ASSESSING AND MODIFYING NEUROMUSCULAR RISK FACTORS FOR ANTERIOR CRUCIATE LIGAMENT INJURY IN FEMALE ATHLETES

By

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A thesis submitted to the Faculty of Graduate Studies of
The University of Manitoba in partial fulfillment
of the requirements of the degree of

DOCTOR OF PHILOSOPHY

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ABSTRACT

Injury to the anterior cruciate ligament (ACL) can have short and long term consequences for an athlete in the form of pain, altered knee joint function, decreased activity levels and early-onset osteoarthritis. Female athletes are at increased risk of injury compared to male athletes, perhaps in part because of differences in the functioning of the neuromuscular system.

Methods of identifying neuromuscular risk factors for ACL injury, as well as training interventions to prevent injury, have traditionally been explored in athletes of high school age or older. However by that age, the risk of injury is already increased and the opportune time to introduce effective prevention programs may have passed. This thesis involves a sequence of studies which measures the neuromuscular function of younger athletes, aged 10-14 years. First, a study was undertaken to establish the reliability of measuring strength and power of the lower extremity on an isokinetic dynamometer. This included a more functional assessment of the hip joint in a standing position. Peak and average torque and power measurements of the hip flexors and knee extensors were the only movements with acceptable absolute reliability. Conversely, peak velocity measures of all the tested hip and knee movements demonstrated acceptable reliability for group comparisons. A high amount of variability was found with all test movements, and so the use of alternate tests of strength and power may need to be used if comparing an individual's performance over time.

From the data collected within the reliability study, a comparison was made between the male and female athletes to determine if neuromuscular power differed at this young age. It was thought that a discrepancy in power could be a factor in the higher ACL injury rates experienced by girls. Using the data from the reliable test movements, it was determined that girls and boys between 10 and 14 years of age do not differ in terms of knee or hip joint movement velocity or power.

There is evidence to suggest that sex differences exist by adulthood; further research is required to determine when the disparity becomes apparent.

The final project was to determine whether strength training would positively influence the manner in which young female athletes land from a jump, which is a common ACL injury mechanism. This randomized controlled trial found no difference between the intervention group who trained their legs, and the control group who trained their arms. However those athletes with the poorest landings appeared to improve their movement pattern regardless of training regime.

This thesis contributes to the literature by providing evidence for proper measurement protocols for young athletes, introducing the use of neuromuscular power instead of strength into the investigation of contributing factors to injury, and by furthering the examination of strength training as an effective component of prevention programs.

ACKNOWLEDGEMENTS

To successfully complete an undertaking such as this requires the assistance of many people. I would like to thank my advisor, Dr. Michelle Porter, for agreeing to take me on as a graduate student in the first place. Her help throughout this process has been invaluable, going beyond the "nuts and bolts" of completing a PhD, and extending to the vast array of practical knowledge that is necessary for someone beginning a career in academia. Thank you also to my committee, Dr. Barbara Shay and Dr. Christine Wu. I appreciate your time and commitment in seeing me through this process, and your valuable input into my work.

I have had much help from the other members of the lab during my time here. Thank you to Glenys Smith, the resident stats expert, who helped me understand the little details. Thank you to Andrew Cull and his programming abilities, which saved me hours of time and made the Biodex data usable. Without Richard Sylvester, the scope of this project would not have been possible. I thank him for the countless hours he dedicated to the training of the girls. Thank you also to Marc Morissette, who made the data collection go smoothly; and to Taylor Post for scoring the videos in such a short time frame.

Thank you to the Canadian Institutes of Health Research, the Manitoba Health Research Council, the Sport Medicine and Science Council of Manitoba, and the Canadian Athletic Therapists Association for funding support. Without the 3-year CIHR support, it would not have been possible to undertake the studies I did. Thank you.

Of course, my research could not have been done without the athletes and parents who volunteered their time for the research studies. I enjoyed their energy and enthusiasm and thank them so much for their willingness to volunteer.

DEDICATION

I would like to dedicate this thesis to the people who stood behind me and supported me every step of the way through this journey. My parents, Albert and Edith Parsons, have encouraged me from the very beginning to value higher education. They did not question my choices, but only offered love and support. I hope they are proud to have a “Dr.” in the family; and that they know their support was the foundation upon which I was able to attain this goal.

Last, but not least, to my wonderful husband, Darren Arndt. He was a courageous man to marry someone who was just beginning graduate school, but he has been my rock throughout the process. I thank him from the bottom of my heart for his love, patience and support.

LIST OF ABBREVIATIONS

°/sec	degrees per second
ACL	anterior cruciate ligament
AP	average power
CV_{TE}	coefficient of variation of the typical error
HAB	hip abduction
HAD	hip adduction
HE	hip extension
HF	hip flexion
ICC	intraclass correlation coefficient
IK	isokinetic
IM	isometric
IT	isotonic
KE	knee extension
KF	knee flexion
LESS	Landing Error Scoring System
LOA	limits of agreement
Nm	Newton-metres
PMOS	Pubertal Maturation Observational Scale
PP	peak power
PT	peak torque
PV	peak velocity
RCT	randomized controlled trial
REC	random error component
RLOA	ratio limits of agreement
RM	repetition maximum
SD	standard deviation
SE	standard error
SEM	standard errors of measurement
T_1	test session one
T_2	test session two
W	Watts

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CHAPTER 1: INTRODUCTION

Injury to the anterior cruciate ligament (ACL) of the knee can be devastating to an athlete, as it causes significant joint instability, pain, and often a lengthy hiatus from competition (Siegel, Vandenakker-Albanese, and Siegel 2012). The long-term consequences also deserve consideration, as ACL injury has been linked to the development of osteoarthritis in the affected joint, especially if damage to other knee ligaments or the menisci has occurred (Oiestad et al. 2009). Injury also has implications for future physical activity participation. Research shows that less than two-thirds of those who suffer an ACL injury return to their pre-injury level of activity (Ardern et al. 2011). The impact on the individual athlete, his or her family, as well as the health care system as a whole can be considerable, and therefore a thorough understanding of the contributing factors to injury and effective preventative measures is essential.

This thesis presents a sequence of studies that build on one another and add to the literature on neuromuscular risk factors and prevention programs for ACL injury. The goal of this work was to: 1) establish the reliability of measuring neuromuscular indices of strength and power that may influence injury risk in a young athletic population, 2) explore neuromuscular power as a possible contributor to injury by assessing sex differences, and 3) investigate the effect of a neuromuscular training program on improving movement patterns considered high risk for injury in young female athletes. The introduction will justify the need for this work by first briefly reviewing ACL injury rates, including the disparity between male and female athletes. A common mechanism of injury will be described, along with neuromuscular factors that may play a role in contributing to the injury mechanism as well as injury rates directly. Finally, existing prevention programs, their components and effectiveness will be reviewed along with an overview of the appropriateness of using resistance training in children. The introduction is followed by a series of four papers, each addressing a stated goal of the work. Two of the four manuscripts have been submitted to peer reviewed journals; the remaining two are in the preparation phase. The thesis concludes with a discussion of the results and their implications for ACL injury prevention and future research directions.

Section 1: ACL Injury Rates

Boys and girls seem to be equally at risk of ACL injury until around the time of puberty, when, in the mid-teen years, the incidence rate in girls rises (Shea et al. 2004). The overall number of ACL injuries is greater in the male athlete population, because of their higher participation rates in sport activities (National Federation of State High School Associations 2009). In terms of relative numbers per participation exposure (one exposure = one practice or game), female athletes are at higher risk, with injury rates that are 3-6 times those of their male counterparts (Arendt, Agel, and Dick 1999; Malone, Hardaker, and Garrett 1993; Prodromos et al. 2007). Translating this information to an annual risk rate enables coaches, parents and athletes to more easily interpret the risk of injury and consider it relative to their own specific sport circumstance. For higher risk sports such as basketball and soccer, it is estimated that female athletes have approximately a 5% yearly risk of incurring an ACL injury, whereas the risk to male athletes is about 1.7% per year (Prodromos et al. 2007). These figures are based on an average of 167 participation exposures annually, which for year-round athletes is quite realistic.

Section 2: ACL Injury Mechanisms

The most common method of injuring the ACL involves a non-contact mechanism such as planting a foot and pivoting, decelerating quickly, or landing awkwardly from a jump (Dai et al. 2012a). In particular, adopting an erect trunk position with minimal hip and knee flexion, as well as a valgus and rotated knee alignment during landing has been suggested as high risk for injury (Ireland 2002; Markolf et al. 1995). There is some disagreement in the literature as to whether male and female athletes differ in their positioning when landing from a jump, especially in the degree of trunk, hip and knee flexion present (Beaulieu and McLean 2012). However there seems to be consensus that women land with an increased valgus, or "knock-kneed" position compared to men (Beaulieu and McLean 2012; Hewett, Torg, and Boden 2009). The results of in vitro studies confirm that valgus positioning of the knee joint increases stress on the ACL, especially when combined with internal tibial rotation (Oh et al. 2012). It is this valgus/internally rotated position that is the focus of many studies, as researchers try to determine the factors leading to the injury mechanism and why female athletes more commonly demonstrate the movement pattern.

Section 3: Neuromuscular Contributions – Strength

The possibility of neuromuscular strength deficits contributing to poor jump landing movement patterns has been explored in various populations, with conflicting results. One study (Barber-Westin et al. 2005) found no relationship between isokinetic quadriceps and hamstrings peak torque and frontal plane alignment during a jump landing in a group of 9 and 10 year old children. These findings concurred with a study involving a large group of young adult army cadets (Beutler et al. 2009). No significant association was found in that group between isometric strength of the major leg muscles and the lower extremity position demonstrated during a jump landing. Similarly, studies involving young adult women (Lepley et al. 2013), high school girls (Sigward, Ota, and Powers 2008) and healthy adult men and women (Homan et al. 2013) failed to find significant relationships between peak isometric torque of the hip musculature and landing movement patterns.

In contrast, some studies have found evidence that supports the assumption that strength deficits play a role in poor landing mechanics. Negative correlations were found between isometric hip extension strength and knee valgus during landing in a group of active young women (Hollman et al. 2013). That is, the women with weaker hip extensors tended to land with increased knee valgus. Those findings were supported by another recent study (Wild, Steele, and Munro 2013) which found that weaker hamstrings led to increased valgus displacement during a single leg landing. Only one study has found a positive correlation between muscle strength and knee valgus (Bandholm et al. 2011). Contrary to their hypothesis, the authors found that increased hip external rotation strength was related to increased knee valgus when landing from a jump. This would suggest that increased strength increases the risk of ACL injury.

Overall, it seems the evidence for a relationship between neuromuscular strength and jump landing movement patterns is highly dependent on the age and sex of the population studied, the muscle group tested and the type of test done (i.e. isometric vs. isokinetic). The functional connection between a peak strength test and a dynamic activity may also be limited, as discussed in the next section.

Section 4: Neuromuscular Contributions – Power

The ambiguous nature of the evidence presented above may be a result of the consideration of *strength* as a main predictor of movement patterns such as knee valgus during landing. Recently there has been growing recognition that neuromuscular *power* may be more significantly related to physical function than neuromuscular strength in some populations (Bean et al. 2010; Mayson et al. 2008). Power is the amount of work performed per unit of time, but is more commonly understood as the product of force x velocity (Bean et al. 2003). Muscle power takes into consideration not only the peak torque producing capabilities of a muscle group, but also the velocity at which that muscle group can move a particular body segment. Humans require a balance of strength and velocity for all functional activities, including sport movements. As a result, there has been a recent call to investigate neuromuscular power in more detail in relation to human function and performance within the applied health arena (Pigozzi, Giombini, and Macaluso 2012).

Within the ACL injury literature, to this point, there has been almost no inclusion of neuromuscular power indices in the discussion of injury mechanisms or contributing factors. One study found an improvement in peak power of the hamstrings in response to a six week neuromuscular retraining program (Hewett et al. 1996). However the authors did not attempt to relate power to jump landing mechanics or vertical jump height, which were the main outcome variables of the study. Based on the positive relationship found between neuromuscular power and function in other populations (Bean et al. 2003; Harrison et al. 2013), the influence of neuromuscular power on ACL injury mechanisms as well as its role in prevention should be explored.

Section 5: ACL Injury Prevention Programs

In addition to exploring the underlying causes of ACL injury, there is also a concerted effort underway to identify effective and efficient means of prevention. While it is recognized that numerous contributing factors exist [e.g. bony alignment, ligament notch width and joint laxity (Ireland et al. 2001)], it is the modifiable elements such as neuromuscular strength and control that are the focus of clinician researchers (Dai et al. 2012b). Prevention programs that aim to improve neuromuscular risk factors for ACL injury were borne out of existing resistance training programs which emphasized skill improvement and performance gains (Hewett et al. 1996). As a result, the programs have traditionally included such diverse components as balance training, plyometric exercises, flexibility training, and traditional strengthening exercises (Heidt et al. 2000; Mandelbaum et al. 2005). The diversity of exercises within these programs probably contributes to the conflicting results as to whether ACL injury risk is decreased with their use; a recent review found that 7 of 10 intervention studies failed to produce a significant decline in ACL injury rates (Donnelly et al. 2012).

The simultaneous use of different components within a training program precludes the ability to determine which elements are actually effective in improving movement patterns or decreasing injury risk. Of all the components of training, only balance exercises have been examined on their own, and their effect on injury rates are inconclusive. Soderman et al. (Soderman et al. 2000) found that a balance training program was not effective in decreasing the incidence of traumatic lower extremity injuries in young adult female soccer players. However, Caraffa et al. (Caraffa et al. 1996) did find a significant reduction in ACL injuries after a 30 day program with semi-professional and amateur male soccer players.

Supportive evidence for ACL injury prevention programs exists from a number of studies that found training programs which include plyometrics, balance and strengthening exercises can be successful in improving landing mechanics (Chappell and Limpisvasti 2008; Lim et al. 2009; Myer et al. 2005; Pollard et al. 2006). In general, these programs have resulted in improved movement patterns during laboratory controlled jump landings, which theoretically should provide some protective advantage. However it seems that these benefits do not always translate directly into decreased ACL injury rates, as found in the review by Donnelly et al. (2012).

Considering that ACL injury rates begin to rise markedly in the mid-teen years (Shea et al. 2004) it is surprising that only one of the studies investigating the effects of a prevention program on the rate of ACL injury involves athletes younger than 14 years of age (Walden et al. 2012). That study of 12-17 year old girls indeed found a protective effect from participation in a neuromuscular training program. However, it has recently been demonstrated that children as young as 10 years of age can respond with favorable improvements to a training program specifically designed to improve movement patterns associated with ACL injury (Distefano et al. 2010). A recent meta-analysis also identified that neuromuscular training at a younger age (less than 18 years) showed more of a protective effective in terms of ACL injury rates (Yoo et al. 2010). Other than these recent contributions to the literature, there remains a paucity of research examining younger athletes' responses to exercise training in terms of ACL injury prevention. It would seem logical to examine the effectiveness of prevention programs at an earlier age, before the chance of injury increases.

Section 6: Resistance Training in Children

Within most academic and exercise professional circles, resistance training is accepted as a safe activity for children, and is in fact now recommended as part of a balanced exercise program (Faigenbaum and Myer 2010). A variety of equipment, including elastic bands, weight machines and free weights, has been shown to be safe and effective when used in resistance training programs involving children (Behm et al. 2008). Unfortunately, some myths still persist that resistance training in children leads to injury and can adversely affect normal growth and development. Research has shown unequivocally that resistance training can increase strength and endurance, improve health, and decrease injury risk as long as the program is appropriate for the age and abilities of the child (Behm et al. 2008). Children and adolescents seem to improve strength and endurance at approximately the same rate as adults, although not with the accompanying hypertrophy. As a result, it is suggested that neural adaptations may play a larger role in the strength improvements found after resistance training in children (Behm et al. 2008).

Gains in strength can vary widely depending on the length of the training intervention as well as the age and sex of the children involved. Girls and younger athletes may show greater gains in strength during training because of their lower baseline strength (Faigenbaum and Myer 2010). Two meta-analyses have calculated effect sizes of 0.57 (Falk and Tenenbaum 1996) and 0.75 (Payne et al. 1997) for children participating in strength training, which clearly delineates the benefit of this type of training in this age group. Overall, an improvement of about 30% over baseline measures can be expected from shorter-term interventions (Faigenbaum et al. 2009).

In addition to improvements in strength levels, resistance training in children has also been positively correlated to motor performance such as vertical jump height and sprint speed in many studies (Faigenbaum et al. 2009). However, a few investigations have failed to show any benefit from resistance training on performance level (Faigenbaum et al. 2005; Faigenbaum et al. 1993).

The difference in findings was likely affected by the length of the interventions as well as the questionable functional overlap of the training to the measured performance variable. The evidence as a whole suggests that there is merit to investigating how strength training in children may influence movement patterns that are considered high risk for ACL injury.

Section 6: Purpose and Hypotheses for Individual Projects

The intention of this thesis is to contribute knowledge that will help fill existing gaps in the ACL injury literature in terms of the measurement, identification and improvement of neuromuscular risk factors for injury. Chapter 2 and Chapter 3 describe the reliability of using a Biodex isokinetic dynamometer to test hip and knee neuromuscular strength and power in young athletes. Chapter 4 explores whether an indirect measure of neuromuscular power, movement velocity, varies between boys and girls. Chapter 5 evaluates the effectiveness of a strength training program on improving jump landing mechanics in young female athletes. Chapter 6 is a summary of the body of work, with a discussion on its relevance and applicability to ACL injury prevention. The specific purpose and hypotheses of the four papers are as follows:

Chapter 2 – Test-Retest Reliability of Hip and Knee Neuromuscular Strength in Young Athletes

Purpose: To determine the relative and absolute test-retest reliability of measuring hip abduction, adduction, extension and flexion and knee extension and flexion isokinetic and isometric peak and average torque, and isotonic peak torque using a Biodex System 3 Pro isokinetic dynamometer in athletes aged 10-14 years.

Hypothesis: As this was a reliability study, no hypotheses were proposed.

Chapter 3 – Reliability of Measuring Hip and Knee Power and Movement Velocity in Active Youth

Purpose: To determine the absolute and relative reliability of measuring hip and knee peak and average neuromuscular power and peak movement velocity in children aged 10-14 years using an isokinetic dynamometer.

Hypothesis: As this was a reliability study, no hypotheses were proposed.

Chapter 4 – Comparison of Lower Limb Movement Velocity between Young Female and Male Athletes

Purpose: To determine whether sex differences exist in the peak movement velocity of the hip abductors and extensors, and knee flexors and extensors in young athletes aged 10-14 years.

Hypothesis: Boys will exhibit a faster movement velocity than the girls in all movements tested.

Chapter 5 – The Effect of Strength Training on Landing Mechanics in Young Female Athletes

Purpose: To determine whether strength training targeted to the lower body affects the mechanics of a jump landing as measured by the Landing Error Scoring System (LESS).

Hypothesis: Lower body strength training will result in a greater improvement in landing mechanics compared to upper body strength training.

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CHAPTER 2: Test-Retest Reliability of Hip and Knee Neuromuscular Strength in Young Athletes

Running Head: Reliability of strength measures in young athletes

MY CONTRIBUTION TO THE MANUSCRIPT

The suggestion to include a reliability study within the body of my PhD work was made by my advisor, Dr. Porter. I performed the bulk of the literature review as a component of my candidacy exam. I carried out extensive equipment trials to finalize the test protocol. I wrote the ethics application, recruited and screened participants and collected all the data. Working in collaboration with Dr. Porter, I analyzed the data and prepared the manuscript for submission to a peer reviewed journal. The results were presented at a thematic poster session at the annual conference of the American College of Sports Medicine in 2013.

ABSTRACT

The ability to quantify leg strength in young athletes may aid in identifying deficiencies that increase injury risk. However, the measurement method must be reliable in order for the results to be clinically useful and for assessment of any subsequent interventions. Our purpose was to establish the absolute and relative reliability of measuring hip and knee strength with a Biodex System 3 dynamometer in young athletes. Standing hip and seated knee strength were measured twice in 52 athletes, about one week apart. Hip abduction/adduction, extension/flexion and knee extension/flexion isokinetic and isometric peak and average torque, and isotonic peak torque were determined. Hip muscle testing demonstrated poor absolute reliability (coefficient of variation of the typical error [CV_{TE}], 15%-35%) with the exception of hip flexion (CV_{TE}, 7%-14%) and isometric hip adduction peak torque tests (CV_{TE}, 14%). Knee extension showed better absolute reliability for all types of tests (CV_{TE}, 8%-13%) compared to knee flexion (CV_{TE}, 22%-32%). If one-time testing is required to quantify strength in a *group* of young athletes, knee extension and hip flexion tests are the better choice. Other measures of strength should be used if assessing *individual* athletes, as variability between test sessions was quite high. The results of this study can guide clinicians as to whether a test possesses sufficient reliability for assessment of neuromuscular strength in young athletes, as well as the margins of error to expect.

KEY WORDS: absolute reliability, functional strength assessment, children

INTRODUCTION

Two out of three injuries sustained by adolescents are related to sport participation (21). Many of these injuries are thought to be due to insufficient neuromuscular strength (26). As a result, test batteries, which include strength assessment, have been developed as a means of identifying those who may be at higher risk of injury (17). Strength measures are also used as a means to assess the effectiveness of an exercise training intervention by researchers, clinicians or team staff (9, 14).

The Biodex System 3 Pro isokinetic dynamometer (Biodex Medical Systems, Shirley, NY) is commonly used to measure neuromuscular strength. The validity of this device was previously established (8). Along with validity, *reliability* (both relative and absolute) must be verified to adequately assess strength. Relative reliability refers to the consistency in the position of an individual's test score within a population when tested on different occasions. Absolute reliability refers to the level of agreement in the scores from one test session to the next (18). With most clinical measures, we are more interested in the dependable measurement of a variable from one time to another rather than the relative position of that measure compared to others. Therefore, Intraclass Correlation Coefficients (ICCs) are not sufficient measures of reliability in studies that deal with clinical questions (18).

Reports of reliability using the Biodex System 3 with a young, athletic population are rare in the literature and only involve the knee joint. Deighan et al. (7) established the test-retest reliability of measuring isokinetic (IK) peak torque of the knee flexors (KF) and extensors (KE) in a small group of 10 boys. These authors found good absolute reliability, with coefficients of variation (CV) ranging from 4%-11%. Santos et al. (19) found slightly higher, but acceptable, CV values (10-14%) for KF and KE peak and average torque measured in children using the passive mode on the dynamometer.

Wiggin and colleagues (25), within a larger study to establish normative data for IK torque production of the quadriceps and hamstrings, reported on Biodex reliability in children. Unfortunately, no specific reliability statistics were reported; only that no significant differences were found when different testers employed the testing protocol on more than 3500 boys and girls ranging in age from 6 to 13 years.

Although commonly used for neuromuscular assessment in young people, there is a paucity of information on the ability of the Biodex isokinetic dynamometer to reliably measure various muscle groups during different contraction types. The only variable studied to date is IK peak torque, and we are not aware of any absolute reliability information related to the use of the isotonic (IT) or isometric (IM) modes on a dynamometer in a young athletic population. There is a need to establish both relative and absolute reliability for movements about the hip and knee in young athletes, as well as present that reliability data in a form which makes it useable to researchers and clinicians alike. The purpose of this study was to determine the relative and absolute test-retest reliability of hip abduction/adduction (HAB/HAD), hip extension/flexion (HE/HF) and knee extension/flexion (KE/KF) isokinetic and isometric peak and average torque, and isotonic peak torque using a Biodex System 3 Pro isokinetic dynamometer in athletes aged 10-14 years.

METHODS

Experimental Approach to the Problem

To determine the test-retest reliability of measuring hip and knee muscular strength, participants attended two test sessions, lasting approximately two hours each. The majority (35) of the 52 athletes returned for the second test session (T2) exactly one week after the first test session (T1) (mean, 7.3±1.1 days); however because of scheduling conflicts, this time frame ranged from 4-11 days. Hip and knee tests were chosen because these muscle groups are frequently assessed to ascertain performance abilities (9, 14) and explore injury mechanisms (26). Relative reliability was evaluated using intraclass correlation coefficients (ICCs), along with the absolute reliability of the strength measures at the group [standard error of the measurement (SEM); coefficient of variation of the typical error (CV_{TE})] and individual [limits of agreement (LOA); ratio limits of agreement (RLOA)] level. This offers a detailed view of the reliability of the tests and enables the clinician to decide whether the test has sufficient reliability for his/her specific need.

Participants

After University Research Ethics Board approval, fifty-two young athletes (26 girls) participated in this study and completed both testing sessions (age, 11.6 ± 1.4 years; height, 153.4 ± 11.2 cm; body mass, 46.5 ± 13.0 kg; Pubertal Maturation Observational Scale score, 3.8 ± 2.7). Two additional athletes attended the first test session but experienced light-headedness during the test protocol. These girls did not continue on in the study. We lost contact with one male athlete after test session one, and one girl suffered an injury unrelated to the study before she could complete test session two. As a result, fifty-two participants completed the study; a sample size of at least 46 participants was required to achieve an ICC of at least 0.80 (24). Volunteers were recruited through local sports organizations via websites, e-mail and posters. Participants were required to be 10-14 years old at the time of testing and have a minimum of one year’s experience in an organized sport that involved jumping, cutting or pivoting (e.g., basketball, soccer). Exclusion criteria included any health condition that adversely affected the athlete’s ability to participate in physical activities, a current musculoskeletal injury with a pain rating of more than 3/10, previous experience using a Biodex dynamometer or participation in resistance training in the 6 months prior to the first test session.

Written informed consent (parent) and assent (athlete) were obtained at the first test session. On average, athletes participated in two different sports at the time of testing (range 1-5). Participants had an average of 3.9 years of experience playing organized sport, with a range of 1-9 years. Four of the girls and one of the boys reported that they would choose their left leg to kick a soccer ball as far as possible; the other 47 athletes reported right leg dominance (10).

Procedures

Testing took place in a university laboratory from January to August 2012. The dynamometer was calibrated according to the manufacturer's instructions prior to each testing session. The time of day at which the athletes were tested was kept constant in all but nine of the participants due to scheduling conflicts. Participants continued with their usual sports and activities during the time between T1 and T2; however they were not permitted to begin any resistance training in that period. Prior to Biodex testing, the athlete walked on a treadmill at a brisk pace for 5 minutes. Standing HAB/HAD testing (4, 16) of the dominant leg preceded standing HF/HE testing. Seated KE/KF testing completed the testing protocol.

T2 exactly replicated T1. The same physical therapist completed all test sessions with all athletes and was blinded to the results of T1 when completing T2. However the athlete's positioning on the dynamometer recorded at T1 was used to replicate each athlete's set-up for T2.

Testing Protocol

Hip Abduction/Adduction The athlete stood facing the dynamometer head, while a hip stabilization pad constructed from the Biodex Limb-Support Pad and T-Bar Adapter was adjusted to the height of the athlete's iliac crest. The athlete was asked to stand with the non-dominant side against the stabilization pad while a Velcro strap was fastened around the waist (Figure 1A). The greater trochanter was used as the landmark for the height of the axis of rotation about the hip. The Hip Attachment was used in combination with the Wrist Adapter to allow the desired range of motion. Depending on the size of the athlete, either an adult or pediatric Hip Attachment was used. It was adjusted in length to allow 5 cm between the knee joint and the bottom of the pad. The thigh strap was then secured in place. Range of motion limits were set at 5° adduction to 30° abduction.

The athlete was instructed to hang on to the top of the dynamometer head, and not to use the sides for added leverage. They were to maintain an upright trunk posture during testing, with the knee of the test leg slightly flexed to avoid contact of the foot on the platform. After completion of all HAB/HAD tests, a static gravity correction measurement was taken at 30° abduction and recorded.

Hip Flexion/Extension The athlete was asked to turn 90° so that the dominant leg was now closest to the dynamometer head. The hip stabilization pad and trunk strap were positioned as for abduction/adduction testing. The dynamometer was aligned with the level of the greater trochanter of the test leg and the resistance arm secured to the athlete's leg, about 5 cm superior to the patella (Figure 1B). Range of motion limits were set at 60° flexion to 20° extension. Hip extension (HE) tests followed hip flexion (HF) tests. A static gravity correction measurement was recorded at 60° flexion before the athlete was unstrapped from the device.

Knee Extension/Flexion Knee testing took place with the athlete seated as per Biodex protocol (2). Athletes were instructed to cross their arms in front of the chest (13). The dynamometer was aligned with the lateral femoral condyle of the test leg. The length of the adult size knee attachment was adjusted to sit 5 cm superior to the lateral malleolus. In athletes of shorter stature, a towel was placed under the thigh to allow the knee to move through the necessary range of motion. Occasionally a pillow was placed behind the athlete's back to allow sufficient space (5 cm) between the front edge of the chair seat and the back of the athlete's lower leg. Range of motion limits were set at 35° flexion to 95° flexion. KE testing preceded KF testing. A static gravity correction measurement was recorded at 35° flexion before testing was complete.

Isometric Tests Isometric tests were performed first for every muscle group. Instructions were given and then athletes performed 3-5 submaximal practice repetitions before 3 maximal test contractions of three seconds each. All isometric hip tests were carried out in a neutral hip position, determined when the athlete stood erect with the feet about shoulder width apart, the knee and hip in

0° flexion. For knee tests, isometric contractions were measured at 90° flexion (15). Ninety seconds of rest separated the three isometric repetitions. As with all tests, verbal encouragement was given through every repetition ("push hard and fast") but the athlete was not allowed to view the computer screen.

Isotonic Tests Isotonic tests were performed after a 2 minute rest. The resistance was set at 1 Nm in order to encourage maximum movement velocity. After instruction, athletes performed 3-5 submaximal practice repetitions before 6 maximal test trials.

Isokinetic Tests Isokinetic tests followed 2 minutes of rest. Participants were given instructions and then time for 3-5 submaximal practice repetitions before 6 contractions at both 60°/sec and 180°/sec. Two minutes of rest divided the two sets of six repetitions. Testing velocity was chosen based on a previous study that found children tended to become discouraged at speeds < 60°/sec, and often could not keep up with speeds of > 180°/sec (25). The isokinetic tests were performed using the passive mode on the dynamometer because it was felt some children may have difficulty producing enough torque to initiate movement against the weight of their leg plus the limb attachment, as is necessary when using the isokinetic mode.

Data Analysis

Biodex data were collected at a frequency of 100 Hz and exported via text file for further analyses. Using RStudio (RStudio, Inc., Boston, MA), all test data were smoothed with 9-point weighted filtering (3). The beginning of each isometric contraction was removed to eliminate the torque overshoot at the initiation of contraction (20). After reviewing graphs of the torque curves, it was decided that 400 milliseconds (ms) was representative of the length of time it took for the torque artifact to subside in this population. Peak and average torque of each isometric contraction were thus extracted from the resulting time frame (400 ms to 3 seconds).

During initial review of the isotonic hip extension data, it was observed that the torque curves contained too much extraneous noise to allow reliable and consistent filtering (See Appendix A). Therefore PT was not calculated for this isotonic joint movement.

In viewing the isokinetic torque curves, transient torque artifacts were observed throughout the range of motion in some participants. This may be due to decreased motor control and increased movement variability in response to a novel task, as children tend to move in a less smooth manner compared to adults (23). As a result, the isokinetic data required additional smoothing before 9-point filtering was performed. It was found that removing any data point greater than 50% of the preceding data point for HAB, HAD, HF, KE and KF, and 100% greater than the preceding data point for HE successfully eliminated the extraneous torque spikes. Although all isokinetic tests were completed at 60°/sec and 180°/sec, it was discovered that during HAB/HAD and KE/KF tests the dynamometer did not reach the pre-set velocity of 180°/sec within the set range of motion; therefore these tests were omitted from analyses. Similar to the isotonic HE test, the amount of extraneous noise present in isokinetic HE testing at 180°/sec was too excessive to filter out reliably and consistently. Therefore, this test was omitted from analyses as well.

After filtering, gravity correction was applied to the isotonic and isokinetic tests to account for the torque due to the weight of the leg. Gravity correction was not applied to the isometric tests as these tests were done in a neutral position, with minimal influence from the effects of gravity. These calculations were done after data collection because the Biodex System 3 does not allow for gravity correction when using a linked testing protocol or for passive mode tests, as were used in this study (3). Gravity correction was applied to the isotonic and isokinetic PT and AT data using the following equation, in consultation with Biodex Medical Systems Inc.:

$$T(corr) = T(limb) * \cos(position\text{-}shaft\ offset)$$

where T(corr) = the corrected torque for a specific joint angle; T(limb) = the measured static gravity correction torque of the appropriate joint for each participant; position = absolute position of the dynamometer at a specific joint angle in radians; shaft offset = 2.91 radians (hip); 1.34 (knee). The shaft offset values are specific to the use of the particular attachments and test protocols used in this study.

After smoothing and gravity correction, the peak and average torque of each repetition for each test for each participant was identified. Means for each athlete for each variable were then calculated from 3 test repetitions (isometric tests) or the latter 5 of the 6 isotonic and isokinetic repetitions.

Statistical Analyses

Statistical analyses were undertaken using SPSS Version 20 (IBM Corporation, Somers, NY) and SigmaPlot Version 11 (Systat Software, Inc., San Jose, CA). Significance level was set at $p \leq 0.05$. Means and standard deviations were calculated for each variable at T1 and T2. A Shapiro-Wilk normality test was done on the difference scores for each variable for each test. A Bland-Altman plot was created and a Pearson Correlation test was conducted on the difference score versus the average score for each participant to determine the presence of heteroscedasticity. If the variable was found to follow a normal distribution and show homoscedasticity, a paired t-test was used to compare the variables at T1 and T2. If the difference scores for the variable failed the test for normality and/or demonstrated heteroscedasticity, a Wilcoxon Signed Rank Test was used to determine whether each variable changed significantly from T1 to T2.

Relative reliability was calculated using $ICC_{2,3}$ for isometric tests and $ICC_{2,5}$ for isotonic and isokinetic tests. Their corresponding 95% confidence intervals (CI) were also determined. $ICC_{2,k}$ was used because the mean of *k* repetitions for each participant was used in analyses (18).

Standard error of the measurement (SEM) was assessed by calculating the square root of the residual mean square error from the analysis of variance table for each variable (22). The 95% confidence limits were calculated as ± 1.96(SEM). The SEM, in the actual units of the variable, describes the degree of change necessary to state that a genuine change has occurred in the group mean from one time to another (18). The coefficient of variation of the typical error (CV_{TE}) on the other hand, describes that change as a percentage, allowing comparison between different equipment and different test protocols (18). Typical error was calculated as the standard deviation (SD) of the difference scores divided by the square root of 2 (12). Typical error divided by the mean of all trials multiplied by 100 produced the CV_{TE} in percent (11).

The limits of agreement (LOA) were calculated as the systematic bias (mean difference between the 2 test sessions) ± the random error component (REC) (1). REC was calculated as 1.96 multiplied by the SD of the difference scores. The LOA explains the error that can be expected when retesting an individual, in the units of the variable. Any test score falling outside of those limits can be considered, with 95% confidence, a true change in performance. To enable comparison to other studies and measurement methods, ratio limits of agreement (RLOA) were also calculated. The RLOA was calculated as the REC divided by the mean of all observations multiplied by 100, and expresses the expected error as a percentage.

RESULTS

Means, standard deviations and *p* values for all variables for isometric, isotonic and isokinetic tests can be found in Table 1. Hip adduction demonstrated systematic bias throughout all types of tests. Isotonic knee flexion PT significantly increased from T1 to T2 while isokinetic hip abduction and flexion PT and AT decreased from T1 to T2. The mean difference scores ranged from 1-6 Nm for those tests that demonstrated systematic bias.

Table 2 displays all calculated relative and absolute reliability statistics. Isometric HF and KE peak and average torque demonstrated better absolute reliability (CV_{TE}, 9%-12%) compared to the other muscle groups (CV_{TE}, 24%-28%). Isotonic HF and KE measures were also better (CV_{TE}, 13%-14%) than other joint movements (CV_{TE}, 19%-22%), as were isokinetic HF and KE torques (CV_{TE}, 7%-10% versus CV_{TE}, 16%-35%). Tests involving HF and KE muscle groups demonstrated better reliability than all other movements, with CV_{TE} values of less than 15%. Most other tests demonstrated CV_{TE} values of 20%-35%, perhaps rendering them unsuitable for a one-time test of strength. All 3 test types demonstrated ICCs between 0.76-0.98 which suggests good relative reliability; however from the absolute reliability results above, we can see that the ICCs do not provide a complete picture of the reliability of these tests.

DISCUSSION

This study was conducted to determine the relative and absolute reliability of testing children on a Biodex System 3 dynamometer using a standing hip and seated knee protocol. The standing hip testing protocol has gained popularity recently for measuring hip muscles in a more functional position, especially within the anterior cruciate ligament (ACL) injury literature (4, 16). Our results suggest that of the movements tested in standing, only HF demonstrated sufficient reliability to be used as a one-time test in young athletes. Any of the test protocols used in this study, with the exception of isokinetic 180°/sec and isotonic hip extension which contained excessive noise, may be used in a test re-test situation if the parameters of error are considered and accounted for.

Few studies have reported on the reliability of isokinetic standing HAB testing. Myer et al. (16) reported similar relative reliability in female high school athletes tested at 120°/sec (average ICC = 0.89 [95% CI: 0.58-0.98]) compared to the results of this study (ICC = 0.85 [95% CI: 0.75-0.92]). Claiborne et al. (5) also found similar isokinetic PT hip abduction ICC values (ICC = 0.87-

0.89) in a small group of men and women tested at 60°/sec. These same authors (5) are the only group to report relative reliability for isokinetic HF, HE and HAD standing hip test protocols. ICC values for HF were lower than our values (ICC = 0.82-0.83 versus ICC = 0.96) while values for HE were slightly higher (ICC = 0.80-0.90 versus ICC = 0.78). Calculated ICC values for HAD were higher in our study (ICC = 0.66 versus ICC = 0.90). Claiborne et al. (5) also described the absolute reliability of standing isokinetic HF/HE and HAB/HAD PT measurements, with results that were slightly higher than those of our study (SEM, 10-24 Nm versus SEM, 6-12 Nm).

A recent study reported the reliability of using the passive mode to measure isokinetic KE/KF at 60°/sec in a group of young children (19). They found similar KE CV_{TE} values compared to our study (10%-13%) but lower values for KF (11%-14%). At isokinetic speeds of 30°/sec and 180°/sec in a small population of 10 year old boys, Deighan et al (7) found better relative reliability for KE (ICC = 0.83-0.90) than KF (ICC = 0.74-0.76). This concurs with the findings of the current study (KE ICC = 0.97; KF ICC = 0.79) although we tested at a velocity of 60°/sec. Our study also found similar absolute reliability for KE isokinetic tests (CV_{TE}, 9%) compared to those authors (CV_{TE}, 4%-7%); however the CV_{TE} for KF in our study was markedly higher (32% versus 6%-9%) (7). Variation in reliability measures between studies may be a result of the different populations used in terms of age, sex and the number of athletes tested.

Regarding actual torque values, our KE/KF isometric results (KE, 93 Nm; KF, 42 Nm) are in line with others (KE, 64-96 Nm; KF, 32-47 Nm) (15). Unfortunately comparisons cannot be made between the norms established by Wiggin et al (25) and the mean isokinetic KE and KF PT values of our study, because gravity correction was not incorporated in that study. Comparisons to the few studies that have measured standing HAB are difficult, as only older teenagers and adults were included, testing velocities were different and it is unclear whether gravity correction was instituted

(4, 5, 16). We are not aware of any studies that have tested PT during isotonic hip and knee movements.

Randomization of the test sequence was not possible due to the linked Biodex protocol that was required to complete the large number of tests in a reasonable amount of time. This did not appear to affect the reliability of the individual tests (i.e., those tests at the beginning or end did not appear to be more or less reliable); however randomization could be incorporated into future investigations to determine the impact. Although it has been suggested that a familiarization session is optimal when testing children, (6) the systematic bias demonstrated (1-6 Nm) suggests that a learning effect had minimal impact on the results of this study. The lengthy testing protocol of almost 2 hours may have caused a lack of motivation and focus in some children for some tests. In retrospect, rest periods of 90 seconds to 2 minutes between tests may have been overly generous (25). Standing still for an extended time almost certainly contributed to two of the athletes experiencing light-headedness during testing. Participants should be monitored closely and encouraged to move their legs as much as possible between tests to improve blood flow if lengthy standing test protocols are done. Future studies should investigate the reliability of these tests using shorter, focused assessments, and calculate both relative and absolute reliability measures. Alternate methods and protocols for testing certain muscle groups should be examined to determine the best method of confidently measuring muscle strength in children.

PRACTICAL APPLICATIONS

This study has outlined the parameters of error to expect when testing neuromuscular function in young athletes, to better guide clinicians and researchers in detecting *genuine* performance or change in performance. Our results suggest that of all the strength tests conducted in this study, HF and KE are the only ones that could be used with some confidence in a one-time test of neuromuscular performance with a *group* of young athletes (e.g. pre-season testing; exploring relationships between strength and injury mechanisms or physical function). If used in a test re-test situation of a group of athletes, any of the tests (except isokinetic 180°/sec and isotonic hip extension) could be used, as long as the range of expected error (e.g. CV_{TE}) is taken into consideration. If the goal is to measure an *individual* athlete's abilities, ideally other methods of measuring hip and knee muscle strength should be utilized, as calculated RLOA values were quite high (e.g. isokinetic KE peak torque may vary 22% or more between test sessions).

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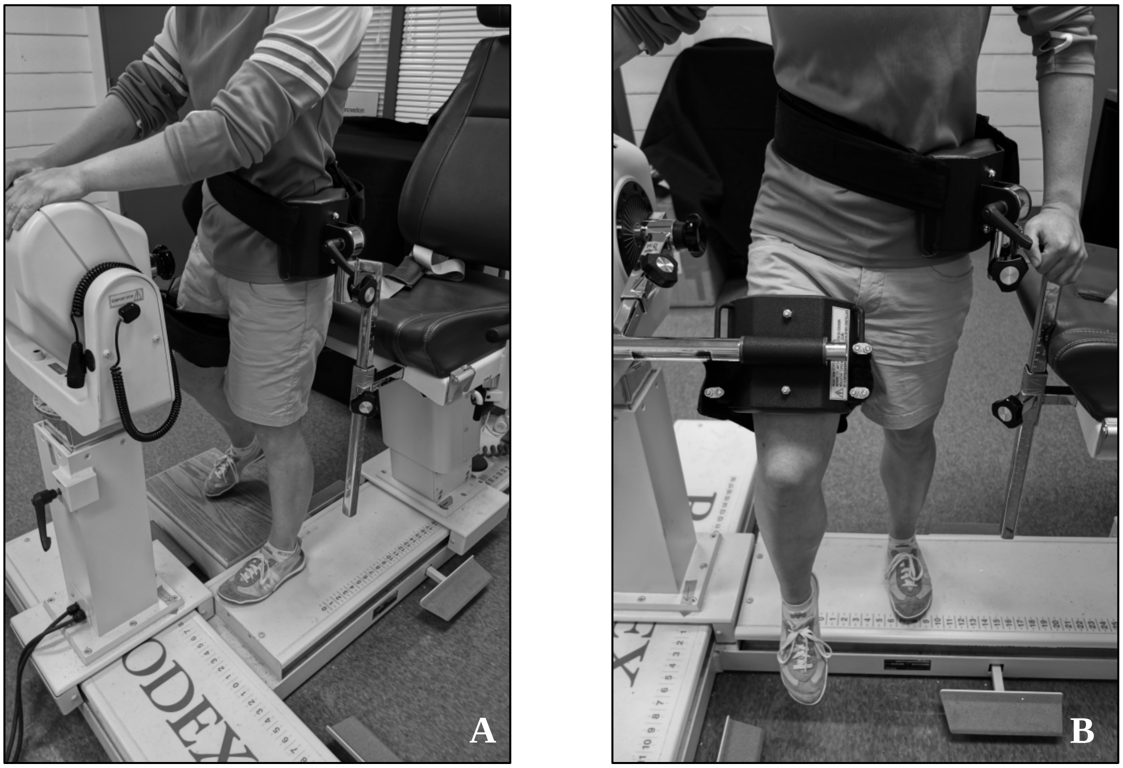

FIGURE 1: Participant set-up for **A)** hip abduction/adduction testing **B)** hip flexion/extension testing.

TABLE 1. Means (standard deviations) of isometric, isotonic and isokinetic tests.

Variable	Time 1 (Nm)	Time 2 (Nm)	*p*
Hip abduction			
Isometric test			
Peak torque	55.1 (22.9)	55.8 (25.6)	0.89
Average torque	47.9 (21.6)	48.3 (23.7)	0.69
Isotonic test			
Peak torque	70.6 (30.0)	70.9 (34.6)	0.43
Isokinetic test (60°/s)			
Peak torque	57.1 (21.1)	56.2 (22.7)	0.18
Average torque	51.6 (19.2)	50.4 (20.8)	0.048
Hip adduction			
Isometric test			
Peak torque	45.4 (14.4)	50.5 (18.7)	0.001
Average torque	38.7(13.5)	43.1 (17.4)	0.001
Isotonic test			
Peak torque	26.2 (10.4)	30.2 (10.2)	<0.001
Isokinetic test (60°/s)			
Peak torque	46.4 (18.2)	42.8 (18.2)	0.02
Average torque	35.1 (14.7)	32.1 (13.8)	0.02
Hip extension			
Isometric test			
Peak torque	53.7 (23.8)	52.1 (24.3)	0.54
Average torque	45.7 (21.8)	43.5 (21.8)	0.21
Isokinetic test (60°/s)			
Peak torque	53.1 (25.6)	51.8 (24.8)	0.82
Average torque	35.7 (19.8)	35.2 (20.1)	0.81
Hip flexion			
Isometric test			
Peak torque	63.4 (21.7)	62.6 (23.4)	0.07
Average torque	54.5 (20.2)	53.8 (21.2)	0.27
Isotonic test			
Peak torque	92.8 (33.4)	98.0 (40.8)	0.11
Isokinetic test			
Peak torque (60°/s)	71.0 (26.6)	66.6 (23.7)	<0.001
Peak torque (180°/s)	65.4 (24.6)	64.7 (24.7)	0.52
Average torque (60°/s)	60.7 (23.4)	57.3 (21.1)	<0.001
Average torque (180°/s)	60.1 (22.9)	58.7 (22.6)	0.11
Knee extension			
Isometric test			
Peak torque	95.0 (39.7)	92.7 (38.9)	0.18
Average torque	86.0 (37.4)	82.5 (34.9)	0.04

TABLE 1 continued. Means (standard deviations) of isometric, isotonic and isokinetic tests.

Variable	Time 1 (Nm)	Time 2 (Nm)	*p*
Isotonic test			
Peak torque	70.9 (26.7)	71.9 (28.3)	0.58
Isokinetic test (60°/s)			
Peak torque	81.3 (32.9)	79.7 (31.5)	0.23
Average torque	63.7 (26.8)	62.8 (25.6)	0.46
Knee flexion			
Isometric test			
Peak torque	42.9 (22.0)	42.8 (17.6)	0.51
Average torque	37.6 (20.8)	37.5 (16.9)	0.69
Isotonic test			
Peak torque	50.7 (24.7)	56.1 (28.5)	0.04
Isokinetic test (60°/s)			
Peak torque	43.9 (24.1)	43.1 (18.8)	0.45
Average torque	33.9 (21.1)	33.5 (15.7)	0.86

TABLE 2. Relative and absolute reliability statistics for isometric, isotonic and isokinetic tests.

Variable	ICC	95% CI for ICC	SEM (Nm)	95% CI for SEM	CV_{TE} (%)	LOA (Nm)	Ratio LOA (%)
Hip abduction							
Isometric test							
Peak torque	0.83	0.70-0.90	13.3	±26.2	24.1	-0.8 ± 37.0	66.7
Average torque	0.82	0.69-0.90	12.5	±24.5	26.0	-0.3 ± 34.7	72.1
Isotonic test							
Peak torque	0.89	0.81-0.94	14.5	±28.4	20.5	-0.2 ± 40.1	56.7
Isokinetic test							
Peak torque (60°/s)	0.85	0.75-0.92	11.1	±21.7	19.6	0.9 ± 30.8	54.3
Average torque (60°/s)	0.87	0.77-0.92	9.7	±19.1	19.1	1.2 ± 27.0	52.9
Hip adduction							
Isometric test							
Peak torque	0.90	0.76-0.95	6.4	±12.6	13.4	-5.1 ± 17.9	37.3
Average torque	0.89	0.77-0.94	6.4	±12.5	15.6	-4.4 ± 17.7	43.2
Isotonic test							
Peak torque	0.81	0.60-0.90	5.4	±10.6	19.2	-4.0 ± 15.0	53.2
Isokinetic test							
Peak torque (60°/s)	0.90	0.82-0.94	7.5	±14.8	16.9	3.6 ± 20.9	46.7
Average torque (60°/s)	0.89	0.81-0.94	6.0	±11.9	18.0	2.9 ± 16.8	49.9
Hip extension							
Isometric test							
Peak torque	0.79	0.63-0.88	14.3	±28.0	27.0	1.6 ± 39.6	74.8
Average torque	0.80	0.66-0.89	12.5	±24.5	28.1	2.2 ±34.7	77.8
Isokinetic test							
Peak torque (60°/s)	0.78	0.62-0.87	15.2	±29.8	29.0	1.3 ± 42.1	80.3
Average torque (60°/s)	0.76	0.58-0.86	12.5	±24.5	35.3	0.5 ± 34.7	97.9
Hip flexion							
Isometric test							
Peak torque	0.93	0.88-0.96	8.1	±15.9	12.9	0.8 ± 22.5	35.7
Average torque	0.94	0.90-0.97	6.8	±13.4	12.6	0.7 ± 18.9	34.9

TABLE 2 continued. Relative and absolute reliability statistics for isometric, isotonic and isokinetic tests.

Variable	ICC	95% CI for ICC	SEM (Nm)	95% CI for SEM	CV_{TE} (%)	LOA (Nm)	Ratio LOA (%)
Isotonic test							
Peak torque	0.92	0.86-0.96	14.0	±27.5	14.7	-5.2 ± 38.8	40.7
Isokinetic test							
Peak torque (60°/s)	0.96	0.91-0.98	6.6	±12.9	9.6	4.4 ± 18.3	26.6
Peak torque (180°/s)	0.98	0.96-0.99	5.1	±10.1	7.9	0.7 ± 14.3	21.9
Average torque (60°/s)	0.95	0.91-0.98	6.3	±12.3	10.6	3.4 ± 17.3	29.4
Average torque (180°/s)	0.97	0.96-0.99	5.0	±9.9	8.5	1.4 ± 14.0	23.5
Knee extension							
Isometric test							
Peak torque	0.97	0.96-0.99	8.7	±17.1	9.3	2.3 ± 24.2	25.8
Average torque	0.97	0.95-0.98	8.5	±16.6	10.1	3.5 ± 23.5	27.9
Isotonic test							
Peak torque	0.94	0.89-0.96	9.5	±18.6	13.3	-1.0 ± 26.3	36.8
Isokinetic test							
Peak torque (60°/s)	0.98	0.96-0.99	6.5	±12.7	8.0	1.6 ± 17.9	22.3
Average torque (60°/s)	0.97	0.95-0.98	6.2	±12.1	9.7	0.9 ± 17.1	27.0
Knee flexion							
Isometric test							
Peak torque	0.85	0.73-0.91	10.3	±20.2	24.1	0.1 ± 28.6	66.8
Average torque	0.85	0.74-0.92	9.7	±18.9	25.7	0.1 ± 26.8	71.2
Isotonic test							
Peak torque	0.88	0.78-0.93	12.2	±23.8	22.8	-5.4 ± 33.7	63.1
Isokinetic test							
Peak torque (60°/s)	0.79	0.63-0.88	12.8	±25.2	29.5	0.8 ± 35.6	81.8
Average torque (60°/s)	0.79	0.63-0.88	11.0	±21.6	32.8	0.4 ± 30.6	90.8

ICC = intraclass correlation coefficient; CI = confidence interval; SEM = standard error of measurement; CV_{TE} = coefficient of variation of the typical error; LOA = limits of agreement.

CHAPTER 3: Reliability of Measuring Hip and Knee Power and Movement Velocity in Active Youth

Running Head: Reliability of measuring leg power in youth

MY CONTRIBUTION TO THE MANUSCRIPT

The suggestion to include a reliability study within the body of my PhD work was made by my advisor, Dr. Porter. I undertook the literature review, wrote the ethics application, recruited and screened participants and collected all the data. Working in collaboration with Dr. Porter, I analyzed the data and prepared the manuscript for submission. As of May 28, 2014, the manuscript was accepted for publication in *Pediatric Physical Therapy*. The results were presented in poster format at the Health, Leisure and Human Performance Research Institute Research Day at the University of Manitoba in 2013.

ABSTRACT

Purpose: The purpose of this study was to determine the reliability of measuring neuromuscular power and movement velocity of the hip and knee musculature in young, active individuals using an isokinetic dynamometer. **Methods:** Peak power (PP), average power (AP) and peak velocity (PV) data were recorded for the hip in standing and the knee in sitting in 52 children aged 10-14 years on two occasions about one week apart. **Results:** The PV measurements demonstrated the best absolute reliability of all variables tested [coefficients of variation of the typical error ($CV_{TE)}$ = 5.0-8.5%; standard errors of measurement (SEM) = 18.1-21.1°/sec]. Hip flexion and knee extension PP and AP exhibited acceptable reliability (CV_{TE} = 8.7-10.8%) compared to the other isokinetic tests (CV_{TE} = 16.9-32.8%). **Conclusion:** Peak velocity appears to be a reliable means of indirectly measuring neuromuscular power in active youth, while direct measurement of power is only reliable for certain movements.

Keywords Young athletes, Neuromuscular power, Isokinetic dynamometer, Movement velocity

INTRODUCTION

Testing neuromuscular function is a key role of the pediatric physical therapist in the assessment and treatment of orthopedic injuries, and often involves the use of an isokinetic dynamometer. The results of testing can be used to help the physical therapist design a rehabilitation plan as well as to gauge the response of an individual or group to a particular treatment. Traditionally, the focus has been on measuring peak muscular strength.[1] However, recent research suggests that neuromuscular power, rather than strength, may be more strongly related to functional movement[2,3] and therefore perhaps more applicable to the goals of the physical therapist.[4] Establishing the reliability of measuring neuromuscular power in young people is a crucial first step upon which clinical decisions and further investigations into the power-function relationship can be based.

Unfortunately, the reliability of outcome measures is not consistently reported within research reports. When reported, often only *relative* reliability is addressed, via intraclass correlation coefficients (ICCs). Relative reliability refers to a test's ability to delineate between individuals' test scores within the sample population on multiple testing occasions.[5] For example, a strength test with good relative reliability (i.e. high ICCs) can consistently identify the strongest and weakest individual in the test population. However, reliability cannot be fully elucidated without the inclusion of *absolute* reliability, which refers to the degree of conformity in the test measures from one time point to another.[5] In a clinical situation, we are mainly interested in the consistent replication of a test measure, and therefore ICC values on their own are insufficient evidence of reliability.

To our knowledge, only one previous study[6] has looked at the reliability of measuring lower limb neuromuscular power in healthy children using an isokinetic dynamometer. However the sample size was less than optimal for a reliability study[7] and the age range of the participants was limited to 5-12 year olds. Other authors have reported specifically on the reliability of measuring average power of the knee flexors and extensors in older[8] and younger adults[9,10] but did not include children or adolescents in their studies. Very few studies overall have used neuromuscular power of the knee or hip as an outcome measure, despite its suggested link to function. One study[11] measured average power of the knee flexors in a small group of high school aged girls in response to a training program; however reliability statistics were not reported. We are only aware of one study that used an isokinetic dynamometer to measure power indirectly, via movement velocity, and that investigation measured the hip flexors and extensors of younger and older adults.[12] Again, reliability statistics were not reported.

Establishing the reliability of using an isokinetic dynamometer to measure power in young people will enable clinicians to confidently determine whether a true change has occurred in response to an intervention. It may also encourage the measurement and investigation of power related variables in addition to strength indices, which may promote more functional interventions. Therefore, the purpose of our study was to determine the absolute and relative reliability of measuring hip and knee neuromuscular power and movement velocity in children using an isokinetic dynamometer.

METHODS

Participants

Ethics approval was received from the University Research Ethics Board before recruitment of volunteers began. Fifty-two participants (26 girls) were recruited via website announcements and group emails through local sports organizations as well as through notices posted around the university and at community centres (see Figure 1 for the participant recruitment flowchart). A sample size of at least fifty participants was required for sufficient estimation of measurement error.[7] Inclusion criteria consisted of: 1) 10-14 years of age at the time of testing, and 2) a minimum of one year's experience in an organized sport that involved jumping, cutting or pivoting. Exclusion criteria included: 1) any health condition that prevented participation in physical activities; 2) a current musculoskeletal injury with a pain rating of more than 3 out of ten; 3) previous experience using a Biodex dynamometer; and 4) participation in resistance training in the 6 months prior to the first test session.

A summary of the participants' characteristics can be found in Table 1. Most of the children played multiple sports, averaging two different sports at the time of testing (range 1-5). Experience with organized sport varied, with an average of 3.9 years of participation (range 1-9 years). Forty-seven reported right leg dominance, determined by asking the child which leg they would prefer to use to kick a ball as far as possible.[13] There were no significant differences found between boys and girls in terms of their descriptive traits.

Instrumentation and Procedures

Data collection occurred over an eight month time frame (January-August 2012) in a university laboratory. Before each test session, the calibration of the Biodex System 3 Pro dynamometer (Biodex Medical Systems, Shirley, NY) was checked according to manufacturer's instructions. Informed written consent (parent) and assent (child) were obtained before the first test session (T1). Participants attended an identical post-test (T2) approximately a week after the first two-hour test session. Thirty-five of the 52 participants attended T2 exactly one week after T1 (mean = 7.3 ± 1.1 days; range = 4-11 days). All but nine of the participants were tested at the same time of day on T1 and T2; we were unable to schedule the other nine at the same time of day due to school or activity related conflicts. Participants were not allowed to start any resistance training between T1 and T2, but could continue with their usual physical activities. The same physical therapist conducted all test sessions with all participants, and was blinded to the results of T1 when completing T2. Participants walked on a treadmill for 5 minutes as a warm-up prior to Biodex testing. Standing hip abduction/adduction (HAB/HAD) tests were completed before standing hip flexion/extension (HF/HE) and seated knee extension/flexion (KE/KF) tests.

Hip abduction/adduction

The standing HAB/HAD testing protocol was modelled after previous work.[14,15] The participants stood facing the dynamometer head, stabilized with a hip pad at the height of the iliac crest and a Velcro strap around the waist (Figure 2A). The greater trochanter was used as the landmark for alignment of the dynamometer axis of rotation. To allow sufficient range of motion, the Hip Attachment (either adult or pediatric, depending on the size of the participant) was used in combination with the Wrist Adapter. The Hip Attachment was secured to the participant's thigh, about 5 cm superior to the knee joint. Range of motion limits were set at 5° adduction to 30° abduction. For all tests, participants were instructed to maintain an upright trunk posture, with the knee of the test leg slightly flexed to avoid contact with the standing platform. After completion of all HAB/HAD tests, a static gravity correction measurement was recorded at 30° abduction.

Hip flexion/extension

The participant was positioned so that the test leg was now closest to the dynamometer head (Figure 2B). The participant was secured at the waist and thigh as described above for HAB/HAD testing. Range of motion limits were set at 60° flexion to 20° hip extension. Hip extension tests followed hip flexion tests. A static gravity correction measurement was recorded at 60° flexion.

Knee extension/flexion

Seated knee testing took place as per Biodex protocol.[16] Participants were instructed to cross their arms in front of the chest.[17] The lateral femoral condyle of the test leg was used for positioning of the dynamometer axis of rotation. The knee attachment was secured to the lower leg about 5 cm superior to the lateral malleolus. In some cases, a folded towel was required under the thigh of the test leg to allow the knee to move through the required range of motion. As well, with some of the shorter participants, a pillow was needed on the backrest to allow sufficient space (5 cm) between the front edge of the chair seat and the back of the participant's lower leg. Range of motion limits were set at 35° flexion to 95° flexion. The knee extensors were tested before the knee flexors. A static gravity correction measurement was recorded at 35° flexion to end the test session.

Test mode

The indirect power measure of peak velocity (PV) was obtained from the isotonic (IT) mode, and direct power measures [average power (AP); peak power (PP)] were recorded from isokinetic (IK) contractions using the passive mode. All isotonic tests were performed before isokinetic tests for all muscle groups. The resistance was set at 1 Nm for isotonic testing in order to encourage maximum movement velocity. Participants performed 3-5 submaximal practice repetitions before we recorded 6 maximal IT test trials. After 2 minutes of rest, participants performed 3-5 submaximal practice isokinetic contractions before 6 test contractions at 60°/sec and 6 test contractions at 180°/sec. Isokinetic testing velocity was chosen based on previous work that found children tended to become discouraged at low testing speeds, and often could not keep up with speeds of more than 180°/sec.[18] We used the passive mode to record the participant's isokinetic muscle contractions because we felt some children may have a hard time overcoming the weight of their leg in addition to the weight of the limb attachment in order to initiate movement, which is necessary when using the isokinetic mode.[6] With all tests, verbal encouragement was given through every repetition ("push hard and fast") but the athlete was not allowed to view the computer screen.

Data Analysis

Biodex data were collected at a frequency of 100 Hz and exported via text file for further analyses. Before analyses, all test data were smoothed with 9-point weighted filtering using RStudio, version 2.15.0 (Boston, MA).[19]

When examining graphs of the IK torque curves, transient torque artifacts were observed throughout the muscle contraction in some participants. Consequently, additional smoothing of the IK data was needed before 9-point filtering could be completed. By removing any data point that was greater than 50% of the preceding data point for HAB, HAD and HF, and KE and KF, and 100% greater than the preceding data point for HE, we successfully removed the unwanted noise without appreciably changing the torque curve. In the initial stage of analyses, we discovered that the dynamometer did not reach the pre-set velocity of 180°/sec within the fixed ROM limits during HAB/HAD and KE/KF isokinetic tests; therefore these tests were omitted from analyses.

Gravity correction was done after data collection because the Biodex System 3 does not allow for its automatic calculation when using a linked testing protocol or for passive mode tests, both of which were used in this study.[19] Using RStudio, gravity correction was applied to the isokinetic data using the following equation, in consultation with Biodex Medical Systems Inc.:

$$T(corr) = T(limb) \times \cos(\text{position} - \text{shaft offset})$$

Where T(corr) = the corrected torque for a specific joint angle; T(limb) = the measured static gravity correction torque of the appropriate joint for each participant; position = absolute position of the dynamometer at the specific joint angle in radians; shaft offset = 2.91 radians (hip); 1.34 (knee). The shaft offset values are specific to the use of the particular attachments and test protocols used in this study.

After cleaning the data, we calculated the peak and average power (IK tests) and peak velocity (IT tests) of each repetition for each test for each participant. Peak and average power were determined by multiplying the angular velocity with the torque measurement for each time point from each repetition. We then used the mean for each participant for each variable (PP, AP and PV) from the latter 5 of the 6 IT and IK repetitions in statistical analyses.

Means and standard deviations were calculated for each variable at T1 and T2. The normality of the difference scores (T1-T2) for each variable was investigated using a Shapiro-Wilk test. We also used Bland-Altman plots and Pearson Correlation tests to determine the presence of heteroscedasticity. If the difference score of a variable was found to be normally distributed and homoscedastic, a paired t-test was used to compare the variable at T1 and T2. If the requirements of normality and homoscedasticity were not satisfied, a Wilcoxon Signed Rank Test was used to determine whether the variable changed significantly from T1 to T2 ($p < 0.05$).

Relative reliability was calculated using ICC (2,5) with the corresponding 95% confidence interval for isotonic and isokinetic tests. ICC (2,*k*) was used because the mean of *k* repetitions for each participant was used in analyses.[5]

Absolute reliability of group results was assessed using the standard error of the measurement (SEM). SEM was calculated as the square root of the residual mean square error from the analysis of variance table.[20] The associated 95% confidence limits were calculated as ± 1.96(SEM). The SEM is given in the actual units of the variable and assesses the degree of change necessary to be confident that an actual change in performance has occurred in the group mean from one test session to another.[5] Describing that necessary change as a percentage allows for comparison between different test methods and equipment, and can be accomplished using the coefficient of variation of the typical error (CV_{TE}).[5] Typical error was calculated as the standard deviation (SD) of the difference scores divided by the square root of two.[21] Dividing the typical error by the mean of all trials and multiplying by 100 produced CV_{TE} in percent.[22]

Absolute reliability of an individual's performance was investigated using the limits of agreement (LOA), which were calculated as the systematic bias (mean difference between the 2 test sessions) ± the random error component (REC).[23] REC was calculated as 1.96 multiplied by the SD of the difference scores. The LOA presents the error that can be expected when re-testing an individual participant on multiple occasions, in the units of the variable.[5] Ratio limits of agreement (RLOA) were also calculated in order to provide a means of comparing different study and measurement protocols. The RLOA was calculated as the REC divided by the mean of all observations multiplied by 100, and is expressed as a percentage.

RESULTS

Means, standard deviations and *p* values for all variables for isotonic and isokinetic tests can be found in Table 2.

Systematic bias was present in some tests, with HAB and HF average and peak power decreasing from T1 to T2, and KF peak velocity increasing from T1 to T2. However, the absolute difference between test sessions was minimal [1-5 Watts (W); 9°/sec]. The PV tests demonstrated the best absolute reliability, with CV_{TE} values of 5.0-8.5% (Table 3). Hip flexion and knee extension peak and average power tests showed acceptable reliability for measuring group means (CV_{TE} = 8-11%) while the other muscle groups did not perform as well (CV_{TE} = 17-33%). RLOA values were better for HF and KE average or peak power than other muscle groups (24-30% vs. 47-91%) but were still quite high. The RLOA results for HE, HF, KE and KF peak velocity (CV_{TE} = 14-15%) suggest these tests could be used at the individual level in a one-time indirect measure of power.

All peak velocity tests demonstrated good relative reliability (ICCs=.85-.94). The range of ICCs for all peak and average power tests except HE and KF were also good. However, considering the absolute reliability results above, relative reliability cannot be used as an indication of the overall dependability of these test protocols on the Biodex dynamometer with this population.

DISCUSSION

This study was conducted to determine the relative and absolute reliability of testing neuromuscular indices of power in young, active individuals on a Biodex System 3 dynamometer using a standing hip and seated knee protocol. The ability to measure power reliably may aid the pediatric physical therapist in the successful rehabilitation of orthopedic injuries, as well as in identifying contributing factors to functional deficits. Although systematic bias was found with some tests, the small change from one test session to another is perhaps clinically irrelevant.

Even though neuromuscular power measures have been used to assess response to an intervention[11] as well as examine relationships to functional activities[24] we could only find one study that looked at the reliability of using a Biodex dynamometer to measure power in young participants.[6] The participants in that study were younger than ours (5-12 years of age) and completed knee flexion and extension tests using the passive mode. The authors found better reliability for knee flexor average power (CV=9.5%; SEM=6.7W) than for knee extensors (CV=14.9%; SEM=12W), while in our study, the opposite was true. A handful of other studies[8,9,10] have examined reliability in adult populations. One looked at the reliability of measuring knee extensor and flexor average power in older adults.[8] Knee extension reliability indices were similar to our study (SEM=5.2W vs. 6.4W; RLOA=25% vs. 28%; ICCs=0.92 vs. 0.97) however their knee flexion measures proved to be more reliable than ours (SEM=2.9W vs. 9.6W; RLOA=31% vs. 86%; ICCs=0.94 vs. 0.80). A small study involving younger adults found better reliability for both knee flexor and extensor average power compared to our results (SEM%=2-7% vs. CV_{TE}=10-31%).[10]

Another study also involved young adult participants, but assessed the reliability of knee extension and flexion average power in a *prone* position on the Biodex.[9] The authors found better absolute reliability for the knee flexors (CV_{TE}=15% vs. 31%) and slightly worse reliability for the knee extensors (CV_{TE} = 19% vs. 10%) compared to our study. The various test protocols (prone vs. standing) and populations (older adults vs. children) undoubtedly contributed to the differences in findings between studies.

We are not aware of any studies that have investigated the reliability of measuring minimally weighted movement velocity of the hip and knee on a Biodex dynamometer in a young population. One study was found that identified a similar ICC value to ours (0.95 vs. 0.92) for measuring standing hip extension in university male athletes; however the testing protocol was quite different. Maximum velocity values were obtained via the isokinetic mode, with a high resistance level set at 500 Nm.[24]

Few studies that measure neuromuscular power or movement velocity, regardless of device or protocol, exist for comparison to the values obtained in our investigation. The study that most relates to ours[6] does not allow for comparison of power values, as only body mass normalized means are given by the authors. In the only other study involving youth (high school aged girls)[11], the mean power of the knee flexors is difficult to compare as those authors tested at 180°/sec, compared to 60°/sec in our younger age group. It is also unclear whether gravity correction was incorporated into that study. The mean knee extensor power of our participants was the same (63W) as that found for young adults measured in a prone position.[9] However mean power of the knee flexors was less (31W) than found in that study (45W). Comparison with the knee power of another group of young adults who were tested similarly to our participants was not possible because means were not reported by those authors.[10] Interestingly, the mean power values of our young participants were slightly greater than those found for a group of older adults (KE=63 W vs. 57 W; KF=31 W vs. 26 W).[8]

In terms of movement velocity, existing studies for comparison are even rarer. Our participants demonstrated similar hip extension (378°/sec vs. 371°/sec) and hip flexion velocity (403°/sec vs. 363°/sec) compared to a group of young adults tested under minimal load conditions on a Biodex.[12] Some of the disparity in findings with that study may be due to the fact that the young adults were tested with their leg braced in an extended position while our participants maintained slight knee flexion. Compared to another study, our participants demonstrated half the knee extension velocities of active young adults (391°/sec vs. 693°/sec) who were measured on a specialized device with no external load present.[25] From our review of the literature, it can be said that the reliability and results of measuring neuromuscular power can vary greatly depending on the age of the population, positioning during testing, muscle group tested and the dynamometer mode used. By evaluating the reliability of commonly measured large muscle groups in customary positions, we believe our results are relevant and useful to many practicing clinicians.

Measuring the hip in a standing position as we did may be a more functional method of ascertaining an individual’s strength and power than the standard method described by the manufacturer[16] and has become more common, especially in the sports injury literature.[14,15] It places the individual in a familiar, comfortable position which may result in a more accurate assessment of their abilities. However there are some disadvantages to this test method. Isokinetic abduction/adduction is limited to slower velocities, as we found the available range of motion in the frontal plane was not sufficient to allow the dynamometer to reach 180°/sec. Also, stabilization of the trunk may not be as fixed as when the individual is lying down. This may affect the test protocol’s ability to assess true isolated joint movement.

The design of the study has some limitations which should be considered. The testing protocol lasted upwards of 2 hours which may have affected the attention span and motivation level of the participants; especially the younger individuals. Future studies should examine the reliability of short, focussed assessments of neuromuscular power. The lengthy time the participant was required to stand for testing also may have contributed to two participants experiencing light-headedness during testing. If hip function is assessed in standing, the participant should be given frequent breaks and/or encouraged to move their legs to improve circulation during rest breaks. In addition, no familiarization session was given to the participants. Due to the large degree of variability observed with some of the tests, it may be valuable for future research to assess reliability over multiple testing sessions to determine whether reliability improves with increased exposure to the testing protocol.

Given that emerging evidence suggests that neuromuscular power rather than strength may be more strongly related to function,[2] the evaluation of power in both clinical and research areas is bound to increase in frequency. There must be reliable methods in place to measure it in diverse populations. The current study offers options for measuring power and movement velocity in a young, active population.

CONCLUSIONS

This is the first study to determine the absolute and relative reliability of measuring hip and knee neuromuscular power and velocity of movement in participants aged 10-14 years using a Biodex dynamometer. The testing protocols possessing adequate absolute reliability ($CV_{TE} \leq 15\%$) described here (all PV tests; HF and KE PP & AP tests) may be used with a *group* of young participants in a one-time assessment of neuromuscular power. Hip and knee flexion and extension peak velocity measures can be used with an *individual* in a stand-alone evaluation of neuromuscular power. The other power variables do not exhibit sufficient reliability to be used confidently in measuring power at the group or individual level on a one-time basis. However, any of the tests presented in Table 3 may be used to describe a change in performance over time or in response to a specific intervention at the group or individual level, as long as the range of expected error is taken into consideration.

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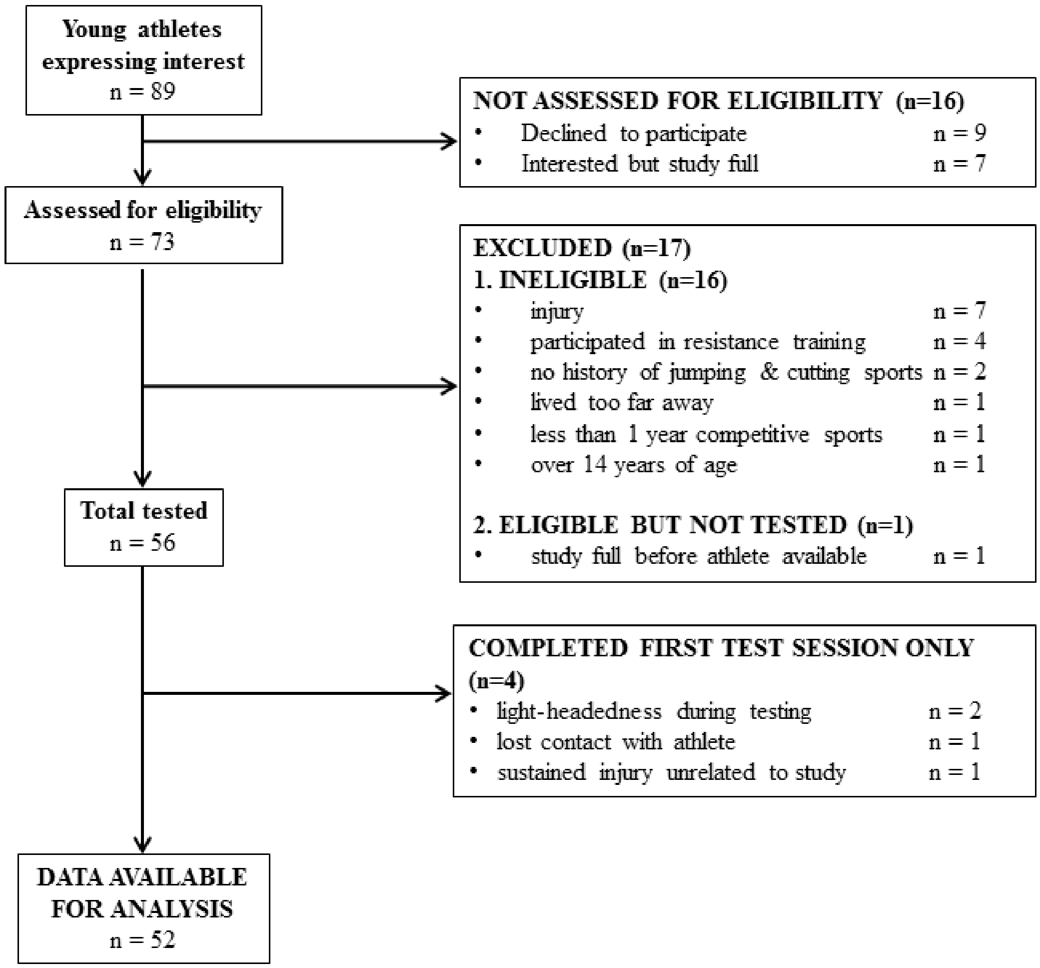

FIGURE 1. Participant recruitment flow diagram

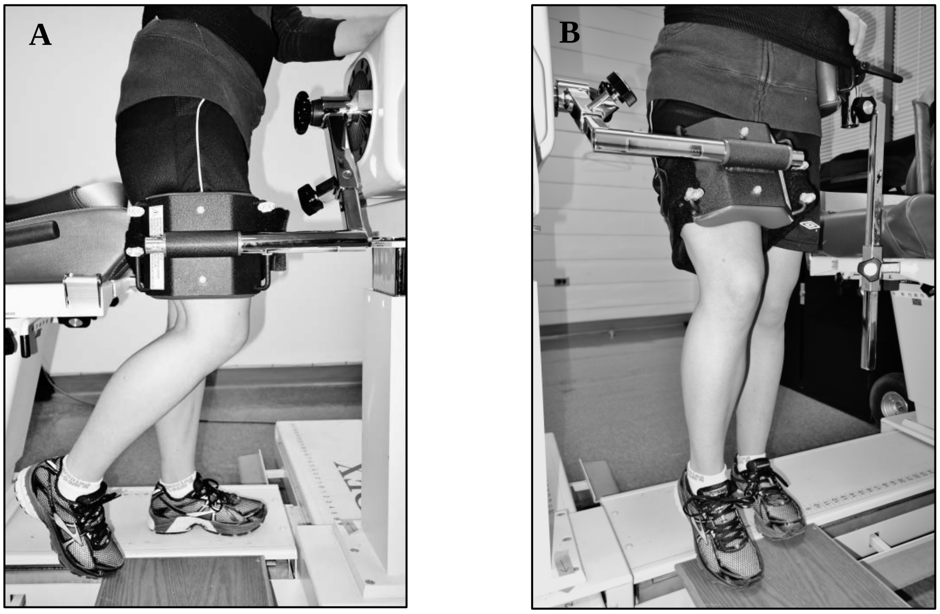

FIGURE 2. Participant set-up for **A)** hip abduction/adduction testing B**)** hip flexion/extension testing

TABLE 1. Participant characteristics

Characteristic	Mean (SD)
Age (y)	11.6 (1.4)
Height (cm)	153.4 (11.2)
Mass (kg)	46.5 (13.0)
PMOS[a]	3.8 (2.7)

[a]Pubertal Maturation Observational Scale

TABLE 2. Means (SD) of isotonic and isokinetic tests

Variable	Time 1	Time 2	*p*
Hip abduction			
Isotonic test			
Peak velocity (°/s)	211.9 (38.6)	217.5 (40.8)	0.12
Isokinetic test			
Peak power (60°/s , W[a])	56.6 (20.7)	55.2 (22.9)	0.03
Average power (60°/s , W)	50.7 (19.0)	49.4 (20.5)	0.04
Hip adduction			
Isotonic test			
Peak velocity (°/s)	245.5 (38.9)	250.9 (44.3)	0.20
Isokinetic test			
Peak power (60°/s , W)	41.4 (16.9)	40.7 (18.3)	0.63
Average power (60°/s , W)	28.1 (11.6)	26.7 (11.8)	0.14
Hip extension			
Isotonic test			
Peak velocity (°/s)	381.9 (52.2)	375.2 (56.8)	0.98
Isokinetic test			
Peak power (60°/s , W)	52.2 (25.2)	50.6 (25.3)	0.60
Average power (60°/s , W)	34.3 (18.6)	33.4 (18.9)	0.51
Hip flexion			
Isotonic test			
Peak velocity (°/s)	400.3 (58.6)	406.4 (60.2)	0.13
Isokinetic test			
Peak power (60°/s, W)	74.8 (28.5)	70.1 (25.4)	<0.001
Peak power (180°/s, W)	194.1 (74.6)	189.0 (72.6)	0.03
Average power (60°/s, W)	63.5 (24.8)	59.9 (22.3)	<0.001
Average power (180°/s, W)	174.2 (66.8)	169.8 (65.6)	0.07
Knee extension			
Isotonic test			
Peak velocity (°/s)	389.9 (50.5)	393.3 (49.4)	0.40
Isokinetic test			
Peak power (60°/s , W)	82.9 (34.6)	81.4 (32.1)	0.34
Average power (60°/s , W)	64.1 (27.1)	63.0 (25.9)	0.39
Knee flexion			
Isotonic test			
Peak velocity (°/s)	360.9 (57.2)	369.8 (54.8)	0.02
Isokinetic test			
Peak power (60°/s , W)	43.9 (23.2)	43.1 (19.0)	0.51
Average power (60°/s , W)	31.1 (18.3)	30.7 (14.4)	0.81

[a]W=Watts

TABLE 3. Relative and absolute reliability statistics for isotonic and isokinetic tests

Variable	ICC[a]	95% CI[b] for ICC	SEM[c]	95% CI for SEM	CV_{TE}[d] (%)	LOA[e]	Ratio LOA (%)
Hip abduction							
Isotonic test							
Peak velocity	0.88	0.49-0.93	18.1	±35.4	8.4	-5.7 ± 50.0	23.3
Isokinetic test (60°/s)							
Peak power	0.86	0.76-0.92	10.8	±21.2	19.4	1.4 ± 30.0	53.7
Average power	0.86	0.76-0.92	9.8	±19.1	19.5	1.3 ± 27.1	54.0
Hip adduction							
Isotonic test							
Peak velocity	0.85	0.74-0.92	21.1	±41.3	8.5	-5.4 ± 58.4	23.5
Isokinetic test (60°/s)							
Peak power	0.91	0.85-0.95	7.1	±13.9	17.3	0.7 ± 19.7	47.9
Average power	0.91	0.85-0.95	4.6	±9.1	16.9	1.4 ± 12.9	46.9
Hip extension							
Isotonic test							
Peak velocity	0.92	0.86-0.96	20.4	±40.0	5.4	6.7 ± 56.6	14.9
Isokinetic test (60°/s)							
Peak power	0.79	0.63-0.88	15.1	±29.6	29.3	1.6 ± 41.8	81.3
Average power	0.79	0.63-0.88	11.1	±21.8	32.8	1.0 ± 30.8	91.0
Hip flexion							
Isotonic test							
Peak velocity	0.94	0.89-0.96	20.2	±39.6	5.0	-6.1 ± 56.0	13.9
Isokinetic test							
Peak power (60°/s)	0.96	0.91-0.98	7.1	±13.9	8.7	4.7 ± 19.6	27.1
Average power (60°/s)	0.95	0.91-0.97	6.7	±13.1	10.8	3.7 ± 18.5	30.0
Peak power (180 °/s)	0.97	0.95-0.99	16.7	±32.7	8.7	5.0±46.3	24.2
Average power (180°/s)	0.97	0.96-0.99	14.6	±28.6	8.5	4.5±40.5	23.5
Knee extension							
Isotonic test							
Peak velocity	0.91	0.84-0.95	20.4	±39.9	5.2	-3.4 ± 56.4	14.4
Isokinetic test (60°/s)							
Peak power	0.97	0.95-0.98	7.9	±15.5	9.6	1.5 ± 21.9	26.6
Average power	0.97	0.95-0.98	6.4	±12.6	10.1	1.1 ± 17.8	28.0
Knee flexion							
Isotonic test							
Peak velocity	0.93	0.88-0.96	19.3	±37.8	5.3	-8.9 ± 53.4	14.6
Isokinetic test (60°/s)							
Peak power	0.82	0.69-0.90	11.7	±22.9	26.9	0.8 ± 32.4	74.5
Average power	0.80	0.64-0.88	9.6	±18.9	31.2	0.4 ± 26.7	86.4

[a]ICC = intraclass correlation coefficient; [b]CI = confidence interval; [c]SEM = standard error of measurement; [d]CV_{TE} = coefficient of variation of typical error; [e]LOA = limits of agreement. SEM & LOA for peak velocity are reported in °/s; for average & peak power, in Watts.

CHAPTER 4: Comparison of Lower Limb Power and Strength between Young Female and Male Athletes

MY CONTRIBUTION TO THE MANUSCRIPT

I devised the research question and developed the study protocol and methods of analyses in consultation with Dr. Porter. I wrote the application for ethics approval and created the data collection documents, including consent and assent forms. I recruited and screened all research participants, and completed all data collection. I analyzed the data and wrote the paper in association with Dr. Porter. I made revisions according to her suggestions in anticipation of submission to a peer-reviewed journal. The results have been accepted for presentation in poster format at the annual conference of the American College of Sports Medicine in 2014.

ABSTRACT

Neuromuscular strength levels in girls and boys diverge around the time of puberty. However, no work has been done to explore the presence of sex differences in neuromuscular power (force x velocity), even though it has been more closely linked with functional ability. **PURPOSE**: To determine whether female and male athletes aged 10-14 years differ in the peak movement velocity, power and strength of the lower limb as measured with a Biodex Dynamometer. **METHODS:** Standing hip abduction, flexion and extension, and seated knee extension and flexion peak velocity (PV), peak power (PP) and peak torque (PT) were measured in fifty-two athletes (26 girls). PV was assessed using the isotonic mode on the dynamometer. PP was determined using the passive mode at 60°/sec. PT was collected via isometric contractions. Multiple linear regression was used to explore factors (age, height, mass, pubertal maturation, age began organized sport, and years playing organized sport) which influenced the dependent variables. Significant factors were then used within an Analysis of Covariance to determine the presence of sex differences in hip and knee movement velocity, power and strength. **RESULTS:** Female and male athletes showed no statistically significant differences for any of the test modes or movements (p = 0.32 -0.89). **CONCLUSION:** Between the ages of 10 and 14, girls and boys do not differ in movement velocity, power or strength of the hip or knee muscle groups. Further research is required to determine whether a neuromuscular power gap appears between girls and boys as they mature; at what age the gap emerges; and how the discrepancy may relate to injury mechanisms and function.

INTRODUCTION

The appearance of sex differences in neuromuscular function with maturation is universally recognized (De Ste Croix 2012) and continues to be confirmed (Brent et al. 2013; Buchanan and Vardaxis 2009; Buchanan and Vardaxis 2003). The disparity seems to emerge during the teenage years (De Ste Croix et al. 2002; Barber-Westin, Noyes, and Galloway 2006; Beunen and Malina 1988), with boys outperforming girls by the mid- to late teens (De Ste Croix 2007). Research suggests that neuromuscular differences such as peak torque output (Lephart et al. 2002) and muscle activation characteristics (Gehring, Melnyk, and Gollhofer 2009) put female athletes at a disadvantage, as they may contribute to movement patterns that predispose to certain sports related injuries, such as rupture of the anterior cruciate ligament (ACL) of the knee. Strength deficits have also been directly linked to an increased risk of ACL injury in a recent study (Myer et al. 2009).

Numerous studies have established that female athletes have a higher incidence of ACL injury (Lindenfeld et al. 1994; Prodromos et al. 2007). This injury rate disparity starts to appear around the age of puberty (Shea et al. 2004), coinciding with the appearance of sex differences in neuromuscular function. As a result, many investigations have ensued to examine the relationship between neuromuscular function and injury mechanisms and injury risk. Some studies have found significant correlations between lower extremity strength and ACL injury mechanisms in both adolescent and adult athlete populations (Claiborne et al. 2006; Stearns, Keim, and Powers 2013; Wild, Steele, and Munro 2013). These authors found that strength deficits were correlated with increased frontal plane motion at the knee during sports movements such as landing from a jump and cutting; increased frontal plane motion is considered a high risk movement for ACL injury (Shultz et al. 2012). However, other studies have failed to find similar correlations between strength and injury mechanisms. Barber-Westin et al. (2005) compared boys and girls aged 9-10 years and found no significant relationships between quadriceps or hamstrings peak isokinetic torque and landing biomechanics. Beutler et al. (2009) also failed to find a relationship between lower extremity muscular strength, as measured by peak isometric force, and landing biomechanics in a group of young adult military cadets.

Clearly, understanding whether there are sex differences in neuromuscular function has important implications for ACL injury risk reduction. Within the last decade, evidence has surfaced that neuromuscular *power* may have a stronger influence on functional abilities and movements when compared to neuromuscular *strength* in some populations (Bean et al. 2010; Mayson et al. 2008). Power is the volume of muscular work performed in a given time frame. More commonly, it is expressed as the product of force x velocity (Bean et al. 2003). To function in activities of daily living as well as in sport, humans require a combination of adequate strength (force production ability) and adequate movement velocity. We rarely, if ever, need to use one without the other. Therefore, it would seem logical to undertake the measurement of *power* indices of specific joint motions to investigate their contribution to our understanding of injury risk as well as sport performance (Pigozzi, Giombini, and Macaluso 2012).

Few studies have looked at sex differences in hip or knee muscle power measured directly via average or peak power, or indirectly, via movement velocity. Using various dynamometers, three studies have looked at the peak knee extension power (Doldo 2004; Petrella et al. 2005) and peak leg press power (Yamauchi et al. 2010) of healthy adults. All three studies determined that men possess greater peak power than women. Interestingly, when movement velocity, an indirect measure of power, is considered the results are less consistent. One study reported that men demonstrated greater movement velocity than women (Yamauchi et al. 2010); two reported no significant sex differences (Houston, Norman, and Froese 1988; Petrella et al. 2005) and one reported that women, in fact, possessed greater lower limb movement velocity when normalized to muscle volume (Doldo 2004).

Sex differences in neuromuscular power (either direct or indirect) of the lower limb have not been explored in a young, athletic population even though hip and knee muscle function likely have a direct impact on ACL injury mechanisms and rates (Wild, Steele, and Munro 2013; Myer et al. 2009). Because ACL injury rates begin to increase in early adolescence (Shea et al. 2004), identifying differences in this population may provide a starting point for the initiation of injury prevention and performance enhancement intervention strategies. Therefore, the primary purpose of this study was to determine whether sex differences exist in peak movement velocity of the hip and knee in young athletes aged 10-14 years. A secondary purpose was to examine sex differences in hip and knee peak power and peak torque levels in the same population. We hypothesized that boys would exhibit greater velocity, power and strength than the girls in all movements tested.

METHODS

Participants

Following Research Ethics Board approval, 52 young athletes were recruited through local sports organizations via websites, e-mails and posters. Participants were required to be 10-14 years old at the time of testing and have at least a year of experience in an organized sport that involved jumping, cutting or pivoting (e.g., volleyball, basketball). Children could not participate if they had any health condition that prohibited them from physical activity participation, a current orthopedic injury with greater than a 3/10 pain rating, previous experience on an isokinetic dynamometer or a history of resistance training in the preceding 6 months.

Procedures

This investigation was undertaken as part of a larger study which collected isokinetic dynamometer data in part to determine the reliability of measuring strength and power in young athletes. Participants were tested on two separate occasions, about one week apart (mean, 7.3 ± 1.1 days; range 4-11 days). The results of the reliability study confirmed that peak hip and knee joint velocity of movement, as well as peak hip flexion and knee extension power and torque measurements, can be used reliably [coefficient of variation of the typical error (CV_{TE}) < 15%] for a one-time assessment of function in young athletes (Parsons, unpublished data under review). As a result, the mean peak movement velocity, power and torque measurements from the first test session were used in the analyses here.

A Biodex System 3 Pro isokinetic dynamometer (Biodex Medical Systems, Shirley, NY) was used for all data collection. The dynamometer's calibration was verified according to the manufacturer's recommendations before each participant was tested. All children were tested by the same physical therapist. Written informed consent was obtained from the parent and the athlete at the time of testing. To warm up, the athlete walked on a treadmill for 5 minutes. Standing hip abduction, extension, and flexion testing was done before knee extension and flexion were assessed in a seated position.

Testing Protocol

Before each muscle group was tested, a verbal and visual explanation was given as to the expected movements for that test mode. The athletes were then asked to perform 3-5 submaximal practice repetitions before the test trials were recorded. Six test repetitions were completed for isokinetic and isotonic contractions, and three test repetitions for isometric contractions. For all tests, the assessor gave verbal encouragement with every repetition ("push hard and fast") but the athlete was not able to see the dynamometer computer screen.

The primary outcome variable, peak velocity of movement, was measured using the isotonic mode on the dynamometer. The resistance on the dynamometer arm was set at 1 Nm in order to assure maximum movement velocity.

Peak power data were collected from isokinetic muscle contractions at a velocity of 60°/sec. Isokinetic muscle contractions were carried out using the passive mode on the dynamometer, because some children may be unable to initiate movement against the weight of their leg in addition to the dynamometer attachment, which is necessary when using the isokinetic mode (Santos et al. 2013).

Strength data were collected via isometric muscle contractions. Peak hip isometric torque readings were taken with the participant's hip in a neutral position, with the athlete standing erect, feet about shoulder width apart and the hip in 0° flexion. For knee tests, isometric contractions were measured at 90° flexion (Mitchell et al. 2011). Ninety seconds of rest separated the three isometric test repetitions.

Hip Abduction This testing procedure was adapted from previous work (Brent et al. 2013). The athlete stood facing the dynamometer head, with a hip stabilization pad secured with a Velcro strap at the level of the athlete's iliac crest on the non-test leg (Figure 1A). The dynamometer axis of rotation was aligned with the greater trochanter of the dominant leg. Depending on the size of the athlete, either an adult or pediatric Hip Attachment was used in conjunction with the Wrist Adapter. This allowed the test hip to move through the target range of motion of 5° adduction to 30° abduction. The thigh strap was secured in place about 5 cm proximal to the knee joint. The athlete was instructed to keep the trunk in an upright position and not allow side-to-side trunk motion during testing. The knee of the test leg was kept slightly bent to avoid contact of the foot on the standing platform. After hip abduction testing was complete, a static gravity correction measurement was taken at 30° abduction and recorded.

Hip Extension/Flexion For these muscle groups, the athlete was positioned with the dominant leg closest to the dynamometer head. The hip stabilization pad and trunk strap were positioned as described above for abduction testing. The greater trochanter remained as the axis of rotation, and the hip attachment was secured to the athlete's dominant leg, about 5 cm superior to the patella (Figure 1B). Range of motion limits were set at 60° flexion to 20° extension. Hip flexor testing occurred prior to hip extensor testing. A static gravity correction measurement was recorded at 60° flexion before the athlete was unstrapped from the device.

Knee Extension/Flexion Knee testing took place according to standard procedures with the athlete seated (Biodex Medical Systems 2006). The lateral femoral condyle was used as the axis of rotation for the knee attachment, which was fixed to the leg with a Velcro strap about 5 cm superior to the lateral malleolus. Some adjustments were required for smaller athletes. If the upper leg was not long enough to allow about 5 cm of space between the front edge of the chair and the back of the athlete's calf muscle, a pillow was placed behind his/her back to create sufficient space. On occasion a towel was placed under the thigh to elevate it to horizontal; this allowed the knee to move through the necessary range of motion (35° flexion to 95° flexion). Knee extension testing preceded knee flexion testing. A static gravity correction measurement was recorded at 35° flexion before testing was complete.

Data Analysis

A sample size calculation using SigmaPlot, based on an alpha level of 0.05 and power of 0.8 yielded a requirement of 26 athletes per group for adequate comparison. The values used in the sample size calculation were obtained from a previous study investigating sex differences in knee extension velocity (Doldo 2004).

Biodex data were collected at a frequency of 100 Hz and exported via text file. The peak velocity from each repetition of each isotonic test movement was extracted using RStudio (RStudio, Inc., Boston, MA) and the mean of the peak velocities from the last five of the six test repetitions was used in statistical analyses. No filtering or smoothing of the velocity data was required.

Prior to extraction of the peak torque from each isometric repetition, data were smoothed with 9-point weighted filtering (Biodex Medical Systems 2007). The initial portion of each isometric contraction was removed to eliminate the torque overshoot at the initiation of contraction

(Sapega et al. 1982). After appraisal of the torque curve graphs, it was decided that 400 milliseconds (ms) was representative of the torque overshoot time in this population. Therefore, peak torque of each isometric contraction was acquired from the remaining time frame (400 ms to 3 seconds). The mean peak torque from the three test trials was used in analyses.

The isokinetic data required additional smoothing as a result of the presence of transient torque artifacts throughout the range of movement in some participants. Children are known to move in an irregular manner compared to adults, especially when responding to a novel task (Thomas 2000). Using RStudio, it was determined that removing any data point greater than 50% of the preceding data point successfully eliminated the extraneous torque spikes.

After filtering and smoothing, a gravity correction calculation was done to adjust the isokinetic tests for the torque due to the weight of the leg. Gravity correction was not applied to the isometric or isotonic tests. The isometric tests were done in a neutral position, with minimal influence from the effects of gravity; and the measurement of movement velocity from the isotonic contractions did not necessitate the consideration of torque due to gravity. Gravity correction calculations were done post-test because the Biodex System 3 does not allow for automatic correction when using a linked testing protocol or for passive mode tests, as were used in this study (Biodex Medical Systems 2007). Gravity correction was applied to the isokinetic peak power data using the following equation, in consultation with Biodex Medical Systems Inc.:

$$T(corr) = T(limb) * \cos(position\text{-}shaft\ offset)$$

where T(corr) = the corrected torque for a specific joint angle; T(limb) = the measured static gravity correction torque of the appropriate joint for each participant; position = absolute position of the dynamometer at a specific joint angle in radians; shaft offset = 2.91 radians (hip); 1.34 (knee). The shaft offset values are specific to the use of the particular attachments and test protocols used in this study.

After filtering, smoothing and gravity correction, the mean peak power from the last five of the six isokinetic test repetitions was used in statistical analysis.

Statistical Analysis

A multiple linear regression was used (SigmaPlot Version 11, Systat Software, Inc., San Jose, CA) to determine the presence of any covariates. Body mass, height, age, pubertal maturation, the number of years playing organized sport and the age at which the participant began playing organized sport were all considered as possible covariates. Any covariates significantly affecting the outcome variable were then used within an ANCOVA (SPSS Version 20, IBM Corporation, Somers, NY) to determine if boys and girls differ in lower limb movement velocity, peak power or peak torque. Significance level was set at $p \leq 0.05$.

RESULTS

A summary of the participants' characteristics can be found in Table 1. The girls and boys did not differ significantly in terms of any of the descriptive traits. Five of the 52 athletes reported left leg dominance, defined as the leg they would choose to kick a soccer ball as far as possible (Hewett, Myer, and Ford 2004). The unadjusted and adjusted means, standard deviations and *p* values for peak movement velocities, power and torque of the hip and knee for boys and girls are found in Table 2. Chronological age was a significant covariate for hip abduction and hip extension movement velocity as well as knee extension and hip flexion power and torque. Height in centimetres was also a significant covariate for hip extension movement velocity and hip flexion peak torque. The number of years playing organized sport and the age at which the athlete began organized sport participation were additional significant covariates for knee extension peak power. Knee extension and flexion and hip flexion velocities were not found to be significantly affected by any of the covariates. Body mass and pubertal maturation status were not significantly associated with any of the outcome variables and so were not used as covariates in the final analysis. After taking all of these factors into consideration, our analyses showed no significant differences between boys and girls in any of the joint movement variables measured.

DISCUSSION

The primary goal of this study was to determine if differences exist in movement velocity of the lower limb between young female and male athletes. The results of our study failed to support our primary hypothesis, and suggest that if a sex difference exists in movement velocity, it occurs after the age of 14 years. Even after considering pubertal maturation status and stature, there were no significant differences.

No previous studies have investigated whether movement velocity, which is an indirect measure of neuromuscular power, differs between the sexes at a young age. Previous work has shown that differences may exist in adults; however it is unknown at what age the differences first become apparent. In a study spanning a large age range, Yamauchi et al. (2010) found that men have a faster unweighted leg press velocity than women in both absolute terms and when normalized for leg length. This sex difference was not consistent in every age group studied, however. No sex differences were apparent in the 30-39 or 50-59 age groups, but they were present in the 18-29, 40-49 and 60+ age groups. Sex differences were also found in an investigation involving older adults and knee extension velocities at 50-70% of an individual's one repetition maximum (1 RM) (Doldo 2004). In absolute terms, men demonstrated a 14% higher peak velocity. However when the peak velocity was normalized to muscle volume, the women actually displayed a 38% greater knee extension velocity.

In contrast, a study involving a small group of young adults aged 18-29 years showed no differences in peak unloaded knee extension velocity between the men and women (Houston, Norman, and Froese 1988). The work of other authors (Petrella et al. 2005) also found no sex differences in movement velocity of the knee extensors in young adults in their mid-twenties or in older adults in their mid-sixties. Velocity in that study was measured while the participants pushed against 20-60% of their maximal strength. These studies as a whole would suggest that once adulthood is reached, there may be a sex difference in neuromuscular function, not just in terms of peak torque production abilities as previously suggested (De Ste Croix 2007), but also in how fast a body segment can be moved. However, sex differences seem to depend on age, muscle group tested and the method of measuring movement velocity.

Comparison of the performance of our participants with those from other studies has limitations, because no other studies have tested such young individuals or the isotonic mode on a Biodex dynamometer to measure minimally weighted movement velocity of the lower limb. Using a pneumatic resistance machine, the older adults in a previous study demonstrated slightly lower knee extension velocities (female = 292°/sec; male = 332°/sec) compared to our participants (female = 384°/sec; male = 396°/sec) (Doldo 2004). In contrast, our young participants were a great deal slower than the young adults of another study who were tested on a lightweight custom apparatus made with low-friction bearings (female = 693°/sec; male = 699°/sec) (Houston, Norman, and Froese 1988). Other studies have looked at leg press velocity, measured in metres per second (Yamauchi et al. 2010), or did not report their final data in anything other than graph form (Petrella et al. 2005), making comparisons impossible.

No significant sex differences were found with our secondary outcome measures of hip and knee peak power and torque, again refuting the hypotheses. There is no information on sex differences in peak power levels in children; however previous studies have found men possess higher peak knee extension power compared to women. Both in young (Petrella et al. 2005) and in older adults (Doldo 2004), men have demonstrated knee extension power values almost double those of women. However, in both studies, and in exact opposition to how power was measured in the present investigation, the load was fixed and the velocity of the movement was variable. This may have contributed to differences in study findings. For this same reason, it is difficult to make comparisons between the absolute leg muscle power of our participants and those in other studies. Against a load equal to 20% of their 1RM, young men and women have demonstrated knee extension peak power values of 150-375 W (Petrella et al. 2005). Older adults, when pushing against a resistance equal to 50-70% of their maximum strength, exhibited even higher power values of 785-1410 W (Doldo 2004). Other studies available for comparison measured *average* power of the knee extensors rather than peak power, but are included here as a reference. These studies used a variety of populations, including children (Santos et al. 2013), young adults (Ayala et al. 2013) and older adults (Hartmann et al. 2009). Average power measures were reported to range from 57-71 W in the three studies, compared to peak power values of 80-85 W found in our study.

Only one study was found that reported isometric hip flexion peak power measured in a standing position. Those authors (Dean, Kuo, and Alexander 2004) found that young adults demonstrated hip flexion peak power of about 245 W when tested against a load of 54 Nm during an isotonic contraction. It is important to note that the sample population consisted only of female participants; therefore sex differences were not examined.

In terms of strength, the knee extension peak torque of our participants (~95 Nm) appears to concur with previous studies of strength indices in children. In a large study of 10-13 year old children, isometric peak torque was 106 Nm when measured with the knee at 90° of flexion (Tsiros et al. 2013). Another study of 9-13 year old boys with similar testing methods found a knee extension peak torque value of 105 Nm (Blimkie et al. 1989). We are not aware of any studies that report standing isometric hip flexion strength in children or adolescents. However two previous studies were found involving adults. One tested the isometric hip flexion strength of adults with the hip in a position of 10° flexion (Cahalan et al. 1989). As would be expected, the values were greater (86-167 Nm) than those generated by our younger participants, and men were stronger than women.

The other study tested the hip of adult female participants in a neutral position and found similar values (Dean, Kuo, and Alexander 2004). Peak isometric hip flexion torque was 83 Nm for the older adults and 107 Nm for the younger adults.

Limitations to our study must be considered. We used the Pubertal Maturation Observational Scale (Davies and Rose 2000) to measure the stage of puberty in our participants. This scale relies heavily on the reports of the athlete and his/her parent to determine the stage of puberty. Parents and athletes especially had difficulty answering the “growth spurt” question with confidence (“The adolescent has grown 3 to 3.5 inches in the past 6 months or is past this growth spurt”). We also found that the questions on the scale were oriented toward lighter-skinned individuals; the questions about the emergence of darker hair were not applicable to our participants with a darker skin tone.

The boys and girls in our sample population demonstrated no difference in neuromuscular power, in agreement with previous work that showed divergence, at least in strength and performance levels, begins in the mid-teens (Beunen and Malina 1988; De Ste Croix 2007). Of the 52 participants in our study, only 12 were post-pubertal, defined as having a PMOS score of at least 6, including a growth spurt (Davies and Rose 2000). We intended to include a younger population to ensure that we identified sex differences, if present, at the earliest age possible. Future study should include slightly older adolescents, perhaps 14-16 years of age, to determine if sex differences in neuromuscular power indices begin to emerge. If so, the introduction of appropriate intervention programs to target those deficits at a younger age (i.e. <14 years of age) should be considered and examined for effectiveness.

CONCLUSIONS

This is the first study to investigate whether boys and girls differ in the movement velocity and power of the hip and knee musculature. Contrary to our hypotheses, no significant or clinical differences were found between boys and girls. This suggests that, similar to neuromuscular strength, any divergence in power abilities begins in the mid-teens or beyond and perhaps coincides with an advanced pubertal stage. The elucidation of the existence and timing of these sex differences has implications for injury prevention as well as sport performance.

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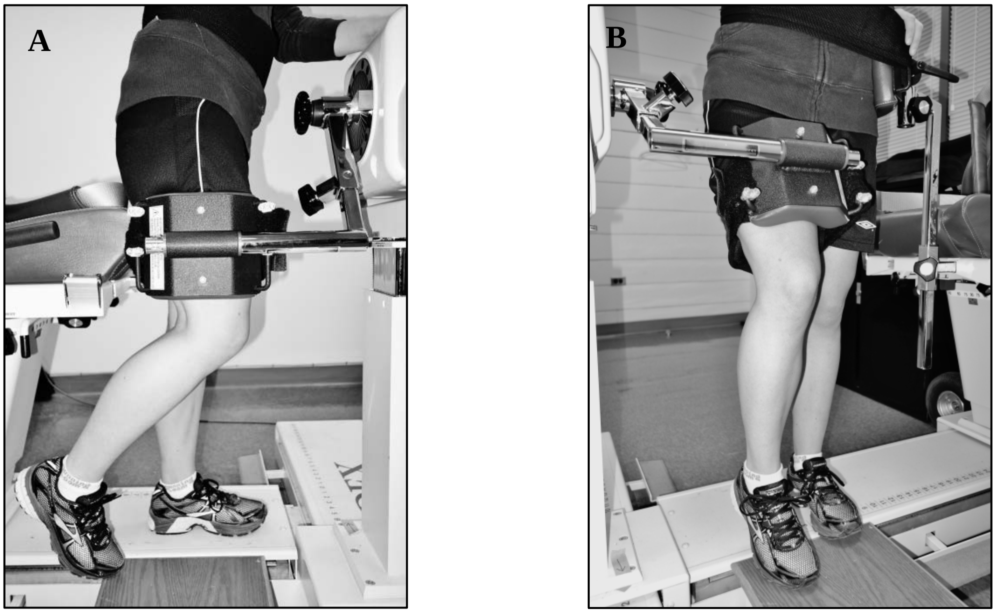

FIGURE 1. Position for testing of **A)** hip abductors and **B)** hip extensors and flexors.

TABLE 1. Participant characteristics.

Characteristic	Group	Mean (SD)	Range
Age (years)	Girls	11.9 (1.5)	10-14.4
	Boys	12.1 (1.5)	10-14.9
	Combined	12.0 (1.5)	10-14.9
Height (cm)	Girls	153.2 (11.7)	131-173
	Boys	153.6 (11.0)	131-173
	Combined	153.4 (11.2)	131-173
Mass (kg)	Girls	46.8 (14.1)	26.5-81.5
	Boys	46.2 (12.2)	27.5-68.0
	Combined	46.5 (13.0)	26.5-81.5
PMOS	Girls	3.8 (2.8)	0-8
	Boys	3.8 (2.8)	0-9
	Combined	3.8 (2.7)	0-9
Sport participation at time of testing (# of sports)	Girls	2.2 (1.3)	1-5
	Boys	2.0 (1.0)	1-4
	Combined	2.1 (1.1)	1-5
Participation in organized sport (years)	Girls	3.7 (2.1)	1-9
	Boys	4.2 (1.9)	1-8
	Combined	3.9 (2.0)	1-9

PMOS, Pubertal Maturation Observational Status. No significant differences were found between girls and boys for any of the descriptive characteristics.

TABLE 2. Comparison of peak movement velocity, peak power and peak torque between girls and boys.

	Girls Unadjusted Mean ± SD	Boys Unadjusted Mean ± SD	Girls Adjusted Mean ± SE	Boys Adjusted Mean ± SE	*p* value
Movement Velocity (°/sec)					
Hip abduction	214.0 ± 36.2	209.7 ± 41.6	215.3 ± 6.6	208.4 ± 6.6	0.47
Hip extension	373.6 ± 53.1	390.3 ± 51.0	375.6 ± 9.0	388.4 ± 9.0	0.32
Hip flexion	395.6 ± 64.1	405.0 ± 53.4	NA	NA	0.57
Knee extension	383.8 ± 56.6	395.9 ± 43.8	NA	NA	0.40
Knee flexion	358.6 ± 60.5	363.1 ± 54.8	NA	NA	0.78
Power (W)					
Hip flexion	72.4 ± 26.9	77.3 ± 30.3	73.8 ± 3.3	75.9 ± 3.3	0.66
Knee extension	83.0 ± 33.5	82.8 ± 36.3	85.7 ± 5.0	80.2 ± 5.0	0.45
Torque (Nm)					
Hip flexion	63.2 ± 21.0	63.6 ± 22.9	63.9 ± 2.4	63.0 ± 2.4	0.79
Knee extension	92.7 ± 39.3	97.4 ± 40.8	94.5 ± 5.6	95.6 ± 5.6	0.89

NA denotes those variables with no significant covariates. °/sec, degrees per second; W, Watts; Nm, Newton-metres; SD, standard deviation; SE, standard error .

CHAPTER 5: The Effect of a Twelve-Week Strength Training Program on the Jump Landing Biomechanics of Young Female Athletes

MY CONTRIBUTION TO THE MANUSCRIPT

With input from Dr. Porter and my committee, I developed the procedures for this research study. I carried out sample size calculations to determine the number of participants to be recruited. I acquired the necessary equipment for the exercise training and coordinated the repair of the Biodex dynamometer when it malfunctioned. Before beginning recruitment, I ran a small pilot study in order to determine appropriate testing and training protocols. As part of the pilot study I supervised a Master's student and an undergraduate fieldwork placement student who worked as research assistants. During the full-scale research study I supervised a Master's student as well as two research assistants who were responsible for data collection. I developed all written materials used during the study, with guidance from Dr. Porter. I shared the supervision of the exercise training with the Master's student. I was responsible for the majority of communication between participants and the research team in terms of scheduling training and testing times. Aside from the scoring of the main outcome measure, I collated all data from the study and undertook statistical analyses. The methods of analyses were discussed with Dr. Porter as the manuscript was written. Revisions were made to the paper in association with Dr. Porter's advice and suggestions.

ABSTRACT

Evidence exists that neuromuscular training programs can be effective in preventing anterior cruciate ligament (ACL) injury as well as the movement patterns associated with injury, such as landing awkwardly from a jump. However it is not known which components of the programs are most effective in eliciting improvement. **PURPOSE**: To determine whether a leg focused strength training program would significantly improve jump landing mechanics as measured by the Landing Error Scoring System (LESS) compared to a control group. **METHODS:** Thirty-six girls aged 10-14 years completed a 12 week strength training program focused on the legs (n=19; intervention) or arms (n=17; control). Athletes trained twice a week for an hour each time. Jump landing mechanics were captured on videotape before and after the exercise intervention, and scored by a blinded assessor using the LESS. An analysis of covariance (ANCOVA), with baseline LESS score as the covariate, was used to determine whether the arm and leg groups differed in their jump landing abilities after training. **RESULTS:** There were no differences between the leg and arm training groups post-intervention [leg group adjusted mean, 6.0 ± standard error (SE) 0.3 vs. arm group adjusted mean 6.1 ± SE 0.3; $p = 0.85$]. A secondary analysis of those participants with a baseline LESS score of 6 or more suggests that LESS score decreases after strength training, regardless of group [pre-training mean, 7.4 ± standard deviation (SD) 1.0 vs. post-training mean, 6.6 ± SD 1.2; $p = 0.01$; $\beta = 0.78$; n = 26). C**ONCLUSION:** Leg focused strength training does not seem to significantly improve jump landing abilities in young female athletes compared to arm focused training. However those with a low baseline LESS score may benefit from strength training in general; further research is warranted.

INTRODUCTION

The rate of anterior cruciate ligament (ACL) injuries in female athletes is approximately 3-6 times higher than the rate for male athletes (Arendt, Agel, and Dick 1999; Malone, Hardaker, and Garrett 1993; Prodromos et al. 2007). The majority of ACL injuries occur with a non-contact mechanism such as landing awkwardly from a jump (Dai et al. 2012). A straight or extended trunk position, combined with minimal hip and knee flexion and a valgus and rotated knee alignment during jump landing has been described as high risk for injury (Ireland 2002; Markolf et al. 1995). There is some discrepancy among studies as to whether trunk, hip and knee positions in the sagittal plane differ between male and female athletes (Beaulieu and McLean 2012). However knee displacement in the frontal plane (valgus or “knock-kneed” position) is generally accepted as being increased in female athletes during landing (Beaulieu and McLean 2012; Hewett, Torg, and Boden 2009). Previous work using in-vitro methods confirmed that a valgus position of the knee joint increases stress on the ACL, especially when combined with internal tibial rotation (Oh et al. 2012). Knowing that female athletes tend to land in a position that increases the vulnerability of the ACL, it is imperative that appropriate, effective interventions to change those movement patterns are identified and instituted.

A number of studies have found that physical training programs can be successful in altering the biomechanics demonstrated during a jump landing (Chappell and Limpisvasti 2008; Lim et al. 2009; Myer et al. 2005). Most prevention programs were developed from existing training programs which emphasized skill improvement and performance gains (Hewett et al. 1996). As a result, programs to improve movement patterns and decrease incidence of injury include such diverse components as balance training, plyometric exercises, flexibility training, and traditional strength exercises (Heidt et al. 2000; Mandelbaum et al. 2005).

Because many different exercise methods have been combined within prevention programs, it is difficult to determine which of the training elements are actually responsible for improving movement patterns during jump landing. Only a few studies have attempted to elucidate the contributions of each type of exercise. Myer et al. (2006) compared a plyometric program with a balance program in high school aged girls. Both programs decreased frontal plane knee joint displacement during landing. However a more recent study found that high-school female athletes participating in either a 4-week plyometric or core stability program failed to decrease knee valgus when landing, and contrary to the goals of an ACL injury prevention program, showed a *decrease* in knee flexion angle (Pfile et al. 2013). Another recent study compared the use of a whole-body resistance training program with an integrated program that included agility and stability exercises (Distefano et al. 2013). In that group of mainly male adults, the integrated program group showed a significant improvement in landing mechanics as measured by the Landing Error Scoring System (LESS) compared to the resistance training only group.

The results of a meta-analysis looking at the effect of prevention programs on ACL injury rates support the findings of DiStefano et al. (2013), by suggesting that successful programs include a combination of both strength and plyometric training components (Yoo et al. 2010). However none of the studies in the meta-analysis examined the effect of either strength or plyometric training on its own. The meta-analysis also found that participation in neuromuscular training at a younger age (less than 18 years) provided a protective effect in terms of ACL injury. The youngest participants included in studies in that review were 14 years of age (Yoo et al. 2010). We are only aware of one study that investigated the effects of a prevention program on the rate of ACL injury in athletes younger than 14 years of age (Walden et al. 2012). That study of 12-17 year old girls indeed found a protective effect from participation in a neuromuscular training program; the intervention group experienced a 64% decrease in ACL injuries compared to the control group. Only a handful of the studies looking at the effect of ACL injury prevention programs on jump landing biomechanics have included participants younger than 14 years of age. Three studies, using a combination of plyometrics, strength, balance and agility exercises, found that young athletes decreased the amount of knee valgus (Barendrecht et al. 2011; Noyes et al. 2005) or overall LESS score (Distefano et al. 2009) demonstrated during a jump landing. However, one study failed to find a decrease in knee valgus after an intervention (Grandstrand et al. 2006).

Since ACL injury rates rise considerably in the mid-teens (Shea et al. 2004) it is surprising more studies that aim to explore the effect of training programs on injury mechanics, as well as ACL injury rates, have not included younger participants. To date, no studies have investigated the contribution of the different components of training programs to improving movement patterns in a young population, although previous work has shown resistance training in children can positively affect functional abilities such as vertical jump height and sprint speed (Faigenbaum et al. 2009). It would seem logical to examine the effectiveness of prevention programs at an earlier age, before the chance of injury increases. Therefore, the purpose of this study was to investigate whether a lower body strength training program would change the movement patterns exhibited by young female athletes aged 10-14 years during a jump landing. We hypothesized that the lower body strength training group would significantly decrease their LESS score after the training program compared to a control group who trained their arms.

METHODS

Participants

Ethics approval was received from the University Research Ethics Board to conduct this study (ClinicalTrials.gov Identifier: NCT02043275). Recruitment posters were placed in high-traffic areas frequented by young athletes and their parents (university and city fitness facilities). Informational emails were also sent to local sport organizations for placement on their websites and in newsletters. Participants were required to be 10-14 years old at the time of the baseline testing session and have at least one year of participation in organized sports involving jumping, cutting or pivoting. Girls were excluded if they had engaged in resistance training in the last six months, had any health condition or injury that would affect participation in testing or training, or had musculoskeletal pain with a rating of more than 3 out of 10 on a visual analog scale.

Forty athletes met the inclusion criteria and agreed to participate in the study (Figure 1). Written informed consent (parent) and assent (athlete) were obtained at the first test session. A blinded assessor conducted all pre- and post-intervention testing. At the end of the first test session, the athlete chose a brown, opaque envelope from a pile and gave it to the assessor. The envelopes contained a piece of paper designating the athlete into either the “arms” or “legs” training group. The assessor did not open the envelope but passed it on to the principal researcher (PI). The athlete and her parents were then contacted by the PI within one or two days by phone or email, told which training group they were in, and the first training session was scheduled. Athletes were randomized in blocks of four to ensure equal numbers in each of the two training groups. Twenty girls were allocated to the intervention group (legs) and twenty girls to the control group (arms).

Procedures

A small pilot study was conducted with 8 girls over the course of a month in late 2012 to finalize the strength training protocols to be used in the randomized controlled trial. Exercises were chosen to ensure all major muscle groups of the upper (arm group) and lower (legs group) body were included. From the pilot study we learned:

1) the maximum instructor to athlete ratio would be 2:1, with one girl doing the exercise while the other one rested

2) only 2-3 sets of four exercises were possible within a one hour time frame

3) the athletes were stronger than we expected; additional weights were purchased as a result

Training Programs

Participant intake and training occurred in two waves, from April to July and August to December 2013. A maximum of twenty participants were in the study at once due to time and resource constraints. Girls in the arm and leg training groups were scheduled at different times to avoid cross-contamination. The girls trained twice per week for twelve weeks, for an hour each time, with at least one day in between. The training schedule varied week to week for most girls, depending on their activity schedule outside the study. During the 12 week program, the athletes, with the help of their parents, recorded how many hours they participated in organized sports activities outside of the study. All training sessions were conducted by one of two trainers; a physical therapist or a certified personal trainer. At the start of each training session, the girls did about 5 minutes of dynamic warm-up exercises including jogging, skipping, side shuffles and cross-overs. As well, the arm group did 10 repetitions of arm circles (forward/backward) and thoracic spine rotations while the leg group did 10 hip swings (forward/backward and side to side) and air squats as part of their warm-up. The first three training sessions were used for familiarization to the exercises and to weight-training in general. Light resistance was used, if any. The athletes were taught to execute the movements correctly and safely.

10 Repetition Maximum (10RM) Testing

At the fourth training session, and again at the last training session, a 10RM test was done for chest press and bicep curls in the arm group, and squats and lunges in the leg group. This was done to determine the starting load for the strength training program as well as provide some feedback to the participants about their improvements over the 12 week program. A maximum weight of 6RM is recommended for children to lift (Kraemer and Fleck 2005), and as the athlete would be doing 10-15 repetitions throughout the training program, a 10RM was chosen as a safe, practical test. Training loads were then calculated as follows: 1st set – 50% of 10RM; 2nd set – 75%

of 10RM; and 3rd set – 100% of 10RM for both leg and arm training. During the training program, as soon as the athlete could complete 15 repetitions of her 10 RM weight, the resistance was increased 10-20% at the next training session and the repetitions decreased back to ten.

Leg Training Group

The leg group did squats, lunges, side-lying leg lifts and supine hamstring curls (see Appendix B). The supine hamstring curls required the athlete to hold a bridge position while flexing and extending her knees, sliding a pillowcase along the floor. They completed three sets of 10-15 repetitions of squats and lunges, followed by two sets of 10-15 repetitions of the leg lifts and hamstring curls. Ankle weights were used for the leg lifts and hamstring curls to gradually increase difficulty level. One athlete in the leg group could not do lunges without discomfort and therefore did step-ups as a replacement.

Arm Training Group

Exercises for the arm group consisted of chest press, bicep curls, shoulder press, and bench rows. They completed three sets of 10-15 repetitions of chest press and bicep curls based on the results of the 10RM testing, and two sets of 10-15 repetitions of shoulder press and bench rows. Because no 10RM testing was done with shoulder press and bench rows, the resistance for those exercises was introduced slowly and increased gradually based on the trainers' observation of the athlete's safety and ability. In a few athletes, an exercise required substitution because of discomfort. Three athletes were unable to do shoulder press without shoulder pain and so bench triceps extensions were done instead.

Testing Protocol

Each athlete attended a pre- and post-training test session lasting about one hour. A number of neuromuscular strength and power tests were performed, along with jump assessments. First, the athlete warmed up by walking on a treadmill at a brisk pace for five minutes. She then underwent

LESS testing to evaluate her jump landing mechanics. The LESS test consists of a list of 17 characteristics that may be observed during a jump landing. A lower LESS score indicates better landing mechanics not associated with ACL injury, with a score of greater than 6 implying “poor” technique (Padua et al. 2009). Intra-rater reliability of the LESS has been established in adult (Padua et al. 2004) and youth (Strickland et al. 2007) populations. Testing followed the protocol as previously described (Padua et al. 2009). The athlete jumped off a 30 cm high box to a horizontal distance of 50% of her height, landed on two feet, and immediately jumped straight up as high as she could before landing straight back down again. The task was videotaped by two video cameras, one capturing the sagittal plane and one the frontal plane. The athlete completed three jumps; if the athlete did not land in the designated area or the landing and jumping movement was not smooth and continuous, the athlete was asked to repeat the jump.

The girls then underwent standard handgrip testing with the use of a Jamar Dynamometer (Lafayette Instrument Company, Lafayette, IN). Three isometric trials were done, alternating between the right and left hands. Following that, the girls were asked to do a maximum push-up test. The tester counted the number of push-ups the athlete could do from her toes, and stopped the test when the athlete was unable to continue or until proper form could not be maintained.

Following the push-up test, peak power and movement velocity of the hip abductors, flexors and extensors, and knee flexors and extensors was measured with a Biodex System 3 Pro Dynamometer (Biodex Medical Systems, Shirley, NY). The testing protocol follows that reported previously (Parsons, unpublished data under review). These data were intended for a separate investigation into the relationship between neuromuscular power indices and jump landing kinematics. The Biodex testing is mentioned here to give the reader a complete picture of the testing protocol.

The final test was a maximum vertical jump test, using The University of Toronto Belt Jump (Sports Books Publisher, Toronto, Ontario, Canada). Three trials were done with the use of the arms and three trials were done without using the arms. The vertical jump data were collected and used as part of a Master's thesis project investigating whether strength training improves vertical jump height.

Data Analysis

The LESS scoring was done after all data for all participants was collected. The first landing of the jump sequence was given a LESS score by a blinded, independent assessor following the guidelines provided by the creators of the test (Padua et al. 2009). Scoring was done with videos arranged in random fashion.

The mean of the score of the three LESS jumps was used as the primary outcome to establish whether there was a change in performance after strength training. To gauge whether strength training had an effect on other indices of neuromuscular function, the mean of the three grip strength trials was calculated for each hand and compared pre- and post-training. The mean number of push-ups, as well as the percentage change in 10 RM scores were also calculated and used to describe changes with strength training in young female athletes.

Statistical Analysis

Independent t-tests were done on the participants' baseline characteristics to identify any initial differences between groups. For the primary outcome variable, IBM SPSS Statistics (Version 20, IBM Corporation, Somers, NY) was used to run an analysis of covariance (ANCOVA) to compare LESS score between the arm and leg training groups after 12 weeks of training, using baseline LESS score as a covariate. Significance level was set at $p \leq 0.05$. This type of analysis, with the inclusion of baseline measurement as a covariate, is the most powerful method of analyzing pre/post intervention studies with a continuous outcome (Tu and Gilthorpe 2011). Two-way repeated measures analyses of variance (RM ANOVA) were used with our secondary outcomes to assess strength differences in group means over time. A paired t-test was used in post-hoc analysis of a subset of participants with higher initial LESS scores to determine if landing patterns improved over time, regardless of group. Linear regression was then used to investigate the contributing factors to that change in performance, if present. An effect size index was also calculated to illustrate the magnitude of change in LESS score as a result of strength training.

RESULTS

Thirty-six girls completed the intervention and their pre- and post-training data were used in statistical analyses. Baseline descriptive characteristics of these 36 athletes can be found in Table 1. The mean attendance was 19.8 training sessions, or 82.5% (range = 15-24). During the course of the 12-week training program, four girls withdrew from the study (see Figure 1). The arm (n=17) and leg (n=19) training groups did not differ in any of the baseline characteristics except for the number of years participating in organized sport. The leg group had a mean of 7.6 years and the arm group, 6.1 years. Analysis was run using the number of participation years as a covariate alongside baseline LESS score; it did not change our results and so was not included in the final analysis or reported results.

The means, standard deviations and *p* values for LESS score, grip strength and push-ups for the groups at pre- and post-testing are presented in Table 2. Two athletes experienced injuries outside of the study that may have affected their performance on post-testing. One girl sprained her ankle 2-3 weeks beforehand, and one girl had a suspected wrist fracture and wore a cast at post-testing. Differences in post-training LESS scores between groups were analyzed with and without these girls; excluding them did not change the results, so we have included them in the final results. However, the athlete with the cast on her arm was unable to complete push-up or left grip strength testing at post-testing. One other girl only had time to complete LESS and vertical jump tests at post-testing due to a scheduling conflict.

Contrary to our hypothesis, there were no statistically significant differences between the arm and leg training groups in any of the neuromuscular function outcome measures, including LESS score. We found a strong and significant correlation between baseline LESS score and change in LESS score after the intervention (Figure 2), justifying the use of baseline LESS as a covariate. We performed a secondary analysis of the group as a whole to determine any differences pre- and post-intervention (Table 3). When including all 36 girls together, there was no significant difference in LESS score after the 12 week intervention. However, when excluding those who demonstrated a baseline LESS score of less than 6, we did find a significant difference. Linear regression analysis of that data showed that baseline LESS score and the number of sport participation hours during the study contributed significantly to the change score (35% and 15%, respectively). The number of push-ups and left grip strength also increased significantly in all athletes, regardless of group (Table 3). Strength gains, as estimated by 10 RM testing, were found in both groups. The leg training group increased squat strength by 78% and lunge strength by 64%. The arm training group increased 31% and 35% for chest press and biceps curl strength, respectively.

DISCUSSION

Strength training is a common component of ACL injury prevention programs (Barber-Westin et al. 2010; Barendrecht et al. 2011), however its individual contribution to improving movement patterns has not been explored in a young, athletic population. Resistance training is accepted as a safe activity for children, and is in fact now recommended as part of a balanced exercise program (Faigenbaum and Myer 2010). Considering that ACL injury rates increase substantially in the mid-teens, the identification of possible methods to decrease injury risk is required at an earlier age. Our results suggest that leg focused strength training does not lead to an improvement in movement patterns compared to an arm focused program within a young, active female population. Our findings agree with those of a recent study of predominantly adult men, which found that isolated whole-body resistance training did not result in a decreased LESS score (Distefano et al. 2013).

Interestingly, in an earlier study of adolescent athletes, the improvement in LESS score after an exercise intervention including plyometrics, flexibility and strength training depended on the participant's initial baseline LESS score (Distefano et al. 2009). Those with higher (worse) LESS scores to begin with experienced the greatest improvement in landing mechanics. A LESS change score of about -2.5 was found in those male and female athletes who displayed the highest baseline LESS score, compared to a mean change for all athletes of -0.7 (Distefano et al. 2009). Considering that our female athlete population possessed a high mean baseline LESS score and a relatively low baseline strength level when compared to adolescent or adult athletes (De Ste Croix 2012), we were optimistic that our hypothesis would be supported, as the girls had more room for improvement. However, that was not the case, as no differences between the groups were detected.

We decided to further investigate the role of baseline LESS score in our study by considering the groups together. Including all 36 girls, the change in LESS score from pre- to post-testing approached, but did not meet, statistical significance (p = 0.07) and demonstrated a relatively small effect size (d = 0.33) (Portney and Watkins 2009). However, in a secondary analysis where we excluded those individuals with a baseline LESS score of less than 6, we did indeed see a change in LESS score after training, regardless of group (p = 0.01; d = 0.60). Further analysis of that data showed that baseline LESS score and the number of participation hours contributed significantly to the change score (35% and 15%, respectively). Interestingly, change in stature or mass, or PMOS score were not significantly associated with LESS change score. Based on the design of our study (no inclusion of a group which continued with regular activities but did not undergo a training intervention) we cannot equivocally state that strength training caused the change in LESS score for the group of athletes with a higher baseline LESS score; however the results are worthy of note and of future exploration.

A small change in LESS score may be enough to move an athlete from one performance category to another. Padua (2009), based on analysis of over 2600 adult participants, classified performance on the LESS test as the following: excellent, ≤4; good, >4 to ≤5; moderate, >5 to ≤6; and poor, >6. With such a small difference between categories, a change of -0.8, such as that found in our study, may be clinically significant. However there is no information on what constitutes a clinically meaningful change in LESS score. The structure of the LESS itself may be problematic, as athletes' scores cluster toward the lower end of the 17 point scale. This presents the possibility of a ceiling effect and a concomitant difficulty in showing differences in performance in response to training. If an athlete already shows good landing technique at baseline, she is unlikely to improve significantly when retested.

Presently, there is conflicting evidence as to whether LESS score, either considered as a continuous or categorical variable, is in fact associated with ACL injury. One study found a significant association between LESS score and ACL injury risk in youth soccer players (DiStefano et al. 2009), while another failed to find any relationship (Smith et al. 2012). One key difference between these two studies is the age range of the athletes used. The soccer players ranged in age from 12-16, while the athletes involved in the other study were older (14-23 years of age). Younger individuals have lower strength levels (De Ste Croix 2012), are undergoing rapid growth and development, and overall have had less time to practice novel neuromuscular tasks. As a result, older children and adults have been found to react to new tasks with higher quality movements (Thomas 2000). This suggests that the LESS test may be more sensitive to measuring landing mechanics in a population that exhibits a larger variability in performance and/or higher scores; that is, a younger, less experienced, less skilled, and female (Beutler et al. 2009) population.

Contrary to our primary hypothesis, there was no difference between the training groups in terms of LESS score after a 12 week strength program. It may be that core stability strength plays a role in improving movement patterns. Indeed, previous evidence links trunk muscle activation to movements in the lower extremities (Willson et al. 2005). Previous studies that included core strengthening as a component of the program have found changes to jump landing mechanics after training. Chappell and Limpisvasti (2008) found that the degree of knee flexion during landing increased in a group of college aged female athletes after a 6 week training program. Myer et al. (2005) found similar results, also after a 6 week program, in high school aged girls. Because other types of training were involved (e.g. plyometrics) in these studies, it is impossible to determine the influence of the core strength exercises on their own. We found one recent study (Pfile et al. 2013) that attempted to elucidate the individual contributions of core and plyometric training. Those authors found that knee flexion during landing actually *decreased* in a group of high school female athletes in response to a stand-alone core strengthening intervention. However, the length of that intervention was quite short (4 weeks) and the size of the groups was perhaps too small (6-9 athletes) for sufficient power.

Both the arm and leg groups in our study were required to engage the use of the abdominal and back muscles to stabilize their bodies in the proper position during exercise. Although no specific core strengthening exercises were given to either group, a training stimulus for those muscle groups may have existed just due to the nature of the prescribed exercises. The official position stand of the Canadian Society for Exercise Physiology recommends ground-based free-weight resistance training as the primary method of improving core stability (Behm et al. 2010). Both the arm and leg training group were exposed to these types of exercises which may have confounded our ability to see group differences in LESS score after training. No pre- or post-intervention tests of core strength were done, which precluded the assessment of core strength as an influence on LESS score.

Unfortunately, due to device failure, we were unable to collect pre- and post-intervention Biodex strength and power data on every participant. As a proxy, we reported the improvement in 10RM test results for both groups, recognizing that these tests were not initially undertaken with the goal of using the results as an outcome measure. The results should therefore be interpreted cautiously. However, our 10RM results are in accordance with existing literature that reports a 30% increase in strength is generally expected from a resistance training program of less than 20 weeks duration (Faigenbaum et al. 2009). Subjectively during the 12 week program, we observed great improvements in the athletes in terms of their ability to perform the exercise movements properly, as well as increase the resistance used. Considering the age of the athletes involved, the relatively large response to the exercise program was probably due to neurological adaptations rather than hypertrophy of the muscle fibres themselves (Behm et al. 2008).

Limitations to our study must be considered. Although we took extensive baseline measurements, we did not repeat PMOS testing at post-test. The change in the athletes' pubertal status over the 12 week program may have provided additional explanation for a change in performance levels. As well, the PMOS relies heavily on self-report of the athlete and the parent and so may not be the most accurate method of measuring pubertal status. The athletes/parents especially had difficulty reporting the existence of a growth spurt. The PMOS questions about darker hair development were also not relevant to athletes with a darker skin tone. The lack of strength and power data for the group pre- and post-intervention was regrettable. However these outcome measures were not directly related to our primary question and did not prevent the investigation of the primary outcome variable, change in LESS score, with neuromuscular training.

It should also be noted that previous work has shown that the validity and reliability of the LESS test is item specific (Onate et al. 2010). Agreement of items that measure knee valgus position show moderate values (68-74%) when comparing the LESS test with gold-standard 3-D motion analysis. However, knee flexion at first contact during jump landing shows very poor agreement (21%) between the LESS and 3-D methods. This knowledge should be considered in conjunction with the practicality and ease of clinical use when considering the use of the LESS test as the main outcome measure for landing ability.

Future work on improving landing mechanics should continue to involve younger populations of athletes, as well as consider baseline LESS score as a contributing factor to change scores. The effect of a whole-body strength training program in a young, female population needs to be investigated, with the inclusion of a control group. Because mechanisms that lead to ACL injury involve higher velocity movements, it would also be beneficial to investigate the effect of a power training program (lower resistance, higher velocity) versus a strength training program (higher resistance, lower velocity), on the landing mechanics of young athletes.

CONCLUSIONS

This study is the first randomized controlled trial to investigate the effect of strength training on landing mechanics in young female athletes. With the use of blinded assessors and a control group who received the same contact and attention as the intervention group, we found that lower body strength training did not lead to a change in LESS score compared to upper body strength training. Secondary analyses suggest that strength training in general may contribute to an improvement in landing mechanics in a sub-set with poorer baseline scores. Future investigations should consider baseline LESS score when evaluating interventions aimed at improving movement patterns in young athletes.

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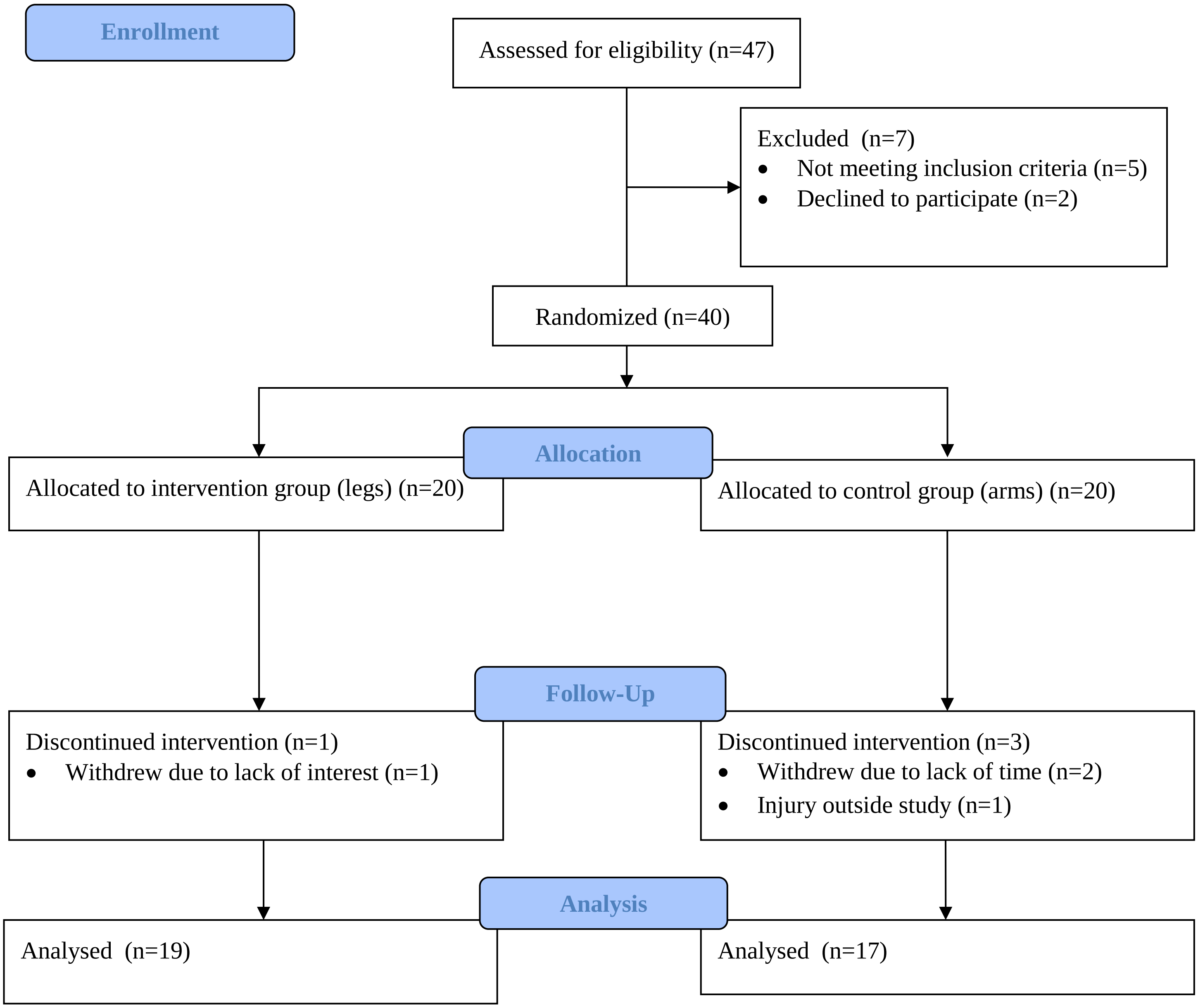

FIGURE 1. Participant recruitment flow diagram

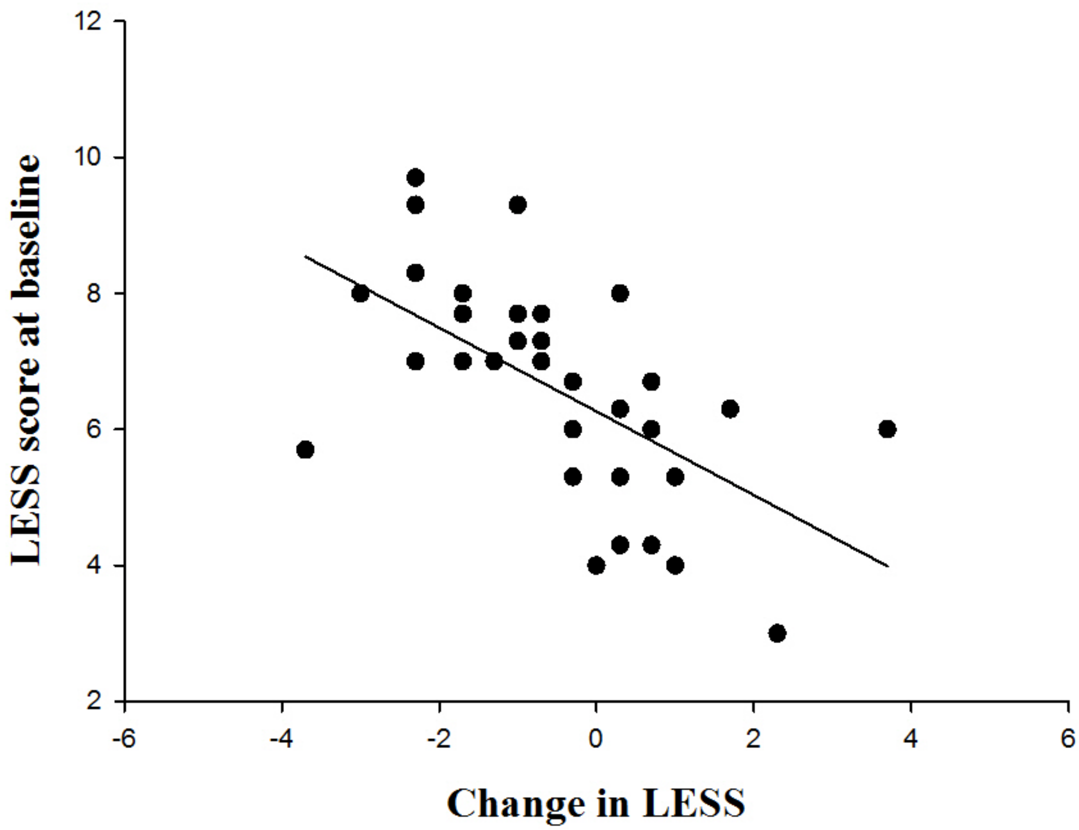

FIGURE 2. Correlation between baseline LESS score and change in LESS score for the group as a whole. A negative change in LESS denotes an improvement in landing mechanics. r = -0.60; *p* = 0.0001.

TABLE 1. Participant characteristics compared between training groups.

Characteristic	Group	Mean (SD)
Age at pre-test (years)	Legs	12.5 (1.4)
	Arms	12.0 (1.3)
	Combined	12.3 (1.4)
Height at pre-test (cm)	Legs	156.9 (11.6)
	Arms	156.4 (10.6)
	Combined	156.7 (11.0)
Mass at pre-test (kg)	Legs	50.8 (15.7)
	Arms	51.5 (12.2)
	Combined	51.1 (14.0)
PMOS at pre-test	Legs	5.2 (2.2)
	Arms	5.4 (2.2)
	Combined	5.3 (2.2)
LESS score at pre-test	Legs	6.8 (1.5)
	Arms	6.4 (1.6)
	Combined	6.6 (1.6)
Participation in organized sport† (years)	Legs	7.6 (2.0)
	Arms	6.1 (2.1)
	Combined	6.9 (2.2)
Physical activity during study period (self-reported hours)	Legs	3228.4 (2134.6)
	Arms	2784.7 (1525.6)
	Combined	3018.9 (1859.5)
Number of workouts attended	Legs	19.7 (2.1)
	Arms	19.8 (2.7)
	Combined	19.8 (2.4)

PMOS, Pubertal Maturation Observational Status. † denotes significant difference between leg and arm training groups.

TABLE 2. Means (standard deviations) for each group for all outcome variables before and after the 12 week exercise intervention.

	Leg Group	**Arm Group**	***p* value**
Pre-training measures			
LESS	6.8 (1.5)	6.4 (1.6)	0.38
Right grip strength (kg)	23.2 (6.9)	23.1 (6.2)	0.95
Left grip strength (kg)	21.1 (6.1)	21.0 (6.6)	0.95
Push-ups	8.4 (6.7)	6.3 (4.6)	0.28
Post-training measures			
LESS (unadjusted)†	6.1 (1.1)	6.0 (1.7)	0.88
LESS (adjusted)‡	6.0 (0.3)	6.1 (0.3)	0.85
Right grip strength (kg)	23.9 (6.5)	23.7 (5.9)	0.95
Left grip strength (kg)	22.2 (6.1)	21.6 (6.6)	0.81
Push-ups	11.6 (7.0)	11.5 (6.2)	0.96

LESS, Landing Error Scoring System. †Denotes mean LESS scores without using baseline LESS score as a covariate. ‡Denotes mean (standard error) LESS scores using baseline LESS score as a covariate.

TABLE 3. Means (standard deviations) for both groups combined for all outcome variables before and after the 12 week exercise intervention.

Outcome Measure	Pre-training	Post-training	*p* value
LESS	6.6 (1.6)	6.1 (1.4)	0.07
LESS (only including participants with baseline LESS >6)†	7.4 (1.0)	6.6 (1.6)	0.01
Right grip strength (kg)	23.2 (6.5)	23.8 (6.2)	0.14
Left grip strength (kg)†	21.1 (6.3)	21.9 (6.3)	0.02
Push-ups†	7.6 (5.9)	11.6 (6.5)	0.000

LESS, Landing Error Scoring System. **†**Post-training values different than pre-training values, $p \leq 0.05$.

CHAPTER 6: DISCUSSION

This thesis includes manuscripts which explore neuromuscular power indices as possible contributors to ACL injury mechanisms, their reliable measurement, as well as the effect of an exercise training prevention program on improving movement patterns linked to injury. The discussion will include a rational for studying these topics in a young athletic population; summarize the findings, implications and limitations of each of the four studies; and suggest areas for future work.

Section 1: Rationale

An increased rate of ACL injuries in female athletes becomes apparent in the mid-teen years (Shea et al. 2004), and can be 3-6 times higher than in male athletes (Arendt, Agel, and Dick 1999; Prodromos et al. 2007). Therefore it is imperative to identify, at the earliest possible age, the characteristics that put a female athlete at increased risk of injury. Once risk factors are known, the effectiveness of implementing prevention programs at that younger age must be elucidated. Only by intervening with female athletes at an early age can we hope to induce the neuromuscular strength growth spurt that is naturally experienced by boys (De Ste Croix 2007).

Many factors have been suggested as playing a role in the disparity between male and female injury rates, including anatomical and hormonal differences (Shultz et al. 2012). As these elements cannot be easily changed or influenced, ACL injury prevention research focuses on the neuromuscular factors that contribute to injury, and how they can be improved with training. Much research has centred around the premise that strength differences between male and female athletes lead to the poor landing mechanics seen in women; however the results are inconclusive (Barber-Westin et al. 2005; Claiborne et al. 2006). There is indication from other areas of research that neuromuscular power, rather than strength, may be more closely linked to functional movement (Bean et al. 2003). Given that athletic maneuvers require a combination of force and velocity, investigation into the relationship between power and ACL injury mechanisms is warranted. The current work is the first to measure and explore neuromuscular power as a possible risk factor for ACL injury mechanisms in young athletes.

Many prevention programs have endeavoured to decrease injury risk (Chappell and Limpisvasti 2008; Lim et al. 2009). A continuing challenge is to parse out the components of these programs to determine those that have the most influence on injury prevention. Studies which compare different types of training (e.g. balance training vs. strength training) are rare, and do not involve athletes younger than 14 years of age (Myer et al. 2006; Pfile et al. 2013; Distefano et al. 2013). Strength training is a safe activity for children, and is recommended to improve health, bone strength and body composition (Behm et al. 2008). It is often included as one component of an integrated ACL injury prevention program. However its individual effect on injury mechanisms and function had not been explored in a young, female athlete population before our randomized controlled trial was undertaken.

Section 2: Results and Implications

The first study completed as part of this body of work provided data for the manuscripts in Chapters 2, 3 and 4. The study involved a large group of boys and girls who were 10-14 years of age. The reliability results, discussed in Chapters 2 and 3, suggest that peak and average torque and power can only be reliably measured in some lower extremity muscle groups using a Biodex isokinetic dynamometer. Hip flexion and knee extension movements showed acceptable absolute reliability ($CV_{TE} \leq 15\%$) and therefore can be used in a one-time assessment of neuromuscular ability in a group of young athletes. All joint movement tests can be used to determine a change in torque and power performance in a group over time only if the degree of expected variability is taken into consideration. The range of variance apparent in the results means that alternate methods of measuring strength and power should perhaps be used if the goal is to assess the performance of an individual athlete.

Of all the outcome measures from the reliability study, peak velocity exhibited the most consistent results. All joint movements possessed adequate reliability ($CV_{TE} \leq 15\%$) for movement velocity to be used as a stand-alone indirect test of neuromuscular power in a group of young athletes. Our findings also suggest that knee and hip flexion and extension movements can be used at the individual athlete level for a one-time assessment of function. As with the strength and direct power measures, any of the movement velocity results can be used on a test-retest basis if the expected variability is considered before deciding if a significant change in performance has occurred.

Measuring hip muscle function in a standing position has been done previously in relation to ACL injury mechanics (Brent et al. 2013; Myer et al. 2008), but not with a population as young as 10 years of age. In addition, comprehensive reliability statistics have not been provided for both sagittal and frontal plane hip movements in previous studies; only intraclass correlation coefficient (ICC) values were reported. ICC values offer an indication of how well a test can distinguish between individuals on multiple testing occasions. However, absolute reliability analyses such as coefficients of variation of the typical error (CV_{TE}) are necessary to determine the conformity of a test result from one test session to another (Portney and Watkins 2009). Our reliability study provides a detailed description of the testing protocol, directed at researchers and clinicians, to enable accurate replication. It also offers the first all-inclusive report of the expected variability when testing the strength and power of the knee and hip joints of a young athlete population using a Biodex dynamometer. These results can be used to determine whether an actual change in performance has occurred in response to an intervention, and establishes a reliable starting point for exploration into the relationships between neuromuscular function and ACL injury mechanics.

The results of the reliability analyses led to the formation of the research question discussed in Chapter 4. No previous research has investigated the difference in neuromuscular power levels between boys and girls aged 10 to 14 years. Since power may be associated with function (Bean et al. 2003), and boys seem to function in a manner that offers protection from ACL injury during athletic performance (Ireland 2002), it was hypothesized that boys would possess greater power than girls. However, our results indicate that male and female athletes at this young age do not differ in measures of direct power (Watts) or indirect power (movement velocity; °/sec). We know that adult men and women exhibit neuromuscular power differences (Doldo 2004; Petrella et al. 2005; Yamauchi et al. 2010). The divergence, based on our results, must occur after 14 years of age. However we must also consider that neuromuscular power as measured by an isokinetic dynamometer may not be able to identify sex differences during maturation. Perhaps other measures, such as vertical jump or broad jump tests, would be more suitable in isolating sex differences.

Only the reliable joint movements and measures, as discussed in Chapters 2 and 3, were used in the sex differences analyses. As a result, we were unable to include direct measures of hip extension, abduction or knee flexion power in the investigation. Considering that these muscle groups (gluteals and hamstrings) may contribute to the prevention of unwanted movement and forces about the knee (Wild, Steele, and Munro 2013; Hollman et al. 2013), it is regrettable that we were not able to include them.

The other study undertaken as part of this thesis is the first randomized controlled trial (RCT) to investigate the effect of a leg based strength training program on jump landing mechanics in young female athletes. Originally it was our goal to include a power training group as well as a strength training group for comparison with a control group. However a number of issues interfered with this plan. First, the resources to support the larger sample size required did not exist in the confines of the PhD program. As well, it is recommended that power training be introduced after a solid base of muscular strength is established (Kraemer and Fleck 2007). This would have expanded the duration of the study, again exceeding resources. It would have also made recruitment and retention of participants more difficult, requiring them to volunteer for a longer period of time.

Within the ACL injury prevention literature, exercise interventions that include strength training have only occasionally included female athletes younger than 14 years of age (Barendrecht et al. 2011; Distefano et al. 2009; Grandstrand et al. 2006; Noyes et al. 2005; Walden et al. 2012), even though this may be an optimal time to improve function. The results of our RCT study suggest that female athletes aged 10-14 who participate in a leg focused strength training program do not significantly improve jump landing mechanics compared to those in an arm focused program. However exploratory analyses suggest that individuals with the highest baseline LESS scores may improve their landing patterns regardless of training group. Due to the design of the study, however, we cannot precisely conclude that the training led to the improvement in landing mechanics. It may be that growth and development, activities outside of the study or other factors we did not measure contributed to the decreased LESS score.

Our RCT results suggest that restricting strength training to the lower body provides no benefit to altering ACL injury mechanisms over training of the upper body only. Our secondary analyses also suggest that strength training may have the most effect on those individuals with the worst baseline movement patterns. Future research should investigate whether prevention programs are more effective if tailored specifically for an athlete's baseline functional ability. Given that the athletes increased in strength by a significant margin (10RM increase, 31-78%), the use of resistance training programs with young female athletes should be encouraged and investigated for their beneficial effects on injury prevention and general health.

Section 3: Limitations and Future Directions

Limitations to the first study, which provided data for three of the four papers included in this thesis, mainly centred on technical and procedural difficulties with the Biodex dynamometer. The range of motion that we chose for hip abduction/adduction and knee flexion/extension movements was too small to allow the dynamometer to reach 180°/sec during the isokinetic contractions. We therefore could not include those data in our analyses, even though there may be more functional overlap between ACL injury mechanisms that occur during sport movements and faster test velocities. We also chose a linked protocol for the testing procedure to save time in setting up the large number of tests done with each participant. Using a linked protocol does not allow automatic gravity correction (Biodex Medical Systems 2007). As a result, the Biodex data required a large amount of post-test cleaning and filtering. Unfortunately, using this method, we were unable to remove the large amount of noise in the isokinetic hip extension data, rendering it unusable.

An issue with testing hip movements in standing is the challenge of ensuring adequate stabilization. Securing the athlete to the hip pad with a trunk strap may not give sufficient stabilization to ensure that isolated joint movement is being tested. Clear instructions need to be given to each athlete to move the test joint in isolation, and if accessory movement occurs, the repetition should be repeated.

In order to gather all the desired data, we chose a lengthy testing protocol lasting upwards of two hours. This may have affected the results due to fatigue of the athletes, as well as a loss of motivation and ability to focus their attention on each individual test. Future studies should report the absolute and relative reliability of these test movements when done as short, focused assessments. As well, there may be value in assessing the reliability of these tests over more than two testing occasions. Although we did not find a large learning effect between the first and second testing sessions, previous research has recommended a familiarization period when assessing strength in children (De Ste Croix 2012). Perhaps these testing protocols would exhibit increased reliability if the number of exposures was increased.

There are limitations to consider within our investigation of sex differences in neuromuscular power. In order to assign a pubertal level, we relied on the PMOS. This tool is largely a self-report of secondary sex characteristics provided by the athlete and a parent. Although most of the items were easily understood, there was often uncertainty about whether a growth spurt had occurred or not. The questions about developing darker body hair were also not applicable to our participants with darker skin tone. Future studies should consider using Tanner staging (Marshall and Tanner 1969) or peak height velocity (Beunen and Malina 1988) instead. An accurate measure of pubertal status would ensure its true influence on neuromuscular function is revealed.

We also had to limit our analyses to the outcome variables that were found to be reliable. We were unable to include knee flexion, hip extension or hip abduction measures of power and movement velocity as a result. Unfortunately, these may be the muscle groups of most interest in terms of ACL injury prevention. The knee flexors, or hamstrings, counteract anterior movement of the tibia on the femur, which is a mechanism of injury for the ligament (Ireland 2002). A recent study also found a correlation between decreased hamstring strength and increased knee valgus when landing from a jump (Wild, Steele, and Munro 2013). The hip extensors and abductors are important for stability and control of the trunk, pelvis and hip (Myer et al. 2008); proximal control of the lower limb has been identified as an important component of ACL injury prevention (Ireland 2002). Recent evidence supports this assertion, with weak hip extensors and abductors showing association with increased valgus positioning of the knee during a jump landing (Hollman et al. 2013). It is our hope that future work will identify reliable means of measuring power and movement velocity in these muscle groups so that relationships to ACL injury mechanisms can be explored.

The randomized controlled trial involved 10-14 year old girls who were involved in organized sport; the findings of the study cannot be generalized to other populations. Another limitation is that without the inclusion of a third group who did not receive any strength training, we cannot equivocally state that strength training resulted in an improvement in jump landing mechanics in those athletes with a high baseline LESS score. Other factors may have led to this finding. As discussed previously, there are issues associated with the use of the PMOS to determine pubertal status. The girls in the RCT also used the PMOS and so the same cautions apply. Because of the location and nature of the training room, some of the girls were exposed to the exercises done by the other training group. However the girls received no instruction or description of the other group's exercises. We have no way of knowing for certain, but we are fairly confident that the girls were not going home and doing the other group's exercises.

A final limitation is the lack of control over the amount of core stability work that was done within the study. It may be that the end result of the strength training programs was to improve core strength in both groups. This may have confounded our ability to evaluate the true nature of group differences. Future work should include a pre- and post-intervention measure of core strength to determine its contribution to movement patterns. A whole-body strength training program should also be compared to a core stability program to see if the effects on ACL injury mechanisms are different. It could be that both these training methods are influencing proximal limb control, but in a different manner.

To summarize, this thesis includes the first comprehensive set of reliability guidelines to use when measuring strength, power and movement velocity in young girls and boys on a Biodex dynamometer. It also begins the task of evaluating whether relationships exist between indices of neuromuscular power and ACL injury mechanisms. The work concludes with the first randomized controlled trial to examine the effect of strength training on the jump landing mechanics of young female athletes. The body of work as a whole contributes to the existing ACL injury literature; it also establishes new avenues for investigation that have implications for injury prevention in young athletes.

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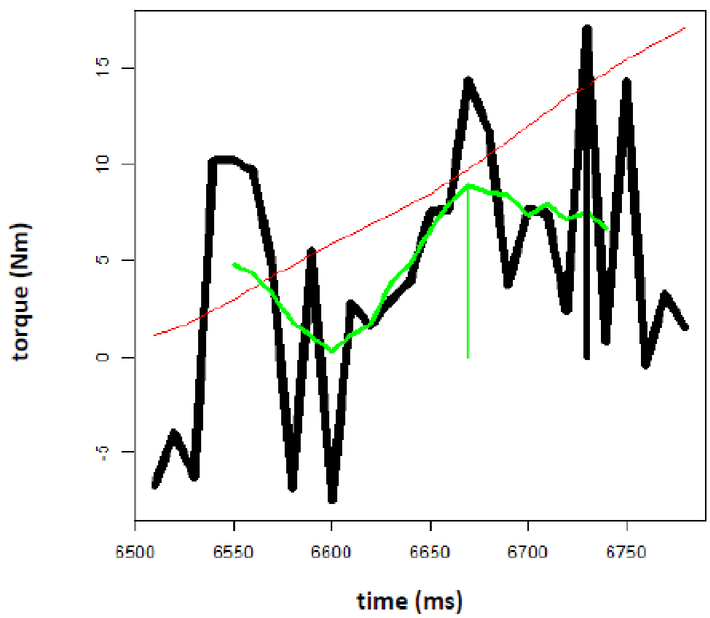
APPENDIX A: Representative isotonic hip extension contraction



Black line, raw torque curve; green line, attempt at filtering the torque curve; red line, velocity

APPENDIX B: Supine hamstring curls