QUANTIFICATION OF LOWER EXTREMITY DYNAMIC CAPABILITY: IMPLICATIONS FOR ANTERIOR CRUCIATE LIGAMENT INJURY AND CHANGE OF DIRECTION ABILITY

by

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DEDICATION

To my family and my wife…

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ABSTRACT

Anterior cruciate ligament (ACL) tears are serious injuries that occur at a higher rate in female athletes when compared to male athletes. Despite considerable research investigating this complex sports medicine problem, the primary factor(s) that underlie the sex disparity in ACL injury remains unknown. Recent literature suggests that diminished lower extremity control may increase the risk of ACL injury in females. The primary objective of this dissertation was to develop a method designed to quantify the capability of the lower limb to dynamically interact with the ground (i.e., the lower extremity dexterity test, or LED-test), and to evaluate whether this method is reliable and informative of lower extremity function in the context of ACL injury risk and change of direction ability. In Chapter III, the LED-test is described, test-retest reliability was assessed, and the extent to which performance was associated with lower limb strength and anthropometry was examined. Test-retest reliability was excellent (ICC = 0.94) and LED-test performance was found to be independent of strength and anthropometry suggesting that the test was capable of quantifying a unique construct. The purpose of Chapter IV was to compare LED-test performance between female and male soccer athletes. Lower extremity biomechanics during a single limb drop jump also were examined. Results revealed that the female athletes exhibited reduced lower extremity dexterity as assessed by the LED-test when compared to the male athletes. Females also were found to land using a movement strategy that has been implicated as increasing the risk of ACL injury (i.e. increased limb stiffness). Our findings suggest that the movement behavior exhibited by the female athletes may represent a heightened feedforward control strategy to compensate for reduced lower extremity dexterity. The purpose of Chapter V was to determine the extent to which LED-test performance (as opposed to lower limb strength and power) was associated with change of direction ability (i.e. agility) in high school soccer athletes. Results revealed that lower extremity dexterity was highly correlated with agility in both males and females, whereas lower limb strength and power were not correlated with agility. Dexterity was the primary predictor of agility performance, explaining almost 50% of the variance in agility after controlling for sex. Overall, the findings of this dissertation indicate that the LED-test measures a unique construct reflective of dynamic lower extremity control. In addition, data from this dissertation suggest that diminished lower extremity dexterity as quantified by the LED-test may influence lower extremity movement patterns considered to place female athletes at risk for ACL injury. Moreover, the results provide evidence that the LED-test quantifies an experimental construct that reveals a dimension of dynamic function that is informative of change of direction ability. As such, impaired lower extremity dexterity may not only contribute to limb mechanics that increase lower extremity injury risk, but reduced dexterity also may impact sport performance by reducing the ability of athletes to change direction quickly.

CHAPTER I

OVERVIEW

Anterior cruciate ligament (ACL) tears are serious injuries that occur at a higher rate in female athletes when compared to male athletes.[2,12,48,179] The higher injury rate in females is believed to result from performing sport maneuvers with inadequate lower limb control. Traditionally, reduced limb control has been inferred using kinematic and kinetic measures. While these measurements have been used to describe a movement behavior considered to increase the risk of ACL injury,[48,56,156] the underlying reason(s) for the higher injury rates and altered movement strategy remains unknown.

The capability of the lower extremity to dynamically regulate the magnitude and direction of foot-ground interactions (i.e. lower extremity dexterity) has been suggested to contribute to higher injury rates. Lower extremity dexterity is relevant as injuries occur during rapid deceleration and change of direction maneuvers[48,71] which require dynamic interactions among muscles to change and/or redirect body momentum and stabilize joints. As such, reduced dexterity could underlie, in part, the at-risk lower extremity movement behavior and compromise the ability to change direction rapidly. The lack of an objective measure to quantify lower limb dexterity is a barrier preventing the study of this sensorimotor ability.

Recently, a test method to quantify hand dexterity was developed that is reliable and valid in children and older adults.[164,169] Because this test method has been informative for hand function and dynamic foot-ground interactions are similar in principle to dexterous manipulation, it is conceivable that adapting this paradigm for the lower extremity also will be informative for lower extremity function. Therefore, the primary objective of this dissertation was to develop a test method designed to quantify lower extremity dexterity (LED-test), and evaluate whether dexterity as assessed by this method is potentially informative of lower extremity function during sport maneuvers in athletes. To accomplish this objective, three studies with the following specific aims were completed.

Specific Aim 1:

Develop a test method designed to quantify lower extremity dexterity and evaluate reliability and the extent to which LED-test performance is independent of strength and anthropometry (Chapter III).

Specific Aim 2:

Compare lower extremity dexterity between male and female soccer athletes. A secondary aim was to compare landing biomechanics during a single limb drop jump between female and male soccer athletes (Chapter IV).

Specific Aim 3:

Determine the extent to which LED-test performance (as opposed to muscle strength and power) is associated with agility. A secondary aim was to compare agility between male and female soccer athletes (Chapter V).

CHAPTER II

BACKGROUND AND SIGNIFICANCE

I. Statement of the problem

Tears of the anterior cruciate ligament (ACL) are one of the most common knee injuries in athletes, especially among soccer and basketball players.[2] It has been estimated that 250,000 individuals tear their ACL annually in the US with the majority being athletes between the ages of 15 and 20.[48] While both male and female athletes sustain ACL injuries, it has been clearly established that ACL injury rates in females are 2 to 6 times higher than males participating in the same sport.[2,12,48,179]

Tearing the ACL is a serious injury that has significant implications concerning short-term and long-term quality of life. These injuries require surgery and physical activity limitations for 4-8 months. Despite surgical reconstruction and intensive rehabilitation, a significant proportion of athletes do not return to the same level of play or stop participating entirely due to symptoms related to their ACL injury.[94,158] For example, 78% of 398 female soccer athletes sustaining ACL tears in Sweden stopped playing due to knee symptoms within 2-7 years of the injury.[158] In addition, radiographic evidence of knee osteoarthritis has been observed as early as 7 years after injury[79] and up to 50% of male and female soccer athletes sustaining ACL injuries have been reported to exhibit signs and symptoms of osteoarthritis within 12 to 14 years.[84,170] These findings have significant implications for long term quality of life for injured adolescent athletes, as many will display signs and symptoms of knee osteoarthritis in their thirties.

As a result, many scientists around the world have dedicated their career to this complex sports medicine problem. It may be surprising that despite > 11,000 publications on the anterior cruciate ligament (using keyword anterior cruciate ligament in PubMed on March 27, 2012), the incidence of ACL injuries has not decreased over the last 15 years.[2] The unfortunate reality is that much remains unknown regarding the primary factors contributing to this injury. As such, the prevalence of ACL injuries will likely increase given that female participation in sports continues to grow.[33,118] Identifying and understanding factors that contribute to ACL injuries is essential to reverse this trend.[5] The principle goal of this dissertation is to advance the understanding of ACL injury by evaluating the potential influence of lower extremity dexterity as a novel theoretical construct that could underlie injury risk.

II. Current understanding of ACL injury

Epidemiological surveillance and video analysis studies have demonstrated that ACL injuries most often occur during a sudden deceleration and change of direction maneuver (e.g., cutting and landing) without physical contact with an opponent.[2,11,12,58,71,122] Sports such as basketball, soccer, and gymnastics require rapid decelerations and as such have similar lower extremity injury rates.[2,12,93] Rupture of the ACL has been estimated from video analysis to occur within 20-105 ms after foot contact with the ground.[71] The joint kinematics at the time of injury have been described as a knee flexion angle close to extension (i.e. less than 30 degrees) often with a knee valgus collapse, tibial rotation, and less than 15 degrees of plantarflexion.[11,71,122]

Although definitive inferences from video analysis are limited by the frame rate and quality of the videos, characteristics of the injury scenario and movement patterns identified by video analysis at the time of injury has directed the focus of biomechanical research. More specifically, the primary focus of biomechanical research has been to identify sex differences in lower extremity mechanics that may increase ACL loading.

Sex differences in kinematics, kinetics, and muscle activation

Sagittal plane kinematics and kinetics

A common theme observed in females when compared to males is a tendency to contact the ground with a more upright and extended limb posture when performing a cutting or landing maneuver. For example, females land from a stop-jump maneuver with less hip and knee flexion when compared to males.[18,182,183] Similar findings have been observed during cutting[87,101,132] and landing from a raised platform on to a single[75,148] or both limbs.[9,25,145] It should be noted that less hip and knee flexion is not a universal finding in biomechanical studies. Some studies have found similar hip and knee flexion angles among males and females during a forward hop on one leg while catching a ball[21] and landing on one limb following a maximal vertical jump.[163] Therefore, the differences in kinematics may be task and/or context dependent. Nonetheless, landing with less flexion is considered a risk factor as ACL strain is greatest at low flexion angles.[10,17,89,184] This is because the patella tendon-tibia shaft angle is greater at smaller knee flexion angles, which in conjunction with a given quadriceps muscle force results in higher anterior shear forces and thus ACL strain when compared to larger knee flexion angles.[121,184] Additionally, the hamstrings capability to resist anterior tibial translation is compromised at lower knee flexion angles due to its more parallel orientation relative to the tibial longitudinal axis.[3,90] Cadaveric,[89,171,174] modeling,[80,103] and in-vivo studies[10,17,34,35,52] support the contention that greater ACL loading occurs at low knee flexion angles. As a result, injury prevention programs have emphasized landing with greater hip and knee flexion angles.[3,115,157]

In addition to sagittal plane kinematics, differences in sagittal plane kinetics also have been observed in females compared to males when performing landing maneuvers. When landing from a jump, the total body center of mass is decelerated by the coordinated eccentric actions of the ankle, knee, and hip. Yu and colleagues[183] reported that females performed a stop jump task with less peak knee flexion and greater ground reaction forces and knee extensor moments when compared to males. The more favorable male kinetic pattern was attributed to greater hip and knee flexion angular velocity at initial contact, which was associated with less posterior and vertical ground reaction forces, respectively ($r > -0.60$). The lower ground reaction forces were associated with decreased peak knee extensor net joint moments and anterior tibial shear forces, whereas no relationship was observed between knee and hip flexion angle and kinetics. These findings suggest that, in addition to the mechanically vulnerable position of landing with lower flexion angles, females may increase their risk of ACL injury by generating greater reaction forces from greater early deceleration of momentum.

There is evidence suggesting that a heightened feedforward motor control strategy may underlie the earlier deceleration of momentum in females based on the relative distribution of energy absorption across joints.[25,148] For example, Decker and colleagues[25] found that females absorbed the most energy at the knee and ankle during double limb landing, whereas males absorbed most energy at the knee and hip. Similarly, Schmitz et al. 2007[148] reported that females absorbed a greater proportion of the energy at the ankle during a single limb landing task. More recently, Sigward et al. 2011[156] has shown that female soccer athletes exhibit a more distal energy absorption strategy compared to their male counterparts across all stages of maturation (i.e. pre-pubertal, pubertal, post-pubertal, young adult). Therefore, the current evidence suggests that females preferentially decrease momentum by absorbing greater relative energy with the ankle and knee joints, which may reflect a planned or default strategy that is facilitated by the tendency to position the limb in more extension at initial contact. Decker et al. 2003[25] suggested that the greater energy absorption at the ankle may be a necessary strategy to dissipate ground reaction forces from landing more upright due to less hip contribution. Schmitz and colleagues[148] theorized that females utilized less relative hip energy absorption in single limb landing in an effort to control the trunk. Other authors have proposed that the landing pattern is a compensation for hip weakness or impaired hip and/or trunk control.[58,116,133,135]

An alternative explanation may be considered from a motor control framework. Assuming that energy absorption or joint work patterns may reflect a global control strategy,[173] females may exhibit a more distal energy absorption strategy due to an increased reliance on feedforward control (i.e. default stiffening). Although the cause of this tendency remains unknown, a movement strategy that absorbs energy at the ankle and knee may place females at greater risk of injury given that gastrocnemius, a primary ankle plantar flexor, contributes to ACL loading.[34] In contrast, a more balanced kinetic pattern using less relative ankle and more hip energy absorption may decrease ACL loading.[133] However, additional studies investigating this phenomenon are warranted as only two studies using recreational athletes have compared the overall energy absorption pattern between males and females.

Frontal plane kinematics and kinetics

Another movement pattern observed frequently in females is increased motion and net joint moments in the frontal plane during sport specific tasks. Numerous studies have reported that females exhibit greater knee valgus (i.e. abduction) motion and moments during cutting[87,101,102,155] and landing.[36,37,43,55,56,182] In the only prospective study linking biomechanical variables to ACL injury risk, Hewett et al. 2005[56] studied 205 adolescent female athletes for 2 sports seasons after they completed a drop-jump biomechanical assessment. Findings revealed that the nine athletes that sustained an ACL tear had a 20% higher ground reaction force, a 16% shorter stance time, and greater knee valgus motion (8 degrees) and moments (2.5 times) than those who did not tear their ACL. A logistic regression analysis indicated that the knee valgus moment had 73% specificity and 78% sensitivity to predict injury status.[56] In vitro[89,175] and computer simulation studies[19,52,103,152,171] have provided support that increased valgus observed during landing and cutting likely result in increased ACL loading. Evidence suggests that greater frontal plane motion and moments in female soccer athletes could arise from increased sagittal plane energy absorption at the ankle and knee as opposed to a hip and knee dominant strategy.[133] In addition, hip adduction and internal rotation contribute to knee valgus and as such are considered risk factors for ACL injury.[48,101,132]

Muscle activation

Muscles crossing the knee joint have both the capacity to stress and support the anterior cruciate ligament. In vivo studies have demonstrated that moderate quadriceps activation during open chain knee extension increases ACL strain.[10] A similar finding of increased in vivo ACL strain was observed during isolated gastrocnemius activation at less than 30 degrees of knee flexion.[34] Co-activation of the quadriceps and gastrocnemius resulted in greater strain when compared to their individual activations.[34] In contrast, hamstring contraction concurrent with quadriceps and/or gastrocnemius activation lowers ACL strain[10,34] due to the posterior shear force provided by the hamstrings.[90] The hamstring muscles' posterior shear vector increases progressively with greater knee flexion (e.g., maximal effectiveness around 60 degrees).[90]

The studies noted above have revealed important potential causal relations regarding muscular stabilization strategies and ACL loading. Such knowledge is important for understanding potential injury mechanisms. Electromyography (EMG) is often used to infer muscular control strategies that may function to provide dynamic stability during a given task. However, the inherent limitation of this approach is the fact that EMG alone does not provide direct insight regarding the effectiveness (i.e. force output) of the recorded muscle activation.[29,83,173] Nonetheless, the muscle activation patterns observed using EMG provides insight regarding general control strategies that may contribute to injury. Similar to characterizing the movement patterns with kinematics and kinetics, most studies aim to identify whether a sex difference exists regarding preferential muscle recruitment strategies during functional tasks. Because movement patterns have generally been shown to differ between males and females, it would be reasonable to expect differences in muscle activation patterns during the same tasks.

Sex differences have been observed in the activation of muscles crossing the knee. For example, studies have identified greater quadriceps EMG amplitude in females compared to males, as reflected by EMG activity of the vastus medialis, vastus lateralis, and rectus femoris during the loading phase of a stop jump,[18] single leg squat,[187] cutting,[49,87,155] running,[87] and drop landing.[117,163,185] Hamstring activity has been reported to be the same or less in females compared to males during the same tasks,[18,87,155,163,185,187] which has prompted the female strategy to be termed "quadriceps dominance." The greater quadriceps activity in females has been reported to occur during the pre-contact[18,49,117,185] and post-contact phases[18,49,185] while landing from a jump. The increased quadriceps activity observed in females, if associated with increased force production, may load the ACL through increasing anterior shear stress, while males' more balanced quadriceps to hamstring activation is thought to decrease the anterior shear stress.[18,48,49,155] The observed muscle activation pattern, though speculative, may arise from a preferred movement strategy that absorbs load at the ankle and knee in females as opposed to knee and hip in males.[25,148]

Sex differences also have been observed in hip muscle activity. Zazulak et al. 2007[185] reported that the peak and mean gluteus maximus EMG amplitude was less in females compared to males immediately after initial contact during a single limb drop landing maneuver. Although landing kinematics were not reported by Zazulak and colleagues,[185] the female strategy may simply reflect the chosen posture at landing. For example, McNitt-Gray[104,105] has reported that landing with a more upright trunk position lowers gluteus maximus activation when compared with a more horizontally oriented trunk during landing. The diminished gluteus maximus activation in females may contribute to an increase in hip internal rotation and adduction motions that have been identified as potential risk factors for ACL injury.[37,48,102,132]

III. Potential causes of altered movement behavior in female athletes

The single most important goal for reducing the incidence of ACL injuries is to identify the principle factor(s) that influence injury risk.[5] ACL injuries are considered a multifactorial and complex problem. As such, many potential causes of ACL injury have been proposed. For practical convenience, potential causes can be characterized as modifiable and non-modifiable factors. Common non-modifiable factors addressed in the literature include structural anatomy (e.g., tibial plateau morphology, ligament laxity, notch width) and environmental conditions.[48] Common modifiable factors proposed include muscle strength and sensorimotor control.[48]

Despite a limited understanding of potential causes of ACL injury, exercise interventions have been developed and implemented to reduce injury rates with encouraging results in select groups.[44,88,123,131,157] Indeed, studies have shown that multimodal prevention programs (i.e. plyometrics, technique instruction, balance, agility, strength) can decrease ACL injury rates in females by up to 74%.[44,88,123,131,157] The fact that injury risk can be decreased by exercise interventions has important implications for understanding ACL injuries. That is, these findings suggest certain factor(s) that may contribute to ACL injury, at least in part, are modifiable. Therefore, the injury rates must decrease as a result of an intrinsic adaptation from training that improves dynamic lower extremity control during rapid transition maneuvers, irrespective of non-modifiable factors such as structural anatomy, hormones, and environmental conditions. Because dynamic knee stability arises from active muscle force production, muscle performance and the processes that result in coordinated motor responses (i.e. sensorimotor control) are potential modifiable factors that may contribute to ACL injury risk.

Influence of muscle strength on movement behavior

Muscle strength can influence a movement pattern and is commonly assessed clinically. Strength testing is most often considered the maximum voluntary torque performed isometrically. The theoretical assumption of strength testing is that a weak muscle is less likely to adequately control a given movement compared to a strong muscle. The trendelenburg sign is a classic example of gluteus medius weakness and is characterized by a contralateral pelvic drop with a compensatory shift of the center-of-mass to the ipsilateral stance side.

The relationship between strength and dynamic knee stability is of particular interest for ACL injury, because strength testing is easily measured and if predictive of injury risk, would be a potential screening procedure. In fact, females have been found to be weaker than males[55,75,76,153] and therefore strength may explain the disproportionate injury rate in females. Strength training is often incorporated into ACL injury prevention training regimens to address this concern. However, the literature is rather sparse regarding a direct link between muscle strength and lower extremity mechanics and/or injury risk.

Indirect evidence for quadriceps muscle strength as a potential factor in lower extremity mechanics was advocated by Hewett et al. 2004[55] who recorded knee strength and lower extremity mechanics during drop jumping in boys and girls 12-16 years old. Boys and girls demonstrated similar lower extremity mechanics until the post-pubertal phase of development. Post-pubertal females had significantly greater knee valgus motion than post-pubertal males. Interestingly, boys peak quadriceps and hamstring isokinetic torque at 300°/s (normalized to body mass) significantly increased across maturation and was significantly greater compared to females, whereas females did not significantly increase their relative strength across maturation. The authors suggest males experience a “neuromuscular spurt” that facilitates a favorable control strategy and likely decreases ACL injury risk compared to females. The results from this study provide evidence that knee strength may influence the lower extremity control strategy; however, other factors such as the influence of hip musculature and lower extremity inter-joint coordination were not considered.

In contrast, several studies have suggested that strength is not a critical factor influencing landing mechanics or injury risk. A recent study has shown that quadriceps and hamstring strength, as well as activation amplitude is a poor predictor of hip and knee excursion and the knee extensor moment in males and females.[153] In a sex comparison of hip abductor strength and lower extremity mechanics during a single limb landing maneuver, Jacobs et al. 2007[64] reported that females had increased peak knee valgus motion (4 degrees) and decreased hip abduction strength (normalized to body weight and height). While sex differences were found, peak hip abduction strength was poorly correlated (r = 0.35) with knee valgus motion in females and not correlated in males. Similarly, a 9-week lower extremity strength training program increased strength (i.e. quadriceps, hamstrings, gluteus medius, gluteus maximus) but did not alter lower extremity mechanics during a stop-jump task in a group of female recreational athletes.[53] In a follow-up study, Herman et al 2009[54] investigated the effects of video-assisted feedback on landing mechanics in a control and strength trained group. Both groups improved their landing mechanics similarly after feedback given to improve landing mechanics. Mizner et al 2008[110] also found that technique instruction improved landing mechanics considered potentially injurious to the ACL, but the improvement was not dependent on trunk or lower extremity strength. In addition, ACL injury prevention programs that decreased injury rates have incorporated multimodal approaches such as technique instruction, plyometrics, balance, agility, and strength training. Strength training in isolation has not been shown to decrease injury rates.[57]

In summary, no definitive relationship between lower extremity mechanics and muscle strength has been established. Although current literature cautiously supports the view that values obtained during strength testing potentially relate to lower extremity mechanics, the fact remains that strength and landing mechanics are weakly correlated[9,64,149,153] and isolated strength training programs do not improve landing mechanics or injury risk.[53,57] Furthermore, the positive effects of technique instruction on landing mechanics appear to be independent of strength,[54] which suggests that strength is not a primary determinant of landing strategy. Other measures of muscle performance such as rate of force development may relate better to movement and injury rates than isometric force, however, no studies have examined rate of force development in the context of potential ACL injury risk.

Influence of sensorimotor control on movement behavior

In the context of ACL injury, recent evidence suggests that muscle strength may not be as important as the ability to activate muscles at the appropriate time and level (i.e. neural drive). It has been proposed, therefore, that the at-risk movement behavior and increased ACL injury rates in females may be the result of inappropriate sensorimotor control.[9,48] Sensorimotor control is the physiological basis underlying the control of movement and is often used in the orthopedic literature to reflect "the ability to produce controlled movement through coordinated muscle activity." [172, p.547]

Sensorimotor integration (SMI) encapsulates the many underlying processes that underlie sensorimotor control.[119] Sensorimotor integration can be operationally defined as the process by which multi-modal sensory signals are transformed into, or affect, motor commands. Using this framework, 1) peripheral receptors, 2) subcortical and 3) cortical structures function to produce control inputs that are integrated continuously at the level of spinal interneurons and motoneurons to perform motor tasks.[67,119]

It is well known that the relative influence of the various control inputs for sensorimotor control is task and context dependent (e.g. standing vs steady locomotion vs perturbing the limb or support surface during locomotion).[63,142] Much of what is currently known about sensorimotor integration derives from invasive animal experiments such as the seminal work of Sir Charles Sherrington,[63,96,142] which continues to be used to various extents to inform our understanding of sensory feedback in locomotion for example.[46,141] The use of noninvasive technologies (e.g., fMRI, TMS) and select sensory perturbations also have provided new insights regarding the neural control of movement in humans primarily for tasks such as locomotion.[1,47,97,188] The neural control of more dynamic tasks such as landing from a jump is not well understood; therefore, potential implications of sensorimotor control for injury risk in athletes are based largely on theoretical inferences.

Perhaps the best support for sensorimotor control as a potential factor in ACL injury risk is based on the ability of the nervous system to adapt with motor practice. Plasticity is an essential and robust feature of the nervous system and is critical for motor adaptation and skill acquisition in sport. Indeed, the functional connectivity resulting in task-specific coordination appears directly linked to expertise/skill.[120,140,160,177,180] As such, it stands to reason that the ability to integrate sensory and motor inputs, like skill, varies across individuals and adapts with motor practice.[120,140,160,161,177,180] It is clear that plasticity occurs within the primary motor cortex during skill acquisition in both upper[65] and lower extremity[7,127,150] tasks. Similarly, skill training has been shown to influence spinal level processes.[160,176,177] For example, sensorimotor balance training in elderly men decreased tibialis anterior onset latency and resulted in greater overall motor activity in the first 120 ms after an unexpected treadmill perturbation.[45] Importantly, the spinal level adaptations resulted in improvement that was meaningful for the task (i.e. decreased maximum ankle angular velocity). Meyer-Lohmann et al. 1986[106] trained monkeys to move a handle to a target as quickly as possible despite random perturbations over the course of 4 years. In response to training, the amplitude of the monkeys' motor response at 33 ms (i.e. medium latency response) was slowly reduced with practice whereas the short latency response amplitude at ~16 ms became larger. These findings represent quick, purposeful motor response adaptations to skill training that were attributed to enhanced sensorimotor processing.

Similar mechanisms are assumed to underlie the control strategies acquired by athletes when performing sport specific maneuvers during competition and in response to the exercise interventions intended to decrease injury rates[115,180]. While there is no evidence to suggest that the neural processes contributing to sensorimotor control is different between sexes, an alternative explanation could be that the sensorimotor system is not adapting in females to the same extent as males during sport participation. The finding that injury rates in female athletes are considerably higher during games than in practice[12,158] suggests that females' sensorimotor system is not adapting or their practice is not preparing them for the level of play required during game competition.

How is sensorimotor control related to lower extremity injury risk?

The ACL injury scenario is most often a functional task characterized by sudden deceleration of the total body center of mass (e.g. landing and cutting). Sudden transitions in momentum are challenging to the sensorimotor system because the rapid and high impact loading requires a time sensitive multi-joint coordination that must act at the whole body and joint level to achieve stability.[105]

Several studies have investigated the muscular control strategy during landing from a jump in cats[100,136] and humans.[28,41,77,78,98,99,146,159,188] Muscle activity is consistently observed prior to landing.[146] It is believed that this muscle activity represents a necessary anticipatory strategy to account for feedback delays, thereby providing an initial muscle stiffness to prepare for the sudden impact with the ground.[74,100,146] In addition, bursts of muscle activity are observed soon after foot contact with the ground similar to that observed in the soleus after quick dorsiflexion perturbations.[28,97,100,146,159] Recent evidence suggests that the motor responses initiated after contact with the ground arise from sensory feedback rather than a pre-programmed motor command.[28,98,188] In addition, findings from studies measuring H-reflex and corticomotor excitability at times typical of short, medium, and long latency reflexes suggest a strong influence from subcortical processes in the early control of landing.[77,159] However, the utility of the sensory feedback mediated responses remain unknown.

Regardless of the primary control inputs and modulatory factors responsible for the controlled early deceleration period after landing from a jump, it is clear that the effective integration of sensory and motor signals is critical for dynamic joint stability.

Indeed, ACL injuries are believed to occur within 20-105 ms of foot contact with the ground during landing and cutting maneuvers.[71] Therefore, it is reasonable to expect that the altered movement behavior and higher ACL injury rates observed in females when compared to males may result from inappropriate sensorimotor control. While inappropriate sensorimotor function is a prevailing theory for higher ACL injury rates in females with strong theoretical support, little direct evidence exists. Rather, many studies attribute the at-risk biomechanical profile to impaired sensorimotor control based solely at the level of movement outcome (i.e. kinematics and kinetics) without an explicit link to potential motor control mechanisms.[48,56] Others suggest impaired sensorimotor control from surface EMG findings.[48,56,163,185] In order to advance the understanding of the role of sensorimotor function on movement behavior and injury risk, a method designed to quantify lower extremity sensorimotor function is needed.

The comprehensive measurement of sensorimotor control during tasks relevant for assessing ACL injury risk is not feasible at this time. Peter B.C. Matthews recently summarized this issue by stating, "…effective science depends on tackling problems that are soluble with the means at hand…the present blossoming of the study of sensorimotor control in humans likewise owes everything to the rapid advance in what can be tackled experimentally…But this still leaves much fine tuning…particularly in the creation and testing of precise tools to tackle a variety of individual physiological problems."[96] Due to the complexity and inability to measure sensorimotor control wholly, we propose a novel approach to address the question, "why do female soccer athletes injure their ACL at greater rates than male soccer athletes?" Instead of trying to determine the extent to which sensorimotor control differs between the sexes, we focus on a specific theoretical construct considered fundamental for effectively performing the change of direction tasks characteristic of the injury scenario.

IV. Lower extremity dexterity as a novel theoretical construct

Almost all functional tasks require dynamic interactions between the distal limb and the environment. Typing this dissertation required repeated dynamic interactions between my fingers and the keyboard, as does the flipping of the page when reading this in hard copy or when using the mouse/keyboard for an electronic version. Likewise, locomotor tasks such as walking require dynamic interactions between the foot and ground to start, stop, turn, and change velocity.[51,69,82] These dynamic interactions constitute an unequivocal link between limb control and the task goal, and thus a potentially meaningful theoretical construct we refer to as dexterity. Dexterity is operationally defined here as the capability of the limb to dynamically regulate endpoint force magnitude and direction when interacting with the environment.[164]

The central hypothesis of this dissertation is that dexterity is a construct critical for lower extremity function and potentially ACL injury risk. The rationale for this hypothesis is based on the fact that the injury scenario (e.g. landing and cutting) involves dynamic interactions of the lower extremity with the ground that are not adequately controlled. Literature reviewed detailing sex differences in landing mechanics at the beginning of this chapter supports this hypothesis. In addition, the primary focus of successful injury prevention programs has been to improve dynamic limb control. Thus, we propose that the higher ACL injury rate in females may arise, in part, from a reduced capability of the lower extremity to dynamically regulate limb-ground interactions.

The potential importance of dexterity can be viewed additionally in the context of motor skill. Dynamic maneuvers involving rapid whole-body deceleration and change of direction are fundamental motor tasks in sport that depend on dynamic foot-ground interactions. The capability to dynamically interact with the ground, therefore, would be expected to affect change of direction ability (i.e. agility). Exercise interventions that have successfully improved agility performance have incorporated jumping and running that emphasize change of direction,[107,109,181] whereas vertical jump and/or strength training in isolation have not improved agility performance.[13,86,162] These findings indicate that challenging athletes to dynamically interact with the ground in various ways (i.e., produce vertical and horizontal ground reaction forces) is an important skill relevant for agility performance, and likely dexterity.

There also is evidence suggesting that the ability to change direction may have implications for injury risk. Injuries occur most often during a sudden deceleration and change of direction maneuver. It would be expected, therefore, that better change of direction ability could mitigate injuries. Interestingly, agility has been shown to be better in male athletes when compared to female athletes.[108,113,114,126,129] In addition, the exercise interventions shown to decrease injury rates share common elements with interventions shown to improve agility.[44,70,88,107,109,123] It should be noted that the basic premise described above can be applied to older adults at risk for falls. That is, tasks that have been shown to predict falls are similar to agility tasks in principle,[27,85] and the exercise interventions to reduce falls aim to improve dynamic interactions with the ground. Taken together, there is strong theoretical support for a link between lower extremity dexterity, injury potential, and motor skill.

While currently available methods are routinely used to characterize the kinematics and kinetics during locomotor tasks, there are no metrics designed to objectively quantify lower extremity dexterity. Unlike the barriers to measuring the complex construct of sensorimotor control, however, defining dexterity as a behavioral proxy of dynamic limb control has allowed this related construct to become soluble. We describe a recent approach to quantify dexterity and describe how this has been adapted for the lower extremity in Chapter III.

V. Quantifying lower extremity dexterity

Recently, a test to quantify dexterity of the thumb and fingers has been developed.[164,165] This behavioral measure, called the strength-dexterity test (S-D test), was inspired by the observation that manipulation of objects with the hand is not merely an exercise of exerting force on an object (i.e. muscle strength testing), but rather a complex interplay between precise orientation of a sufficient force vector to achieve the task objective (e.g. button a shirt). A primary goal was to design a task that would assess the limits of sensorimotor function at submaximal forces.[164,165]

The paradigm developed to fulfill this purpose utilizes helical compression springs prone to buckling. The task is performed by compressing the springs with the fingers and/or thumb so as to compress the spring fully without it buckling.[165] Because the spring becomes increasingly unstable (i.e. harder to control) with higher compression force as an inherent property of the spring, this behavioral measure challenges the sensorimotor system by requiring simultaneous control of fingertip motion and force direction.

Evidence suggests that the S-D test quantifies a unique construct (i.e. dexterity) that is reflective of sensorimotor processing for skilled finger function because it is independent of strength,[164,165,169] is affected by aging[164,169] and sensory feedback,[165] and engages distinct cortico-striatal-cerebellar networks in a context-sensitive way.[112] In addition, the S-D test has been shown to discriminate between older adults with and without thumb osteoarthritis,[164] and recently has been validated as a metric of hand dexterity in children.[169] Interestingly, although there was a non-significant difference in mean performance between sex overall (i.e. low power to detect difference), a steeper slope in S-D performance was found across age in boys when compared to girls suggesting that dexterity develops at a faster rate in boys.[169] Given that the S-D test has been an informative measure of dynamic finger control and dexterous manipulation is similar to foot-ground interactions in principle, the paradigm is anticipated to be a fruitful construct to apply to the lower extremity.

VI. Summary

Female athletes sustain ACL injuries at higher rates than their male counterparts. Biomechanically based methods have characterized sex differences during athletic tasks that may influence ACL injury risk. When compared to males, the movement pattern exhibited by females includes less hip and knee joint excursion and decreased time to peak hip and knee flexion,[75,148] a greater relative energy absorption at the ankle,[25,148] and larger frontal plane motion and moments at the knee.[56,101,155] Moreover, EMG recorded during functional tasks suggest a potential gender specific muscle activation strategy (i.e. quadriceps bias and decreased hip muscle activation in females) that appears consistent with previously reported kinematic and kinetic findings. Importantly, a plausible link between the movement behavior exhibited by female athletes and ACL loading has been established.

A critical barrier to decreasing ACL injury rates is the limited understanding of factors that underlie ACL injury. In particular, factors that are informative of dynamic lower extremity control remain to be identified. To date, literature suggests that altered sensorimotor control (as opposed to strength) is a modifiable factor likely responsible for the movement behavior considered to underlie the sex disparity in ACL injury rates. However, the many neural pathways that underlie sensorimotor control makes this complex construct challenging to assess objectively. The evidence in support of this theory, therefore, is based on motion analysis and electromyography. To further our understanding of sensorimotor factors that may contribute to dynamic lower extremity control during sudden deceleration and change of directions, an objective measure of the capability of the lower limb to dynamically regulate foot-ground interactions is needed.

If a reliable and valid measure of dynamic lower extremity control can be linked to lower extremity function that increases injury potential, then screening and monitoring improvement due to training would become feasible. As a first step, the primary focus of this dissertation has been to develop a method designed to quantify lower extremity dexterity (i.e. dynamic lower extremity control). Studies were designed to evaluate reliability (Chapter III) and begin to establish construct validity (Chapters III, IV, and V). It is anticipated that this newly developed test method designed to quantify lower extremity dexterity will significantly advance the current state of knowledge regarding the role of dynamic limb control on movement behavior and change of direction ability during sport maneuvers.

CHAPTER III

THE LOWER EXTREMITY DEXTERITY TEST AS A MEASURE OF LOWER EXTREMITY DYNAMICAL CAPABILITY

The capability of the lower extremity to dynamically interact with the ground is important for skilled locomotor performance. There is however, no currently available method that can specifically quantify this sensorimotor ability we refer to as lower extremity dexterity. The purpose of this chapter is to describe a method designed to quantify lower extremity dexterity, assess its reliability, and determine the extent to which performance was independent of lower limb strength and anthropometry. The lower extremity dexterity test (LED-test) consists of using the lower extremity to compress a slender spring prone to buckling with the goal to sustain the highest force possible. As applying higher forces makes the spring increasingly unstable, achieving higher forces during the LED-test represents better ability to dynamically interact with the unstable test device. As such, the LED-test provides a novel way to identify impairments in the capability of the lower extremity to regulate foot-ground interactions. We propose that the unique lower extremity capability quantified by the LED-test could be informative of skilled locomotor performance and injury risk.

Introduction

Dynamic interactions between the lower limb and the environment are required to control and redirect body center of mass movement during walking, running, rapid turning, and landing.[51,69,82,95] Therefore, it is conceivable that the capability of the lower extremity to regulate the dynamic interactions between the foot and ground could influence locomotor skill and potentially contribute to injuries that occur during sudden deceleration and change of direction maneuvers. Currently, there is no test method designed to objectively quantify this sensorimotor ability, referred to in this chapter as lower extremity dexterity. We define lower extremity dexterity as the capability of the lower limb to dynamically regulate endpoint force magnitude and direction when interacting with the environment.[164]

The current paper describes a test method to quantify lower extremity dexterity that is based on a test designed to quantify dynamic finger pinch capability.[164,165] The Strength-Dexterity test (the S-D test) uses the fingertips to compress a slender spring as far as possible without buckling, which requires precise control of fingertip motions and force vector direction at submaximal forces. The S-D test has been shown to discriminate between older adults with and without thumb osteoarthritis,[164] and recently has been validated as a metric of hand dexterity in children.[169] Moreover, evidence suggests that the S-D test quantifies a unique construct (i.e. dexterity) that is reflective of sensorimotor processing for skilled finger function because it is independent of strength,[164,165,169] is affected by development and aging,[169] and engages distinct cortico-striatal-cerebellar networks in a context-sensitive way.[112] Given that dynamic interactions between the foot and ground are similar in principle to dexterous manipulation of the hand, we adapted the S-D test to evaluate whether this approach can be used to quantify lower extremity dexterity.

The current study had three objectives. First, we describe a test method designed to quantify lower extremity dexterity (the LED-test). Second, reliability of LED-test performance was assessed. Lastly, the extent to which LED-test performance is independent of strength and anthropometry was examined.

Methods

Subjects

Thirty-nine subjects (19 females, 20 males) between the ages of 15 and 25 participated in this study (**Table 3-1**). Participants were excluded if they had a previous knee ligament injury or knee surgery, or lower extremity injury or medical condition that resulted in an inability to participate in the study without pain. All subjects provided written informed consent as approved by the Institutional Review Board of the University of Southern California Health Sciences Campus.

Table 3-1. Participant characteristics (values are mean ± SD).

Age (yrs)	17.7 ± 3.1
Height (m)	1.74 ± 0.09
Body Mass (kg)	66.8 ± 10.2

Procedures

Prior to testing, height and body mass were recorded and participants were fitted with the same style of athletic shoe (New Balance Inc., Boston, MA). This was done to mitigate the potential influence of footwear. Participants completed the LED-test, as well as hip and knee strength testing during a single testing session. Only the dominant lower extremity was tested (i.e. preferred foot to kick a ball). To assess test-retest reliability and precision, 10 of the subjects repeated the LED-test on a separate occasion separated by a minimum of 3 and maximum of 9 days (average: 5.1 ± 2.2 days).

Lower extremity dexterity test

The LED-test is a dynamic contact control task based on the ability to compress a slender spring that is prone to buckling.[164,165] The LED-test device consists of a 25.4 cm helical compression spring mounted on a stable base (i.e. fixed end) with a 20 x 30 cm platform affixed to the free end. The spring characteristics were as follows: mean diameter: 3.08 cm, wire diameter: 0.04 cm, spring rate: 36.8 N/cm, total coils: 28.7, hard drawn wire (#850, Century Spring Corp., Los Angeles, CA). The spring parameters (i.e. stiffness and slenderness) were chosen such that spring instability occurred at low forces. This was done to minimize the influence of lower extremity strength on performance and to mitigate fatigue. The test device was positioned on a force plate and the vertical ground reaction force during testing was recorded at 1500 Hz (AMTI, Waterton, MA). The raw vertical ground reaction force was low-pass filtered with a 4th order Butterworth filter at 15 Hz and displayed as force feedback using LabVIEW software (National Instruments Corp., Austin, TX).

The LED-test was performed as shown in **Figure 3-1.** Participants were positioned in an upright partially seated posture on a bicycle saddle and were supported at the trunk by leaning forward approximately 20 degrees against a strap at the level of the xiphoid process. The non-tested foot rested on a step and was adjusted so that the hip and knee were extended (0 degrees) and the pelvis was level. Individuals were instructed to support their weight equally through the bicycle saddle and the non-test limb. The forearms rested on a crossbar adjusted to the level of the xiphoid process. Subject positioning was intended to be stable and minimize the extraneous use of the contralateral limb and upper extremities during testing. The test limb was positioned with the foot on the device platform in a standardized posture (i.e. 75-80 degrees of hip and knee flexion). A computer monitor provided visual force feedback of the vertical force (**Figure 3-1**).

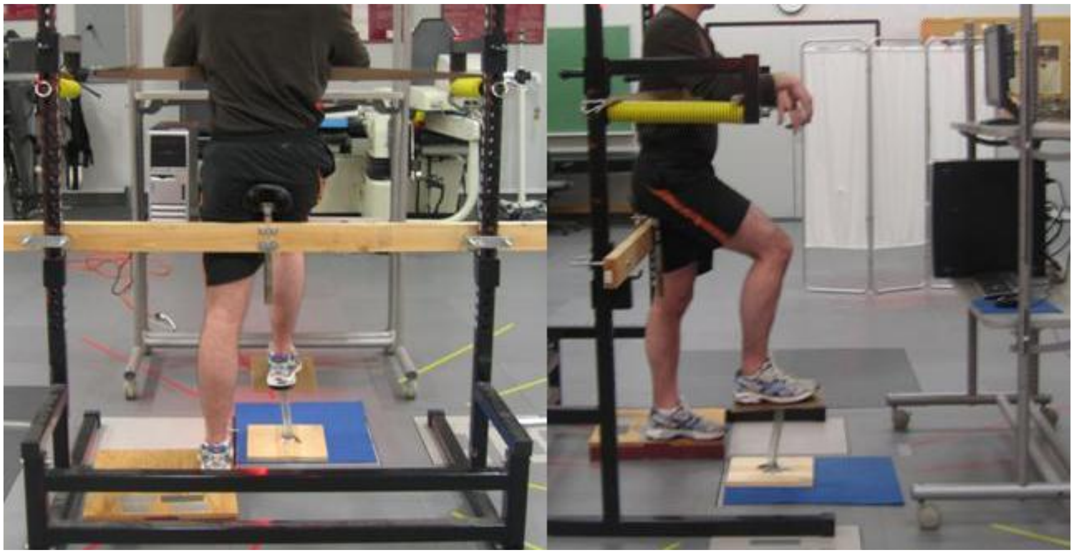

Figure 3-1. Experimental set-up for the lower extremity dexterity test.

Prior to testing, participants were familiarized with the force feedback system by performing 5 practice trials. After familiarization, subjects completed between 21 and 25 trials. Testing was stopped after trial 21 if performance on this trial was not among the best 3 of the previous 20 trials. Additional trials were completed up to 25 if performance on the 21st trial was one of the top 3 achieved. The number of trials was selected based on pilot testing that demonstrated best performance typically was achieved within 20 to 25 attempts. As shown in **Figure 3-2**, LED-test performance calculated using the first 10, 15, 20, and 25 trials obtained from the subjects completing the test-retest reliability portion of this study support this criterion. Specifically, stable performance was observed after 20 trials on day 1 which was maintained during the second test session.

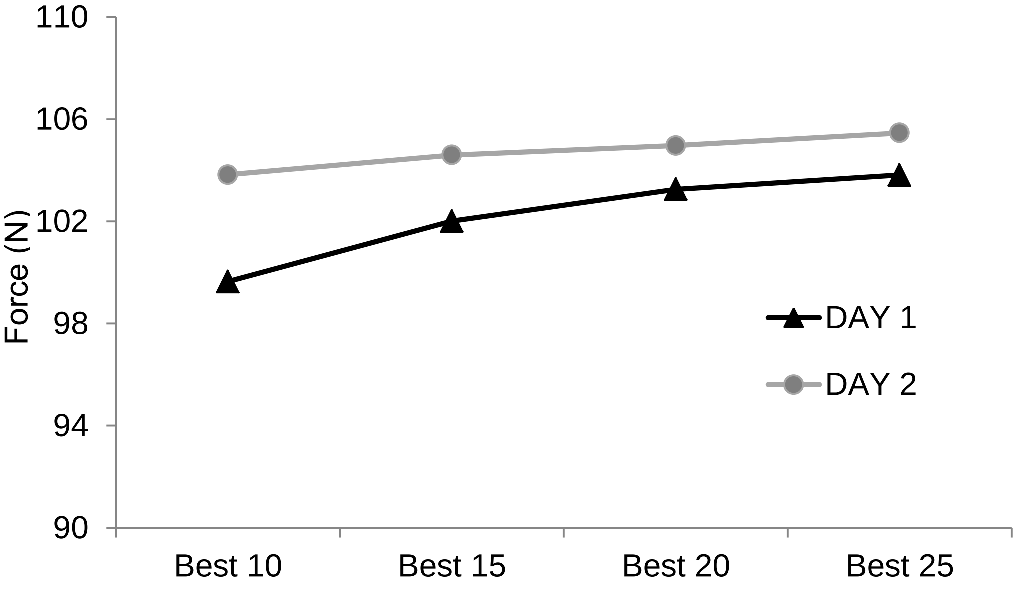

Figure 3-2. LED-test performance averaged across the 10 subjects that completed the test-retest reliability portion of this study. The data points represent the average of the best 3 of 10, 15, 20, and 25 trials, respectively. As can be seen, stable performance was observed after 20 trials on day 1 that was maintained throughout day 2.

Participants were instructed to slowly compress the spring with their foot with the goal to raise the force feedback line as high as possible (i.e. maximize vertical compression force). Participants were informed that it is natural for the spring to bend and become unsteady. Despite the inherent instability of the spring, the goal was to achieve and sustain the highest vertical force possible during each 16-second trial. Throughout testing, subjects were instructed to avoid using the contralateral limb or arms to help direct the movement of the test limb. To minimize physical and mental fatigue, 30 seconds of rest was provided between trials and 2 minutes of rest was provided after every 5th trial. Verbal encouragement was provided to facilitate maximum performance.

The dependent variable for the LED-test was the highest average vertical force over a 10-second period during the sustained hold phase of each trial. The maximal value was identified for each trial using a point-by-point 10-second moving average calculated from the raw vertical ground reaction force **(Figure 3-3)**.[165] Maximum values were determined using a custom program written in MATLAB (The Mathworks, Natick, MA), and were considered for analysis if the coefficient of variation was ≤ 10% for each moving window time step. The coefficient of variation criterion was chosen as an indicator of performance stability.[165] To assure that test performance had stabilized, we required that subjects complete at least 15 trials that met the coefficient of variation criterion. Failure to meet this criterion resulted in a subject being excluded from the analysis. The average of the best 3 trials was used for analysis.

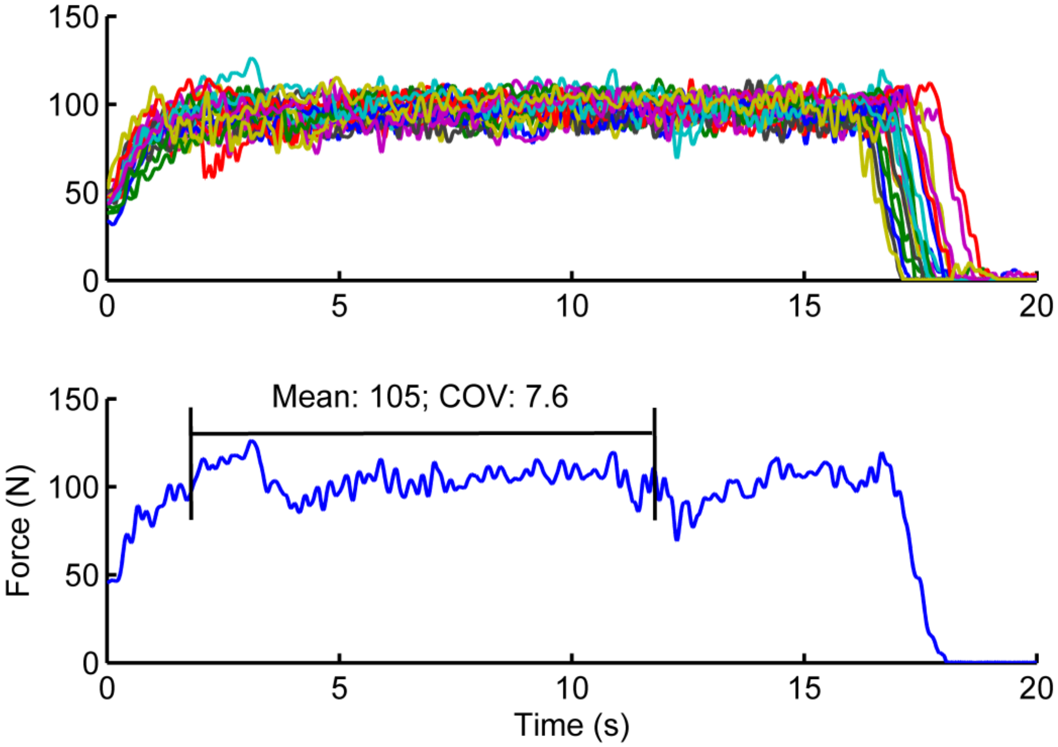

Figure 3-3. Example of data analysis for the LED-test. The top graph illustrates a time series of raw force data from a representative subject with each color representing a different trial. The bottom graph illustrates a time series from a single trial with the vertical black bars denoting the moving window period in which the maximal force value (Newtons) was identified and the coefficient of variation (COV) of the force values within the window.

Lower extremity strength

Peak isometric torque was obtained for the knee extensors, knee flexors, and hip extensors using a Humac Norm Dynamometer (CSMi, Stoughton, MA). For knee extensor and flexor strength, subjects were seated with the hip at 90 degrees and the knee flexed to 60 degrees. The thigh was secured to the dynamometer seat with a strap. The resistance pad was placed just proximal to the ankle. Hip extension strength was evaluated in the prone position with the pelvis supported at the edge of the dynamometer testing table and the hip in 60 degrees of flexion. Participants were asked to extend their hip into a resistance pad positioned against the posterior thigh with the knee flexed to 90 degrees. To facilitate a maximum effort, real-time torque was displayed as feedback during each trial and verbal encouragement was provided. One practice trial was provided for each testing position. Three maximal effort repetitions consisting of 5 second holds were then recorded. A rest period of ≥ 30 seconds was provided between repetitions. The maximal torque value obtained from each muscle group was divided by body mass and used for statistical analyses.

Statistical Analysis

Test-retest reliability of LED-test performance was assessed using the intraclass correlation coefficient, $ICC_{(2,3)}$. Test precision was assessed using standard error of the measurement [SEM = SD√(1-ICC)] and the minimal detectable difference [1.96*SEM*√2].[26,134] In addition to test-retest reliability, a paired-t test was used to determine whether performance differed between days. Pearson correlation coefficients were used to examine the relationships between LED-test performance and strength, body weight, and body height. Statistical analyses were performed with SPSS software (IBM, Armonk, NY) using a significance level of $P \leq 0.05$.

Results

Test-retest reliability

The forces achieved by participants during the LED-test were similar across days (103.4 ± 8.4 vs. 105.3 ± 8.8 N, $P = 0.13$, **Figure 3-4**). Performance on the LED-test had excellent test-retest reliability ($ICC_{(2,3)} = 0.94$). Likewise, precision was excellent with a standard error of the measurement of 2.0 N. The minimal detectable difference was 5.5 N.

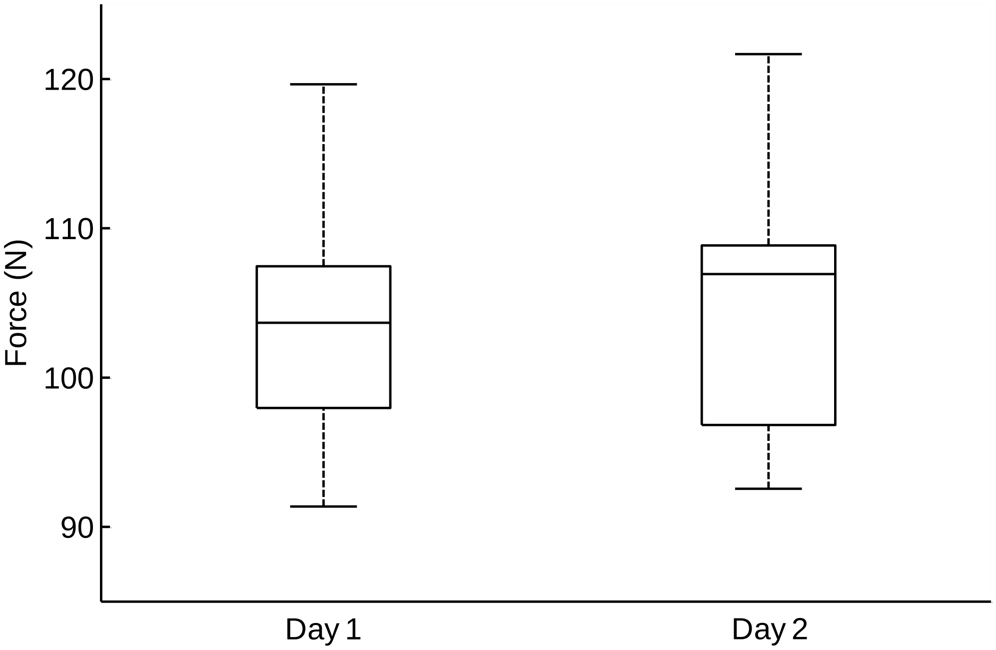

Figure 3-4. Test-retest reliability results (n = 10). No difference was observed in LED-test performance across days (*P* = 0.13). The central horizontal line within the box represents the median value, the box edges represent 25th and 75th percentile, and the whiskers represent the outermost data points.

Association with strength and anthropometry

One male participant was excluded from this analysis because the subject did not complete the minimum of 15 LED-test trials that met the coefficient of variation criterion of 10%. LED-test performance was not significantly associated with hip and knee muscle strength (**Table 3-2**). Although LED-test performance was not correlated with height, a small but significant correlation was found between LED-test performance and body mass (r = 0.34, *P* = 0.04).

Table 3-2. Correlation between LED-test performance and strength and anthropometry. (n = 38)

	Hip Extensor Strength	Knee Extensor Strength	Knee Flexor Strength	Body Mass	Height
LED-test performance	r = 0.19 *P* = 0.26	r = 0.05 *P* = 0.75	r = 0.14 *P* = 0.41	r = 0.34 *P* = 0.04	r = 0.23 *P* = 0.17

Discussion

The goal of this Chapter was to describe a test method to quantify the dynamical capability of the lower extremity to regulate foot-ground interactions. Given that the instability of the spring increased with greater compression force, we propose that the highest sustained vertical force achieved during the LED-test was representative of the maximal sensorimotor ability to dynamically regulate contact with the unstable spring-platform system at submaximal force levels. In support of this premise, LED-test performance was independent of lower extremity strength suggesting that the ability to coordinate muscles to dynamically regulate force direction is important for LED-test performance. This finding is consistent with previous investigations that have used this paradigm in the upper extremity to assess dynamic pinch capability.[164,165,169]

With respect to the association between anthropometric measures and LED-test performance, body height was not correlated with LED-test performance. However, a small but significant correlation was found between LED-test performance and body mass. It should be noted however that only 11.5% of the variance in LED-test performance could be explained by body mass, suggesting that limb mass was not a meaningful determinant of LED-test performance.

Dynamic interactions between the lower limb and the environment are required to change speed and direction during locomotion and skilled whole-body tasks.[51,69,82,95] We propose that dynamic lower extremity control as assessed by the LED-test could underlie locomotor skill particularly during rapid deceleration and change of direction maneuvers. Although the LED-test does not mimic dynamic functional tasks in terms of force magnitudes or whole-body mechanical demands in a traditional sense, the regulation of such task features are in principle very much related to the goal of the LED-test. For example, the LED-test was designed to quantify the dynamic sensorimotor coordination required to regulate foot-ground interactions, which may be related to the regulation of foot-ground interactions that occur when controlling and redirecting the center of mass during whole-body dynamical maneuvers. Thus, the LED-test and its conceptual framework open new opportunities to quantify dynamic lower extremity control that may underlie functional mobility. The ability to maximally challenge the sensorimotor system using this approach has been informative of dexterous manipulation for hand function,[112,164,165,169] and we anticipate that further development of the LED-test will advance the understanding of able and impaired lower extremity dexterity and perhaps injury risk.

There are several advantages of the LED-test that have important implications for future study. First, the LED-test assesses lower extremity dynamical capability at submaximal forces. The large force magnitudes and mechanical demands associated with the performance of dynamic whole body tasks may confound attempts to quantify sensorimotor ability of the lower extremity. In addition, the submaximal forces required for the LED-test is anticipated to allow dynamic limb capability to be quantified in individuals with conditions that would otherwise be limited by pain in more demanding testing scenarios. Second, a unique feature of the LED-test is its ability to challenge and quantify the dynamical capability of the lower extremity at the limits of performance in a safe manner.[165] We anticipate the well-supported posture will enable individuals to exhibit their true lower extremity capability, whereas performance during dynamic function tasks may be compromised by other factors such as fear-avoidance behavior. As such, the LED-test could provide a safer and potentially more sensitive way to identify impairments in the capability of the lower extremity to regulate foot-ground interactions (e.g. older adults at risk for falls).

Conclusion

This Chapter described a method to quantify lower extremity dexterity that was found to be reliable and independent of strength and anthropometry. Because dynamic interactions between the lower limb and ground are needed to change speed and direction during locomotion and skilled whole-body tasks,[51,69,82,95] objective measures of lower extremity dexterity could advance the understanding of functional mobility and injury risk. The discriminant ability of the LED-test in the context of ACL injury in young soccer athletes will be evaluated in Chapter IV. The extent to which dexterity is associated with change of direction ability (i.e. agility) will be examined in Chapter V.

CHAPTER IV

LOWER EXTREMITY DEXTERITY AND LEG STIFFNESS DURING A SINGLE LIMB DROP JUMP: A SEX COMPARISON

Female athletes tear the anterior cruciate ligament (ACL) at higher rates compared to their male counterparts. Females also exhibit lower extremity biomechanics that are thought to increase injury risk during landing and cutting maneuvers. To date, factors that contribute to the higher injury rates and at-risk biomechanics in female athletes remain unknown. The purpose of this study was to determine if reduced dynamic lower extremity control, as measured by the lower extremity dexterity test (i.e. LED-test), potentially contributes to the altered movement behavior observed in female athletes. To test this hypothesis, lower extremity dexterity was compared between 14 female and 14 male high school soccer players. In addition, leg stiffness, time to peak vertical ground reaction force, and co-contraction of the ankle and knee musculature prior to foot contact were compared between sexes during a single limb drop jump.

Introduction

Anterior cruciate ligament (ACL) tears are a serious and complex problem in sports medicine that affects female athletes at a rate 2-6 times higher than males participating in the same sport.[2,12,48,139,179] The higher ACL injury rate in females is believed to result from performing sport maneuvers in a way that increases ACL loading. In particular, females have been shown to land and cut with decreased hip and knee flexion and increased knee valgus angles and moments.[5,24,30,31,52,147-149] In addition, several studies have shown that females preferentially attenuate impact forces during landing using the ankle and knee, whereas males preferentially attenuate impact using the knee and hip.[25,148] Moreover, a recent study suggests that females who land with less hip and knee flexion (i.e. increased stiffness) exhibit higher frontal plane angles and moments.[133] Although a plausible link between such movement behavior in females and ACL loading has been established,[10,19,52,80,89,103,171,174,175] the underlying reasons for this "at-risk" biomechanical profile remains unknown.

Several factors have been proposed to explain the sex differences in movement behavior.[48] For example, impaired muscle strength is commonly believed to influence movement; however, recent literature suggests that lower extremity strength does not significantly relate to landing mechanics.[9,53,54,110,153] Sex differences in lower extremity biomechanics also have been widely attributed to impaired sensorimotor control.[48,55,56,172] Given that sensorimotor control is the physiological basis underlying the control of movement,[96] the at-risk movement behavior in females could represent a compensatory strategy to account for reduced sensorimotor capability of the lower limb to dynamically interact with the ground during sport specific maneuvers.

In Chapter III, a test method to quantify lower extremity dexterity (i.e. the LED-test) was described. The LED-test was designed to assess the capability of the lower limb to dynamically interact with the ground, a theoretical construct related to sensorimotor control. We previously have demonstrated that this measure of dynamic lower extremity control is reliable and evaluates a dimension of dynamic lower limb function that is independent of strength and anthropometry (see Chapter III).

The purpose of the current study was two-fold. First, LED-test performance was compared between female and male high school soccer athletes. Second, we compared landing biomechanics between the male and female athletes during a single limb drop jump. Leg stiffness was chosen as the primary biomechanical variable to represent a global measure of multi-joint coordination that is informative of the manner by which persons attenuate vertical forces.[15,30,31,62,73] In addition, the time to peak ground reaction force, as well as ankle and knee muscle co-contraction during the 80 ms period prior to foot contact with the ground was evaluated to represent the preparatory regulation of active muscle stiffness.[39,59,100,146] We hypothesized that female soccer athletes would exhibit reduced lower extremity dexterity (as measured by the LED-test), higher leg stiffness, and an earlier time to peak ground reaction force. We also hypothesized the females would exhibit higher ankle and knee co-contraction prior to foot contact when compared to male athletes. Taken together, findings in support of these hypotheses would raise the possibility that the higher ACL injury rates and stiffening movement strategy typically observed in female athletes may represent compensatory behavior to account for reduced dynamic lower extremity control.

Methods

Subjects

Fourteen female and 15 male high-school soccer athletes between the ages of 15 and 18 participated in this study. Adolescent soccer athletes were chosen as this group has been shown to be at high risk for ACL injury.[48,139,179] To control for the potential confound of experience, the female and male soccer athletes enrolled in this study were matched by age and skill level. This was achieved by recruiting players from the same competitive club or high school soccer division (i.e. varsity vs. junior varsity). Total years of soccer experience, as well as club experience, was similar between the female and male athletes (**Table 4-1**).

Table 4-1. Participant characteristics (values are mean ± SD).

	Females n = 14	Males n = 14	*P*
Age, yrs	16.2 ± 0.8	15.9 ± 0.7	0.33
Height, m	1.67 ± 0.06	1.79 ± 0.07	< 0.001
Body Mass, kg	63.9 ± 11.6	67.8 ± 8.9	0.34
Total soccer experience, yrs	10.9 ± 1.8	10.3 ± 2.1	0.46
Club soccer experience, yrs	5.4 ± 1.9	4.5 ± 1.8	0.24

To be considered for the study, participants had to be free of current lower extremity pain or injury. Participants were excluded from the study if they reported any of the following: 1) history of previous anterior cruciate ligament injury; 2) previous knee surgery; or 3) recent injury that had prevented them from participating fully in soccer for greater than 3 weeks within the last 6 months. Prior to participation, subjects and their parent/guardian provided written informed consent as approved by the Institutional Review Board of the University of Southern California Health Sciences Campus.

Instrumentation

Lower extremity dexterity test

The LED-test device consists of a 25.4 cm helical compression spring mounted on a stable base (i.e. fixed end) with a 20 x 30 cm platform affixed to the free end. The spring characteristics were as follows: mean diameter: 3.08 cm, wire diameter: 0.04 cm, spring rate: 36.8 N/cm, total coils: 28.7, hard drawn wire (#850, Century Spring Corp., Los Angeles, CA). The spring parameters (i.e. stiffness and slenderness) were chosen such that spring instability occurred at low forces. This was done to minimize the influence of lower extremity strength on performance and to mitigate fatigue. The test device was positioned on a force plate and the vertical ground reaction force during testing was recorded at 1500 Hz (AMTI, Waterton, MA). The raw vertical ground reaction force was low-pass filtered with a 4th order Butterworth filter at 15 Hz and displayed as force feedback using LabVIEW software (National Instruments Corp., Austin, TX).

Biomechanical testing

Three-dimensional kinematics were recorded using an 11-camera motion analysis system (Qualisys, Gothenburg, Sweden) at a sampling frequency of 250 Hz. Ground reaction forces were recorded from a force platform (Advanced Mechanical Technologies, Inc., Newton, MA, USA) at a sampling frequency of 1500 Hz. Electromyographic (EMG) signals were recorded using a Motion Lab Systems MA-300 EMG system (Motion Lab Systems, Baton Rouge, LA) at 1500 Hz. EMG data were collected with pre-gelled bipolar surface electrodes (Norotrode 20, Myotronics Inc., Kent, WA). EMG signals were amplified with a double-differential input design with a bandwidth of 20-3000 Hz, input impedance > 100 MΩ, and common-mode rejection > 100 dB at 65 Hz. EMG signals were transferred to a 16-bit analog to digital converter, and were recorded using Qualisys Track Manager software (Qualisys, Gothenburg, Sweden).

Procedures

Participants attended a single session in which they completed the LED-test and the single limb drop jump task. For both testing procedures, participants were fitted with the same style of athletic shoe (New Balance Inc., Boston, MA). This was done to mitigate the potential influence of footwear. For purposes of this study, only the dominant lower extremity was tested (i.e. preferred foot used to kick a ball).

Lower extremity dexterity test

The LED-test was performed as shown in **Figure 3-1.** Participants were positioned in an upright partially seated posture on a bicycle saddle and were supported at the trunk by leaning forward approximately 20 degrees against a strap at the level of the xiphoid process. The non-tested foot rested on a step and was adjusted so that the hip and knee were extended (0 degrees) and the pelvis was level. Individuals were instructed to support their weight equally through the bicycle saddle and the non-test limb. The forearms rested on a crossbar adjusted to the level of the xiphoid process. Subject positioning was intended to be stable and minimize the extraneous use of the contralateral limb and upper extremities during testing. The test limb was positioned with the foot on the device platform in a standardized posture (i.e. 75-80 degrees of hip and knee flexion). A computer monitor positioned directly in front of the participant provided visual force feedback of the vertical compression force (**Figure 3-1**).

Prior to testing, participants were familiarized with the force feedback system by performing 5 practice trials. After familiarization, subjects completed between 21 and 25 trials. Testing was stopped after trial 21 if performance on this trial was not among the best 3 of the previous 20 trials. Additional trials were completed up to 25 if performance on the 21st trial was one of the top 3 achieved. The number of trials was selected based on pilot testing that demonstrated best performance typically was achieved within 20 to 25 attempts.

Participants were instructed to slowly compress the spring with their foot with the goal to raise the force feedback line as high as possible (i.e. maximize vertical compression force). Participants were informed that it is natural for the spring to bend and become unsteady. Despite the inherent instability of the spring, the goal was to achieve and sustain the highest vertical force possible during each 16-second trial. Throughout testing, subjects were instructed to avoid using the contralateral limb or arms to help direct the movement of the test limb. To minimize physical and mental fatigue, 30 seconds of rest was provided between trials and 2 minutes of rest was provided after every 5th trial. Verbal encouragement was provided to facilitate maximum performance.

Biomechanical testing

Prior to biomechanical evaluation, the skin was prepared by shaving and lightly abrading with alcohol-soaked gauze. Self-adhesive surface electrodes were then placed over the rectus femoris (RF) proximally one-third the distance from the anterior superior iliac spine and superior patella and on the midpoint of the muscle bellies for lateral hamstring (LH), medial hamstring (MH), tibialis anterior (TA), and soleus (SOL). The electrodes and pre-amplifiers were secured to the skin with pre-wrap to minimize movement artifacts. The electrode leads were connected to a hardwire unit, which was secured with Velcro to the back of a custom neoprene vest worn by the subjects.

Muscle activation was normalized to the highest value recorded during either maximal voluntary isometric contractions (MVIC) or the single limb drop jump.[8,143,168,186] Three MVIC trials lasting 3 seconds were recorded for each muscle group. The MVIC value for the RF was obtained during seated isometric knee extension at 60 degrees of knee flexion. LH and MH MVIC values were obtained during seated isometric knee flexion with the knee flexed to 60 degrees. The MVIC value for SOL was obtained while subjects performed an isometric single limb heel raise. Resistance was provided by a stable bar placed across the shoulders. The MVIC value for TA was obtained in a seated position while subjects' dorsiflexed their foot against a stable bar with the knee flexed to 90 degrees.

Twenty-one reflective markers (14 mm spheres) were affixed to the following anatomical landmarks: distal second toe, first and fifth metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanters, iliac crests, anterior-superior iliac spine, and L5-S1. Additionally, non-collinear tracking marker clusters were placed on the shoe heel counters, lateral shanks, and lateral thighs. The thigh and shank clusters were secured to elastic wraps, while the heel clusters were taped to the shoe. A standing calibration trial was then obtained to establish the local segmental coordinate system. Following the calibration trial, the anatomical markers were removed. The tracking marker clusters, L5-S1, and iliac crest markers remained on the participant during the jump trials.

For the single limb drop jump task, participants were instructed to hop down from a 30 cm platform with their dominant limb, land in the middle of a force plate, and jump up as high as possible. Four trials were obtained from each subject.

Data Analysis

Lower extremity dexterity test

The dependent variable for the LED-test was the highest average vertical force over a 10-second period during the sustained hold phase of each trial. The maximal value was identified for each trial using a point-by-point 10-second moving average calculated from the raw vertical ground reaction force **(Figure 3-2)**.[165] Maximum values were determined using a custom program written in MATLAB (The Mathworks, Natick, MA), and were considered for analysis if the coefficient of variation was ≤ 10% for each moving window time step. The coefficient of variation criterion was chosen as an indicator of performance stability.[165] To assure that test performance had stabilized, we required that subjects complete at least 15 trials that met the coefficient of variation criterion. Failure to meet this criterion resulted in a subject being excluded from the analysis. The average of the best 3 trials was used for analysis.

Biomechanical testing

Three-dimensional marker coordinates were reconstructed using Qualisys Track Manager (Qualisys, Gothenburg, Sweden). Visual 3D software (C-motion, Rockville, MD) was used to process raw coordinate data and compute segmental kinematics. Trajectory data were filtered with a fourth-order zero-lag Butterworth low-pass filter at 12 Hz. The pelvis was modeled as a cylinder and the lower extremity segments as a frustra of cones. The local coordinate system for each segment was derived from a standing calibration trial. Joint kinematics were calculated using Euler angles with the following order of rotations: flexion/extension, abduction/adduction, internal/external rotation.

The primary biomechanical variable of interest was average leg stiffness (K_{leg}) during the deceleration phase of landing.[30,31] This was calculated as the ratio of the peak vertical ground reaction force (F_{peak}) to the center of mass displacement (COM_{disp}) from initial contact to the time of peak vertical ground reaction force:[30,31,62,73]

$$\mathrm{K}_{leg} = \frac{\mathrm{F}_{peak}}{\mathrm{COM}_{disp}} \qquad (1)$$

Center of mass displacement from initial contact to the time of peak vertical ground reaction force was calculated by double integration of the vertical acceleration.[16,30,42,137] The initial center of mass velocity was estimated from the kinematic trajectory of the pelvis segment center of mass at the time of foot contact. Leg stiffness values were normalized by body mass.[20,124]

Raw EMG signals were band-pass filtered (35-500 Hz), rectified, and smoothed with a 20 Hz zero-phase lag Butterworth low-pass filter. The smoothed EMG data were normalized to the highest EMG value recorded from either the maximal voluntary isometric contractions (MVIC) or the single limb drop jump.[8,143,168,186] EMG data were processed using a custom MATLAB program (MathWorks, Natick, MA, USA).

Co-contraction was calculated during the 80 ms period prior to landing using the following equation,[147]

$$\left[\sum_{i=1}^{n}\left(\frac{\mathrm{EMG}low_{(i)}}{\mathrm{EMG}high_{(i)}}\right) \times \left(\mathrm{EMG}low_{(i)} + \mathrm{EMG}high_{(i)}\right)\right] \div n \qquad (2)$$

where i is the timestep, n is the total number of samples, $\text{EMG}low_{(i)}$ the lower of the two muscle amplitudes, and $\text{EMG}high_{(i)}$ the higher of the two muscle amplitudes. The ankle co-contraction index was calculated using TA and SOL, while the knee index was calculated using RF and the average of the LH and MH muscles.

Statistical Analysis

A one-way multivariate analysis of variance (MANOVA) was used to examine sex differences for LED-test performance, leg stiffness, time to peak vertical ground reaction force, as well as ankle and knee co-contraction. If a significant sex difference was found for the MANOVA, the results from univariate tests were reported for each dependent variable. The one-way MANOVA and post-hoc univariate ANOVAs were justified as the data were normally distributed with homogeneity of covariances and variances between groups. All statistical analyses were conducted with SPSS software (IBM, Armonk, NY) using a significance level of $P \leq 0.05$.

Results

One male participant was excluded from the analyses because this subject did not complete the minimum of 15 LED-test trials that met the coefficient of variation criterion of 10%. Leg stiffness and associated biomechanical variables from an additional male subject exceeded 1.5 times the interquartile range when both groups were combined. Therefore, his single limb landing data was excluded as an outlier. The ankle co-

contraction index could not be calculated for 1 female participant due to EMG technical issues.

The multivariate test of overall differences was statistically significant (*P* = 0.005). Lower extremity dexterity was significantly lower in the female soccer players when compared to male soccer players (99.6 ± 5.5 vs. 109.3 ± 7.9, *P* = 0.001, **Figure 4-1**). In addition, leg stiffness was significantly higher in the female athletes (395.7 ± 101.6 vs. 304.8 ± 54.9, *P* = 0.008, **Figure 4-2**). Furthermore, the time to peak vertical ground reaction force occurred significantly earlier in females and co-contraction of the ankle and knee muscle pairs was significantly greater in the female group (**Table 4-2**).

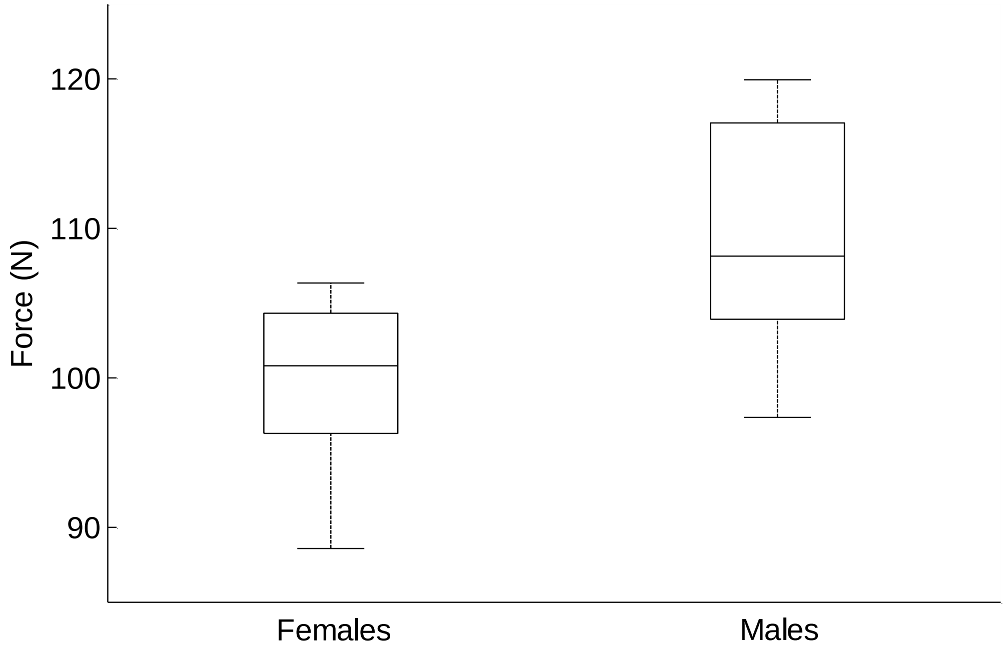

Figure 4-1. LED-test performance between sexes. Male soccer athletes (n = 14) achieved significantly greater vertical compression force when compared to female soccer athletes (n = 14) during the LED-test (*P* = 0.001). The central horizontal line within the box represents the median value, the box edges represent 25th and 75th percentile, and the whiskers extend to the outermost data points.

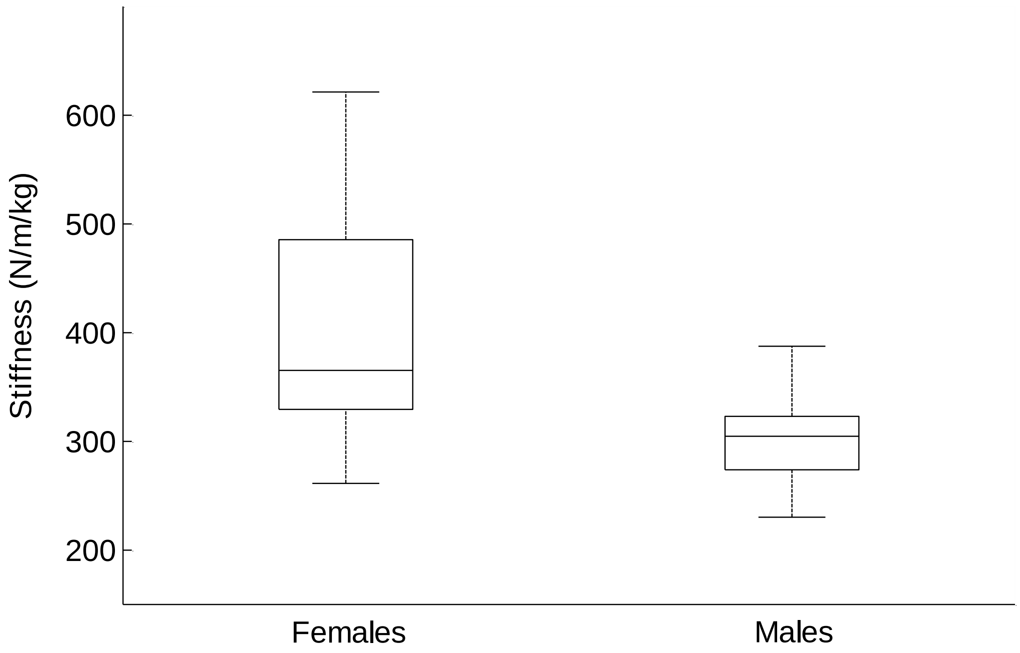

Figure 4-2. Average leg stiffness during a single limb drop jump between sexes. Female soccer athletes (n = 14) had significantly greater stiffness when compared to male soccer athletes (n = 13) during the single limb drop jump (*P* = 0.008). The central horizontal line within the box represents the median value, the box edges represent 25th and 75th percentile, and the whiskers represent the outermost data points.

Table 4-2. Sex comparison of biomechanical variables during the single limb drop jump (values are mean ± SD)

	Females	Males	*P*
Time to peak force (ms)[a]	47.8 ± 7.4	54.1 ± 7.7	0.04
Ankle co-contraction[b]	14.9 ± 4.5	8.5 ± 3.7	0.001
Knee co-contraction[a]	11.6 ± 3.9	7.9 ± 3.4	0.02

[a] females: n = 14; males: n = 13; [b] females: n = 13; males: n = 13

Discussion

Consistent with the proposed hypotheses, female soccer athletes exhibited reduced lower limb dexterity and higher leg stiffness when performing a single limb drop jump. Furthermore, females demonstrated higher ankle and knee co-contraction, and an earlier time to peak ground reaction force during the single limb drop jump. The results of this study provide support for the premise that reduced lower extremity dexterity may, in part, underlie the sex differences in movement behavior while performing sport specific tasks.

The primary finding of this study was a significantly lower LED-test performance in the females when compared to the males. Although the absolute difference between groups was low (10 N), the effect size was large (1.43). In addition, the sex difference exceeded the previously established minimal detectable difference of 5.5 N (see Chapter III). Importantly, post-hoc testing revealed that the coefficient of variation of the vertical force during the LED-test did not differ between groups (6.8 ± 1.2 vs. 7.4 ± 1.7, $P = 0.34$) suggesting that the female and male athletes similarly approached their limits of stability.

In the current study, the female athletes landed with higher average leg stiffness, which is characteristic of a movement strategy thought to increase the risk for ACL injury.[56,133,148,156] The higher leg stiffness in females was attributed to both a higher vertical ground reaction force and decreased center of mass displacement. The finding of higher vertical ground reaction forces in females is consistent with a previous study examining single limb landing.[148]

Consistent with the increase in leg stiffness, higher ankle and knee co-contraction also was observed in the female athletes. Higher co-contraction prior to landing has previously been shown to contribute to higher ground reaction forces and leg stiffness during similar tasks.[4,39,59,61] In addition, the sex differences in muscle activation, particularly the higher rectus femoris activation in the female group, is consistent with previous investigations during single limb landing.[117,185]

We propose that the higher leg stiffness and greater ankle and knee co-contraction observed in the female athletes may represent a compensatory motor control strategy attributed, in part, to reduced lower extremity dexterity. Muscle activity consistently observed prior to landing in cats[111,112] and humans[28,41,77,78,98,99,146,159,188] is believed to provide the muscle stiffness required to control limb dynamics immediately following ground impact. Bursts of muscle activity that occur 30-50 ms after impact are attributed to sensory feedback (e.g., muscle spindle, golgi tendon organ) rather than a pre-programmed motor command.[28,98,100,159,188] For this reason, the sex differences in leg stiffness, which occurred on average within 51 ms of impact (Table 4-2), can be attributed primarily to preparatory regulation of muscle stiffness provided by feedforward control.[39,59,111] Although center of mass velocity and joint angles[30] at impact also could have explained the sex difference in leg stiffness, post-hoc analysis demonstrated that joint angles and center of mass velocity were similar between groups at foot contact. Taken together, the findings raise the possibility that the female movement behavior observed in this study could represent a heightened feedforward strategy to compensate for reduced lower extremity dexterity.

This study provides the first experimental evidence suggesting that the capability of the lower limb to dynamically interact with the ground is reduced in females when compared to males. It stands to reason, therefore, that reduced dynamic lower extremity control as assessed by the LED-test could explain the sex differences in lower extremity function previously reported in numerous publications. For example, the ability to change direction quickly (i.e. agility), which represents a functional domain related to dynamical foot-ground interactions, has been shown to be better in males compared to female athletes.[107,113,126] Similarly, females exhibit lower extremity mechanics considered to increase ACL injury risk when compared to male athletes.[9,101,155,156] It is conceivable that sex differences in lower extremity mechanics may reflect reduced dynamic lower extremity capability given that these differences are not explained by anthropometry or strength.[9]

In addition to providing a potential explanation for the altered movement behavior in female athletes, the findings of this study also provide insight concerning the mechanism by which injury prevention programs reduce ACL injury rates. For example, intervention programs that incorporate plyometrics and agility training have been shown to reduce injury rates in females by up to 74%.[44,70,88,123] In contrast, exercise interventions that include only muscle strengthening have not been shown to reduce ACL injuries.[57] These findings suggest that exercise interventions may reduce injury rates by enhancing an athlete’s capability to dynamically coordinate lower extremity muscles to interact more effectively with the ground during landing and cutting maneuvers.[44,70,88,123]

While the reason for the sex difference in lower extremity dexterity is not known, it is conceivable that the higher values exhibited by male soccer athletes reflect a practice related enhancement of their sensorimotor system.[180] Regardless of the origin of the difference in dexterity between sexes, the results of this study provide a potential explanation for the higher injury risk in females and the potential benefits of exercise interventions shown to reduce injury risk. Further research is necessary to determine whether LED-test performance is predictive of injury or if dexterity improves after participating in an exercise intervention.

Conclusion

Male soccer athletes performed better on a test of lower limb dexterity than female soccer athletes. In addition, the female athletes performed a single limb drop jump with higher vertical stiffness and higher co-contraction of the ankle and knee prior to foot contact compared to their male counterparts. We propose that reduced dynamic lower extremity control (i.e. LED-test performance) resulted in a compensatory feedforward stiffening of the lower extremity to control landing in female soccer athletes. This compensatory stiffening strategy observed in the female soccer athletes may increase the risk of ACL injury.

CHAPTER V

LOWER EXTREMITY DEXTERITY IS ASSOCIATED WITH CHANGE OF DIRECTION ABILITY IN HIGH SCHOOL SOCCER ATHLETES

In Chapter IV, it was shown that female soccer athletes have reduced lower extremity dexterity and land with increased leg stiffness when compared to males. The primary purpose of this chapter was to examine the extent to which lower extremity dexterity (as opposed to strength and power) is associated with agility performance in high school soccer athletes. Lower extremity strength was assessed using maximal effort isometric trials and lower extremity power by vertical jump height. Lower extremity dexterity was quantified using the LED-test described in Chapter III. Agility was assessed using a hopping sequence intended to quantify the ability to change direction quickly. Sex comparisons were examined and the association between agility and dexterity, strength and power was evaluated.

Introduction

The ability to rapidly change the velocity and direction of whole body momentum is a fundamental locomotor skill in most sports. It is not surprising therefore that this ability, typically referred to as agility, has been shown to discriminate among skill levels in soccer,[68,113,138,167] football,[154] and rugby.[40] In fact, agility performance has been identified as the best variable to discriminate between elite and sub-elite soccer players.[138] Therefore, identifying factors that influence agility performance could be useful for the development of training programs aimed at improving sport performance.

Currently, little is known regarding factors that influence agility performance. Sprint speed, strength, and vertical jump height have been evaluated as potential indicators of agility performance, but no consistent relationships have been identified.[13] For example, agility tests that only include quick change of directions have been shown to correlate weakly with sprint speed ($r = 0.24$-0.46).[81,126,181] Conversely, moderate correlations ($r = 0.55$-0.77) have been reported between sprint speed and agility tests that include running as a component of the test.[66,113,126,166]

Dynamic maneuvers involving rapid whole-body change of direction are physically demanding and require stretch-shortening of the lower extremity muscles. It stands to reason that countermovement jump height or strength would be associated with agility performance. However, poor to moderate correlations between vertical jump performance and agility have been found ($r = 0.14$-0.69).[6,66,91,92,108,144,166] Similar associations have been reported between agility and strength measured during a squat[6,66,91,129] and during isokinetic testing.[66]

Exercise programs that have been shown to improve agility performance may provide insight into the factors that influence change of direction ability. For example, interventions that have improved agility performance have incorporated jumping and landing in multiple planes of motion.[107,109] Similarly, agility performance has been shown to improve in athletes that practiced change of direction sprints for 6 weeks, whereas athletes that practiced only straight ahead sprints did not improve agility performance.[181] Vertical jump and/or strength training in isolation also do not improve agility performance.[13,86,162] These findings suggest that lower extremity strength and the ability to accelerate the body vertically are not critical determinants of agility performance.

Based on the current literature, training programs that challenge athletes to dynamically interact with the ground may be an important attribute relevant for agility performance. This attribute has been referred to as lower extremity dexterity and operationally defined as the capability of the lower limb to dynamically regulate foot-ground interactions (see Chapter III). In a previous chapter, we described a test method designed to assess lower extremity dexterity (the LED-test). The LED-test has been shown to be independent of strength and anthropometry (Chapter III). Lower extremity dexterity also has been shown to be reduced in female soccer athletes when compared to their male counterparts (Chapter IV), which could underlie the reduced agility performance previously reported in females.[108,113,114,126,129]

The primary purpose of this study was to examine the extent to which lower extremity dexterity, as opposed to strength and power, is associated with change of direction ability in female and male soccer athletes. It was hypothesized that lower limb dexterity (as assessed by the LED-test) would be correlated with agility performance. A secondary purpose was to compare agility performance between female and male soccer athletes. We hypothesized female soccer athletes would exhibit slower times to complete an agility task that focuses exclusively on the ability to change direction rapidly. By identifying attributes that underlie change of direction performance, it is anticipated that more effective interventions can be developed to improve agility.

Methods

Subjects

Fourteen female and 15 male high-school soccer athletes participated in this study. To control for the potential confound of experience, the female and male soccer athletes enrolled in this study were matched by age and skill level. This was achieved by recruiting players from the same competitive club or high school soccer division (i.e. varsity vs. junior varsity). Total years of soccer experience, as well as club experience, was similar between females and males (**Table 4-1**).

To be considered for the study, participants had to be free of lower extremity pain or injury. Participants were excluded from the study if they reported any of the following: 1) history of previous anterior cruciate ligament injury; 2) previous knee surgery; or 3) recent injury that had prevented them from participating fully in soccer for greater than 3 weeks within the last 6 months. Prior to participation, subjects and their parent/guardian provided written informed consent as approved by the Institutional Review Board of the University of Southern California Health Sciences Campus.

Procedures

Subjects attended a single session that included the LED-test, hip and knee strength testing, double and single limb agility tests, and vertical jump testing. Prior to testing, participants were fitted with the same style of athletic shoe (New Balance, X700, Boston, MA) and their body mass was recorded. Each athlete then performed a dynamic warm-up which consisted of the hopping sequence for the agility tests (see below for task description). Testing was performed on the dominant limb as determined by the preferred foot used to kick a ball.

Lower extremity dexterity test

The LED-test is a dynamic contact control task based on the ability of participants to compress a slender spring that is prone to buckling.[164,165] The LED-test device consists of a 25.4 cm helical compression spring mounted on a stable base (i.e. fixed end) with a 20 x 30 cm platform affixed to the free end. The spring characteristics were as follows: mean diameter: 3.08 cm, wire diameter: 0.04 cm, spring rate: 36.8 N/cm, total coils: 28.7, hard drawn wire (#850, Century Spring Corp., Los Angeles, CA). The spring parameters (i.e. stiffness and slenderness) were chosen such that spring instability occurred at low forces. This was done to minimize the influence of lower extremity strength on performance and to mitigate fatigue. The test device was positioned on a force plate and the vertical ground reaction force during testing was recorded at 1500 Hz (AMTI, Waterton, MA). The raw vertical ground reaction force was low-pass filtered with a 4th order Butterworth filter at 15 Hz and displayed as force feedback using LabVIEW software (National Instruments Corp., Austin, TX).

The LED-test was performed as shown in **Figure 3-1.** Participants were positioned in an upright partially seated posture on a bicycle saddle and were supported at the trunk by leaning forward approximately 20 degrees against a strap at the level of the xiphoid process. The non-tested foot rested on a step and was adjusted so that the hip and knee were extended (0 degrees) and the pelvis was level. Individuals were instructed to support their weight equally through the bicycle saddle and the non-test limb. The forearms rested on a crossbar adjusted to the level of the xiphoid process. Subject positioning was intended to be stable and minimize the extraneous use of the contralateral limb and upper extremities during testing. The test limb was positioned with the foot on the device platform in a standardized posture (i.e. 75-80 degrees of hip and knee flexion). A computer monitor positioned directly in front of the participant provided visual force feedback of the vertical compression force (**Figure 3-1**).

Prior to testing, participants were familiarized with the force feedback system by performing 5 practice trials. After familiarization, subjects completed between 21 and 25 trials. Testing was stopped after trial 21 if performance on this trial was not among the best 3 of the previous 20 trials. Additional trials were completed up to 25 if performance on the 21st trial was one of the top 3 achieved. The number of trials was selected based on pilot testing that demonstrated best performance typically was achieved within 20 to 25 attempts.

Participants were instructed to slowly compress the spring with their foot with the goal to raise the force feedback line as high as possible (i.e. maximize vertical compression force). Participants were informed that it is natural for the spring to bend and become unsteady. Despite the inherent instability of the spring, the goal was to achieve and sustain the highest vertical force possible during each 16-second trial. Throughout testing, subjects were instructed to avoid using the contralateral limb or arms to help direct the movement of the test limb. To minimize physical and mental fatigue, 30 seconds of rest was provided between trials and 2 minutes of rest was provided after every 5th trial. Verbal encouragement was provided to facilitate maximum performance.

The dependent variable for the LED-test was the highest average vertical force over a 10-second period during the sustained hold phase of each trial. The maximal value was identified for each trial using a point-by-point 10-second moving average calculated from the raw vertical ground reaction force **(Figure 3-2)**.[165] Maximum values were determined using a custom program written in MATLAB (The Mathworks, Natick, MA), and were considered for analysis if the coefficient of variation was ≤ 10% for each moving window time step. The coefficient of variation criterion was chosen as an indicator of performance stability.[165] To assure that test performance had stabilized, we required that subjects complete at least 15 trials that met the coefficient of variation criterion. Failure to meet this criterion resulted in a subject being excluded from the analysis. The average of the best 3 trials was used for analysis.

Lower extremity strength and power

Peak isometric torque was obtained for the knee extensors, knee flexors, and hip extensors using a Humac Norm Dynamometer (CSMi, Stoughton, MA). For knee extensor and flexor strength, subjects were seated with the hip at 90 degrees and the knee flexed to 60 degrees. The thigh was secured to the dynamometer seat with a strap. The resistance pad was placed just proximal to the ankle. Hip extension strength was evaluated in the prone position with the pelvis supported at the edge of the dynamometer testing table and the hip in 60 degrees of flexion. Participants were asked to extend their hip into a resistance pad positioned against the posterior thigh with the knee flexed to 90 degrees. To facilitate a maximum effort, real-time torque was displayed as feedback during each trial and verbal encouragement was provided. One practice trial was provided for each testing position. Three maximal effort repetitions consisting of 5 second holds were then recorded. A rest period of ≥ 30 seconds was provided between repetitions. The maximal torque value obtained from each muscle group was divided by body mass and used for statistical analyses.

Lower extremity power was quantified using countermovement jump height recorded by a Vertec measuring device. First, participants reached as high as possible with their dominant arm while keeping their feet flat on the ground. Countermovement jump height was recorded as the difference between reach height and the highest point reached with the fingertip during the jump in centimeters. The best of 3 trials was used for statistical analysis.

Agility

Most measures of agility require running as part of the test. Because studies have reported moderate correlations between sprint speed and agility measures with running,[66,113,126,166] the task chosen for the current study focused solely on quick change of direction movements. Specifically, 4 target positions were marked on the floor anterior, posterior, right, and left of a center position on a 1.2 x 1.2 m force plate (AMTI, Waterton, MA) (**Figure 5-1**). With their hands on their hips, participants were instructed to hop to each target and back to the center as fast and as accurate as possible. Subjects moved in a clockwise direction if they were right-foot dominant and counterclockwise if they were left-foot dominant. Two clockwise or counterclockwise cycles were completed per trial (i.e. 18 touches). Each athlete first completed the hopping sequence using both limbs. Following the double limb trials, subjects completed trials on their dominant limb. The distance of the targets was 40 cm when using both limbs and 30 cm during single limb hopping.

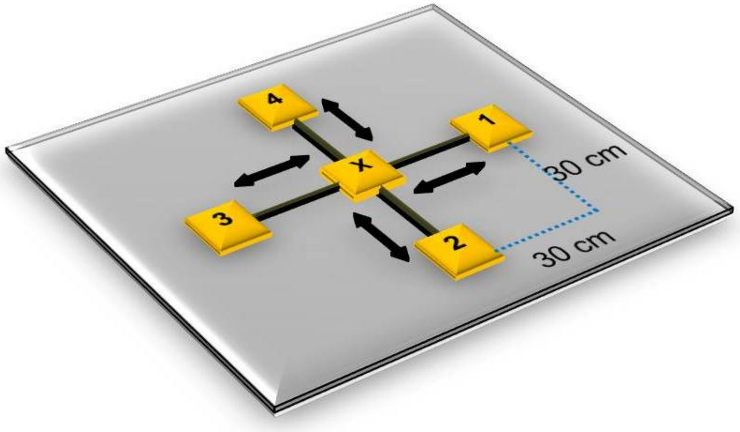

Figure 5-1. Schematic depicting force plate and target positions spaced 30 cm apart for the single limb agility hopping sequence. The double limb hopping sequence uses the same configuration with targets spaced 40 cm apart.

In an effort to capture the best possible performance, at least 6 trials were recorded for both the double limb and single limb agility conditions. Subjects were allowed additional trials up to 10 if they felt they could improve or a clear trend of improvement was observed. The number of trials attempted was similar for males and females for both the double limb and single limb agility tests (double limb: 6.9 ± 0.7 vs. 7.3 ± 1.3; single limb: 6.8 ± 0.8 vs. 7.1 ± 0.8). The time to complete the task was determined by the vertical ground reaction force, which was sampled at 1500 Hz. The test time started at toe off (< 20 N) of the first hop and ended upon foot contact (> 20 N) on the force plate of the last hop. The average of the best 3 trials was used for statistical analysis.

Statistical Analysis

The primary dependent variable for this study was the time to complete the agility test. The independent variables included the LED-test performance, maximum isometric hip extensor, knee extensor, and knee flexor muscle torques (normalized to body mass), and vertical jump height.

Pearson correlation coefficients were used to examine the relation between agility performance and each of the independent variables. Correlation analyses were evaluated separately for male and female soccer players. For independent variables that had a significant correlation with agility in both males and females, multiple linear regression models were used to examine the association between agility performance and each independent variable while controlling for sex.

One-way multivariate analysis of variance (MANOVA) was used to examine between group differences in agility performance (double limb and single limb) and lower extremity strength and power. Univariate tests were performed if the omnibus MANOVA was significant. The one-way MANOVA and post-hoc univariate ANOVAs were justified as the data were normally distributed with homogeneity of covariances and variances between groups. All statistical analyses were conducted with SPSS software (IBM Corporation, Armonk, NY) using a significance level of $P \leq 0.05$.

Results

One male participant was excluded from the analyses because the subject did not complete the minimum of 15 LED-test trials that met the coefficient of variation criterion of 10%. Double limb and single limb agility performance was found to be highly correlated with lower extremity dexterity in both females and males (double limb: $r = -0.78$, $P = 0.001$ and $r = -0.62$, $P = 0.02$; single limb: $r = -0.65$, $P = 0.01$ and $r = -0.73$, $P = 0.003$, **Figure 5-2**). In contrast, measures of lower extremity strength and power were not significantly associated with time to complete the agility tests ($r = 0.32$ to -0.43, $P > 0.05$). Given that LED-test performance was significantly correlated with agility across sex, a linear regression analysis was performed examining the association between LED-test performance and agility controlling for sex. Both double limb and single limb agility performance remained significantly correlated with LED-test performance after controlling for sex (double limb: $r = -0.68$, $R^2 = 0.46$, $P < 0.001$; single limb: $r = -0.70$, $R^2 = 0.49$, $P < 0.001$).

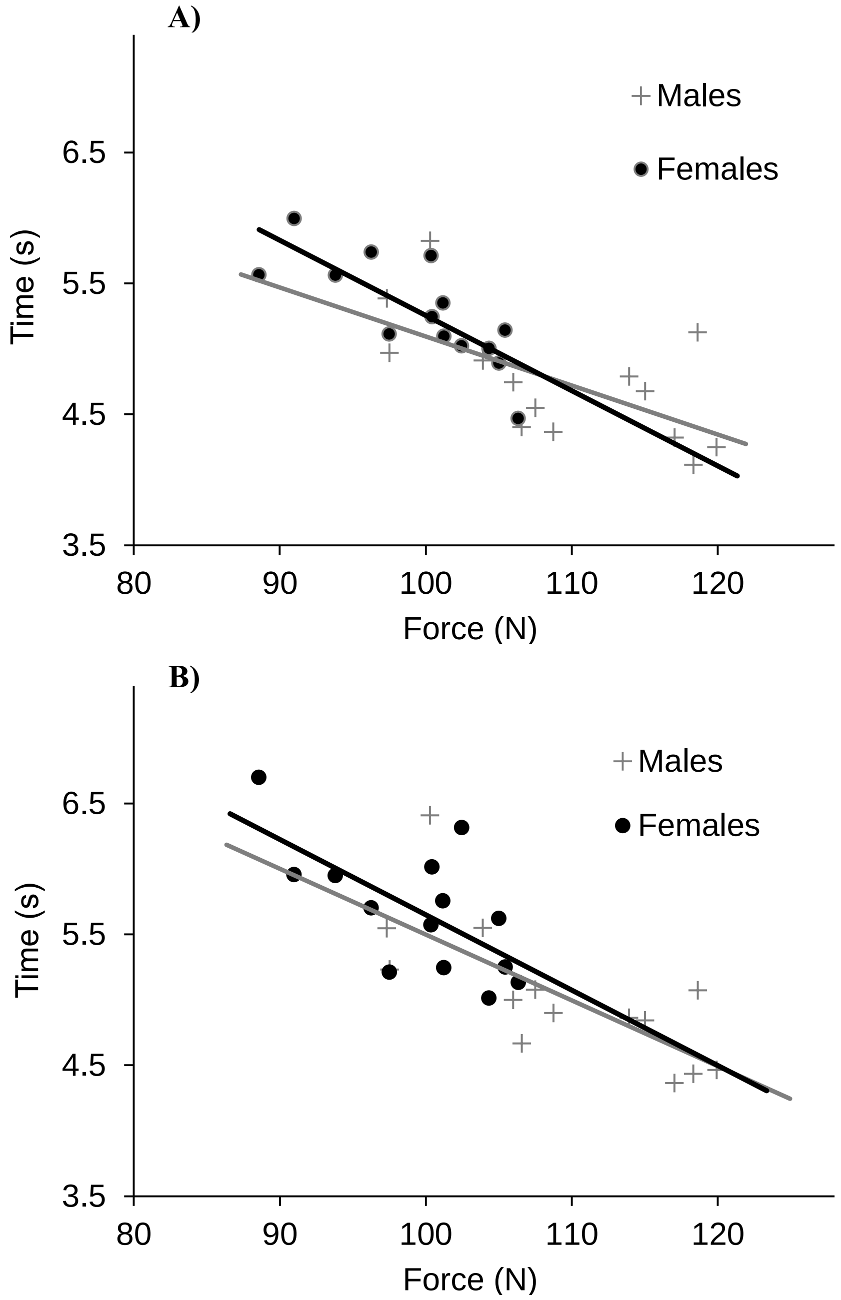

Figure 5-2. Scatter plot of **A)** double limb agility and LED-test performance. A strong and significant correlation was found for both females (r = -0.78, *P* = 0.001, n = 14) and males (r = -0.62, *P* = 0.02, n = 14). Scatter plot of **B)** single limb agility and LED-test performance. A strong and significant correlation was found for both females (r= -0.65, *P* = 0.01, n = 14) and males (r = -0.73, *P* = 0.003, n = 14).

The multivariate test of overall sex differences was statistically significant (P = 0.001). On average, male soccer athletes took less time to complete the double limb and single limb agility tests when compared to the female athletes (double limb: 4.74 ± 0.47 vs. 5.28 ± 0.4, P = 0.003; single limb: 5.0 ± 0.54 vs. 5.67 ± 0.49, P = 0.003, **Figure 5-3**). Male soccer athletes also had better lower extremity strength and power than female athletes (**Table 5-1**).

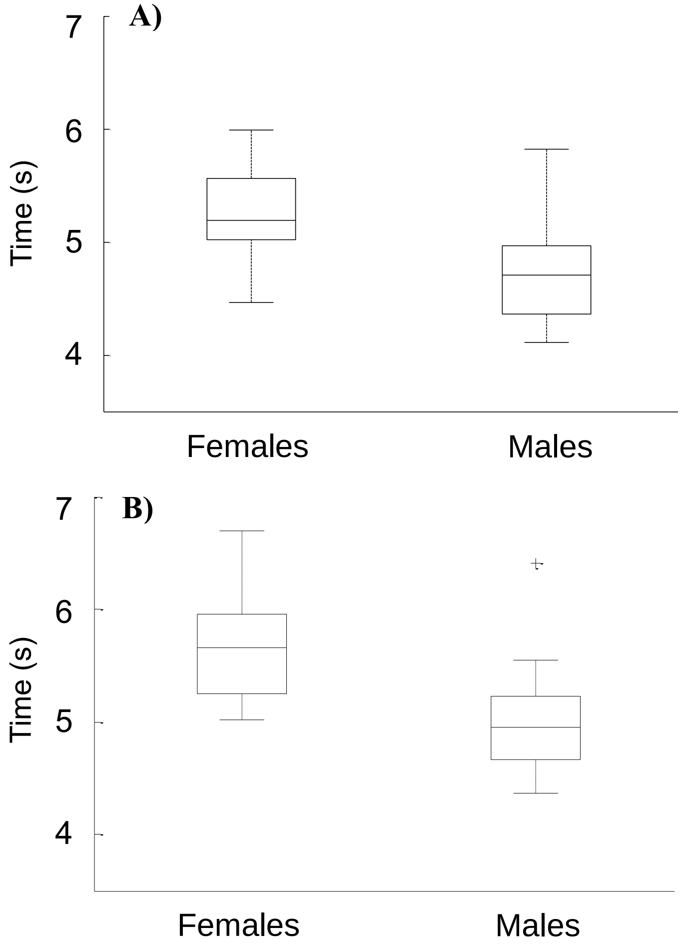

Figure 5-3. Males (n = 14) completed the **A)** double limb and **B)** single limb agility tests in significantly less time when compared to females (n = 14) (P = 0.003). The central horizontal line within the box represents the median value, the box edges represent 25th and 75th percentile, and the whiskers represent the outermost data points up to 1.5 times the interquartile range (plus sign represents an outlier).

Table 5-1. Sex comparison of lower extremity strength and power.[a,b]

	Females n = 14	Males n = 14	P [c]
Knee extensor strength, $N \cdot m \cdot kg^{-1}$	3.09 ± 0.46	3.47 ± 0.41	0.03
Knee flexor strength, $N \cdot m \cdot kg^{-1}$	1.43 ± 0.33	1.75 ± 0.35	0.02
Hip extensor strength, $N \cdot m \cdot kg^{-1}$	2.57 ± 0.55	3.29 ± 0.43	0.001
Vertical jump height, cm	39.5 ± 4.9	55.3 ± 10.5	< 0.001

[a] All values are mean ± SD; [b] Significant MANOVA; [c] *P* values are from univariate tests.

Discussion

Dynamic interactions between the lower limb and ground are required to initiate, decelerate, and change direction during locomotor tasks.[122-124,142] The primary aim of this Chapter was to examine whether a test designed to quantify the capability of the lower extremity to dynamically interact with the ground was associated with change of direction ability in high school soccer athletes. Consistent with our hypothesis, a robust association was observed between LED-test performance and agility in both female and male soccer athletes. In contrast, strength and power were not associated with agility performance. Our results suggest that the LED-test assesses a construct that is informative of the ability to perform a change of direction task.

Previous studies examining potential attributes that influence agility performance have focused on lower extremity strength and vertical jump height. While these measures of function are likely important for some aspects of sport performance, the relatively weak correlations between lower extremity muscle performance and agility found in the current study and in other investigations[6,66,91] suggest that maximal strength and power have a limited role concerning ones ability to change direction quickly. We propose that the ability to coordinate lower limb muscles to dynamically regulate the foot-ground interactions is more important for performing change of direction maneuvers. This premise is supported by the fact that performance on the LED-test explained approximately 50% of the variance in agility after controlling for sex.

On average, females were less skillful at regulating the leg-ground interactions when compared to males. However, sex was not the primary determinant of agility performance. Rather, dynamic lower extremity muscle coordination as assessed by the LED-test was the distinguishing feature, which appears to be less developed in females (see Chapter IV).

The sex differences in agility performance in the current study are consistent with previous studies. For example, performance on agility tests that require some sprinting has been shown to be better in males (11-17.5%) when compared to females.[108,113,114,126] Pauole et al.[126] reported a performance difference of 7% on a test focused on change of direction (i.e. hexagon test) in recreational athletes and 5% in collegiate athletes. In the current study, males completed the double limb agility test 10% faster (i.e. 540 ms), whereas single limb agility was completed 12% (i.e. 670 ms) faster than the females.

Apart from sex differences in agility performance, females exhibited decreased strength and vertical jump height when compared to the males in this study. Our findings compare well to other studies evaluating vertical jump height in skilled soccer athletes. The vertical jump height of skilled female club soccer athletes in a study by Vescovi et al.[167] was almost identical to the female athletes in the current study (i.e. 39 vs. 39.5 cm).

The male athletes in the current study jumped slightly higher compared to a group of skilled male soccer athletes in a previous report (52 vs. 55.3 cm).[113]

The findings of the current study provide a potential explanation for agility performance in the context of dynamic lower extremity control. It is evident from the literature that training programs that incorporate landing and change of direction can improve agility performance.[107,109,181] Our results provide empirical evidence for this approach and suggest that training aimed at improving agility should focus on tasks that challenge athletes' ability to dynamically interact with the ground. Varied levels of agility performance (e.g. sex difference) and dexterity could be attributed to varied levels of exposure or practice that challenges dynamic lower extremity coordination.[180] Advancing skill level within a sport would, therefore, be expected to provide a higher competitive level and potentially a stimulus to improve lower extremity dexterity. Indeed, studies have shown that agility performance is better in higher division players.[68,113,126,138,167] In addition, sex differences in agility performance narrows with advancing skill level.[23,113,126] Given that the years of soccer experience and relative level of competitive play were similar for the male and female athletes in the current study, examining whether male athletes adapt differently or challenge their sensorimotor system more often and to a greater extent than females during practice and competition may provide insight regarding the sex disparity in agility performance.

Although 50% of the variance in agility performance could be explained by performance on the LED-test, a significant amount of variance in agility performance remains unexplained. An implicit goal of the agility task at the whole body level is to redirect total body momentum to each target as quickly as possible. We speculate that a potential source of unexplained variance could arise from technique in this regard. For example, orienting the trunk in line with the subsequent ground reaction force during foot contact would minimize angular momentum and likely assist in effectively redirecting the center of mass.

A limitation of the current investigation is that we examined the performance of a fairly homogenous sample of skilled soccer athletes. The extent to which the findings from this study can be generalized to other populations remains unknown. In addition, a single agility task focusing on change of direction ability was examined. Evaluating the influence of lower extremity dexterity in other agility tasks would provide additional insight regarding the unique construct of human performance assessed by the LED-test.

Conclusion

The primary finding of this study was that lower extremity dexterity as assessed by the LED-test was significantly associated with change of direction ability. In contrast, lower extremity strength and power were not associated with agility. As such, this study provides evidence that lower extremity dexterity is an important construct required for sudden deceleration and change of direction maneuvers in male and female soccer athletes. Our results provide a scientific rationale for focusing exercise interventions intended to improve agility on tasks that challenge the capability of the lower limbs to dynamically interact with the ground.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Anterior cruciate ligament injuries are a serious sports medicine problem primarily affecting young female athletes. While arthroscopic reconstruction of the ACL and post-operative rehabilitation guidelines are well-established for this condition, the long-term outcomes are generally poor. For example, despite many athletes returning to play sports within a year of injury, most do not return to play at the same level of competition,[94,158] and approximately 1 in 4 suffer a second ACL injury.[125,130,178] In addition, it is estimated that half of the athletes that tear their ACL will exhibit signs and symptoms of knee osteoarthritis within 12 to 14 years.[79,84,94,170]

The best solution to mitigate the poor long-term outcomes after ACL reconstruction is to prevent these injuries from happening in the first place. Importantly, numerous studies have demonstrated that ACL injury rates can be decreased in female athletes after participating in specific exercise interventions.[50,74-77] Such exercise interventions have included plyometrics, technique instruction during landing and cutting, agility, balance, and strengthening. While the specific attribute(s) that the training enhances to reduce injury rates remains unknown, a potential benefit of the exercise training is improved dynamic lower limb control.[115] The rationale for this hypothesis is based on the primary emphasis of the exercise interventions, which focus on challenging the sensorimotor system to control lower limb alignment when performing multiplanar sport specific maneuvers.[115] Moreover, female athletes typically exhibit reduced dynamic limb control compared to male athletes during landing and cutting maneuvers.[55,56,101,132,148,155,156,183]

The reduced dynamic limb control observed in female athletes during landing and cutting maneuvers is thought to underlie the higher injury rates observed in this population. To test the hypothesis that the ability of the lower extremity to dynamically interact with the ground (i.e. dexterity) is a potentially important construct for injury risk, the development of a method designed to quantify this ability was required. As such, a primary objective of this dissertation was to develop a test method designed to quantify the capability of the lower extremity to dynamically interact with the ground. The test method, called the lower extremity dexterity test (the LED-test), was used to evaluate whether dexterity as assessed by this method is potentially informative of dynamic lower extremity function relevant for ACL injury risk in female athletes.

In Chapter III, the LED-test was described, reliability was assessed, and the association between LED-test performance and strength, body height, and body mass were evaluated. The LED-test consists of using the lower limb to compress a slender spring with the goal to achieve the highest average vertical force over a 10-second period during trials lasting 16 seconds. The LED-test was based on the inherent tendency of slender helical compression springs to buckle when compressed. That is, a slender spring becomes increasingly unstable as higher compression force is applied. Therefore, achieving higher forces was representative of the maximal sensorimotor capability to dynamically regulate foot-ground interactions. Because individuals perform the test while in an upright and well-supported posture, the LED-test represents a novel behavioral approach to objectively quantify dynamic lower extremity control without the potential confound of whole-body movement. Results revealed that performance across days was highly consistent in a group of healthy college-aged participants (ICC = 0.94). In addition, dexterity as assessed by the LED-test was independent of lower extremity strength. LED-test performance also was found to be independent of body height and mass. Taken together, the results from this study provide support that the LED-test is reliable and informative of a unique theoretical construct we refer to as dexterity.

As discussed earlier, reduced dynamic lower extremity control is a potential explanation for the higher ACL injury rates in female athletes. The purpose of Chapter IV was to compare lower extremity dexterity as assessed by the LED-test between female and male soccer athletes matched by age and skill level. A sex difference in dexterity as assessed by the LED-test would support the hypothesis that the capability of the lower limb to dynamically interact with the ground is a construct potentially associated with injury risk. Consistent with our hypothesis, it was found that female soccer athletes had reduced dexterity when compared to their male counterparts.

Several physiological mechanisms could underlie performance during the LED-test. The task goal specifies that participants direct force into an unstable surface with the lower limb, which necessitates dynamic stabilization of the test platform and regulation of force direction. This goal could be accomplished by using sensory feedback and/or feedforward pathways that may include voluntary co-contraction. It is well known that these options increase limb impedance but have inherent compromises when used in isolation.[60,151] Sensory feedback is metabolically efficient but suffers from delays due to sensory transmission. Voluntary co-contraction has no response delays but is metabolically inefficient and adds sensorimotor noise that could be destabilizing.[50] Furthermore, the ability to stiffen the limb by voluntary co-contraction is influenced by strength.[60] In Chapter III, LED-test performance was found to poorly correlate with lower extremity strength. Thus, it is unlikely that strength can account for the sex difference in LED-test performance or that the male and female athletes utilized a whole limb co-contraction stiffening strategy.

Several lines of evidence favor the interpretation that control during the LED-test is largely dependent on sensory feedback[24,72,128] and potentially selective co-contraction.[14,38] First, it has been established that task specific reflex modulation can regulate multi-joint limb mechanics and stability when interacting with a compliant environment.[24,72,128] Second, anesthetizing the thumbpad compromised the ability of otherwise healthy participants to compress a slender spring with the thumb.[165] Lastly, a differential increase in cortico-striatal-cerebellar networks has been observed when using the fingers to compress springs with increasing levels of instability, and not just increased primary motor cortex drive as would be anticipated for a strategy based on finger stiffness.[112] Therefore, we speculate that reflex tuning, and potentially selective co-contraction, was used more effectively by the male athletes to direct force while dynamically interacting with the unstable platform-spring system.

To evaluate the potential behavioral implications of reduced dexterity, sex differences during a single limb drop jump also were examined between the female and male high school soccer athletes (Chapter IV). Leg stiffness, which represents a global variable of multi-joint coordination,[15,30,31] was the primary biomechanical variable of interest. In addition, we compared ankle and knee co-contraction prior to foot contact and the time to peak vertical ground reaction force between sexes. A finding of higher leg stiffness in females would be consistent with a movement behavior considered to increase the risk of ACL injury.

Results of Chapter IV revealed that the female athletes performed the single limb drop jump with higher leg stiffness. The higher leg stiffness in females was attributed to both higher peak ground reaction forces and less center of mass displacement. Secondary biomechanical variables suggest that the female athletes decelerated total body momentum with a heightened feedforward control strategy for the following reasons: 1) limb geometry and center of mass velocity were similar between sexes at initial contact with the ground,[30] 2) the peak vertical ground reaction force occurred on average within 51 ms, and 3) female athletes exhibited higher ankle and knee co-contraction prior to foot contact presumably to actively regulate muscle stiffness in preparation for impact with the ground. Higher co-contraction prior to landing has previously been shown to result in higher ground reaction forces and leg stiffness.[151,152,163,164] Combined with the findings of sex differences in lower extremity dexterity, these results raise the possibility that the female athletes used a heightened feedforward motor control strategy as a compensation for reduced dynamic lower limb control. To our knowledge, this is the first empirical evidence demonstrating that dynamic lower extremity control is potentially responsible for the sex disparity in movement behavior and ACL injury rates.

Maneuvers involving rapid whole-body deceleration and change of direction are essential in sport. For this reason, the ability to change direction rapidly, often referred to as agility, is an important motor skill for sport performance.[132,166-168] Because dynamic foot-ground interactions are needed to change direction, Chapter V examined the extent to which LED-test performance (as opposed to muscle strength and power) was associated with agility. A secondary aim was to compare agility between male and female soccer athletes. Agility was assessed using a hopping sequence intended to quantify the ability to change direction quickly. The study was designed to test the hypothesis that agility performance would be significantly correlated with dexterity, whereas agility would not be correlated with strength and power. The primary finding of this study was that dexterity was highly correlated with agility performance in female and male athletes. In fact, approximately 50% of the variance in agility performance was explained by LED-test performance after controlling for sex. The results suggest that the LED-test assesses an experimental construct that reveals a dimension of dynamic function informative of change of direction ability. No correlation was found between agility and strength or power. Therefore, the findings suggest exercise interventions that aim to improve agility should focus on challenging athletes' ability to dynamically interact with the ground.

Apart from sport performance, the findings from this study may have implications for ACL injury risk. Non-contact ACL injuries occur most often during sudden deceleration and change of direction maneuvers requiring dynamic interactions of the lower limb and the ground (i.e. cutting and landing).[2,12,48] In addition, exercise programs that have incorporated plyometrics and sport-specific change of direction training[107,109,181] have been shown to improve agility performance. Importantly, the studies that have been shown to reduce ACL injury rates in female athletes[74,75,77,136] share common elements with the exercise interventions shown to improve agility. It is plausible therefore that the sensorimotor adaptations that improve agility may underlie reduced injury risk as well.

Identification of factors that are associated with injury risk is important for implementing effective injury screening and exercise interventions to prevent ACL injuries. Whereas current biomechanical methods provide limited insight regarding underlying reasons for the sex differences, the development of the LED-test may provide an explanation for the sex differences in movement behavior during sport maneuvers such as landing (Chapter IV) and change of direction ability (Chapter V). As previously discussed, there is evidence that the movement behavior exhibited by female athletes and reduced agility performance could contribute to the sex disparity in ACL injury rates. As such, the results from this dissertation provide support for including dexterity as a component of ACL injury screening procedures. While the findings of this dissertation are promising, whether performance on the LED-test is in fact predictive of ACL injury risk remains unknown. Prospective studies would be needed to formally test this hypothesis.

The findings from this dissertation are anticipated to advance the scientific basis for preventing ACL injuries and enhancing change of direction ability. For example, exercise interventions that have been shown to reduce injury rates and improve change of direction ability incorporate multiplanar landing and change of direction maneuvers. Results suggest that reduced dynamic lower extremity control in the female soccer athletes was responsible for their at-risk movement behavior during a single limb drop jump (Chapter IV) and reduced change of direction ability (Chapter V) when compared to their male counterparts. As such, this dissertation offers an empirical rationale for the current training approach. Based on our findings, we propose that exercise interventions should emphasize landing and cutting maneuvers in multiple planes and sequences to enhance athletes' sensorimotor ability to dynamically regulate foot-ground interactions such that they are able to control limb posture and smoothly attenuate impact forces.

Although the focus of this dissertation was on advancing the understanding of ACL injury risk and change of direction ability in athletes, the theoretical construct assessed by the LED-test is anticipated to advance our understanding of lower limb function in other populations as well. For example, the ability to dynamically interact with the ground would appear particularly relevant for maintaining balance during locomotor tasks implicated to cause falls in older adults. Therefore, a future application of the LED-test could be to examine whether older adults at risk for falls exhibit reduced LED-test performance. Interestingly, functional tests that predict risk of falls are similar in principle to the agility test used in this dissertation.[27,85] It is possible that the LED-test could also be used to assist with the early diagnosis of neuromuscular conditions such as Parkinson's disease. Persons with Parkinson's disease are known to have problems with turning, for example, but this impairment is not sensitive to observational gait analysis in the early stages.[22,32] In both cases discussed above, we anticipate that the LED-test would provide a more sensitive means to identify true impairments in limb dynamical capability that could otherwise be confounded by fear avoidance behavior.

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