics (10 mins)
15 mins	20 mins	10 mins	15 mins
Total time	60 mins		

What are the discomforts and risks?
Most children will not be familiar with running on a treadmill, so the opportunity will be provided prior to the first testing session for each child to be familiarised with this. The treadmill run will be at a self-selected speed, so children shouldn't be fatigues at the end of the test.

What are the benefits?
Some of the benefits of participating in this research include finding out whether there are any factors related to how your child runs that could contribute to future injury or discomfort.

What compensation is available for injury or negligence?
In the unlikely event of a physical injury as a result of your child's participation in this study, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

How will my child's privacy be protected?
All information and data related to your will coded in order to ensure that they cannot be identified. The data collected will remain in locked storage and will only be accessible to the principal investigators of the project in accordance with the Privacy Act 1993. No-one at the Millennium Institute of Sport and Health will be able to identify participants from any findings that they are given.

What are the costs of participating in this research?
Your child will be required to attend 2 testing sessions, of one-hour duration each. You will be given a petrol voucher to assist with any travel costs involved.

What opportunity do my child and I have to consider this invitation?
You may take the time you need to consider this invitation to participate in the study. Your child has the opportunity to withdraw from the study at any point. Your child's participation in this study should be voluntary.

How do I and my child agree to participate in this research?
If you and your child decide that you would like to be involved in the study please contact Kelly Sheerin (contact details below).

Will I receive feedback on the results of this research?
Yes, a report will be provided to you and your child with your child's individual results.

What do I do if I have concerns about this research?
Any concerns regarding the nature of this project should be notified in the first instance to the Primary Researcher:

Primary Researcher Contact Details: Kelly Sheerin, Institute of Sport and Recreation Research New Zealand, School of Sport and Recreation, AUT University. Email: kelly.sheerin@aut.ac.nz or phone +64 9 917 9999 ext 7354.

Project Supervisor Contact Details: Associate Professor Patria Hume, Sport Performance Research Institute New Zealand, School of Sport and Recreation, AUT University. Email: patria.hume@aut.ac.nz or phone +64 9 917 9999 ext 7306.

Concerns regarding the conduct of the research should be notified to the Executive Secretary, AUTEC, Madeline Banda, *madeline.banda@aut.ac.nz*, 921 9999 ext 8044.

Approved by the Auckland University of Technology Ethics Committee on 10/12/2008, AUTEC Reference number 08/258.

Parent / Guardian Consent Form

Date Information Sheet Produced: 22nd October 2008

Project Title: Relationship of hip strength to running mechanics in young athletes

Primary Researcher: Kelly Sheerin

- I have read and understood the information provided about this research project in this Information Sheet.
- I have had an opportunity to ask questions and to have them answered.
- I understand that I may withdraw my child/children and/or myself or any information that we have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.
- If my child/children and/or I withdraw, I understand that all relevant information including tapes and transcripts, or parts thereof, will be destroyed.
- My child/children are not suffering from heart disease, high blood pressure, any respiratory condition, any illness or injury that impairs my physical performance, or any infection.
- I permit the researcher to use the videos that are part of this project and/or any photographs from them and any other reproductions or adaptations from them, either complete or in part, alone or in conjunction with any wording and/or drawings solely and exclusively for research or educational purposes.
- I understand that the videos will be used for academic purposes only and will not be published in any form outside of this project without my written permission.
- I understand that any copyright material created by the video is deemed to be owned by the researcher and that I do not own copyright of any of the video.
- I agree to my child/children taking part in this research.
- I wish to receive a copy of the report from the research (please tick one):

Yes ○ No ○

Child's name :…………………………………………………………………….

Parent/Guardian's signature:.....................................………………………

Parent/Guardian's name:...........………………………………………………….

Parent/Guardian's Contact Details (if appropriate):
……………………………………………………………………………………..
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……………………………………………………………………………………..

Date:.....………………

Note: The Participant should retain a copy of this form.

Approved by the Auckland University of Technology Ethics Committee on 10/12/2008, AUTEC Reference number 08/258.

Participant Assent Form

Date Information Sheet Produced: 22nd October 2008

Project Title: How does the strength of my hip affect my running?

Primary Researcher: Kelly Sheerin

- I have read and understood the information provided about this project in the Information Sheet.
- I have had a chance to ask questions and have them answered.
- I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of the project activities, without being disadvantaged in any way.
- I will allow the researcher to use the videos and photographs that are part of this project exclusively for research or educational purposes
- I understand that the videos will be used for academic purposes only and will not be published in any form outside of this project without my written permission.
- I understand that any copyright material created by the video is deemed to be owned by the researcher and that I do not own copyright of any of the video.
- I agree to take part in this project.
- I wish to receive a copy of the report from the project (please tick one):
  Yes○ No○

Participant's signature: ....……….........……..

Participant's name: ....…………………………………………………

Participant Contact Details (if appropriate):
………………………………………………………………………………………..

Date:

Note: The participant should retain a copy of this form.

Approved by the Auckland University of Technology Ethics Committee on 10/12/2008, AUTEC Reference number 08/258.

AUTEC APPROVAL MEMORANDUM

To: Patria Hume
From: Madeline Banda Executive Secretary, AUTEC
Date: 10 December 2008
Subject: Ethics Application Number 08/258. Relationship of hip strength to running mechanics in young athletes.

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 10 November 2008 and that 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 19 January 2009.

Your ethics application is approved for a period of three years until 10 December 2011.

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

- A brief annual progress report using form EA2, which is available online through *http://www.aut.ac.nz/about/ethics*. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 10 December 2011;
- A brief report on the status of the project using form EA3, which is available online through *http://www.aut.ac.nz/about/ethics*. This report is to be submitted either when the approval expires on 10 December 2011 or on completion of the project, whichever comes sooner;

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are reminded that, as applicant, you are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

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. When communicating with us about this application, we ask that you use the application number and study title to enable us to provide you with prompt service.

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 AUTEC 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: Kelly Sheerin, Chris Whatman, James Croft

APPENDIX 2

ADDITIONAL DATA: RELIABILITY OF 3D FRONTAL PLANE HIP AB/ADDUCTION RANGE OF MOTION DURING RUNNING IN YOUNG ATHLETES.

Table 12: **Within-session statistics, including 90%CL, for frontal plane hip ab/adduction range of motion during the stance phase of running for healthy young athletes (n=18).**

	Session 1		**Session 2**	
	Right	**Left**	**Right**	**Left**
Trial 1 mean ±SD (degrees)	6.2 ±2.0	5.6 ±1.7	6.1 ±1.8	5.2 ±1.6
Trial 2 mean ±SD (degrees)	7.1 ±2.5	5.9 ±1.6	6.7 ±2.1	5.4 ±1.9
ES (within-session, between-trials)	0.40	0.19	0.30	0.12
Change in mean % (90%CL)	13.4 (4.5 to 23.1)	6.7 (0.3 to 13.6)	8.1 (0.6 to 16.2)	1.9 (-8.1 to 12.9)
Typical error as a CV% (90%CL)	15.2 (11.7 to 21.9)	11.3 (8.8 to16.2)	13.3 (10.3 to 19.1)	19.3 (14.9 to 28.1)
Total error (%)	17.8	12.1	14.2	18.8
Intraclass r (90%CL)	52.5	37.8	45.0	69.5
Trial 1 mean ±SD (degrees)	0.82	0.88	0.87	0.75
Trial 2 mean ±SD (degrees)	0.82 (0.62 to 0.92)	0.87 (0.72 to 0.94)	0.86 (0.71 to 0.94)	0.74 (0.48 to 0.88)

Table 13: **Between-session statistics, including 90%CL, for frontal plane hip ab/adduction range of motion during the stance phase of running for healthy young athletes (n=10).**

	Right		**Left**	
	Trial 1	**Trial 2**	**Trial 1**	**Trial 2**
Session 1 mean ±SD (degrees)	6.2 ±2.0	7.1 ±2.5	5.6 ±1.7	5.9 ±1.6
Session 2 mean ±SD (degrees)	6.1 ±1.8	6.7 ±2.1	5.2 ±1.6	5.4 ±1.9
ES (for a trial, between-sessions)	-0.03	-0.17	-0.24	-0.29
Change in mean % (90%CL)	-0.7 (-9.6 to 9.2)	-5.3 (-15.7 to 6.4)	-6.9 (-16.3 to 3.6)	-11.2 (-23.0 to 2.5)
Typical error as a CV% (90%CL)	17.7 (13.7 to 25.7)	22.2 (17.1 to 32.5)	20.2 (15.5 to 29.4)	28.0 (21.4 to 41.2)
Total error (%)	17.2	22.0	20.4	28.9
Intraclass r (90%CL)	62.8	82.0	73.1	108.7
Session 1 mean ±SD (degrees)	0.7	0.7	0.7	0.5
Session 2 mean ±SD (degrees)	0.72 (0.45 to 0.87)	0.68 (0.38 to 0.85)	0.66 (0.36 to 0.84)	0.44 (0.05 to 0.72)

APPENDIX 3

CONFERENCE ABSTRACT: RELIABILITY OF LOWER LIMB STRENGTH, FLEXIBILITY AND 3D GAIT MEASURES DURING RUNNING IN YOUNG ATHLETES

Sheerin, K. R., Hume, P. A., & Whatman, C. (2010). Reliability of lower limb strength, flexibility and 3D gait measures during running in young athletes Symposium conducted at the meeting of the Sports Medicine New Zealand Conference, Wellington, New Zealand.

RELIABILITY OF LOWER LIMB STRENGTH, FLEXIBILITY AND 3D GAIT MEASURES DURING RUNNING IN YOUNG ATHLETES

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Background: The use of gait screening to evaluate lower limb movement quality, as well as the measurement of lower limb strength and flexibility variables is becoming commonplace. Hip abductor strength and hamstring flexibility, as well as poor frontal plane knee control during running have been associated with running-related injuries[1,2]. Few studies have investigated the reliability of these variables, and none have assessed children. However, it is crucial to know if measures of kinematics, as well as strength and flexibility are consistent enough from day to day for making clinical decisions for young athletes.

Aim: To assess the reliability of four strength, four flexibility and a range of three-dimensional (3D) frontal plane knee range of motion measures during treadmill running in young athletes.

Methods: Twenty-three athletes (11.4 ±1.3 years old) from a long-term athlete development programme were assessed at baseline. Re-test data were collected 10 weeks later on 23 athletes for flexibility, 10 athletes for strength and 18 athletes for gait measures. Three isometric strength (hip abduction, internal rotation, external rotation and flexion) and three flexibility (hip internal rotation, external rotation, flexion and hamstrings) trials were taken using a dynamometer and a goniometer respectively. Athletes completed a treadmill-based assessment of running kinematics (e.g., maximum knee abduction angle) using a nine-camera 3D motion analysis system. Children ran for five minutes at a self-selected speed (2.19 ±0.22 m/s) and kinematic data were collected in two 30-second trials. Ten continuous steps for each limb were extracted from each trial for analyses. Descriptive statistics, including means and standard deviations, and within-day and between-day (10 weeks in our case) reliability measures including mean differences (Mdiff), effect sizes (ES), typical error of measurement (TE) and intra-class correlation coefficients (ICC) were calculated.

Results: Excellent within-day reliability but poor to moderate between-day reliability for strength measures (within-day ICC 0.85 to 0.93 and TE 1.6 to 3.9 N; between-day ICC 0.33 to 0.89 and TE 1.7 to 6.2 N) and flexibility measures (within-day ICC 0.85 to 0.92 and TE 1.5 to 3.7^{o}; between-day ICC 0.42 to 0.87 and TE 2.8 to $8.9\,^{o}$) existed. There was good to excellent within-day reliability for mean maximum knee abduction angle (ES 0.01 to 0.26 and ICC 0.9), however, the between-day reliability was only fair to good (ES 0.01 to 0.16 and ICC 0.4 to 0.6).

Discussion: A change in strength and flexibility measures, as well as frontal plane knee motion when running, is potentially important for designing injury prevention interventions. It is crucial to know if lower limb strength, flexibility and kinematic gait variables are consistent enough from day to day for making clinical decisions.

Conclusion: Lower extremity strength, flexibility and gait measures demonstrated good within-day reliability, however their use is questionable for assessing young athletes across days, given the between-day variability for these measures.

References:

Powers, C. M. (2003). The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: a theoretical perspective. *JOSPT , 33*(11), 639-646.

Ireland, M. L., Willson, J. D., Ballantyne, B. T., & Davis, I. M. (2003). Hip strength in females with and without patellofemoral pain. *JOSPT, 33*(11), 671-676.

APPENDIX 4

CONFERENCE ABSTRACT: THE RELIABILITY OF LOWER LIMB ISOMETRIC STRENGTH AND HIP FLEXIBILITY MEASURES FOR YOUNG ATHLETES

Sheerin, K. R., Whatman, C., Hume, P. A., & Croft, J. (2010). *The reliability of lower limb isometric strength and hip flexibility measures for young athletes*. Paper presented at the meeting of the International Conference of Physical Education and Sports Science, Singapore.

THE RELIABILITY OF LOWER LIMB ISOMETRIC STRENGTH AND HIP FLEXIBILITY MEASURES FOR YOUNG ATHLETES

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Context: Lower limb strength and flexibility variables, such as hip abductor strength and hamstring flexibility, have been associated with running-related injuries. However, few studies have determined the reliability of such variables for young athletes. Objective: To assess the within and between-day reliability of four isometric strength and four passive flexibility measures in young athletes. Participants: Twenty-three athletes from a long-term athlete development programme (11 males; 12 females; age: 11.4 ±1.3 years) were assessed. Data Collection and Analyses: All isometric strength (hip abduction, internal rotation, external rotation and flexion) and flexibility (hip internal rotation, external rotation, flexion and hamstrings) measures were taken by a single physiotherapist using a dynamometer and a goniometer respectively according to a standarised protocol. All athletes were assessed at baseline and ten athletes were randomly selected for retest 10 weeks later. All strength measures were normalised to the athlete's bodyweight. For all variables typical error of measurement (TE) and intra-class correlation coefficients (ICC) were calculated. Results: There was good to excellent within-day reliability but poor to moderate between-day reliability for lower extremity strength (within-day ICC 0.85 to 0.93 and TE 1.6 to 3.9 N; between-day ICC 0.33 to 0.89 and TE 1.7 to 6.2 N) and flexibility (within-day ICC 0.85 to 0.92 and TE 1.5 to 3.7^{o}; between-day ICC 0.42 to 0.87 and TE 2.8 to 8.9^{o}) measures. Conclusions: The use of the lower extremity strength and flexibility tests is questionable for assessing young athletes given the between-day variability for these measures.