BIOMECHANICAL EVALUATION OF LANDING MANEUVERS IN SOCCER PLAYERS WITH AN ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

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DEDICATION

To my family for their prayers, patience, and support throughout my graduate study.

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ABSTRACT

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This dissertation is composed of 3 studies. The first study included the following purposes 1) to evaluate within-session reliability of kinematics and kinetics during 2 landing tasks to determine the number of trials needed to achieve acceptable reliability, 2) to determine between-session reliability of kinematics, kinetics, and F-Scan system during the 2 landing maneuvers performed by healthy soccer players, 3) to evaluate the validity (concurrent validity) of the F-Scan system in relation to a platform system as a criterion reference during both landing maneuvers. The results indicated that F-Scan and 3D motion analysis systems are reliable during planned and unplanned landing maneuvers in healthy soccer players. Additionally, both landings can be used as functional tasks to assess lower extremity performance in this population if 4 trials of each landing are used in order to achieve good trial-to-trial reliability. Moreover, the F-Scan system is a valid instrument to measure ground reaction forces during planned and unplanned landing maneuvers.

The second study aimed to compare kinematics, kinetics, and neuromuscular performance between soccer players with an ACLR and healthy non-injured soccer players during planned and unplanned landing maneuvers. The results showed that unplanned landing demonstrated greater injury predisposing factors compared with planned landing by exhibiting a stiff landing technique characterized by decreased hip and knee flexion angles. Generally, soccer players with ACLR showed nearly similar landing mechanics and neuromuscular strategies to healthy non-injured soccer players during both planned and unplanned landing maneuvers. However, soccer players with ACLR appear to utilize a protective landing strategy by decreasing activation of the gastrocnemius muscle, when averaged across both landing tasks.

The purpose of the third study was to evaluate the effect of fatigue on landing biomechanics during an unplanned landing task in soccer players following ACLR compared with healthy non-injured soccer players. The results indicted that fatigue caused changes in landing biomechanics; however, these changes were not significantly different when the groups were compared. These results indicate that having an ACLR (at least 1 year post-surgery) does not appear to lead to sustained changes in landing biomechanics induced by fatigue.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

BACKGROUND

The anterior cruciate ligament (ACL) is one of the most commonly seen injuries in sport.[1] ACL injury has an annual incidence of more than 200,000 cases in the United States,[2,3] most of which are seen in adolescents playing sports that involve pivoting such as football, soccer, and basketball.[4-7] Soccer requires the athlete to perform high-risk maneuvers such as pivoting, cutting, and landing at high speed. Therefore, soccer players are particularly at high risk for ACL injuries.[6,8-10] Soccer has the highest prevalence among other sports with a rate ranging from 3.7 to 29.1 injuries per 1000 hour of practice and games.[11]

Rehabilitation following ACL reconstruction (ACLR) surgery is widely accepted as the proper intervention for restoring knee joint function, predominantly for athletes who want to return to their prior level of sport participation.[12] Investigators have reported that individuals with ACLR demonstrated significant improvements in functional tasks such as step-up, step-down, and the shuttle run.[13,14] On the other hand, some investigators claim that ACLR and post-surgical rehabilitation does not fully restore the normal function of the knee joint and some impairments might persist such as muscle weakness, proprioceptive and neuromuscular deficits, excessive tibial rotation, impaired postural control, and altered landing strategies.[15-19] The persistent impairments are usually cited as a factor hindering successful return to pre-injury level of sporting activities.[20] A systematic review and meta-analysis reported that at a mean of 3.5 years after ACLR surgery, only 63% of athletes were able to return to their prior level of sport participation and 44% were able to return to competitive sports.[21]

Landing from a jump has been cited as one of the most common athletic maneuvers to cause ACL injuries.[5,6,22-26] Therefore, in an attempt to prevent future injuries, substantial attention has focused on landing mechanics in patients following ACLR. In an attempt to mimic sport-specific activities in the clinical setting, landing mechanics in ACLR patients have been evaluated by functional tasks such as drop jump and up-down hop. Decker et al.[27] compared kinematics and kinetics performance between 11 healthy and 11 hamstring ACLR recreational athletes during a 60-centimeter vertical hop landing. They found that the ACLR group demonstrated a more erect landing posture at initial ground contact and a reduced rate of force application to the body. Compared with the healthy group, those in the ACLR group landed with more ankle plantarflexion and decreased hip and knee flexion. This stiff landing technique does not sufficiently allow the hip and knee joints to control the downward momentum during landing.[28] As a consequence, high forces at the knee joint will be generated resulting in excessive loading on the ACL that increases the risk of ACL injury.[1]

Gokeler et al.[29] analyzed muscle activity and movement patterns during landing from a single leg hop for distance in 9 ACLR patients 6 months after surgery. They found that the limb on the ACLR side had significant earlier onset times for gluteus maximus, vastus lateralis, rectus femoris, biceps femoris, semimembranosus, medial gastrocnemius, lateral gastrocnemius, and soleus compared with the uninvolved limb. Also, the involved limb demonstrated a significant decrease in knee flexion during the take-off and an increase in plantarflexion at initial contact. Some researchers have shown that patients with ACL reconstruction and ACL deficiency demonstrate neuromuscular compensatory strategies that help them to increase functional knee stability. Paterno et al.[30] showed that female ACL- reconstructed patients had higher vertical ground reaction forces (GRFs) on the uninvolved limb during a drop vertical jump when compared with the involved limb and the control group. Specifically, patients demonstrated this biomechanical limb asymmetry until a mean of 27 months after surgery. It has been suggested that landing with high vertical GRFs can predispose the knee joint to injuries.[31,32]

Even though some studies have investigated kinematics, kinetics, and neuromuscular strategies in people with ACLR, the same variables have not been investigated in soccer players with ACLR during planned and unplanned landing tasks. Planned landing such as a forward jump allows the athlete to preplan the landing pattern. On the other hand, unplanned landing, such as landing after heading a soccer ball, might affect muscle activation strategy that might alter the landing pattern. These 2 landing tasks are common in soccer and were selected in order to closely simulate soccer match situations.

Fatigue has been reported by several studies as one of the predisposing factors for musculoskeletal injuries.[33-39] Several researchers reported that neuromuscular fatigue causes various biomechanical changes that may place individuals at a greater risk of a non-contact ACL injury during landing.[33,40-42] Fatigue has specific effects on movement coordination,[43] motor control precision,[44] and altering multiple biomechanical parameters including lower extremity kinematics and kinetics.[33,45] Furthermore, some researchers have reported decreased vertical jump height,[46] decreased knee flexion,[47-49] impaired balance,[50,51] and increased electromyography (EMG) activity of quadriceps and hamstrings after a fatigue protocol.[46,52] Therefore, alteration in biomechanical parameters might predispose the knee to injury and more specifically might rupture the ACL. Some researchers have evaluated the effect of fatigue on kinematics and kinetics during landing by inducing fatigue locally around the knee joint,[41,53,54,] whereas others used a more general neuromuscular fatigue protocol.[33,40,55,56] Some of these studies indicated that neuromuscular fatigue causes biomechanical alterations during landing.[33,40-42] Particularly, a landing pattern characterized by increase in both knee abduction and hip internal rotation was reported.[33,42] Knee abduction and hip internal rotation are among the main biomechanical risk factors leading to non-contact ACL injuries because the ACL serves as a secondary restraint to knee internal rotation and abduction.[57,58] Therefore, increase in knee abduction and internal rotation can increase the load on the ACL that might strain and tear it.[57,58]

In a study of 10 male ACLR patients and 11 male non-injured control participants who were exposed to a general fatigue protocol to evaluate landing biomechanics during single limb landing, the researchers found that fatigue induced many biomechanical changes in the ACLR limb such as decrease in knee flexion and adduction moments.[18] Nevertheless, for the most part, the biomechanical changes in the ACLR limb were also seen in the uninvolved limb and in the control group. On the other hand, some researchers didn’t find significant differences in biomechanical and performance assessments between fatigued and non-fatigued sessions.[54,55,59] Individuals who have undergone ACLR might be at higher risk for the effect of fatigue. Specifically, soccer players may be vulnerable to the biomechanical effects of fatigue due to the fact that playing time and fatigue are increased throughout a soccer match.[39]

PURPOSE OF THE STUDY

The purpose of the study was threefold: 1) to determine the reliability of kinematics, kinetics, and foot pressure profile during 2 landing tasks (planned and unplanned) performed by healthy soccer players, 2) to compare kinematics, kinetics, foot pressure profile, and neuromuscular performance between soccer players with an ACL reconstruction and healthy non-injured soccer players during 2 different types of landing (planned vs. unplanned), and 3) to evaluate the effects of fatigue on kinematics, kinetics, foot pressure profile, and neuromuscular performance during unplanned non-fatigue and fatigue landings accomplished by the 2 groups.

SPECIFIC AIMS AND HYPOTHESES

The first study aimed to determine the test-retest reliability of kinematics, kinetics, and foot pressure profile during 2 landing tasks (planned and unplanned) performed by healthy soccer players. The proposed hypothesis for this study was that kinematics, kinetics, and foot pressure profile during the 2 landing tasks performed by healthy soccer players will be reliable, with Intraclass Correlation Coefficient (ICC) values > .75. Consequently, 2 sessions were performed to determine the test-retest reliability and the number of trials needed to achieve acceptable reliability.

The aim of the second study was to compare kinematics, kinetics, foot pressure profile, and neuromuscular performance between soccer players with an ACLR and healthy non-injured soccer players during 2 different types of landing (planned vs. unplanned). The proposed hypotheses were: 1) there will be significant main effects of landing on kinematics, kinetics, foot pressure profile, and EMG variables; 2) there will be significant main effects of group (ACLR and healthy) on kinematics, kinetics, foot pressure profile, and EMG variables; 3) there will be significant interaction effects between the type of landing and group on kinematics, kinetics, foot pressure profile, and EMG variables.

The third study aimed to compare kinematics, kinetics, foot pressure profile, and neuromuscular performance between soccer players with an ACLR and healthy non-injured soccer players during unplanned non-fatigue and fatigue landings. The proposed hypotheses were: 1) there will be significant main effects of fatigue on kinematics, kinetics, foot pressure profile, and EMG variables; 2) there will be significant main effects of group (ACLR and healthy) on kinematics, kinetics, foot pressure profile, and EMG variables; 3) there will be significant interaction effects between fatigue and group on kinematics, kinetics, foot pressure profile, and EMG variables.

INSTRUMENTATION

Each participant had 12 retro-reflective markers placed according to Vicon Plug-in gait model (Vicon Motion Systems Ltd. Denver, CO, USA) over both anterior superior iliac spines, second sacral vertebra, greater trochanters, lateral femoral epicondyles, mid-distance between greater trochanters and lateral femoral epicondyles, medial femoral epicondyles, lateral malleoli, mid-distance between lateral femoral epicondyles and lateral malleoli, medial malleoli, calcaneal tuberosities, and second metatarsophalangeal joints. A Vicon Motion Analysis System consisting of 10 digital cameras (240 Hz sampling rate) and 4 AMTI (Advanced Mechanical Technology Inc. Watertown, MA, USA) force platforms (1000 Hz sampling rate) was used to collect data. Peak ankle dorsiflexion/plantarflexion joint angles, peak plantarflexion moment, peak knee flexion and extension joint angles, peak knee extension moment, peak hip flexion and extension joint angles, peak hip extension, abduction and adduction moments, peak vertical and shear ground reaction forces were recorded for data analysis.

Surface EMG was recorded (1000 Hz sampling rate) using the Trigno Wireless EMG System (Delsys Inc. Boston, MA, USA). Sixteen bipolar Ag/AgCl wireless electrodes (contact dimension: 5mm×1mm; inter-bar distance: 10mm; bandwidth: 20-450 Hz; CMRR: > 80db) was placed on the skin over the 8 following muscles: gluteus maximus, vastus lateralis, rectus femoris, vastus medialis, lateral and medial hamstrings, and gastrocnemius according to Cram et al.[60] The skin was cleaned with a cotton ball soaked in 70% isopropyl alcohol before placing the electrodes. Adhesive tape was used to secure the placement of the electrodes during the jumps with the purpose of decreasing movement artifact.

The F-Scan wireless plantar-pressure measurement system (Tekscan Inc. Boston, MA, USA) was time-synchronized to the Vicon and EMG system and was used to capture in-shoe pressure information. Peak pressure was recorded for data analysis during the landing phase of both maneuvers.

A portable Lactate Plus Analyzer (Sports Resource Group Inc. USA; Measuring range: 0.3 to 25 millimoles per liter (mmol)/1 whole blood) was used for determining blood lactate concentration after the fatigue protocol. An accumulation of 4mmol of lactate was indicative of the desirable level of fatigue for each participant.[61]

A KT-1000 Arthrometer (MEDmetric Corp. San Diego, CA, USA) was used to determine if there was an anterior tibial translation difference between knees. The KT-1000 has been frequently used to obtain measurements in millimeters of the anterior tibial translation in clinical setting involving ACL disruption and ACL reconstruction.[62-65] The KT-1000 has been found to be a reliable and valid instrument.[65-70]

METHODS

All 3 studies were conducted at the Texas Woman's University Balance/Motion Analysis Research laboratory in Houston, Texas (Room# 10134). Before participating in each study, all participants were asked to read and sign an informed consent approved by the Institutional Review Board of TWU. Height, weight, age, level of play, and dominant leg were obtained from each participant. In addition, ACLR side, time and type of repair were obtained from each participant in the ACLR group.

Study One

Test-retest reliability of kinematic, kinetics, and foot pressure profile during planned and unplanned landing tasks.

Participants

Ten healthy soccer players were recruited using convenience sampling for this study. Inclusion criteria were current participation in soccer at recreational level (4 hours or more per week), and between the age of 18 and 35 years. Exclusion criteria were inability to perform a soccer-specific jump heading task, history of low back or lower extremity surgery, lower extremity injury in the 6 months before participating in the study, neurological disease, injury of other major ligaments of the lower extremity, and pregnancy.

Procedure

Each participant was asked to kick a soccer ball for determining the dominant leg.[71] The dominant leg was used as the tested leg for all the measurements in control subjects.[71] Participants were then asked to perform a warm-up protocol consisting of 5 minutes of cycling at 40 to 60 rotations per minute (rpm) on a cycle ergometer, 10 half squats, and 5 continuous vertical jumps. Also, each participant was given demonstration of functional tasks and instructed to perform 2 practice trials since these have shown good reliability (ICC $\geq$ 0.76).[72]

In this study, the landing tasks included a forward jump onto 4 force platforms (planned landing) and a forward jump to head a soccer ball and land on the 4 force platforms (unplanned landing). The order of these tasks was randomized for each participant. For the planned landing, each participant was instructed to jump from a distance (starting point) that was 80% of his/her maximum long jump away from the force platforms and land on the 4 force platforms.[73] The unplanned landing was executed by having each participant jump forward to head a soccer ball and then land on the 4 force platforms. The soccer ball was suspended from the ceiling at a location in the middle between the starting point and the 4 force platforms (40% of participant's maximum long jump). The height of the middle of the soccer ball was placed at half of the participant's maximum vertical jump height. Each participant was asked to perform 5 trials for each landing in the same session. Within 3 days from initial testing, each participant was asked to perform the same 5 trials.

Data Analysis

A univariate repeated measures analysis of variance (ANOVA), a two-way mixed model, was performed to develop within-session ICC values for the averages of 2 to 5 trials of each landing (ICC [3, k]). ICC values were calculated for a single trial (ICC [3,1]). Reliability was interpreted based on the following criteria: >0.75 good reliability, 0.50-0.74 moderate reliability, <0.49 poor reliability.[74] Another univariate repeated measures analysis of variance (ANOVA) was performed to develop between-session ICC. Alpha α will be set at 0.05 with adjustments as needed.

Study Two

Comparisons of kinematics, kinetics, foot pressure profile, and neuromuscular performance between soccer players with an ACLR and healthy non-injured soccer players during planned and unplanned landing maneuvers.

Study Three

Evaluation of the effects of fatigue on kinematics, kinetics, foot pressure profile, and neuromuscular performance during unplanned non-fatigue and fatigue landing in soccer players with an ACLR and healthy non-injured soccer players.

Participants

With an effect size of 0.20,[75] α set at 0.05, power = 0.80, the results of the power analysis revealed that 36 participants were needed for both groups to find differences between the 2 landing tasks if a difference exists. Eighteen participants were recruited using convenience sampling for each group in this study. Inclusion criteria for ACLR participants were: 1-10 years post ACLR, current participation in soccer at recreational level (4 hours or more per week), and between the age of 18 and 35 years. Exclusion criteria for these participants were: inability to perform a soccer-specific jump heading task, more than 3 mm anterior tibial translation difference between knees as measured by a knee arthrometer, low back or other lower extremity surgery, other lower extremity injury in the 6 months before participating in the study, neurological disease, bleeding disorders (e.g. hemophilia), injury of other major ligaments of the lower extremity, and pregnancy.

Inclusion criteria for healthy participants were: current participation in soccer at recreational level (4 hours or more per week), between the age of 18 and 35 years. Exclusion criteria for these participants were: inability to perform a soccer-specific jump heading task, low back or other lower extremity surgery, other lower extremity injury in the 6 months before participating in the study, neurological disease, bleeding disorders (e.g. hemophilia), injury of other major ligaments of the lower extremity, and pregnancy.

Procedure

Participants were given the same warm-up protocol as well as a demonstration of the 2 landing tasks before performing the 2 practice trials as described in Study One. They were asked to perform 4 trials of each landing tasks as described in Study One. The order of these tasks was randomized for each participant to avoid learning effect.

For Study Three, participants performed the fatigue session within the same day following the non-fatigue session. With the purpose of inducing metabolic fatigue, each participant was instructed to perform 30-second Wingate anaerobic protocol.[76] Before performing the fatigue protocol, participants were asked to perform the same warm-up as completed in Study One. Following the warm-up, participants were asked to read a script to standardize the amount and type of verbal encouragement throughout the Wingate protocol. Each participant was asked to pedal as fast as possible against a pre-determined resistance for 30 seconds. The constant 0.090 kilopond was multiplied by each subject's weight to calculate the resistance on the cycle ergometer.[77] Immediately after completing the Wingate protocol, the principal investigator obtained blood samples from each participant's fingertip for determining the blood lactate concentration. To make sure that each participant reaches the accepted level of fatigue, 4 mmol of lactate or more was considered as the desirable level of exhaustion as this level is cited as the anaerobic threshold.[61] A participant who did not reach this level was instructed to perform an additional 30-second bout of pedaling. Participants then performed the same number of trials of the 2 landing tasks needed in the non-fatigue session. In order to limit recovery from fatigue throughout the fatigued session, all trials were performed within 30 seconds of each other. Furthermore, participants were asked to continue performing squats as data were saved in the computer and the Vicon system was being prepared for the following trials.

Data Analysis

For Study Two, to compare between the ACLR and control group, a 2 × 2 mixed ANOVA (group × landing) was performed for each of the dependent variable. Group (ACLR and control group) was the between-subjects factor and landing (planned and unplanned) was the within-subjects factor. An α level of .05/3 or .0167 was used to represent statistical significance. Alpha levels were adjusted for simple effects and follow-up comparisons.

For Study Three, to compare between the ACLR and control group, a 2×2 mixed ANOVA (group $\times$ fatigue) was performed for each of the dependent variables. Group (ACLR and control group) was the between-subjects factor and fatigue (fatigued and nonfatigued) was the within-subjects factor. An α level of .05/3 or .0167 was used to represent statistical significance. Alpha levels were adjusted for simple effects and follow-up comparisons.

CHAPTER II

LITERATURE REVIEW

EPIDEMIOLOGY

The anterior cruciate ligament (ACL) injury is commonly seen in sports and has an annual incidence of more than 200,000 injuries in the United States.[1-4] It commonly occurs in sports activities such as soccer, basketball, football, and handball; however, the ACL is most frequently ruptured in soccer, representing 43% of all soccer-related injuries. [5-10] Soccer players are presumably at higher risk for ACL injuries due to the frequent performance of high-risk maneuvers such as cutting, pivoting, and landing at high speed.[7,11-13] A prospective cohort study reported a rate of 0.4 ACL injuries per season for professional men's soccer team and 0.7 ACL injuries per season for professional women's soccer team from the 2001 season to 2009 season.[14]

ANATOMY AND BIOMECHANICS OF THE ANTERIOR CRUCIATE LIGAMENT

The ACL originates from the intercondylar notch of the lateral femoral condyle and runs to its insertion at the anterior part of the tibial plateau.[15-17] This ligament is functionally composed of 2 bundles (anteromedial bundle [AM] and posterolateral bundle [PL]) that are named based on their attachments on the tibia.[16,18] The mean length of the AM bundle is 33 mm whereas the PL bundle is 18 mm.[18-22] The ACL has an overall width ranging from 7 to 17 mm in cadavers.[18] Men have an average ACL cross-sectional area of 47 mm^2 whereas women have an average of 36 mm^2.[18,23] Type I collagen fibers make up the ACL which is vascularized mainly by the middle genicular artery and partially by the middle inferomedial and inferolateral genicular arteries.[18] This ligament contains several mechanoreceptors, which have been cited as a key factor in functional stability of the knee joint, including Ruffini corpuscles, Golgi-like organs, Pacinian corpuscles, and free nerve ends.[24,25]

The ACL serves as the primary restraint against anterior tibial translation, receiving approximately 85% of the anterior tibial translation load between 30° and 90° knee flexion and 75% during full knee extension.[26] Therefore, tearing the ACL may lead to an unstable knee due to a reduction in the resistance against the anterior tibial translation. In addition, the ACL may serve as a restraint to internal tibial rotation during anterior tibial translation. Previous researchers have reported a significant increase of internal tibial rotation when the ACL was sectioned.[27] Moreover, the ACL is considered as a secondary restraint against valgus load at the knee joint, with the medial collateral ligament (MCL) being the primary restraint.[28,29] Previous researchers have reported that injury of the MCL might increase the loading on the ACL during valgus stress.[29] These biomechanical characteristics of the ACL suggest that the most vulnerable maneuver for an ACL injury would be a position in which increased valgus and knee internal rotation load are combined near full knee extension.[27-30]

RISK FACTORS

Many theories have been proposed to identify the factors associated with the increased risk of ACL injury, with the goal of designing intervention and prevention programs for those who are at increased risk of sustaining an ACL injury. These risk factors have been classified into intrinsic and extrinsic factors.[31] However, other common classification scheme has been proposed that classifies these risk factors into 4 categories: environmental, hormonal, anatomical, and neuromuscular.[6,32]

Environmental Factors

Environmental factors are those that are outside the body including: weather, the type of playing surface, footwear, and the use of protective devices.[32] Weather condition has been found to be associated with increased risk of ACL injury due to its effect on the shoe-surface traction.[32] Previous studies have shown that the number of ACL injuries decreased during periods of high rainfall, presumably due to decreased traction between the shoe and the ground.[33,34] The type of the surface has been reported to have a significant impact on ACL injury rates.[32] Previous studies suggest that playing on artificial floors is more risky due to the increased shoe-surface traction that might hold the foot to the ground during pivoting or cutting.[32,35] Furthermore, footwear is thought to be a potential risk factor for ACL injuries due to its significant role in controlling the foot fixation during the match.[32] Previous researchers have reported that longer cleat length was significantly associated with higher ACL injury rate due to the increased shoe-surface torsional resistance.[36] Lastly, the use of protective equipment such as knee braces has been reported to provide support to the knee joint during functional activities such as reducing anterior tibial translation.[32,37,38] Previous researchers have reported that the rate of knee injury in the braced cadets was lower than non-braced cadets.[39]

Anatomical Factors

Anatomical factors are those related to the body including: quadriceps-angle (Q-angle), foot pronation, intercondylar notch width, pelvic-to-femoral-length ratios, and body mass index.[32] The Q-angle has been suggested as a risk factor for ACL injuries by altering lower extremity kinematics.[6,40-42] The Q-angle is the angle between a line from the anterior superior iliac spine to the center of the patella and a second line from the center of the patella to the tibial tubercle.[43] Larger Q-angle is thought to place individuals at higher risk of sustaining knee injuries caused by increased forces applied to the knee joint.[44] In addition, excessive foot pronation has been postulated to contribute to ACL injury by increasing internal tibial rotation.[45-47]

Moreover, an association between narrow intercondylar notch and increased risk of ACL injury has been proposed.[48,49] Narrower intercondylar notch might limit the ACL to move in a smaller space placing the ACL at risk of injury during rotational movements.[49] Research suggests that greater pelvic-to-femoral-length ratios may contribute to ACL injury by creating greater valgus forces that may increase the stress on the ACL.[50] Another commonly purported anatomical risk factor associated with increased risk of ACL injury is increased body mass index.[32] Previous investigators have reported that increased BMI may lead to a more extended landing strategy, a landing pattern associated with increased risk of ACL injury.[51]

Hormonal Factors

The rate of the ACL injury in females is 2 to 6 times higher than males in soccer.[7] It has been well established that the human ACL has estrogen and progesterone receptors, which may indicate a hormonal impact on ACL injury.[52] The mechanical properties of the ACL in females are influenced by the hormonal fluctuations during the menstrual cycle.[53] Particularly, estrogen has been reported to reduce fibroblast proliferation and collagen formation that may increase the laxity of the ACL and thus make the ACL more prone to injuries.[54] Previous investigators have evaluated the potential relationship between the menstrual cycle and the risk of ACL injuries.[53,55] Some researchers have reported that the number of ACL injuries seem to increase in the first half of the menstrual cycle due to the high level of estrogen concentration during this phase.[53,55]

Neuromuscular Factors

Neuromuscular factors are subdivided into altered movement patterns, altered muscle activation patterns, and inadequate muscle stiffness.[32] Previous researchers have identified specific movement patterns during functional tasks that might predispose individuals to ACL injuries such as decreased hip and knee flexion angles, increased internal hip rotation, increased knee valgus, increased external tibial rotation, and greater ground reaction forces.[56-62] In addition, fatigue has been cited as a factor that has negative effects on movement patters that may increase the loading on the ACL.[32] Quadriceps-dominant contraction during landing and cutting tasks has been proposed as a contributing factor to the development of ACL injury by increasing the anterior displacement of the tibia.[32,58,63,64] Previous researchers have found that women recreational athletes had greater quadriceps muscle activity and lower hamstrings activity compared with men.[65] Research suggests that decreased muscle stiffness may contribute to the incidence of ACL injury by altering the stability of the knee joint.[32,66-70] It has been found that female athletes have significantly lower maximum activation of the knee muscles compared with male athletes, suggesting that females might not generate adequate muscular protection of the knee ligaments such as minimizing anterior tibial translation.[32,70]

MECHANISM OF INJURY

Mechanism of ACL injury is divided into 2 categories: contact and non-contact ACL injury.[71] Contact ACL injuries occur in the presence of contact with another player or an object such as hitting the lateral side of the knee. On the other hand, non-contact ACL injuries occur in the absence of contact with another player or an object such as landing form a jump. Up to 84% of all ACL injuries occur as non-contact mechanism in both males and females.[72-76]

In soccer, most ACL injuries occur as non-contact mechanism involving maneuvers such as landing from a jump, sudden deceleration, changing of direction, cutting, and pivoting.[72,73,77] These maneuvers, which are frequently performed throughout a soccer match, involve anterior translation force, knee hyperextension, knee hyperflexion, excessive knee valgus, excessive knee varus, internal rotation, and external rotation moments.[72,78-83] Previous researchers have reported that these maneuvers may place greater forces at the knee joint that may result in excessive loading on the ACL. [72,74,78,84] For example, applying anterior shear force on the tibia when the knee joint is at 20-30 degrees of flexion produces high strain on the ACL.[72,74,78,84] This force has been cited as the most isolated force associated with ACL injury.[72,74,78,84] It has been reported that combining forces such as anterior shear force with knee valgus creates higher strain on the ACL than an isolated force.[77,78,84]

CONSEQUENCES OF ACL INJURY

Rupture of the ACL is considered as one of the most devastating injuries in sports worldwide.[1,85-88] This injury often results in pain, knee effusion and instability, increased anterior tibial translation, muscle weakness, and excessive tibial rotation.[1,89] Therefore, individuals with ACL tears often demonstrate lower extremity biomechanical and neuromuscular changes that reduce their functional performance as well as sport participation.[1] Furthermore, this injury may lead to economical and social consequences that influence the athletes' quality of life.[89,90] The annual estimated cost for ACL reconstruction surgery and rehabilitation is over $1.7 billion in the United States.[91] Although rehabilitation after ACL reconstruction (ACLR) is claimed to be successful at restoring knee joint function, this injury might hinder athletes from participating in sports.[1,89,90]

Long-term clinical squelae have been cited in individuals with ACL injury such as chondral lesions, meniscal tears, and posttraumatic knee osteoarthritis.[92-96] In a retrospective study of 219 male soccer players 14 years after an ACL injury, Porat et al.[95] reported that significant radiographic changes were found in approximately 80% of the subjects, and more than 40% had radiographic knee osteoarthritis. Similarly, in a retrospective study of 103 female soccer players 12 years after an ACL injury, Lohmander et al.[89] reported that significant radiographic changes were found in 82% of the subjects, and more than 50%

had radiographic knee osteoarthritis. Consequently, treatment of the long-term clinical squelae associated with ACL injury might escalate the total health care spending.

ACL RECONSTRUCTION

Multiple approaches have been developed to treat the ACL deficient knee; however, the current gold standard of treatment is surgical reconstruction of the ACL, predominantly for individuals who wish to return to high level sports participation.[97] The goal of the ACLR is to restore the stability of the knee joint by surgically harvesting a graft to replace the torn ACL.[97] Bone-patellar tendon bone (BPTB) and hamstring tendon grafts are the most widely used techniques for ACLR.[97] Indeed, the most ideal graft for ACLR is still controversial. Previously, bone-patellar tendon bone graft was considered as the gold standard in ACLR.[98-101] However, the number of surgeries using this graft has been decreased due to the potential complications associated with this graft such as arthrofibrosis, anterior knee pain, and quadriceps weakness and thus the hamstring tendon graft has become the most popular graft in ACLR.[102,103] In a systematic review of 9 randomized controlled trials, Li et al.[104] concluded that restoration of knee joint function was similar for both BPTB autografts and hamstring autografts. In a recent meta-analysis of 22 studies, Xie et al.[105] reported that BPTB autografts are superior to four-strand hamstring tendon (4SHT) autografts in terms of restoration of rotation stability of the knee joint as well as returning to higher levels of sports participation.

Several authors have reported that the ACLR can improve the stability of the knee joint by decreasing the anteroposterior joint motion that might decrease the potential risk of meniscal injuries.[106-111] Moreover, individuals with ACLR have demonstrated improved biomechanics during functional tasks such as step up and shuttle run.[112,113] On the other hand, some investigators claim that ACLR and post-surgical rehabilitation does not fully restore the normal function of the knee joint and some impairments might persist such as muscle weakness, proprioceptive and neuromuscular deficits, excessive tibial rotation, impaired postural control, and altered landing strategies.[114-118] The persistent impairments are usually cited as a factor hindering successful return to pre-injury level of sporting activities.[119] A systematic review and meta-analysis reported that at a mean of 3.5 years after ACLR surgery, only 63% of athletes were able to return to their prior level of sport participation and 44% were able to return to competitive sports.[120]

Biomechanical Evaluation after ACL Reconstruction

Several studies have been conducted to evaluate the lower extremity biomechanics in patients with ACLR. Some investigators have reported that individuals with ACLR demonstrated significant improvements in several functional tasks.[112,113,121] For instance, Kanisawa et al.[112] evaluated knee kinematics in 11 subjects with ACLR during step-up and step-down activity using lateral fluoroscopy. According to their results, there were no statistical differences between the operated and the normal knee in terms of axial rotation, lateral or medial condylar anterior/posterior translation. The researchers concluded that the operated knees demonstrated kinematics values that were within the normal range. Furthermore, Keays et al.[113] evaluated quadriceps and hamstring muscle strength and functional performance in 31 subjects with ACLR 1 week prior to and 6 months after surgery. Subjects performed 5 functional tests including: shuttle run, side step, carioca, single hop for distance, and triple hop. The researchers reported that despite the significant loss of quadriceps and hamstring muscles strength, there were significant improvements previous to and after surgery for all the 5 functional tests: shuttle run (9%, $p < 0.01$), side step (15%, $p < 0.001$), carioca (24%, $p < 0.001$), single hop for distance (11%, $p < 0.01$), and triple hop (6.3%, $p < 0.01$). Additionally, in a cross-sectional study of 22 male professional soccer players, Chaves et al.[121] utilized isokinetic dynamometer, EMG and electronic baropodemeter to investigate neuromuscular characteristics of the vastus medialis oblique and postural balance after ACLR (4-12 months post-operatively). All participants underwent an accelerated functional rehabilitation protocol. Their results showed that there were no significant differences between the involved and uninvolved limb in the neuromuscular efficiency of the vastus medialis oblique and postural balance. The investigators concluded that the involved limb successfully restored the neuromuscular efficiency of the vastus medialis oblique and postural balance after the ACLR.

On the other hand, some investigators claim that ACLR and post-surgical rehabilitation does not fully restore the normal function of the knee joint and some impairments might persist. Mouzopoulos et al.[122] compared hip flexors strength between 64 healthy male recreational athletes and 68 male recreational athletes with ACLR. The researchers reported that the hip flexion strength was statistically lower in the ACLR group than the healthy group ($p < 0.001$). Moreover, in a cross-sectional study, Schmitt et al.[119] evaluated the impact of quadriceps femoris strength asymmetry on functional performance in 35 healthy individuals and 55 individuals with ACLR. Isokinetic dynamometer, international knee documentation committee subjective evaluation form, and single-leg hop tests were utilized to assess maximum voluntary isometric contraction of the quadriceps femoris, self-reported function, and functional performance, respectively. The researchers reported that individuals with ACLR had significantly weaker quadriceps femoris strength than the control group ($p < 0.001$). Additionally, ACLR group demonstrated a significant decrease in function and performance compared with the control group, with p-values of < 0.01: $p \leq 0.03$, respectively.

Cordeiro et al.[123] evaluated knee joint functionality (measured by Knee Injury and Osteoarthritis Outcome Score), movement confidence (measured by Tampa Scale of Kinesiophobia), knee kinematics, and muscle (quadriceps and hamstring) activation pattern during the extension phase of the inside soccer kick. Their sample included 8 professional soccer players with ACLR and 9 healthy non-injured professional soccer players. The results showed that the knee joint functionality and movement confidence were significantly different between the ACL group and the healthy group. Specifically, the ACL group demonstrated decreased level of confidence as well as knee joint functionality when compared with the healthy group. In addition, the ACL group demonstrated significantly higher maximum extension angles during the inside kick than the healthy group ($p < 0.021$). In terms of muscle activation pattern, the ACL group showed significantly higher rectus femoris activation than the healthy group ($p < 0.034$).

Stearns et al.[124] conducted a study to compare frontal plane knee joint biomechanics between 12 female soccer players with ACLR (46.3 ± 39.7 months after surgery) and 12 female non-injured soccer players during a side-step cutting task. According to their findings, female soccer players with ACLR showed significantly higher knee abduction angles ($p = 0.03$) as well as peak knee adduction moment ($p = 0.004$) than their counterparts during the early deceleration phase. The investigators concluded that athletes who returned to sport participation after ACLR might exhibit some biomechanical alterations that might place them at a greater risk of reinjury. In lieu of utilizing the traditional kinematic variables such as knee angles, Pollard et al.[125] used lower extremity coupling variability approach to evaluate lower extremity mechanics in female soccer players with ACLR during a side-step cutting maneuver. Ten female soccer players with ACLR (42.4 ± 41.8 months after surgery) and 10 healthy female non-injured soccer players were included in this study. Their findings showed that hip rotation/ knee abduction-adduction ($p = 0.04$), hip flexion-extension/ knee abduction-adduction ($p = 0.05$), knee abduction-adduction/ knee flexion-extension ($p < 0.01$), and knee abduction-adduction/ knee rotation ($p = 0.03$) were significantly higher in the ACL group than the healthy group. The investigators concluded that female soccer players with ACLR demonstrated increased movement variability during side-step cutting task indicating alterations in neuromuscular control.

In a prospective study of 40 competitive soccer players, Alvarez-Diaz et al.[126] evaluated the muscular mechanical and contractile properties of the lower extremity as measured by tensiomyography before and 1 year after ACLR using bone-patellar tendon bone autograft. Tensiomyography is widely used to evaluate mechanical and contractile characteristics of the muscles in response to electrical stimulation.[126] All participants underwent a standardized rehabilitation protocol after the surgery. The investigators reported that the injured limb showed a significant decrease after the ACLR in the following parameters: vastus lateralis contraction time, semitendinosus contraction time, gastrocnemius medialis contraction time, gastrocnemius lateralis half relaxation time, and gastrocnemius lateralis delay time. Additionally, the injured limb showed significantly higher magnitude of before and after surgery differences than the uninvolved limb in the following parameters: rectus femoris contraction time, semitendinosus contraction time, biceps femoris maximal displacement, and gastrocnemius lateralis half relaxation time. Compared with pre-operative parameters, the percentage of symmetry between both limbs was significantly higher after the ACLR in vastus medialis, vastus lateralis, rectus femoris, and gastrocnemius medialis ($p \leq 0.02$).

In conclusion, although some investigators reported improvement in functional tasks after ACLR, the majority of the studies have shown that rehabilitation following ACLR may not restore the normal function of the knee joint and some impairments may persist. The persistent impairments are thought to hinder successful return to pre-injury level of sporting activities.[119]

FATIGUE

Fatigue may be defined as the transient decrease to generate maximum power or force during repeated or sustained muscle contractions.[127-129] Fatigue is divided into central fatigue and peripheral fatigue.[127-129] Central fatigue (above the neuromuscular junction) occurs due to changes within the central nervous system such as loss of recruitment of high threshold motor units.[128,129] On the other hand, peripheral fatigue (below the neuromuscular junction) occurs due to lactate accumulation and changes within the muscle such as alterations of sarcoplasmic reticulum calcium uptake and release rates.[127,128] Also, muscles can anaerobically, when oxygen is not sufficient, convert pyruvate into lactic acid which can be cleared by the body.[127,128,130] However, during prolonged sporting activities, production of lactic acid might surpass the clearance rate that results in high accumulation of lactic acid in bloodstream.[127,128,130] Neuromuscular fatigue is caused by various changes within both the central and peripheral components and is a common process in sports such as soccer.[127-129] As a consequence, these changes may require the neuromuscular system to adopt specific strategies such as altering muscle activity and movement patterns in an effort to maintain stable performance levels. In other words, an athlete may utilize certain muscles and alter his/her movement maneuvers in an attempt to compensate for the effects of fatigue. These alterations in the central and peripheral components may reduce the muscle's ability to efficiently perform its function.[127-129]

Fatigue has been found to be one of the main predisposing factors for musculoskeletal injuries.[131-137] Several researchers reported that neuromuscular fatigue causes various biomechanical changes that may place individuals at a greater risk of a non-contact ACL injury during landing.[131,138-140] Fatigue has specific effects on movement coordination,[141] motor control precision,[142] and altering multiple biomechanical parameters including lower extremity kinematics and kinetics.[131,143] Furthermore, some researchers have reported decreased vertical jump height,[144] decreased knee flexion,[145,146] impaired balance,[147,148] and increased electromyography (EMG) activity of quadriceps and hamstrings after a fatigue protocol.[144,149]

Therefore, alteration in biomechanical parameters might predispose the knee to injury and more specifically might rupture the ACL. Some researchers have evaluated the effect of fatigue on kinematics and kinetics during landing by inducing fatigue locally around the knee joint,[139,150,151,] whereas others used a more general neuromuscular fatigue protocol.[131,138,152,153] Some of these studies indicated that neuromuscular fatigue causes biomechanical alterations during landing.[131,138-140] Particularly, a landing pattern characterized by increase in both knee abduction and internal rotation was reported.[131,140] Knee abduction and internal rotation are among the main biomechanical risk factors leading to non-contact ACL injuries because the ACL serves as a secondary restraint to knee internal rotation and abduction.[79,80] Therefore, increase in knee abduction and internal rotation can increase the load on the ACL that might strain and tear it.

Effects of Fatigue after ACL Reconstruction

Previous researchers have compared the effect of fatigue between normal individuals and individuals with ACLR. The persistent impairments that have been reported in individuals with ACLR may suggest greater vulnerability to the effect of fatigue. However, findings from previous investigations are controversial where some results supported this notion and others were inconsistent. In response to the effect of fatigue, some researchers found that fatigue effects were more exacerbated in normal individuals than individuals with ACLR. For example, in study of 12 ACLR patients (at a mean of 10 ± 24 months after surgery) and 10 normal subjects, the researchers evaluated the effect of fatigue on landing performance assessed with the Landing Error Scoring System (LESS).[154] The LESS is a clinical tool utilized to identify movement patterns that may predispose individuals to lower extremity injuries during drop landing maneuvers.[154] It is composed of 17 landing patterns errors, where scores greater than 6 indicates poor landing technique and scores less or equal to 4 indicates better landing strategy.[154] In this study, subjects were asked to jump off a 30-centimeter high box to a distance of 50% of subjects' body weight and immediately perform a maximal vertical jump. In order to induce a generalized fatigue protocol, participants were asked to perform 10 double-legged squats followed by 2 repetitions of countermovement jump (CMJ) until they were no longer able to reach 70% of their maximum CMJ height for 2 consecutive trials. The landing performance was assessed before and after the fatigue protocol. The researchers found that in the pre-fatigue condition, the ACLR patients had a median LESS of 6.5, whereas the control group had 2.5. In response to the fatigue, the median LESS increased in both groups indicating poor landing technique, where the ACLR patients had an average LESS of 7 and the control group had LESS of 6. The control group demonstrated a greater LESS increase compared with the ACLR patients; however, this difference did not reach statistical difference ($p = 0.16$). The authors reported that changes in the LESS induced by fatigue were more pronounced in the control group than the ACLR patients. The researchers suggested that due to the difference between groups at pre-fatigue, the control group might have more room for increasing their LESS score in the post-fatigue condition. Other researchers found a similar result that changes due to fatigue may be more pronounced in the control group than patients with ACLR. Kuenze et al.[155] examined the effect of fatigue on knee extension torque, quadriceps central activation ratio (CAR), and soleus motoneuron-pool excitability after ACLR. Twenty-six ACLR participants (minimum of 6 months post-surgery) and 26 healthy participants were examined before and after completing a fatigue exercise that included a 30 minutes of treadmill walking, body-weight-resisted squats, and set-ups. The treadmill incline was increased 1°/min until 15° of incline was reached. Subjects were asked to rate their level of exertion using the Borg scale of perceived exertion. The authors reported that there was a significant group × time interaction in knee extension torque ($F_{1,50} = 11.16$, $p = 0.002$), quadriceps CAR ($F_{1,50} = 5.01$, $p = 0.03$), and soleus V-wave to M-wave (V:M) ratio ($F_{1,50} = 5.33$, $p = 0.03$). The ACLR group demonstrated less knee extension torque, quadriceps CAR, and soleus V:M ratio than the healthy group before and after the exercise. However, the magnitude of the reduction was smaller for the ACLR group than the healthy group for knee extension torque (ACLR: %Δ = -4.2 [-8.7, 0.3]; Healthy: %Δ = -14.2 [-18.2, -10.2]), quadriceps CAR (ACLR: %Δ = -5.1 [-8.0, -2.1]; Healthy: %Δ = -10.0 [-13.3, -6.7]), and soleus V:M ratio (ACLR: %Δ = 37.6 [2.1, 73.0]; Healthy: %Δ = -24.9 [-38.6, -11.3]). The researchers concluded that adaptation in lower extremity muscle function might be present in patients with ACLR, thus altering lower extremity function in response to fatigue.

On the other hand, other investigators found no significant differences between individuals with ACLR and healthy non-injured subjects in response to the fatigue effect. For instance, Webster et al.[117] conducted a study to evaluate the effect of fatigue on lower limb kinematics and kinetics after ACLR during landing. Ten male ACLR patients and 11 non-injured control male participants were exposed to a general fatigue protocol consisting of 10 consecutives bilateral squats to a 90^{o} of knee flexion with arms parallel to the ground. The subjects were instructed to perform additional squats if they did not reach the acceptable fatigue level. Single leg landings from a 30 cm platform were divided into 3 fatigue groups; pre-fatigue, 50% fatigue, and 100% fatigue. The researchers reported that fatigue altered many biomechanical variables in the ACLR limb, uninvolved limb, and the control group as well. Nonetheless, no statistical differences were found between the ACLR group and the control group as well as the ACLR limb and the uninvolved limb. The researchers reported that the ACLR limb did not respond to the fatigue differently compared with the uninvolved limb and the control group during single-leg landing. They concluded that the biomechanical changes that fatigue induces might not be more pronounced in individuals with ACLR compared with the normal individuals. Furthermore, Lepley et al.[156] examined the effect of fatigue on quadriceps:hamstring muscle cocontraction index (CCI) and muscle activation pattern for the vastus lateralis and lateral hamstring muscles during a dynamic jumping-landing task. Their sample consisted of 12 ACLR patients (7-10 months after surgery) and 13 healthy participants. Dynamic jumping-landing task consisted of a forward jump off a 17 cm box and land on one leg followed by an immediate lateral jump to the opposite side. Each participant was required to perform 8 sets of double-leg squats at a self-selected pace and without resistance followed by 3 dynamic landings until maximal fatigue was reached. Fatigue was established if a subject could not perform 5 consecutive squats to 90° of knee flexion or unable to reach the force platform during the landing task. The authors hypothesized that higher level of muscle cocontraction would be seen in the ACLR patients compared with the healthy participants during a dynamic landing maneuver. They also hypothesized that higher levels of muscle cocontraction would be observed in the ACL patients at post-fatigue than pre-fatigue. According to their results, all participants had a significantly higher quadriceps:hamstring muscle CCI ($F_{1,23} = 66.94$, $p \leq 0.001$) as well as quadriceps

($F_{1,23} = 41.52$, $p \leq 0.001$) and hamstring muscles activity ($F_{1,23} = 55.64$, $p \leq 0.001$) in the pre-fatigue condition compared with the post-fatigue condition. However, quadriceps:hamstring muscle CCI did not show significant differences between ACLR patients and the healthy participants ($F_{1,23} = 0.59$, $p = 0.44$). The investigators concluded that regardless of fatigue status, ACLR patients used a similar muscle activation patterns as the healthy participants.

Conversely, some investigators found that effect of fatigue were more exacerbated in individuals with ACLR compared with normal individuals. Dalton et al.[157] evaluated the neuromuscular effect of aerobic exercise in people with ACLR. Dynamic balance measured as normalized maximum reach distance in 3 directions (anterior, posteromedial, posterolateral) of the Star Excursion Balance Test (SEBT), EMG gluteus medius muscle activation during the SEBT, maximum single-legged vertical jump height, and maximum isometric strength for hip abduction, extension, and external rotation were recorded before and after the exercise. Seventeen ACLR participants and 17 healthy participants performed a fatigue protocol that consisted of a 20 minutes walking on treadmill at a speed of 3.5 mph. The treadmill incline was increased 1°/min during the first 15 minutes. The fatigue level was examined using the Borg Rate of Perceived Exertion Scale. The treadmill incline was modified by participants during the last 5 minutes with the purpose of maintaining rate of perceived exertion of 15 to 17. The authors reported shorter reach distances were observed in the ACLR group than the healthy group for the posteromedial ($F_{1,32} = 4.4$, $p = 0.04$, $\eta^2 = 0.12$) and posterolateral ($F_{1,32} = 6.7$, $p = 0.02$, $\eta^2 = 0.17$). In addition, the strength of the hip extensors was significantly reduced after the exercise only in the ACLR group ($t_{16} = 3.0$, $p = 0.01$). The researchers concluded that individuals with ACLR demonstrated greater deficits in response to the fatigue effect than the healthy individuals.

In summary, controversy exists regarding the effect of fatigue on the lower extremity function being more pronounced in individuals with ACLR than healthy individuals. The majority of the studies found that individuals with ACLR did not demonstrate greater vulnerability to the effect of fatigue, possibly due to a compensation strategy used before the fatigue that does not require further compensation.

However, only 1 study reported that the effects of fatigue were more pronounced in individuals with ACLR compared with normal individuals.

MOTION ANALYSIS

Measures commonly used to evaluate lower extremity landing patterns include kinematics, kinetics, electromyography (EMG), and foot pressure profile. Kinematics is the study of the body's motion regardless of the forces producing the motion, whereas kinetics evaluates the forces acting on the body during movement.[158] Electromyography (EMG) is a measure used to evaluate the electrical activity of muscles.[158,159] Plantar pressure system evaluates the pressure on the interface between the foot and the shoe.

Kinematics

Human movement occurs in 3 cardinal anatomical planes including sagittal, frontal, and transverse planes.[160] Movements occur in the sagittal plane are flexion and extension, whereas abduction and adduction occur in the frontal plane.[160] Internal and external rotation occur in the transverse plane.[160] Joint angles of the hip, knee, and ankle play a significant role in dissipating the forces experienced during landing.[59] Research suggests that increased hip and knee flexion and ankle dorsiflexion (soft landing technique) is recommended to sufficiently absorb the large forces experienced during landing.[59] On the other hand, stiff landing, which is characterized by decreased hip and knee flexion and ankle dorsiflexion, may place lower extremity joints at greater forces during landing, predisposing them to greater risk of injury.[59]

Furthermore, previous researchers have identified specific kinematic parameters during functional tasks that might predispose individuals to ACL injuries such as increased internal hip rotation, increased knee valgus, and increased external tibial rotation.[56-62] Studies have shown that these movements can increase the load on the ACL that might strain and tear it, especially when 2 movements or more are combined such as increased internal hip rotation and increased knee valgus.[56-59]

Kinetics

Kinetics is the study of the causes of the motion by evaluating the forces (external and internal forces) creating movements.[158,161] The ground reaction forces are a 3-dimensional vector that can be divided into its components including anterior-posterior, medial-lateral, and vertical forces.[158,161] Those forces can be measured by force platforms that are the most commonly force transducers used to measure the force and the moment of force.[161] When ground reaction forces are used to make comparisons among participants, those forces are usually normalized to the participant body weight in order to control for the inter-subject variability. Therefore, the ground reaction forces are usually reported as force times the body weight. An important point is that angular motion occurs when ground reaction forces are not on the longitudinal axis of the lower extremity.[158] Moments of force are forces that do not pass the axis of rotation inducing movement around that axis.[158] The moments of force are obtained by multiplying the ground reaction forces by the distance between the axis of rotation and the point of application.[158] Those moments of force are usually reported in Newton-meters (N-m).[158]

Similar to kinematic parameters, moments that occur at the hip, knee, and ankle joints during landing are one of the main contributors to the mechanism of ACL injury.[58-62] Previous researchers have reported specific kinetics parameters that can place individuals at greater risk of sustaining an ACL injury such as increased anterior-posterior shear forces, greater ground reaction forces, increased varus and valgus moments, increased knee internal rotation moments, or increased hip internal rotation moments.[58-62,162] The aforementioned moments (forces) may further increase the ACL loading when more forces are applied such as a combination of increased knee valgus moment and greater anterior-posterior shear forces.[58-62,162]

Landing technique plays a major role in attenuating the impact forces experienced during landing.[59] Landing softly (greater hip, knee, and ankle flexion angles) may move ground reaction force vector away from the joints center line (anteriorly relative to the hip and ankle joints and posteriorly relative to the knee joint) that can decrease the load of the external moments on the non-contractile tissues such as ligaments.[163] On the other hand, decreased hip, knee, and ankle flexion angles (stiff landing) during landing may move ground reaction force vector close to the joints' center line that may predispose the non-contractile structures of the hip and knee joints to the external moments acting on these joints.[163] In addition, studies have shown that stiff landing can increase ground reaction forces which may result in excessive loading on the ACL that increases the risk of ACL injury.[164] Therefore, it has been suggested for athletes to adopt a soft landing technique to sufficiently allow the lower extremity joints to control the downward momentum in order to reduce the high impact forces experienced during landing.[59]

Electromyography

There are several considerations pertinent to collecting electromyography (EMG) data. In many clinical and laboratory settings, telemetry EMG system is used to ensure participants are able to move freely during performing functional tasks without the hindrance of cabling.[159] Due to improved comfort and easy application, surface electrodes are extensively utilized to evaluate electrical activity of superficial muscles that occurs during movement and postures.[159] An important point, however, is that EMG signal tend to involve unwanted artifacts when electrode are applied to pick up activity from the underlying muscles.[159] One method to reduce movement artifacts is using preamplified electrodes that enlarge the signal close to the measuring site.[159]

Two configurations are used to record EMG activity, including monopolar and bipolar.[159] However, bipolar configuration is the most common recording method that requires placing 2 electrodes over the muscle of interest.[159] In this configuration, a differential amplifier is used to determine the electrical difference between the 2 electrodes.[159] Common-mode rejection is a feature that allows the amplifier to eliminate non-identical signals.[159] Surface electrodes should be placed parallel to the muscle fibers and between the motor point and the tendon insertion.[159] Following the differential amplification, the EMG data are filtered to remove the undesired signals from the environment in order to increase the quality of the recorded signals.[159] High frequency noise and low frequencies associated with movement artifact are removed by band pass filter.[159] Band pass filter should be in the frequency range of 10 to 500 Hz.[159] Another important aspect associate with collecting EMG data is sampling rate that represents the number of the samples recorded per second.[159] The sampling rate of each channel is recommended to be greater than 700 Hz.[159]

Raw EMG data give preliminary information about the activity of the muscle. However, those data usually need some EMG signal processing methods for later interpretation. One of the EMG signal processing methods is the full wave rectification process that converts all negative amplitudes to positive amplitudes.[165] The rectification process ensures the raw EMG signals to have positive amplitudes and facilitates calculating the mean.[165] The EMG data must be normalized in order to be able to make comparisons of muscle activity levels among different participants or in the same participant on different days.[165] The normalization process controls inter-subjects differences by converting the raw or the processed signals into a standard value.[165] There are several approaches for normalization of EMG data. The dynamic normalization procedure, which was chosen for this investigation, is one of the most commonly used methods during dynamic functional tasks.[165,159] This procedure is calculated by dividing the average value during each task by the maximum value obtained during the same task trial.[159]

Lower extremity muscles play a major role in controlling the 3 cardinal planes of motion of lower extremity joints during dynamic tasks such as landing, cutting, and pivoting.[166-168] Specifically, gluteus maximus, quadriceps, and gastrocnemius produce significant eccentric contraction to sufficiently allow the hip, knee, and ankle joints to control the downward momentum during landing.[166-168] Studies have shown that increased eccentric action of the gluteus maximus, quadriceps, and gastrocnemius muscles may decrease hip, knee and ankle flexion angles during landing that may lead to increased joints loading.[166-168] In addition, increased activation of the quadriceps and gastrocnemius muscles (ACL antagonists) during landing may increase anterior tibial translation and consequently increase the load on the ACL.[162] On the other hand, increased knee flexion has been associated with increased concentric contraction of the hamstring muscles (ACL agonist) that may decrease the load on the ACL.[59] Previous researchers have reported that deficits in hamstrings strength may place individuals at greater risk of ACL injuries.[169,170] Therefore, deficits in the lower extremity muscles may negatively alter the landing pattern that may predispose individuals to ACL injury.[166-169]

Foot Plantar Pressure Measurement System

Ground reaction forces (GRFs) have been cited as a major contributor to the mechanism of ACL injury.[61,62,162,171] The magnitude of GRFs to which individuals are subjected is greatly influenced by the type of landing technique.[59] An association between stiff landings and greater GRFs has been previously reported.[171] Several researchers have reported that increased GRFs may place individuals at a greater risk of sustaining ACL injuries by increasing the anterior tibial shear force, a factor that can stress and strain the ACL.[61,62,162] Therefore, it has been suggested that increased flexion angles of lower extremity joints may decrease the risk of injury by sufficiently dissipating GRFs acting on these joints during landing.[59,171]

Several instruments can be used to quantify GRFs during static and dynamic locomotion activities including force plates and plantar pressure systems.[172,173] Platform systems are the most commonly used instruments and considered to be the gold standard for measuring forces between the foot and floor.[174] An alternative to the platform systems is the plantar pressure systems used to assess the pressure between the shoe and the foot. The use of the plantar pressure sensors is advantageous in sports-related research because participants are not restricted to walk or land on a predetermined area as with platform systems.[175] Plantar pressure systems have been reported to have moderate-to-good between-sessions reliability (ICC ≥ 0.60) and high correlation ($r>0.93$) with force platform in different populations.[176-180]

The F-Scan plantar-pressure measurement system has 2 in-shoe sensors that are placed in the shoe to measure pressure occurring between the foot and the shoe. Each sensor is made up of 960 individual pressure-sensing locations that are called sensels. Each insole sensor is connected to a cuff unit that is wrapped around the ankle. The other end of each cuff unit was connected to the wireless data-logger by Category 5 Enhanced (CAT 5E) cables. A waist belt is used to hold the wireless data-logger at the back of each participant.

CHAPTER III

RELIABILITY OF KINEMATIC, KINETIC AND FOOT PRESSURE DURING TWO LANDING MANEUVERS IN HEALTHY SOCCER PLAYERS

ABSTRACT

Functional tasks are frequently used to evaluate lower extremity performance in athletes in clinical settings. However, no study has evaluated test-retest reliability of kinematic, kinetic, and F-Scan system during planned and unplanned landing maneuvers in healthy soccer players. **Purpose:** This study included the following purposes 1) to evaluate within-session reliability of kinematics and kinetics during 2 landing tasks to determine the number of trials needed to achieve acceptable reliability, 2) to determine between-session reliability of kinematics, kinetics, and F-Scan system during the 2 landing maneuvers performed by healthy soccer players, 3) to evaluate the validity (concurrent validity) of the F-Scan system in relation to a platform system as a criterion reference during both landing maneuvers. **Methods:** Ten healthy soccer players (age: 25.6 ± 2.67; BMI: 22.74 ± 2.33) participated in this study. The landing tasks included a forward jump onto 4 force platforms (planned landing) and a forward jump to head a soccer ball and land on the 4 force platforms (unplanned landing). Each participant performed 5 trials of each landing maneuvers. Within 3 days from initial testing, participants were asked to perform the same 5 trials of each landing. Peak hip, knee, and ankle joint angles and moments; peak vertical ground reaction forces; and peak pressure were measured. **Results:** The 4-trial averages showed good reliability for all kinematics and kinetics measures during planned landing (ICC ≥ 0.81) and unplanned landing (ICC ≥ 0.76). Test-retest reliability exhibited good reliability for majority of kinematic and kinetic variables (ICC ≥ .77) during planned and unplanned landing. Peak pressure yielded good test-retest reliability during both planned and unplanned landing (ICC ≥ .89). Peak plantar pressure and peak vertical GRFs showed a significant good-to-excellent positive correlation ($r=0.80$, $p<0.001$) during the unplanned landing, whereas a significant moderate-to-good positive correlation ($r=0.67$, $p=0.03$) was observed during the planned landing.

Conclusion: The results indicated that both landings could be used as functional tasks to assess lower extremity performance in this population if 4 trials of each landing are used in order to achieve good trial--to-trial reliability. Additionally, F-Scan and 3D motion analysis systems are reliable during planned and unplanned landing maneuvers in healthy soccer players. Moreover, the F-Scan system is a valid instrument to measure ground reaction forces during planned and unplanned landing maneuvers.

INTRODUCTION

Three-dimensional motion analyses as well as plantar pressure systems have been widely used in biomechanical and clinical movement research to assess lower extremity performance during different functional activities.[1-4] Evaluating the lower extremity movement during functional tasks such as landing can contribute to designing intervention and prevention programs in order to reduce the risk of ACL injuries.[5-7] Clinical and laboratory studies which seek to evaluate the lower extremity performance may assess the instrument's ability to reproduce the measurements.[2] Investigators who have evaluated the reliability of three-dimensional motion analyses have reported moderate-to-good within and between-sessions reliability during drop vertical jump and stop jump landing tasks, with Intraclass Correlation Coefficient (ICC) values greater than 0.59.[1,2] Furthermore, plantar pressure systems have been reported to have moderate-to-good between-sessions reliability in different populations ($ICC \geq 0.60$).[3,4,8] These previous studies suggest that both three-dimensional motion analyses and plantar pressure systems are reliable and appropriate for research and clinical practice.

Several instruments can be used to quantify ground reaction forces (GRFs) during static and dynamic locomotion activities including force plates and plantar pressure systems.[9-12] Platform systems are the most commonly used instruments and considered to be the gold standard for measuring forces between the foot and floor.[13] An alternative to the platform systems is the plantar pressure systems used to assess the pressure between the shoe and the foot. The use of the plantar pressure sensors is advantageous in sports-related research because participants are not restricted to walk or land on a predetermined area as with platform systems.[14] Previous researchers have reported high correlations ($r>0.93$) between in-shoe peak plantar pressure and force platform measures during walking in different populations.[15,16] The previous investigations suggest that the plantar pressure system could be an appropriate instrument to assess ground reaction forces in research and clinical settings.

Despite previous investigators reporting moderate to good reliability of three-dimensional motion analyses and plantar pressure systems,[1-4,8] the literature is still lacking of reliability studies for soccer-specific landing tasks. Specifically, no study has evaluated the reliability of kinematics and kinetics during soccer-specific planned and unplanned landing tasks in order to determine the minimum number of trials needed to achieve acceptable reliability. Also, no study has examined between-sessions reliability of kinematics, kinetics, and foot pressure profile during soccer-specific planned and unplanned landing maneuvers. Lastly, no study has established the concurrent validity of the peak plantar pressure measured by the F-Scan system during both the planned and unplanned landing maneuvers.

In an attempt to closely simulate soccer game situations, soccer-specific planned and unplanned landing maneuvers were chosen because they are frequently performed throughout a soccer game. Planned landing allows the athlete to preplan the landing pattern. For example, an athlete might preplan the landing pattern when performing a forward jump. On the other hand, unplanned landing might occur when the landing pattern changes due to alteration in muscle activation patterns and movements during the airborne phase of the jump. For instance, an athlete might change the landing strategy when performing landing after heading a soccer ball.

Establishing the minimum number of trials needed to achieve acceptable reliability can help decrease the time of data collection and decrease the risk of injury during testing procedures.[17,18] Determining the between-sessions variability of the measurement can help obtain a better understanding of an individual's landing mechanics in order to appropriately interpret real differences attributable to an injury or an intervention. Additionally, determining the concurrent validity of the peak pressure obtained using the F-scan system may provide greater insight into evaluating the forces on the musculoskeletal structures of the lower extremity during dynamic locomotion activities.

Therefore, the first purpose of this study was to determine within-session reliability (trial-to-trial) of kinematics and kinetics during soccer-specific planned and unplanned landing maneuvers in order to determine the minimum number of trials needed to achieve acceptable reliability (ICC ≥ 0.75). A second purpose was to determine between-session reliability (day-to-day) of kinematics, kinetics, and foot pressure profile during the 2 landing maneuvers performed by healthy soccer players. A third purpose was to evaluate the criterion-related validity (concurrent validity) of the peak plantar pressure measured by the F-Scan system in relation to the peak vertical ground reaction forces (vGRF) obtained using a platform system as a criterion reference during both landing maneuvers.

METHODS

Participants

Five male and 5 female healthy recreational soccer players (age: 25.6 ± 2.67; BMI 22.74 ± 2.33) were recruited using convenience sampling for this study. All participants were currently participating in soccer at recreational level (4 hours or more per week), were between the age of 18 and 35 years, were able to perform a soccer-specific jump heading task, had no history of low back or lower extremity surgery, had no lower extremity injury in the 6 months before participating in the study, had no neurological disease, had no injury of other major ligaments of the lower extremity, and were not pregnant. All participants read and signed an informed consent form approved by the Institutional Review Board of Texas Woman's University, Houston Center.

Instrumentation

Each participant had 15 retro-reflective markers placed according to Vicon Plug-in gait model (Vicon Motion Systems Ltd. Denver, CO, USA) recommendations, including over both anterior superior iliac spines, second sacral vertebra, and bilaterally at lateral femoral epicondyles, mid-distance between greater trochanters and lateral femoral epicondyles, lateral malleoli, mid-distance between lateral femoral epicondyles and lateral malleoli, calcaneal tuberosities, and second metatarsophalangeal joints (Figure 3.1). A Vicon Motion Analysis System consisting of 10 digital cameras (240 Hz sampling rate) and 4 AMTI (Advanced Mechanical Technology Inc. Watertown, MA, USA) force platforms (1000 Hz sampling rate) were used to collect data. The equipment was calibrated according to the manufacturer's recommendations and a static trial was conducted before each data collection session to estimate each subject's joint centers and center of mass for lower extremity segments.

A Just Jump System (Probotics Inc. Huntsville, AL, USA) was used to determine maximum vertical jump. The Just Jump System has been widely used to assess vertical jump height in many strength and conditioning studies.[19-23] The Just Jump System has been found to be a reliable device (ICC $\geq$ 0.87) in men and women who were involved in sports such as football and volleyball.[23] Also, the Just Jump System has been found to have a high correlation (r=0.96) with the 3-camera motion analysis system as a criterion reference in male and female college students.[22]

The F-Scan wireless plantar-pressure measurement system (Tekscan Inc. Boston, MA, USA) was time-synchronized to the Vicon system and used to capture individual in-shoe pressure information. This system uses a thin insole sensor made up of 960 individual pressure-sensors. Two insole sensors were placed inside both shoes and connected to the cuff units. Each cuff unit was attached to the ankle band wrapped around the ankle. The other end of each cuff unit was connected to the wireless data-logger by Category 5 Enhanced (CAT 5E) cables. A waist belt was used to secure the wireless data-logger at the back of each participant (Figure 3.1). Prior to each data collection session, the equipment was calibrated according to the manufacturer's guidelines (step calibration).

Figure 3.1: Participant with retro-reflective markers and F-scan system.

Procedure

Age, height, weight, and level of play were obtained from each participant. Participants were then asked to perform a dynamic warm-up protocol consisting of 5 minutes of cycling at 40 to 60 rotations per minute (rpm) on a cycle ergometer, 10 half squats, and 5 continuous vertical jumps. Following the dynamic warm-up protocol, each participant was instructed to perform 3 long jumps as far as possible and land on both feet in order to determine maximum long jump distance. Participants were then asked to step on the Just Jump System jump mat to perform 3 vertical jumps as high as possible without bending the legs and land on both feet to determine maximum vertical jump height. Each participant was then given a demonstration of functional landing tasks included in the study. Two practice trials were completed, based on the demonstrated good reliability values in the literature (ICC $\geq$ 0.76).[17]

The landing tasks included a forward jump onto a landing area with 4 force platforms (planned landing) and a forward jump to head a soccer ball and land on the same force platforms (unplanned landing). The order of these tasks was randomized for each participant. For the planned landing, each participant was instructed to jump from a distance (starting point) 80% of his/her maximum long jump and land on the force platforms.[24] The unplanned landing was executed by having each participant jump forward to head a soccer ball and then land on the force platforms. The soccer ball was suspended from the ceiling at a location equidistant between the starting point and the force platforms. The height of the center of the soccer ball was placed at 50% of the participant's maximum vertical jump height. Each participant was asked to perform 5 trials for each landing in the same session. Within 3 days from initial testing, each participant was asked to perform the same 5 trials. Participants were asked to wear the same athletic shoes during both sessions.

Data Reduction

All kinematic and kinetic measures were synchronized and analyzed with Vicon Nexus 1.8 and Polygon (v4.0, Vicon Motion System Ltd. Denver, CO) software. The 3-dimensional trajectory of retro-reflective markers, from which joint angles were derived, were filtered through a second order low-pass Butterworth filter at a frequency of 6 Hz. The kinematics and kinetics outcomes evaluated during both landing maneuvers focused on the sagittal plane mechanics. The kinematic variables included peak ankle dorsiflexion, peak knee flexion, and peak hip flexion joint angles. The kinetic variables included peak plantarflexion, peak knee extension, peak hip extension moments, and peak vertical GRFs. Peak vertical GRFs were calculated by adding all the forces distributed among the force platforms where participants landed. Joint angles, peak vertical GRFs, and joint moments data were exported to Microsoft Excel™ and then transferred to SPSS for analysis. For each variable, peak values were defined as the greatest values from initial contact to maximum knee flexion angle. For each participant, the average of the peak values of both limbs for each variable was calculated for statistical analysis.

The F-Scan Research software (v7.00, Tekscan Inc. Boston, MA, USA) was used to analyze pressure data. Peak pressure was recorded during the landing phase of both maneuvers. Peak pressure values were defined as the greatest values from initial contact to maximum knee flexion angle. Peak pressure values were exported to Microsoft Excel™ and then transferred to SPSS for analysis. Similar to kinematics and kinetics data, the average of the peak pressure values of both limbs was calculated for statistical analysis.

Data Analysis

The kinematic, kinetic, and peak pressure data were screened for normality assumptions and outliers utilizing Kolmogorov-Smirnov test and box plots, respectively. Means, standard deviations, standard errors of measurement (SEM), intraclass correlation coefficient (ICC), and 95% confidence intervals (CIs) around the mean and ICC values were calculated for each variable in both maneuvers. An ICC (3,k) model was used to calculate within-session reliability for the averages of 2 to 5 trials of each landing maneuver. Another ICC (3,2) model was used to calculate between-session ICC to establish day-to-day reliability. Reliability was interpreted based on Portney and Watkins criteria,[25] as follows: >0.75 good reliability, 0.50-0.74 moderate reliability, <0.49 poor reliability. Also, Pearson product-moment coefficient of correlation (r) was calculated to compare the peak plantar pressure measured by the F-Scan system with the peak vertical GRFs measured by force plates. Correlations were also interpreted based on Portney and Watkins criteria: 0.00-0.25 little or no relationship, 0.25-0.50 fair relationship, 0.50-0.75 moderate-to-good relationship, >0.75 good-to-excellent relationship.[25] Alpha levels were set at 0.05 for all analyses. All data analyses were performed using SPSS® 23 (SPSS Inc., Chicago, IL USA).

RESULTS

All kinematic, kinetic, and peak pressure data met the assumptions of normality and outliers. Means, standard deviations, and 95% CIs around the mean for planned and unplanned landing maneuvers are shown in Tables 3.1 and 3.3, respectively. ICC values, SEMs, and 95% CIs around ICC values for planned and unplanned landing maneuvers are shown in Tables 3.2 and 3.4, respectively. The 4-trial averages showed good reliability for all kinematics and kinetics measures during planned landing (ICC ≥ 0.81) and unplanned landing (ICC ≥ 0.76).

All kinematic and kinetic variables exhibited good between-sessions reliability (ICC ≥ 0.83) except for the hip and knee flexion angles (ICCs=0.73 and 0.50, respectively) for the planned landing (Table 3.5). With regard to the unplanned landing, all kinematic and kinetic variables showed good reliability (ICC ≥ 0.83) except for the knee extension moment that had only moderate reliability (ICC = 0.57) (Table 3.5). Peak pressure demonstrated good between-sessions reliability during both planned and unplanned landing (ICC ≥ 0.89) (Table 3.5).

Peak plantar pressure and peak vertical GRFs showed a significant good-to-excellent positive correlation ($r=0.80$, $p<0.001$) during the unplanned landing, whereas a significant moderate-to-good positive correlation ($r=0.67$, $p=0.03$) was observed during the planned landing.

DISCUSSION

The first purpose of this investigation was to determine the reliability of kinematics and kinetics during the 2 landing tasks in order to determine the minimum number of trials needed to achieve acceptable reliability. Allowing participants to perform multiple trials may help them optimize their practice, familiarization, and confidence in order to obtain reliable results.[17,18] On the other hand, performing multiple trials might increase the potential effect of fatigue jeopardizing maximum performance.[26] Fatigue has been reported as one of the most common factors impairing physical performance and reducing reliability of measurements during testing procedures.[27-29] Therefore, the number of trials that insures optimum performance as well as decreases the possibility of fatigue is needed during the research protocol.

The results of this investigation suggest that 4 trials are sufficient to achieve reliable results during both planned and unplanned landing maneuvers for all kinematic and kinetic measures. During the planned landing, the 4-trial averages exhibited good reliability for all kinematic and kinetics measures (ICC ≥ 0.81). Similarly, the 4-trial averages showed good reliability for all kinematic and kinetics measures (ICC ≥ 0.76) during the unplanned landing. Furthermore, the SEM, which is used to estimate the individuals' true scores,[25] showed less error scores during the 4 trials compared with the 2 and 3 trials in both landing maneuvers. Performing 4 trials of each landing maneuvers demonstrated good reliability (ICC ≥ 0.76) in this investigation (Tables 3.2 and 3.4). Therefore, it seems reasonable to recommend 4 trials for both types of landing maneuvers in order to obtain ICC values greater than 0.75.

Similar to the first purpose of this investigation, Ortiz et al.[30] evaluated the reliability of kinematic and kinetic measures during 2 unilateral functional tasks performed by 16 physically active young women.

Each participant was instructed to perform 5 trials of a 40-cm single-leg drop jump and 2 trials of 20-cm 10 consecutive single-leg up-down hops. The researchers reported that the average of 5 trials of the single-leg drop jump and 1 trial of the single-leg up-down were needed to obtain acceptable reliability for hip and knee kinematic and ground reaction forces. Other researchers evaluated the number of trials needed to reach maximum performance during functional tasks in 70 participants who had either an ACL reconstruction or ACL deficiency.[18] The researchers concluded that 15 trials of the horizontal and vertical hops and 10 trials of the crossover hop were needed to achieve reliable distance and height measurements. Specifically, participants were able to perform 99% of the maximum distance when they performed 10 trials of the crossover hop, whereas 15 trials of the horizontal hop insured 97.6% of the maximum distance. Nevertheless, performing a large number of trials such as 15 trials might predispose individuals to injuries during task performance due to the potential effect of fatigue.[26] The combined findings of the previous studies suggest that multiple trials are needed in order to obtain accurate measurements. The results of this investigation agree with these studies that multiple number of trials are needed in order to obtain acceptable trial-to-trial reliability.

The second purpose of this study was to determine the between-sessions reliability of kinematics, kinetics, and foot pressure profile during planned and unplanned landing maneuvers performed by healthy soccer players. Previous studies have reported moderate-to-good between-sessions reliability of kinematics, kinetics, and plantar pressure system during different functional tasks such as drop vertical jump in soccer and basketball players, stop jump in female recreational athletes, and walking in patients with rheumatoid arthritis.[1,2,4] With planned and unplanned landing maneuvers being performed frequently throughout a soccer game, it is very important to assess subjects' repeatedly while performing these tasks in laboratory settings.

The findings of the present investigation indicate that the majority of kinematic and kinetic variables in healthy soccer players during planned and unplanned landing maneuvers have good between-sessions reliability. These findings agree with a previous investigation in which moderate-to-good between-sessions reliability was reported for all sagittal plane outcomes ($ICC \geq 0.59$) during a drop vertical jump in soccer and basketball players.[1] In the present investigation, most of the ICC values during unplanned landing were higher than those ICC values during planned landing. Furthermore, most of the kinematic and kinetic variable exhibited lower SEM values during unplanned landing than planned landing, giving a better estimation of the participants' true landing performance (Table 3.5). We hypothesize that the procedure of the current study's unplanned landing was more controlled due to the presence of the ball that might restrict participants to land in a more confined landing area compared with the area available during the planned landing procedure. Therefore, this might explain the high reliability observed during the unplanned landing compared with planned landing.

Several factors could have affected the between-sessions reliability during both landing maneuvers, including marker reapplication variation, changes in the referenced static alignment, and task difficulty increasing variability between sessions.[1] With the purpose of decreasing variability between sessions, only 1 tester was used in this investigation to attach the reflective markers in all sessions. Techniques that help accurate marker reapplication were not used such as permanent markers and site tattoo. Another possible reason for the observed variability in both landings could be attributed to the learning effect or performance variability.[31]

In regards to the reliability of the peak pressure, the findings of this investigation indicate that peak pressure has good between-sessions reliability during planned and unplanned landing maneuvers. Previous studies have reported that peak pressure can be reliably evaluated using the F-Scan system.[3,4,8] Our current investigation confirms the high between-sessions reliability for the peak pressure during planned and unplanned landing maneuvers. Furthermore, it is interesting to note that the ICC values for both landing maneuvers are comparable to those values reported previously for walking ($ICC \geq 0.89$).[4] Also, the SEM values represent less than 14% of the means in both landing maneuvers providing a closer estimate of the participants' true peak pressure (Table 3.5). This suggests that utilizing the F-Scan system is also appropriate to assess peak pressure in study designs where longitudinal comparisons are needed.

In this investigation, the peak pressure revealed the highest ICC value during planned landing, whereas the vertical GRF had the highest ICC value during unplanned landing. This finding is supported by previous investigations in which vertical GRF data were found to be more reliable than joint angles and moments during gait, single leg squat, and single leg landing.[32-34] Unlike kinematic and kinetic data, peak pressure as well as the GRF data are not subject to potential between-session error, such as accurate reapplication of reflective markers, given GRF values depend on the gravitational forces and acceleration. Consequently, less variability between-session was observed in both the peak pressure and the GRF compared with some joint angles and moments.

The third purpose was to evaluate the concurrent validity of the peak plantar pressure measured by the F-Scan system in relation to the peak vertical ground reaction forces obtained using a platform system as a criterion reference during both landing maneuvers. Previous investigations have reported high correlations (r>0.93) between in-shoe peak plantar pressure and force platform measures during walking.[15,16] In this investigation, there was a good-to-excellent positive correlation (r=0.80) between the peak plantar pressure and ground reaction forces during the unplanned landing. Moreover, a moderate-to-good positive correlation (r=0.67) was observed between the peak plantar pressure and ground reaction forces during the planned landing. The orientation of the F-Scan insole sensors should be flat in order to obtain more accurate GRF readings.[12] During landing, however, the orientation of the sensors might change depending on how participants land.[12] For instance, landing with flat foot keeps the orientation of the insole sensors flat and thus provides more accurate GRFs recordings than landing on the heels. Forward jump is characterized by a landing strategy that generally requires participants to land with the heels first.[35] We hypothesize that unplanned landing allows participants to land with flat foot whereas participants may utilize heel-toe landing pattern during planned landing. Consequently, the correlation between the peak pressure and ground reaction forces was higher during the unplanned landing than the planned landing.

There are some limitations that should be taken into consideration when interpreting the results of this study. Participants' level of play in this study was at the recreational level and therefore might limit the generalizability to those who participate in highly competitive sports and/or have many more hours of training a week. Also, movement of the markers relative to the bony landmarks during the landing performance may hinder accurate assessment of kinematic and kinetic variables. Furthermore, day-to-day trials were not performed at the same time of day and therefore participants might perform landing tasks differently depending on the time of day.

CONCLUSION

The present findings indicated that good trial-to-trial reliability could be obtained for both landing maneuvers in a population of recreational soccer players if 4 trials of each landing are used. Additionally, F-Scan and 3D motion analysis systems are reliable during planned and unplanned landing maneuvers in healthy soccer players. Moreover, the F-Scan system is a valid instrument to measure ground reaction forces during planned and unplanned landing maneuvers and therefore may be a useful outcome measure in studies that involve sport-related tasks.

Table 3.1. Means, S.D, and 95% CI values for planned landing (Session 1)

Variables	Trial 1 Mean ± S.D 95% CI	2 Mean ± S.D 95% CI	3 Mean ± S.D 95% CI	4 Mean ± S.D 95% CI	5 Mean ± S.D 95% CI
Kinematics (°)					
Hip Flexion	77.50 ± 7.81 70.97 - 84.04	78.63 ± 9.83 70.41 - 86.86	78.12 ± 9.11 70.50 - 85.74	81.78 ± 9.56 73.78 - 89.78	82.25 ± 7.39 76.07 - 88.42
Knee Flexion	85.00 ± 5.57 81.01 - 88.98	83.31 ± 10.79 75.58 - 91.03	86.34 ± 10.62 78.73 - 93.94	84.68 ± 5.98 80.40 - 88.96	89.55 ± 9.28 82.91 - 96.20
Ankle Dorsiflexion	23.85 ± 6.75 19.01 - 28.68	22.15 ± 6.92 17.20 - 27.10	26.24 ± 7.60 20.80 - 31.68	23.91 ± 5.37 20.06 - 27.75	25.84 ± 7.18 20.70 - 30.97
Kinetics (Nm/kg)					
Hip Extension	1.76 ± 0.55 1.36 - 2.16	1.55 ± 0.34 1.30 - 1.80	1.54 ± 0.68 1.04 - 2.03	1.35 ± 0.44 1.03 - 1.67	1.39 ± 0.33 1.15 - 1.63
Knee Extension	0.77 ± 0.40 0.48 - 1.05	0.92 ± 0.66 0.44 - 1.39	0.97 ± 0.78 0.41 - 1.53	0.88 ± 0.71 0.37 - 1.39	0.98 ± 0.59 0.55 - 1.40
Ankle Plantarflexion	0.32 ± 0.16 0.20 - 0.44	0.34 ± 0.22 0.18 - 0.50	0.37 ± 0.24 0.20 - 0.55	0.32 ± 0.18 0.19 - 0.45	0.33 ± 0.17 0.20 - 0.45
Vertical GRF (N)	242.85 ± 70.98 192.06 - 293.63	245.85 ± 78.91 189.39 - 302.30	240.40 ± 73.44 187.86 - 292.93	209.04 ± 78.35 152.99 - 265.09	252.95 ± 78.22 196.98 - 308.91

Table 3.2. ICC, SEM, and ICC 95% CI values for planned landing (Session 1)

Variables	Avg. of Trial 1 & 2 ICC (SEM) ICC 95% CI	Avg. of Trial 1-3 ICC (SEM) ICC 95% CI	Avg. of Trial 1-4 ICC (SEM) ICC 95% CI	Avg. of Trial 1-5 ICC (SEM) ICC 95% CI
Kinematics (°)				
Hip Flexion	0.88 (3.40) 0.54 - 0.97	0.90 (2.88) 0.71 - 0.97	0.94 (2.34) 0.84 - 0.98	0.92 (2.09) 0.78 - 0.98
Knee Flexion	0.63 (6.56) -0.45 - 0.91	0.81 (4.62) 0.44 - 0.94	0.86 (2.23) 0.64 - 0.96	0.83 (3.82) 0.58 - 0.95
Ankle Dorsiflexion	0.74 (3.52) -0.04 - 0.93	0.85 (2.94) 0.58 - 0.96	0.89 (1.78) 0.73 - 0.97	0.91 (2.15) 0.79 - 0.97
Kinetics (Nm/kg)				
Hip Extension	0.50 (0.24) -1.01 - 0.87	0.70 (0.37) 0.13 - 0.92	0.81 (0.19) 0.50 - 0.94	0.84 (0.13) 0.61 - 0.95
Knee Extension	0.87 (0.23) 0.48 - 0.96	0.92 (0.22) 0.77 - 0.97	0.95 (0.15) 0.87 - 0.98	0.94 (0.14) 0.86 - 0.98
Ankle Plantarflexion	0.91 (0.06) 0.65 - 0.97	0.94 (0.05) 0.85 - 0.98	0.90 (0.05) 0.75 - 0.97	0.91 (0.05) 0.79 - 0.97
Vertical GRF (N)	0.96 (15.78) 0.86 - 0.99	0.95 (16.42) 0.88 - 0.98	0.96 (15.67) 0.89 - 0.98	0.96 (15.64) 0.90 - 0.98

Table 3.3. Means, S.D, and 95% CI values for unplanned landing (Session 1)

Variables	Trial 1 Mean ± S.D 95% CI	2 Mean ± S.D 95% CI	3 Mean ± S.D 95% CI	4 Mean ± S.D 95% CI	5 Mean ± S.D 95% CI
Kinematics (°)					
Hip Flexion	63.92 ± 12.35 55.08 - 72.75	61.45 ± 18.24 48.39 - 74.50	63.49 ± 13.83 53.60 - 73.38	69.36 ± 12.31 60.55 - 78.17	66.36 ± 12.57 57.36 - 75.36
Knee Flexion	75.42 ± 9.73 68.45 - 82.39	71.65 ± 8.45 65.60 - 77.69	71.17 ± 9.09 64.66 - 77.67	73.81 ± 8.66 67.79 - 80.01	71.08 ± 8.24 65.18 - 76.98
Ankle Dorsiflexion	26.58 ± 6.41 21.99 - 31.17	25.86 ± 6.83 20.96 - 30.75	24.68 ± 7.18 19.54 - 29.82	26.73 ± 8.94 20.33 - 33.12	26.07 ± 6.92 21.12 - 31.02
Kinetics (Nm/kg)					
Hip Extension	1.83 ± 1.02 1.10 - 2.56	1.93 ± 0.61 1.49 - 2.37	1.92 ± 0.66 1.44 - 2.39	2.14 ± 0.92 1.47 - 2.80	2.02 ± 0.70 1.52 - 2.53
Knee Extension	0.49 ± 0.12 0.40 - 0.58	0.53 ± 0.24 0.36 - 0.71	0.51 ± 0.22 0.35 - 0.67	0.52 ± 0.21 0.36 - 0.68	0.50 ± 0.22 0.34 - 0.89
Ankle Plantarflexion	0.22 ± 0.12 0.14 - 0.32	0.28 ± 0.21 0.13 - 0.44	0.41 ± 0.38 0.13 - 0.68	0.24 ± 0.21 0.09 - 0.39	0.19 ± 0.18 0.06 - 0.33
Vertical GRF (N)	221.46 ± 120.36 135.36 - 307.57	243.87 ± 88.69 180.41 - 307.32	243.77 ± 85.04 182.93 - 304.60	245.94 ± 75.26 192.10 - 299.78	260.00 ± 79.84 202.88 - 317.11

Table 3.4. ICC, SEM, and ICC 95% CI values for unplanned landing (Session 1)

Variables	Avg. of Trial 1 & 2 ICC (SEM) ICC 95% CI	Avg. of Trial 1-3 ICC (SEM) ICC 95% CI	Avg. of Trial 1-4 ICC (SEM) ICC 95% CI	Avg. of Trial 1-5 ICC (SEM) ICC 95% CI
Kinematics (°)				
Hip Flexion	0.92 (5.15) 0.68 - 0.98	0.94 (3.38) 0.84 - 0.98	0.86 (4.60) 0.63 - 0.96	0.84 (5.02) 0.62 - 0.95
Knee Flexion	0.96 (1.69) 0.86 - 0.99	0.91 (2.72) 0.75 - 0.97	0.94 (2.12) 0.85 - 0.98	0.92 (2.33) 0.82 - 0.98
Ankle Dorsiflexion	0.91 (2.04) 0.65 - 0.97	0.95 (1.60) 0.85 - 0.98	0.95 (1.99) 0.88 - 0.98	0.97 (1.19) 0.92 - 0.99
Kinetics (Nm/kg)				
Hip Extension	0.80 (0.27) 0.19 - 0.95	0.89 (0.21) 0.70 - 0.97	0.91 (0.27) 0.78 - 0.97	0.92 (0.19) 0.80 - 0.97
Knee Extension	0.68 (0.13) -0.27 - 0.92	0.65 (0.13) -0.01 - 0.90	0.76 (0.10) 0.36 - 0.93	0.79 (0.10) 0.48 - 0.94
Ankle Plantarflexion	0.41 (0.16) -1.34 - 0.85	0.69 (0.21) 0.10 - 0.19	0.77 (0.10) 0.42 - 0.93	0.82 (0.07) 0.57 - 0.95
Vertical GRF (N)	0.89 (29.41) 0.58 - 0.97	0.91 (25.51) 0.75 - 0.97	0.91 (22.57) 0.78 - 0.97	0.93 (21.12) 0.84 - 0.98

Table 3.5. Between-sessions reliability values for both landings (Avg. 5 Trials)

Variables	Planned Landing		Unplanned Landing	
	ICC (95% CI)	SEM	ICC (95% CI)	SEM
Kinematics (°)				
Hip Flexion	0.73 (-0.08 - 0.93)	4.79	0.83 (0.33 - 0.95)	4.67
Knee Flexion	0.50 (-0.99 - 0.87)	6.33	0.86 (0.47 - 0.96)	3.68
Dorsiflexion	0.83 (0.34 - 0.96)	2.70	0.93 (0.71 - 0.98)	1.75
Kinetics (Nm/kg)				
Hip Extension	0.83 (0.31 - 0.95)	0.16	0.89 (0.58 - 0.97)	0.28
Knee Extension	0.86 (0.44 - 0.96)	0.17	0.57 (-1.12 - 0.91)	0.07
Plantarflexion	0.84 (0.36 - 0.96)	0.08	0.84 (0.39 - 0.96)	0.07
Vertical GRF (N)	0.88 (0.52 - 0.97)	25.26	0.97 (0.90 - 0.99)	14.64
F-Scan (KPa)				
Peak pressure	0.96 (0.84 - 0.99)	88.70	0.89 (0.53 - 0.97)	114.33

CHAPTER IV

BIOMECHANICAL EVALUATION OF THE LOWER EXTREMITY DURING PLANNED AND UNPLANNED LANDING MANEUVERS IN SOCCER PLAYERS WITH AN ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

ABSTRACT

Landing adaptation has been reported in individuals with an ACL reconstruction (ACLR) during dynamic landing tasks. However, no study has evaluated landing biomechanics during soccer-specific landing tasks in soccer players with an ACLR. **Purpose:** To compare kinematics, kinetics, and neuromuscular performance between soccer players with an ACLR and healthy non-injured soccer players during planned and unplanned landing maneuvers. **Methods:** Eighteen soccer players with an ACLR (age, 26.11 ± 3.95 years; height, 1.70 ± 0.09 m; weight, 68.15 ± 9.64 kg, BMI, 23.52 ± 2.69 kg/m^2, time since surgery, 5 ± 3.30 years) and 18 healthy non-injured soccer players (age, 25.83 ± 3.51 years; height, 1.66 ± 0.05 m; weight, 66.88 ± 10.37 kg, BMI, 24.09 ± 3.73 kg/m^2) participated in the study. The landing tasks included a forward jump onto 4 force platforms (planned landing) and a forward jump to head a soccer ball and land on the 4 force platforms (unplanned landing). Each participant performed 4 trials of each landing maneuvers. The outcome measures were peak flexion angles and extension moments of the hip, knee, and ankle joints, peak pressure and electromyography activity of gluteus maximus, quadriceps, hamstrings, and gastrocnemius muscles. A 2×2 ANOVA (fatigue × group) was performed for each outcome measure. **Results:** Kinematics data showed significant interaction of group × landing for knee flexion angles only ($F_{1,34} = 11.26$, $p = 0.002$). Follow-up pairwise comparisons showed that the ACL group landed with significant greater knee flexion angles during planned landing compared with unplanned landing ($p < 0.001$). Also, significant main effects for landing were found, which demonstrated that all participants had greater hip and knee flexion angles during planned landing than unplanned landing ($F_{1,34} = 48.55$, $p < 0.001$; $F_{1,34} = 40.58$, $p < 0.001$, respectively). For kinetics data, significant main effects for landing were

found, which demonstrated that all participants had greater hip and knee extension moments and peak pressure during planned than unplanned landing ($F_{1,34} = 6.82$, $p < 0.013$; $F_{1,34} = 27.18$, $p < 0.001$; $F_{1,34} = 20.98$, $p < 0.001$, respectively). For electromyography (EMG) data, main effect for group for gastrocnemius muscle was significant showing that the ACL group landed with decreased gastrocnemius activity compared with the control group ($F_{1,34} = 11.27$, $p = 0.002$). **Conclusion:** The results indicated that unplanned landing showed greater injury predisposing factors compared with planned landing. Generally, soccer players with ACLR showed nearly similar landing mechanics and neuromuscular strategies to healthy non-injured soccer players during both planned and unplanned landing maneuvers. However, soccer players with ACLR appear to utilize a protective landing strategy by decreasing activation of the gastrocnemius muscle, when averaged across both landing tasks.

INTRODUCTION

The anterior cruciate ligament (ACL) is one of the knee ligaments most frequently injured in sports.[1] ACL injury has an annual incidence of more than 200,000 injuries in the United States,[2,3] most of which are seen in adolescents participating in sports that involve landing from a jump such as soccer and football.[4-7] Soccer requires the athlete to perform high-risk maneuvers such as, pivoting, cutting, and landing at high speed. Therefore, soccer players are particularly at high risk for ACL injuries.[6,8-10] Soccer has the highest prevalence among other sports with a rate ranging from 3.7 to 29.1 injuries per 1000 hour of practice and games.[11]

Rehabilitation following ACL reconstruction (ACLR) surgery is widely accepted as the proper intervention for restoring knee joint function, predominantly for athletes who want to return to their prior level of sport participation.[12] Investigators have reported that individuals with ACLR (at least 6 months post-surgery) demonstrated significant improvements in functional tasks such as step-up, step-down, and the shuttle run.[13,14] On the other hand, some investigators claim that ACLR and post-surgical rehabilitation does not fully restore the normal function of the knee joint and some impairments might persist such as muscle weakness, proprioceptive and neuromuscular deficits, excessive tibial rotation, impaired postural control, and altered landing strategies.[15-19] The persistent impairments are usually cited as a factor hindering successful return to pre-injury level of sporting activities.[20] A systematic review and meta-analysis reported that at a mean of 3.5 years after ACLR surgery, only 63% of athletes were able to return to their prior level of sport participation and 44% were able to return to competitive sports.[21]

Landing from a jump has been cited as one of the most common athletic maneuvers to cause ACL injuries.[5,6,22-26] Therefore, in an attempt to prevent future injuries, substantial attention has focused on landing mechanics in patients following ACLR. In an attempt to mimic sport-specific activities in the clinical setting, landing mechanics in individuals with ACLR have been evaluated by functional tasks such as drop jumps and up-down hops. Decker et al.[27] compared kinematics and kinetics performance between 11 healthy and 11 hamstring ACLR recreational athletes during a 60-centimeter vertical hop landing. They found that the ACLR group exhibited a stiff landing technique and a decreased rate of force application to the body at initial ground contact. Compared with the healthy group, those in the ACLR group landed with more ankle plantarflexion and decreased hip flexion. This stiff landing technique does not sufficiently allow the hip and knee joints to control the downward momentum during landing.[28] As a consequence, higher forces at the knee joint will be generated resulting in excessive loading on the ACL that increases the risk of ACL injury.[1]

Gokeler et al.[29] analyzed muscle activity and movement patterns during landing from a single leg hop for distance in 9 ACLR patients 6-months after surgery. They found that the ACLR limb had significant earlier onset times for gluteus maximus, vastus lateralis, rectus femoris, biceps femoris, semimembranosus, medial gastrocnemius, lateral gastrocnemius, and soleus compared with the uninvolved limb. Also, the involved limb demonstrated a significant decrease in knee flexion during the take-off and an increase in plantarflexion at initial contact. Other researchers have shown that patients with ACLR and ACL deficiency demonstrate neuromuscular compensatory strategies that help them to increase functional knee stability. For example, Paterno et al.[30] showed that females with ACLR had higher vertical ground reaction forces (GRFs) on the uninvolved limb during a drop vertical jump when compared with the involved limb and the control group. Specifically, patients demonstrated this biomechanical limb asymmetry until a mean of 27 months after surgery. It has been suggested that landing with high vertical GRFs can predispose the knee joint to further injuries.[31,32]

Despite that previous investigators have evaluated kinematics, kinetics, and neuromuscular strategies in individuals with ACLR, there has been a paucity of studies investigating the same variables specifically in soccer players with ACLR during planned and unplanned landing tasks. Critical to the study of landing biomechanics after ACLR is the selection of the landing maneuvers. Planned landing allows the athlete to preplan the landing pattern such as a broad jump. On the other hand, unplanned landing, such as landing following heading a soccer ball, may influence muscle activation strategies and consequently alter the lower extremity mechanics. These 2 landing tasks are common in soccer and were selected in order to closely simulate soccer match situations.

The purpose of the study was to compare kinematics, kinetics, and neuromuscular performance between soccer players with an ACLR and healthy non-injured soccer players during planned and unplanned landing maneuvers. We hypothesized that participants would demonstrate greater injury predisposing factors during unplanned landing compared with planned landing. In addition, we hypothesized that injury predisposing factors would be more pronounced in the ACLR group than the control group.

METHODS

Participants

With an effect size of 0.20,[33] α set at 0.05, power = 0.80, the results of the power analysis revealed that 36 participants will be needed for both groups to find differences between the 2 landing tasks if a difference exists. Consequently, 18 recreational soccer players who had undergone ACLR and rehabilitation (Men: n=8; Women: n=10; Unilateral ACLR: n=15) were recruited in this study using convenience sampling. Of these 15 participants with unilateral ACLR, 7 participants had the surgery on the dominant leg. The ACLR participants had undergone different surgical reconstructive procedures (patellar tendon autograft: n=10; hamstrings autograft: n=7; allograft: n=1). Inclusion criteria for ACLR participants were: 1-10 years post ACLR and between the age of 18 and 35 years. Exclusion criteria for these participants were: inability to perform a soccer-specific jump heading task, more than 3 mm anterior tibial translation difference between knees as measured by a knee arthrometer, low back or other lower extremity surgery, other lower extremity injury in the 6 months before participating in the study, neurological disease, injury of other major ligaments of the lower extremity, and self-reported pregnancy.

The normal group included 18 gender-matched healthy non-injured recreational soccer players. Inclusion criterion for healthy participants was between the age of 18 and 35 years. Exclusion criteria for these participants were: inability to perform a soccer-specific jump heading task, low back or other lower extremity surgery, other lower extremity injury in the 6 months before participating in the study, neurological disease, injury of other major ligaments of the lower extremity, and self-reported pregnancy. All participants read and signed an informed consent approved by the Institutional Review Board of Texas Woman's University, Houston Center.

Instrumentation

A 10-camera motion analysis system (Vicon Motion Systems Ltd. Denver, CO, USA) at a sampling rate of 240 Hz and 4 AMTI force platforms (Advanced Mechanical Technology Inc. Watertown, MA, USA) at a sampling rate of 1000 Hz were used to collect kinematic and kinetic data. Using hypo-allergenic double-sided tape, 15 retro-reflective markers were attached to the participants' lower extremities according to Vicon Plug-in gait model. Markers were placed over both anterior superior iliac spines, second sacral vertebra, and bilaterally at lateral femoral epicondyles, mid-distance between greater trochanters and lateral femoral epicondyles, lateral malleoli, mid-distance between lateral femoral epicondyles and lateral malleoli, calcaneal tuberosities, and second metatarsophalangeal joints. Before each data collection session, the equipment was calibrated according to the manufacturer's recommendations and a static trial was carried out in order to estimate each participant's joint centers and center of mass for lower extremity segments.

A Just Jump System (Probotics Inc. Huntsville, AL, USA) was used to determine maximum vertical jump. The Just Jump System is one of the most common devices used to determine the height of the vertical jump.[34-38] The Just Jump System has been reported to have good reliability (ICC $\geq$ 0.87) in male and female athletes.[38] Previously, the concurrent validity of the Just Jump System was established (r=0.96) when compared with the 3-camera motion analysis system as a criterion reference in 39 college students.[37]

The F-Scan wireless plantar-pressure measurement system (30 Hz; Tekscan Inc. Boston, MA, USA) was time-synchronized to the Vicon system and utilized to collect foot pressure data. The F-Scan system uses 2 insole sensors embedded in both shoes. Each insole sensor, which is connected to the cuff unit, contains 960 individual sensors. The cuff unit was secured around the ankle by an ankle band. Category 5 Enhanced (CAT 5E) cables were used to connect each cuff unit to the wireless data-logger that was secured at the back of each participant by a waist belt. The equipment was calibrated using a step calibration procedure using participant's weight prior to each data collection session as recommended by the F-Scan system guidelines.

A KT-1000 Arthrometer (MEDmetric Corp. San Diego, CA, USA) was used to determine if there was an anterior tibial translation difference between knees. The KT-1000 has been frequently used to obtain measurements in millimeters of the anterior tibial translation in clinical setting involving ACL disruption and ACL reconstruction.[39-42] The KT-1000 has been reported as a reliable device (ICC ≥ 0.84) in male college participants[43] and has been found to have a specificity of 0.72 and a sensitivity of 0.90 in patients with unilateral ACL deficiency.[44]

A Trigno Wireless EMG System (Delsys Inc. Boston, MA, USA) was utilized to quantify the activity level of the following muscles: gluteus maximus, vastus lateralis, rectus femoris, vastus medialis, lateral and medial hamstrings, and gastrocnemius. Fourteen pre-amplified bipolar Ag wireless electrodes (contact dimension: 5mm×1mm; inter-bar distance: 10mm; bandwidth: 20-450 Hz; CMRR: > 80db) were placed bilaterally on the skin of each muscle according to Cram et al.[45] The skin was cleaned with a cotton ball soaked in 70% isopropyl alcohol before placing the electrodes. Adhesive tape was used to secure the placement of the electrodes during the jumps with the purpose of decreasing movement artifact.

Procedure

Anthropometric measures were obtained from all participants. Each participant was asked to kick a soccer ball to identify the dominant leg. Participants were then asked to perform a warm-up protocol consisting of 5 minutes of cycling on a cycle ergometer at 40 to 60 rotations per minute (rpm), 10 half squats, and 5 continuous vertical jumps. To determine maximum long jump distance, each participant performed 3 long jumps as far as possible. Three maximum vertical jumps subsequently were carried out to determine maximum vertical jump height. The highest vertical jump and the longest forward jump were recorded for each participant. To familiarize participants with the landing tasks included in the study, each participant was given demonstration of functional tasks and instructed to perform 2 practice trials since these have shown good reliability (ICC ≥ 0.76).[46]

In this study, the landing tasks included a forward jump onto the force platforms (planned landing) and a forward jump to head a soccer ball and then land on the same force platforms (unplanned landing). For the planned landing, each participant was instructed to jump from a distance (starting point) that was 80% of his/her maximum long jump and land on the force platforms. The unplanned landing was executed by having each participant jump forward to head a soccer ball and then land on the force platforms. The soccer ball was suspended from the ceiling at a location in the middle between the starting point and the force platforms (40% of participant's maximum long jump). The height of the middle of the soccer ball was placed at half of the participant's maximum vertical jump height. The results of the first reliability study (Chapter 3) revealed that 4 trials exhibited good reliability for all kinematics and kinetics measures during planned landing (ICC ≥ 0.81) and unplanned landing (ICC ≥ 0.76). Consequently, each participant was asked to carry out 4 trials of each landing task. The order of these tasks was randomized for each participant to avoid a learning effect.

Data Reduction

Vicon Nexus 1.8 and Polygon (v4.0, Vicon Motion System Ltd. Denver, CO) software were utilized to analyze all kinematics and kinetics outcomes. The 3-dimensional trajectory of retro-reflective markers, from which joint angles were derived, were filtered at a frequency of 6 Hz through a second order low-pass Butterworth filter. Kinematics and kinetics of the sagittal plane were used to evaluate landing mechanics during both landing tasks. The kinematic variables included peak ankle dorsiflexion, peak knee flexion, and peak hip flexion joint angles. The kinetic variables included peak plantarflexion, peak knee extension, and peak hip extension moments. All kinematics and kinetics data were exported to Microsoft Excel™ and then transferred to SPSS for analysis. Peak values for each variable were defined as the greatest values from initial contact to maximum knee flexion angle. The average of the peak values of both limbs for each variable was calculated for each participant.

Electromyographic (EMG) data were time-synchronized to kinematic and kinetic data and analyzed by Polygon (v4.0, Vicon Motion System Ltd. Denver, CO) software. For each muscle, the mean and maximum signals from initial contact to maximum knee flexion angle were exported to Microsoft Excel™. Subsequently, the EMG data for each muscle was normalized utilizing a dynamic normalization procedure in which the mean signals were divided by the maximum signals. The dynamic normalization procedure is a commonly used method to normalize EMG signals during dynamic maneuvers.[47-52] This method helps minimize inter-subject variability and the variability originated from performing multiple trials.[47,48,53] The average of the normalized data for vastus lateralis, rectus femoris, and vastus medialis was calculated to represent quadriceps muscle group, whereas hamstring muscle group was represented by the averaged normalized data of medial and lateral hamstrings. The normalized EMG data were then transferred to SPSS for statistical analysis.

Peak pressure was analyzed using the F-Scan Research software (v7.00, Tekscan Inc. Boston, MA, USA). Peak pressure values were defined as the greatest values from initial contact to maximum knee flexion angle. Peak pressure values were exported to Microsoft Excel™ and then transferred to SPSS for analysis. For each participant, the peak pressure values of both limbs were averaged for statistical analysis.

Data Analysis

The kinematics, kinetics, and EMG data were verified for the assumptions of normality and outliers using Kolmogorov-Smirnov test and box plots, respectively. An independent t-test was performed for each anthropometric measure to evaluate differences between groups at baseline. A 2 × 2 mixed

ANOVA (group × landing) was performed for each of the dependent variables. Group (ACLR and control group) was the between-subjects factor and landing (planned and unplanned) was the within-subjects factor. Adjustment of alpha level was considered in this study to reduce the chance of committing type I errors. Therefore, the level of statistical significance was set at .05/3 or .0167. Further adjustment for alpha level was made (0.0167/2 or 0.0083) for simple effects and follow-up comparisons. Effect size and power were calculated for all analyses. All data analyses were performed using SPSS® 23 (SPSS Inc., Chicago, IL USA).

RESULTS

Kinematic, kinetic, and EMG data met the normality and outliers assumptions. All anthropometric measures showed no significant differences between groups at baseline (Table 4.1). Kinematics data showed significant interaction of group × landing for knee flexion angles ($F_{1,34} = 11.26$, $p = 0.002$, ES = 0.24, $\beta = 1.00$) (Table 4.2). Follow-up pairwise comparisons showed that the ACL group landed with significant greater knee flexion angles during planned landing compared with unplanned landing ($p < 0.001$). Also, significant main effects for landing were found, which demonstrated that all participants had significantly greater hip and knee flexion angles during planned landing than unplanned landing ($F_{1,34} = 48.55$, $p < 0.001$, ES = 0.58, $\beta = 1.00$; $F_{1,34} = 40.58$, $p < 0.001$, ES = 0.54, $\beta = 1.00$, respectively) (Table 4.2). Additionally, main effect for group (regardless of landing) trended ($F_{1,34} = 3.25$, $p = 0.08$, ES = 0.09, $\beta = 0.41$) toward an increase in hip flexion in the ACL group compared with the control group (Table 4.2).

For kinetics data, main effects for landing were found, which demonstrated that all participants had significantly greater hip and knee extension moments and peak pressure during planned than unplanned landing ($F_{1,34} = 6.82$, $p < 0.013$, ES = 0.16, $\beta = 0.71$; $F_{1,34} = 27.18$, $p < 0.001$, ES = 0.44, $\beta = 0.99$; $F_{1,34} = 20.98$, $p < 0.001$, ES = 0.38, $\beta = 0.99$, respectively) (Table 4.2).

For electromyography (EMG) data, main effect for group for gastrocnemius muscle was significant showing that the ACL group landed with a significant decrease in gastrocnemius activity compared with the control group ($F_{1,34} = 11.27$, $p = 0.002$, ES = 0.24, $\beta = 0.90$) (Table 4.3). In addition, strong trends toward decreased quadriceps ($F_{1,34} = 6.22$, $p < 0.018$, ES = 0.15, $\beta = 0.67$) and hamstrings

($F_{1,34}$ = 5.93, $p < 0.02$, ES = 0.14, β = 0.65) muscles activity in the ACL group (regardless of landing) compared with the control group (Table 4.3).

DISCUSSION

This investigation was conducted to compare kinematics, kinetics, and neuromuscular performance between soccer players with an ACLR and healthy non-injured soccer players during planned and unplanned landing maneuvers. Our findings support the first hypothesis that unplanned landing would demonstrate greater injury predisposing factors compared with planned landing. The results of the current investigation showed that the peak hip and knee flexion angles were significantly smaller during the unplanned landing compared with planned landing in both groups. Landing with less hip and knee flexion is usually cited as a stiff landing, a landing technique that does not sufficiently allow the hip and knee joints to control the downward momentum during landing.[28] As a consequence, higher forces at the knee joint will be generated resulting in excessive loading on the ACL increasing the risk of ACL injury.[1] Our findings suggest that both landings are biomechanically different and each landing maneuver produces a specific landing pattern. Additionally, changing the landing task from planned to unplanned landing may predispose individuals to lower extremity injuries as a consequence of lower hip and knee flexion angles. Previous investigators have reported that greater hip and knee flexion may assist the lower extremity to sufficiently attenuate the large load experienced during landing.[28,54] Therefore, soccer players should be trained to adopt a landing technique, characterized by adequate hip and knee flexion, during unplanned landing in order to decrease the risk of lower extremity injuries.

One possible explanation for smaller hip and knee flexion during the unplanned landing could be due to the difference in the GRFs magnitude between the 2 landings that resulted in different landing strategies. To quantify GRFs experienced during landing, plantar pressure system was used in this investigation to evaluate peak pressure between the shoe and the foot. The current findings revealed that all participants demonstrated significantly greater peak pressure during the planned landing compared with unplanned landing ($p<0.001$) (Table 4.2). Greater peak pressure experienced during landing may require greater lower extremity joint angles to assist in shock attenuation.[55,56] Therefore, participants in this investigation increased peak pressure during the planned landing compared with unplanned landing. We hypothesized that the jumping distance during unplanned landing was small due to the presence of the ball compared with the greater jumping distance available during planned landing. In other words, participants may be more familiar with planned landing that allowed them to increase the jumping distance and thus resulted in greater peak pressure. On the other hand, participants may have been more cautious when heading the soccer ball that resulted in decreased jumping distance that led to decreased peak pressure during the unplanned landing. Hence, this might explain the greater peak pressure during the planned landing compared with unplanned landing.

Greater hip flexion angles may move the ground reaction force vector anteriorly relative to the hip joint resulting in greater external flexion moments.[57] As a consequence, greater internal hip extension moments (gluteus maximus activation) may be necessary to counteract the increased external flexion moment at the hip (Figure 4.1).[57] Similar to the hip joint, greater knee flexion angles may transfer the line of gravity posterior to the knee joint axis and thus generating greater external flexion moment.[57] As a result, increased activation of knee extensors may be required to generate internal knee extension moment to balance the increased external knee flexion moment (Figure 4.1).[57] McNitt et al. found that the extension moment of the lower extremity tended to increase as the landing height increased in 12 gymnastic and recreational male athletes.[58] In the present investigation, planned landing exhibited significantly greater internal hip and knee extension moments compared with unplanned landing among all participants ($p<0.001$) (Table 4.2). These data may indicate that the mechanical demand of the hip and knee extensors muscles increases as the landing maneuver changes from unplanned to planned landing. During planned landing, the increased internal hip and knee extension moments used by participants in the current study may decrease the load of the external moments on the non-contractile tissues such as ligaments. On the other hand, the lower hip and knee extension moments during unplanned landing may predispose the non-contractile structures of the hip and knee joints to the external moments acting on these joints. Our findings suggest that unplanned landing exhibit kinetic factors that may place individuals at greater risk for ACL injury.

Contrary to our second hypothesis, the ACLR group did not demonstrate greater injury predisposing factors compared with the normal group. The primary finding was the overall lack of differences in landing mechanics and neuromuscular performance between soccer players with an ACLR and healthy non-injured soccer players during planned and unplanned landings. These findings may suggest that soccer players with ACLR were able to utilize landing mechanics and neuromuscular performance similar to those healthy non-injured soccer players. Our findings are supported by previous investigations in which no differences in peak hip and knee joint flexion were found between individuals with ACLR and healthy recreational athletes during a single-leg 40-cm drop jump and a bilateral 60-cm drop jump.[27,59] Previous researchers found contradictory results in which individuals with ACLR (2 years post-surgery) demonstrated increased tibial rotation compared with healthy athletes during high-level of sporting activities.[19]

In addition to the main dynamic stabilizers of the knee joint (quadriceps and hamstrings), the gastrocnemius muscle provides additional support to the knee joint during dynamic functional tasks.[60] Previous researchers have reported that increased activation of the gastrocnemius muscle (ACL antagonist) may increase anterior tibial translation and consequently increase the ACL loading.[61] Therefore, it may be reasonable to assume that individuals with ACLR may adopt a protective landing strategy by decreasing gastrocnemius muscle activity in order to decrease the ACL loading. The results of this investigation revealed that the normalized EMG for gastrocnemius muscle, when averaged across both landings, was significantly decreased in the ACLR group compared with the normal group ($p=0.002$) (Table 4.3). This finding is supported by a previous investigation in which significant decrease of gastrocnemius activity was observed in the ACL deficits participants compared with the healthy participants during walking.[62]

In comparison with the healthy group, a significant increase in knee flexion angles was observed in the ACLR group during planned landing compared with unplanned landing ($p<0.001$). The significant increase in knee flexion observed in the ACLR group during planned landing, which was not found in the normal group, might indicate that the ACLR group used different quadriceps and hamstrings muscles activation pattern than the control group. In addition, deficits in quadriceps and hamstring muscles strength have been reported in individuals with ACLR.[63,64,65] In the present investigation, the normalized EMG for quadriceps and hamstrings muscles did not show significant differences between the ACLR and control group during both landings (Table 4.3). However, strong trends toward decreased quadriceps (p=0.018) and hamstring (p=0.02) muscles activity, when averaged across both landings, were found in the ACLR group compared with the control group. This may suggest that soccer players with ACLR in this investigation have lower quadriceps and hamstring muscles activation compared with the normal group, thus generating greater knee flexion angles during planned landing. A recent study has reported that increased activation of quadriceps and hamstring muscles is significantly associated with a landing pattern characterized by decreased hip and knee flexion angles during drop vertical jumps.[66] Therefore, this might explain the reason soccer players with ACLR responded differently than the control group in terms of knee flexion as the landing maneuver changed from unplanned to planned landing.

While not statistically different, hip flexion angles, when averaged across both landings, trended (p=0.08) toward an increase in the ACLR group compared with the control group. Activation pattern of the gluteus maximus muscle, which acts eccentrically to decrease the hip flexion, might explain the difference in hip flexion between group.[67,68] However, our findings revealed that the normalized EMG for gluteus maximus did not exhibit significant differences between the 2 groups during both landings (Table 4.3). Therefore, it can be hypothesized that the increased flexion at the hips of the soccer players with ACLR was a consequence of neuromuscular control of the trunk. Clarke et al.[69] found significantly increased hip flexion in individuals with ACLR compared with normal individuals during a 30-cm drop jump task. The investigators claimed that the increased hip flexion observed in the ACL group was due to deficits in trunk control. Previous researchers have observed concomitant increases in hip and knee flexion as a result of neuromuscular control of the trunk during a drop landing task in 40 healthy individuals.[70] An association between ACL injuries and deficits of neuromuscular control of the trunk has been reported in female athletes.[71-73] Clinicians should be aware of this potential compensatory landing pattern and implement an intervention plan targeting at improving trunk neuromuscular control during landing in order to decrease the risk of ACL injury.

The findings of this investigation should be interpreted considering the following limitations. First, soccer players with ACLR in this study had undergone different surgical reconstructions (allograft and autograft) that were not performed by the same orthopedic surgeon. Second, the recreational level of play for participants in this study might limit the generalizability to highly competitive athletes. Third, this investigation did not evaluate neuromuscular control of trunk, which might have influenced the results. Fourth, although playing hours did not show significant differences between the 2 groups, differences in landing may still exist due to the proficiency in landing, particularly during unplanned landing. Previous researchers have reported that strikers and center backs perform more jumping and heading the ball than defenders during a soccer match.[74,75] Therefore, this may indicate that position role may have an influence on proficiency of landing that might lead to different landing strategies.

CONCLUSION

The present findings indicated that unplanned landing demonstrated greater injury predisposing factors compared with planned landing by exhibiting a stiff landing technique characterized by decreased hip and knee flexion. Soccer players should be trained to show adequate hip and knee flexion joint angles during unplanned landing to decrease the risk of ACL injury. Generally, soccer players with ACLR showed nearly similar landing mechanics and neuromuscular strategies to healthy non-injured soccer players during both planned and unplanned landing maneuvers. However, soccer players with ACLR appear to utilize a protective landing strategy by decreasing activation of the gastrocnemius muscle, when averaged across both landing tasks.

Table 4.1. Anthropometric data

Anthropometric Measure	ACLR (n=18)	Control (n=18)	P Value
	Mean ± S.D	Mean ± S.D	
Age (years)	26.11 ± 3.95	25.83 ± 3.51	0.82
Height (m)	1.70 ± 0.09	1.66 ± 0.05	0.20
Weight (kg)	68.15 ± 9.64	66.88 ± 10.37	0.70
BMI (kg/m^2)	23.52 ± 2.69	24.09 ± 3.73	0.60
Playing time (hrs/week)	4.11 ± 3.42	3.77 ± 3.07	0.76
Time of Surgery (years)	5 ± 3.30	NA	NA

S.D, standard deviation; n, number of participants.

Table 4.2. Means, S.D, and P values for kinematics and kinetics variables

Variables	Planned		Unplanned		P value		
	Mean	S.D	Mean	S.D	ME-G (β)	ME-L (β)	Interaction (β)
Kinematics (°)							
Hip Flexion							
ACLR	91.24	14.44	69.96	15.57	0.08 (41.8)	<0.001*	0.03 (55.1)
Control	76.63	19.54	65.38	19.54			
Knee Flexion							
ACLR	96.84	19.25	74.17	12.86	0.11 (35.8)	<0.001*	0.002*
Control	80.64	21.31	73.62	11.90			
Dorsiflexion							
ACLR	22.54	5.01	23.25	6.07	0.74 (6.20)	0.03 (57.40)	0.17 (26.80)
Control	21.86	5.62	24.93	4.22			
Kinetics (Nm/kg)							
Hip Extension Moment							
ACLR	2.83	1.12	2.27	0.65	0.41 (12.7)	0.013*	0.90 (55.1)
Control	2.63	0.94	2.11	0.86			
Knee Extension Moment							
ACLR	2.28	0.33	1.80	0.43	0.17 (26.7)	<0.001*	0.77 (5.90)
Control	2.10	0.47	1.56	0.78			
Plantarflexion Moment							
ACLR	0.55	0.16	0.79	0.35	0.64 (7.40)	0.03 (56.9)	0.14 (30.5)
Control	0.61	0.30	0.66	0.39			
Peak Pressure (KPa)							
ACLR	613.92	225.34	498.75	122.86	0.28 (18.4)	<0.001*	0.31 (16.6)
Control	706.36	264.21	525.98	107.37			

S.D, standard deviation; ME-G, main effect for group; ME-L, main effect for landing; β, power.
*Significant ($p<0.0167$)

Table 4.3. Means, S.D, and P values for EMG variables

Variables	Planned		Unplanned		P value		
	Mean	S.D	Mean	S.D	ME-G (β)	ME-L (β)	Interaction (β)
Muscle Activity							
Glut Max							
ACLR	74.85	15.37	73.60	17.26	0.43 (11.9)	0.71 (6.50)	0.26 (19.7)
Control	69.09	14.79	71.54	15.11			
Quadriceps							
ACLR	77.70	9.36	79.18	8.91	0.018 (67.8)	0.58 (8.40)	0.31 (16.8)
Control	85.05	7.84	84.62	6.28			
Hamstring							
ACLR	61.10	14.86	60.86	6.29	0.02 (65.8)	0.44 (11.7)	0.51 (9.80)
Control	69.97	13.52	67.07	6.91			
Calf							
ACLR	57.21	8.04	56.26	13.46	0.002*	0.74 (6.20)	0.95 (5.00)
Control	66.68	15.21	66.00	5.59			

S.D, standard deviation; ME-G, main effect for group; ME-L, main effect for landing; β, power.
*Significant ($p<0.0167$)

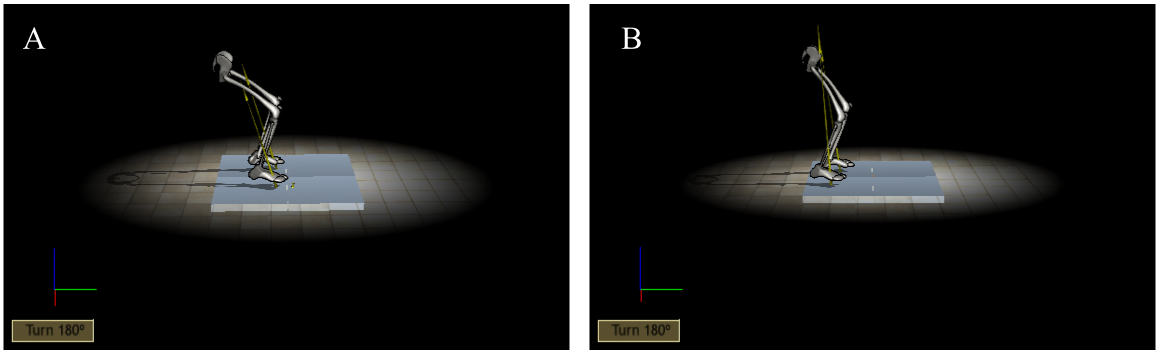

Figure 4.1: Moments at the hip and knee joints. (A) Planned landing: The ground reaction force vector is positioned anteriorly relative to the hip joint and posteriorly to the knee joint resulting in greater external flexion moment, creating greater internal hip and knee extension moment. (B) Unplanned landing: The ground reaction force vector is positioned relatively close to the hip and knee joints resulting in less external flexion moment, creating less internal hip and knee extension moment.

CHAPTER V

EFFECT OF FATIGUE ON LANDING BIOMECHANICS IN SOCCER PLAYERS WITH AN ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

ABSTRACT

Fatigue has been shown to influence landing biomechanics in individuals with an anterior cruciate ligament reconstruction (ACLR). However, no study has evaluated the effect of fatigue on landing biomechanics during a soccer-specific landing task in soccer players with an ACLR. **Purpose:** To evaluate the effect of fatigue on landing biomechanics during an unplanned landing task in soccer players following ACLR compared with healthy non-injured soccer players. **Methods:** Eighteen soccer players with an ACLR (age, 26.11 ± 3.95 years; height, 1.70 ± 0.09 m; weight, 68.15 ± 9.64 kg, BMI, 23.52 ± 2.69 kg/m^2, time since surgery, 5 ± 3.30 years) and 18 healthy non-injured soccer players (age, 25.83 ± 3.51 years; height, 1.66 ± 0.05 m; weight, 66.88 ± 10.37 kg, BMI, 24.09 ± 3.73 kg/m^2) participated in the study. Subjects were assessed during an unplanned landing task before and after completing a Wingate fatigue protocol. The landing task included jumping forward to head a soccer ball and landing on the force plates. An accumulation of 4mmol of lactate was indicative of fatigue. The outcome measures were peak flexion angles and extension moments of the hip, knee, and ankle joints, peak pressure, and electromyography activity of gluteus maximus, quadriceps, hamstrings, and gastrocnemius muscles. A 2×2 ANOVA (fatigue×group) was performed for each outcome measure. **Results:** There were no significant fatigue×group interactions for any of the outcome measures. There were significant main effects of fatigue (as compared to the non-fatigued landing) regardless of group. The fatigued landing showed greater hip flexion ($F_{1,34}$ = 7.24, p = 0.01), greater knee flexion ($F_{1,34}$ = 12.16, p = 0.001), and greater ankle dorsiflexion ($F_{1,34}$ = 10.97, p = 0.002). Also, the fatigued landing demonstrated significantly greater hip extension moments ($F_{1,34}$ = 7.71, p = 0.009), greater knee extension moments ($F_{1,34}$ = 7.04, p = 0.012), greater ankle plantarflexion moments ($F_{1,34}$ = 10.38, p = 0.003), and decreased quadriceps activity

($F_{1,34}$ = 8.18, p = 0.007). **Conclusion:** Fatigue caused changes in landing biomechanics; however, these changes were not significantly different when the groups were compared. These results indicate that having an ACLR (at least 1 year post-surgery) does not appear to lead to sustained changes in landing biomechanics induced by fatigue.

INTRODUCTION

Soccer is characterized by high-intensity activities in which a series of physical actions are performed throughout the match.[1,2] Soccer players perform a variety of game-related activities at different intensity such as running, dribbling, heading, and changing directions.[2] During a match, the total distance covered is approximately 10 km, with 0.65 km of these being covered when sprinting.[1] Previous studies have reported a reduction in total distance covered during the second half compared with the first half.[2,3] In addition, reductions in high-intensity actions, jumping ability, and sprinting have been reported after the soccer game.[4,5] Several researchers have attributed this reduction of physical activity to the development of fatigue.[6] Consequently, a great deal of attention has been paid to evaluate the influence of fatigue on lower extremity biomechanics.

Fatigue has been reported by several studies as one of the predisposing factors for musculoskeletal injuries.[7,8] Several researchers reported that neuromuscular fatigue causes various biomechanical changes that may place individuals at a greater risk of a non-contact ACL injury during landing.[7,9-11] Fatigue has specific effects on movement coordination,[12] motor control precision,[13] and altering multiple biomechanical parameters including lower extremity kinematics and kinetics.[7,14] Furthermore, some researchers have reported decreased vertical jump height,[15] decreased knee flexion,[16,17] impaired balance,[18,19] and increased electromyography (EMG) activity of quadriceps and hamstrings after fatiguing conditions.[15,20] Therefore, alteration in biomechanical parameters might predispose the knee to injury and more specifically might rupture the ACL. Some researchers have evaluated the effect of fatigue on kinematics and kinetics during landing by inducing fatigue locally around the knee joint,[10,21,22,] whereas others used a more general neuromuscular fatigue protocol.[7,9,23,24] Some of these studies indicated that neuromuscular fatigue causes biomechanical alterations during landing.[7,9-11] Particularly, a landing pattern characterized by increase in both knee abduction and hip internal rotation was reported.[7,11] Knee abduction and hip internal rotation are among the main biomechanical risk factors leading to non-contact ACL injuries because the ACL serves as a secondary restraint to knee internal rotation and abduction.[25,26] Therefore, increase in knee abduction and hip internal rotation can increase the load on the ACL and the risk of ACL rupture.[25,26]

Several researchers reported that individuals with ACL reconstruction (ACLR) have persistent impairments such as muscle weakness, proprioceptive and neuromuscular deficits, excessive tibial rotation, impaired postural control, and altered landing strategies.[27,28] Therefore, individuals who have undergone ACLR may be at higher risk for the effect of fatigue. However, findings from previous investigations are controversial where some results supported this notion and others were inconsistent. In a study of 10 male ACLR patients and 11 male non-injured healthy participants who were exposed to a general fatigue protocol to evaluate landing biomechanics during single limb landing, the researchers found that fatigue induced many biomechanical changes in the ACLR limb such as decrease in knee flexion and adduction moments.[29] Nevertheless, most biomechanical changes in the ACLR limb were also observed in the uninvolved limb and in the healthy group. On the other hand, some researchers found that individuals with ACLR demonstrated greater deficits in response to the fatigue effect than the healthy individuals.[30] Specifically, a significant reduction in hip extensors strength was observed only in the ACL group following a fatigue protocol.

Although some studies have investigated the effect of fatigue on kinematics, kinetics, and neuromuscular strategies in people with ACLR, the same variables have not been investigated in soccer players with ACLR during soccer-specific landing maneuvers. Specifically, no study has compared kinematics, kinetics, and neuromuscular performance between soccer players with ACLR and healthy non-injured soccer players during unplanned non-fatigued and fatigued landings. Unplanned landing maneuvers are one of the most common activities performed repeatedly throughout a soccer game such as landing after heading a soccer ball. The combination of fatigue and soccer-specific unplanned landing maneuver may further alter landing biomechanics that may place soccer players at high risk of sustaining ACL injury.

The purpose of this investigation was to compare kinematics, kinetics, and neuromuscular performance between soccer players with ACLR and healthy non-injured soccer players during soccer-specific unplanned non-fatigued and fatigued landings. We hypothesized that all participants would demonstrate changes in landing biomechanics following the neuromuscular fatigue. We also hypothesized that these biomechanical changes would be more pronounced in the ACLR group compared with the control group.

METHODS

Participants

With an effect size of 0.30,[29] α set at 0.05, power = 0.80, the results of the power analysis revealed that 24 participants would be needed for both groups to find differences between the fatigue and non-fatigue landing tasks if a difference exists. A sample of convenience including 18 (men: n=8; women: n=10) soccer players with ACLR (patellar tendon autograft: n=10; hamstrings autograft: n=7; allograft: n=1) was recruited for this investigation. Fifteen of the ACL participants had unilateral ACLR (surgery on the dominant leg: n=7). Inclusion criteria for ACLR participants were: 1-10 years post unilateral ACL reconstruction, current participation in soccer at recreational level (4 hours or more per week), and between the age of 18 and 35 years. Exclusion criteria for these participants were: inability to perform a soccer-specific jump heading task, more than 3 mm anterior tibial translation difference between knees as measured by a knee arthrometer, low back or other lower extremity surgery, other lower extremity injury in the 6 months before participating in the study, neurological disease, bleeding disorders (e.g. hemophilia), injury of other major ligaments of the lower extremity, and self-reported pregnancy.

The control group consisted of 18 gender-matched healthy non-injured recreational soccer players. Inclusion criteria for healthy participants were: current participation in soccer at recreational level (4 hours or more per week), between the age of 18 and 35 years. Exclusion criteria for these participants were: inability to perform a soccer-specific jump heading task, low back or other lower extremity surgery, other lower extremity injury in the 6 months before participating in the study, neurological disease, bleeding disorders (e.g. hemophilia), injury of other major ligaments of the lower extremity, and self-reported pregnancy.

Instrumentation

Using hypo-allergenic double-sided tape, 15 retro-reflective markers were attached according to Vicon Plug-in gait model (Vicon Motion Systems Ltd. Denver, CO, USA) over both anterior superior iliac spines, second sacral vertebra, and bilaterally at lateral femoral epicondyles, mid-distance between greater trochanters and lateral femoral epicondyles, lateral malleoli, mid-distance between lateral femoral epicondyles and lateral malleoli, calcaneal tuberosities, and second metatarsophalangeal joints. Trials were collected with a Vicon Motion Analysis System consisting of 10 digital cameras (240 Hz sampling rate) and 4 AMTI (Advanced Mechanical Technology Inc. Watertown, MA, USA) force platforms (1000 Hz sampling rate). The equipment was calibrated according to the manufacturer's recommendations and a static trial was conducted before each data collection session.

A Trigno Wireless EMG System (Delsys Inc. Boston, MA, USA) was utilized to measure muscle activity of the gluteus maximus, vastus lateralis, rectus femoris, vastus medialis, lateral and medial hamstrings, and gastrocnemius in both legs. Fourteen pre-amplified bipolar Ag wireless electrodes (contact dimension: 5mm×1mm; inter-bar distance: 10mm; bandwidth: 20-450 Hz; CMRR: > 80db) were placed bilaterally on the skin of each muscle according to Cram et al.[31] The skin was cleansed with a cotton ball soaked in 70% isopropyl alcohol before placing the electrodes. With the purpose of reducing movement artifact, hypoallergenic tape was used to secure the placement of the electrodes during functional tasks performance.

The F-Scan wireless plantar-pressure measurement system (Tekscan Inc. Boston, MA, USA) was time-synchronized to the Vicon system and used to capture individual in-shoe pressure information at a sampling rate of 100 Hz. This system uses a thin insole sensor made up of 960 individual pressure-sensors. Two insole sensors were placed inside both shoes and connected to the cuff units. Each cuff unit was attached to the ankle band that was wrapped around the ankle. The other end of each cuff unit was connected to the wireless data-logger by Category 5 Enhanced (CAT5E) cables. A waist belt was used to secure the wireless data-logger at the back of each participant. As recommended by the F-Scan system guidelines, the equipment was calibrated to each participant's weight using a step calibration procedure before each data collection session.

A portable Lactate Plus Analyzer (Sports Resource Group Inc. USA) with a measuring range of: 0.3 to 25 millimoles per liter (mmol)/1 whole blood was used for determining blood lactate concentration after the fatigue protocol. An accumulation of 4mmol of lactate was indicative of the desirable level of fatigue for each participant.[32] The lactate plus analyzer has been widely used for measuring blood lactate in clinical and laboratory settings. The lactate plus analyzer has been reported to have excellent reliability (r=0.99) in 12 healthy male participants.[33] Also, the concurrent validity of the lactate plus analyzer was established (r=0.97) when compared with the Yellow Springs Instrument 2300 (YSI Inc. Yellow Springs, Ohio, USA) as a reference instrument in 15 men and women.[34]

A Just Jump System (Probotics Inc. Huntsville, AL, USA) was used to determine maximum vertical jump. The Just Jump System has been widely used to assess vertical jump height in many strength and conditioning studies.[35-39] The Just Jump System has been found to be a reliable device (ICC $\geq$ 0.87) and have a high correlation with the 3-camera motion analysis system as a criterion reference (r=0.96).[38,39]

A KT-1000 Arthrometer (MEDmetric Corp. San Diego, CA, USA) was used to determine if there was an anterior tibial translation difference between knees. The KT-1000 has been frequently used to obtain measurements in millimeters of the anterior tibial translation in clinical setting involving ACL disruption and ACL reconstruction.[40,41] The KT-1000 has been found to be a reliable and valid instrument.[41,42] The KT-1000 has been reported as a reliable device (ICC $\geq$ 0.84) in male college participants[43] and has been found to have a specificity of 0.72 and a sensitivity of 0.90 in patients with unilateral ACL deficiency.[44]

Procedure

Anthropometric measures were obtained from all participants. Each participant was asked to kick a soccer ball to determine the leg dominance.[45] Participants were then asked to perform a warm-up protocol consisting of 5 minutes of cycling at 40 to 60 rotations per minute (rpm) on a cycle ergometer, 10 half squats, and 5 continuous vertical jumps. To determine maximum vertical jump height and maximum long jump distance, each participant was instructed to perform 3 maximum vertical jumps and 3 long jumps as far as possible. The highest vertical jump and the longest forward jump were recorded for each participant. With the purpose of familiarizing participants with the landing task included in this study, each participant was given a demonstration of the functional tasks and instructed to perform 2 practice trials. Two practice trials were selected based on previous work demonstrating good reliability (ICC ≥ 0.76).[46]

The unplanned landing task included a forward jump to head a soccer ball and land on the force platforms. The soccer ball was suspended from the ceiling at a location in the middle between the starting point and the force platforms (40% of participant's maximum long jump). The center of the soccer ball was placed at half of the participant's maximum vertical jump height. The results of the first reliability study (Chapter 3) revealed that 4 trials exhibited good reliability for all kinematics and kinetics measures during the unplanned landing (ICC ≥ 0.76). Therefore, each participant was asked to carry out 4 trials of the unplanned landing task.

With the purpose of inducing metabolic fatigue, each participant was instructed to perform a 30-second Wingate anaerobic protocol.[47] Before performing the fatigue protocol, participants were asked to read a script to standardize the amount and type of verbal encouragement throughout the Wingate protocol. After a warm-up period of 2 minutes, each participant was then asked to pedal as fast as possible against a pre-determined resistance for 30 seconds. The constant 0.090 kilopond was multiplied by each subject's weight to calculate the resistance on the cycle ergometer.[48] Immediately after completing the Wingate protocol, blood samples were taken from each participant's fingertip to determine the blood lactate concentration. To ensure that each participant reached the accepted level of fatigue, 4 mmol of lactate or more was considered the desirable level of metabolic fatigue, as this level is cited as the anaerobic threshold.[32] A participant who did not reach this level was instructed to perform an additional 30-second bout of pedaling. All participants reached the desirable level of metabolic fatigue within their first trial of the Wingate test (Table 1). Participants were then instructed to perform 4 trials of the unplanned landing maneuvers. In order to limit recovery from fatigue throughout the fatigued session, all trials were performed within 30 seconds of each other. Furthermore, participants were asked to continue performing squats while data were saved in the computer and the Vicon system was being prepared for the subsequent trials.

Data Reduction

All kinematic and kinetic measures were synchronized and analyzed with Vicon Polygon (V 4.0, Vicon Motion System Ltd. Denver, CO). The 3-dimensional trajectory of retro-reflective markers, from which joint angles were derived, were filtered through a second order low-pass Butterworth filter at a frequency of 6 Hz. The kinematics and kinetics outcomes evaluated during the landing maneuver focused on the sagittal plane mechanics. The variables included peak ankle dorsiflexion joint angles, peak plantarflexion moments, peak knee flexion joint angles, peak knee extension moments, peak hip flexion joint angles, and peak hip extension moments. Joint angles and moments data were exported to Microsoft Excel™ and then transferred to SPSS for analysis. For each variable, peak values were defined as the greatest values from the moment each participant landed on the force plates to maximum knee flexion angle. For each participant, the average of the peak values of both limbs for each variable was calculated for statistical analysis.

Electromyographic (EMG) data were time-synchronized to kinematic and kinetic data and analyzed by Polygon (v4.0, Vicon Motion System Ltd. Denver, CO) software. For each muscle, the mean and maximum signals from initial contact to maximum knee flexion angle were exported to Microsoft Excel™. Subsequently, the EMG data for each muscle was normalized utilizing a dynamic normalization procedure in which the mean signals were divided by the maximum signals. The dynamic normalization procedure is a commonly used method to normalize EMG signals during dynamic maneuvers. [15,49-53] This method helps minimize inter-subject variability and the variability originated from performing multiple trials.[49,50,54] The average of the normalized data for vastus lateralis, rectus femoris, and vastus medialis was calculated to represent quadriceps muscle group, whereas hamstring muscle group was represented by the averaged normalized data of medial and lateral hamstrings. The normalized EMG data were then transferred to SPSS for statistical analysis.

The F-Scan Research ver. 7.00 software (Tekscan Inc. Boston, MA, USA) was used to analyze pressure data. Peak pressure values were defined as the greatest values from the moment each participant landed on the force plates to maximum knee flexion angles. Peak pressure values were exported to Microsoft Excel™ and then transferred to SPSS for analysis. The average of the peak pressure values of both limbs was calculated for statistical analysis.

Data Analysis

The kinematic, kinetic, and EMG data were screened for normality assumptions and outliers utilizing Kolmogorov-Smirnov test and box plots, respectively. For each anthropometric measure, an independent t-test was conducted to check for differences between groups at baseline. A 2 × 2 mixed ANOVA (group × fatigue) was performed for each of the dependent variables. Group (ACLR and control group) was the between-subjects factor and fatigue (pre-fatigue and post-fatigue) was the within-subjects factor. Adjustment of alpha level was considered in this study to reduce the chance of committing type I errors. Therefore, an α level .05/3 or .0167 was used to represent statistical significance. Further adjustment for alpha level was made (0.0167/2 or 0.0083) for simple effects and follow-up comparisons. Effect size and power were calculated for all analyses. All data analyses were performed using SPSS® 23 (SPSS Inc., Chicago, IL USA).

RESULTS

All kinematic, kinetic, and EMG data met the assumptions of normality and outliers. None of the anthropometric measures showed significant differences between groups (Table 5.1). There were no significant fatigue × group interactions for any of the outcome measures. There were significant main effects of fatigue (as compared to the non-fatigued landing) regardless of group. The fatigued landing showed greater hip flexion ($F_{1,34} = 7.24$, $p = 0.01$, ES = 0.17, $\beta = 0.74$), greater knee flexion ($F_{1,34} = 12.16$, $p = 0.001$, ES = 0.26, $\beta = 0.92$), and greater ankle dorsiflexion ($F_{1,34} = 10.97$, $p = 0.002$, ES = 0.24, $\beta = 0.89$) (Table 5.2). Also, the fatigued landing demonstrated significantly greater hip extension moments ($F_{1,34} = 7.71$, $p = 0.009$, ES = 0.18, $\beta = 0.77$), greater knee extension moments ($F_{1,34} = 7.04$, $p = 0.012$, ES = 0.17, $\beta = 0.73$), greater ankle plantarflexion moments ($F_{1,34} = 10.38$, $p = 0.003$, ES = 0.23, $\beta = 0.87$), and decreased quadriceps activity ($F_{1,34}$ = 8.18, p = 0.007, ES = 0.19, β = 0.79) regardless of group assignment (Tables 5.2 and 5.3).

DISCUSSION

The purpose of this study was to evaluate the effect of fatigue on kinematics, kinetics, and neuromuscular performance during a soccer-specific landing maneuver in soccer players with an ACLR compared with healthy non-injured soccer players. Our findings support the first hypothesis that participants would demonstrate alterations in landing biomechanics during the fatigued landing compared with the non-fatigued landing. In the present investigation, all participants landed with significantly increased hip and knee flexion and ankle dorsiflexion during the fatigued landing compared with the non-fatigued landing (Table 5.2). These findings are consistent with previous studies in which fatigue increased flexion angles at the hip[10,23] and knee[23,24,55] and ankle dorsiflexion[24] during a single-legged drop landing in non-injured men and women athletes. However, contradictory results have been reported by previous researchers who observed decreased hip[21] and knee[21] flexion and ankle dorsiflexion[23] during a single legged drop landing. These findings indicate that fatigue induces alterations in landing mechanics by either increasing or decreasing the lower extremity joint angles. In other words, individuals may respond to the effect of fatigue by utilizing either a stiff or soft landing technique to absorb the landing impact. While stiff landing techniques are thought to increase the potential of sustaining lower extremity injuries, soft landings are suggested to assist lower extremity joints in absorbing the forces experienced during landing.[56]

The soft landing technique induced by the fatigue protocol in this investigation could be a consequence of a decreased power of gluteus maximus, quadriceps, and gastrocnemius muscles that act eccentrically to decrease flexion angles at the hip, knee and ankle joints.[57,58] In the current investigation, only the normalized EMG for quadriceps muscles was significantly decreased during the fatigue landing compared with non-fatigue landing in both groups (Table 5.3). Previous researchers have reported significant association between decreased hip and knee flexion angles and increased quadriceps activation in 50 female athletes during a drop vertical jump.[59] This finding may indicate that decreased activation of the quadriceps may increase the flexion angles at the hip and knee joints. In addition, previous researchers have reported that an increased hip and knee flexion angle during landing is accompanied by increased ankle dorsiflexion angle.[60,61] Therefore, we hypothesized that the soft landing technique induced by the Wingate fatigue protocol in this investigation was a consequence of decreased activation of the quadriceps muscles.

Similar to the kinematics data, the results of this investigation showed that fatigued landing demonstrated greater internal hip and knee extension and plantarflexion moments than non-fatigued landing (Table 5.2). The increased internal hip and knee extension and plantarflexion moments might be explained by the increased hip and knee flexion and dorsiflexion angles.[62] At the hip and knee joints level, greater flexion angles may lead to greater external flexion moments that need to be counteracted by greater internal extension moments.[62] At the ankle joint level, greater dorsiflexion angles may lead to greater external dorsiflexion moments that need to be counteracted by greater internal plantarflexion moments.[62] The findings of this investigation indicate that the mechanical demand of the hip and knee extensors and plantarflexors muscles increased following the Wingate fatigue protocol.

The results of this investigation did not support the second hypothesis that alterations induced by fatigue would be more pronounced in the ACLR group compared to the control group. In this investigation, the ACLR group demonstrated similar landing mechanics and neuromuscular performance to the control group in response to the Wingate fatigue protocol. This finding is supported by a previous investigation in which both the ACL and the control groups demonstrated similar kinematics and kinetics parameters during a single-leg landing task after completing a fatigue protocol that consisted of 10 bilateral squats to 90 degrees of knee flexion.[29] Contradictory results were reported in a previous study in which individuals with ACLR demonstrated greater hip extensor strength loss than the healthy individuals in response to the fatigue protocol that included a 20-min anaerobic exercise on treadmill.[30] The results of our investigation indicate that having an ACLR (at least 1 year post-surgery) does not appear to lead to sustained changes in landing biomechanics induced by fatigue.

There are some limitations that should be taken into consideration when interpreting the results of the current investigation. The generalizability of the results might be limited due to the participant population that consisted of recreational soccer players. Also, participants with an ACLR had undergone different ACL reconstruction techniques (allograft and autograft) that were not performed by the same orthopedic surgeon. Furthermore, the fatigue protocol used in the current study might not mimic the fatigue that soccer players usually experience during a match.

CONCLUSION

The results of this investigation indicated that fatigue caused changes in landing biomechanics, however these changes were not significantly different between these with and without a reconstructed ACL. Also, these results indicated that having an ACLR (at least 1 year post-surgery) does not appear to lead to sustained changes in landing biomechanics induced by fatigue.

Table 5.1. Anthropometric data

Anthropometric Measure	ACLR (n=18)	Control (n=18)	P Value
	Mean ± S.D	Mean ± S.D	
Age (years)	26.11 ± 3.95	25.83 ± 3.51	0.82
Height (m)	1.70 ± 0.09	1.66 ± 0.05	0.20
Weight (kg)	68.15 ± 9.64	66.88 ± 10.37	0.70
BMI (kg/m^2)	23.52 ± 2.69	24.09 ± 3.73	0.60
Playing time (hrs/week)	4.11 ± 3.42	3.77 ± 3.07	0.76
Lactate Level	11.92 ± 4.56	11.30 ± 5.40	0.71
Time of Surgery (years)	5 ± 3.30	NA	NA

S.D, standard deviation; n, number of participants.

Table 5.2. Means, S.D, and P values for kinematics and kinetics variables

Variables	Pre-Fatigue		Post-Fatigue		P value		
	Mean	S.D	Mean	S.D	ME-G (β)	ME-F (β)	Interaction (β)
Kinematics (°)							
Hip Flexion							
ACLR	69.96	15.57	79.33	18.53	0.15 (0.29)	0.011*	0.03 (0.58)
Control	65.38	19.54	66.25	21.45			
Knee Flexion							
ACLR	74.17	12.86	83.22	15.72	0.34 (0.15)	0.001*	0.04 (0.53)
Control	73.62	11.90	75.83	12.73			
Dorsiflexion							
ACLR	23.25	6.07	26.11	5.65	0.62 (0.07)	0.002*	0.11 (0.34)
Control	24.93	4.22	25.91	2.41			
Kinetics (Nm/kg)							
Hip Extension Moment							
ACLR	2.27	0.65	3.15	1.15	0.02 (0.64)	0.009*	0.11 (0.35)
Control	2.11	0.86	2.34	0.61			
Knee Extension Moment							
ACLR	1.80	0.43	2.37	0.93	0.07 (0.44)	0.012*	0.70 (0.06)
Control	1.56	0.78	1.99	0.75			
Plantarflexion Moment							
ACLR	0.79	0.35	1.07	0.35	0.08 (0.40)	0.003*	0.58 (0.08)
Control	0.66	0.39	0.86	0.40			
Peak Pressure (KPa)							
ACLR	498.75	122.86	549.12	181.53	0.35 (0.15)	0.019 (0.66)	0.44 (0.11)
Control	525.98	107.37	622.97	275.94			

S.D, standard deviation; ME-G, main effect for group; ME-F, main effect for fatigue; β, power.
*Significant ($p<0.0167$)

Table 5.3. Means, S.D, and P values for EMG variables

Variables	Pre-Fatigue		Post-Fatigue		P value		
	Mean	S.D	Mean	S.D	ME-G (β)	ME-F (β)	Interaction (β)
Muscle Activity							
Glut Max							
ACLR	73.60	17.26	70.93	18.36	0.99 (0.05)	0.83 (0.05)	0.52 (0.09)
Control	71.54	15.11	72.90	17.67			
Quadriceps							
ACLR	79.18	8.91	74.66	3.67	0.02 (0.61)	0.007*	0.94 (0.5)
Control	84.62	6.28	80.32	12.70			
Hamstring							
ACLR	60.86	6.29	65.19	14.66	0.078 (0.42)	0.17 (0.26)	0.67 (0.06)
Control	67.07	6.91	69.38	14.14			
Calf							
ACLR	56.26	13.46	59.48	10.77	0.08 (0.41)	0.44 (0.11)	0.04 (0.54)
Control	66.00	5.59	59.16	11.08			

S.D, standard deviation; ME-G, main effect for group; ME-F, main effect for fatigue; β, power.
*Significant ($p<0.0167$)

CHAPTER VI

SUMMARY OF FINDINGS

Three studies were conducted to carry out this dissertation. The purpose of the first study was threefold. The first purpose was to determine within-session reliability (trial-to-trial) of kinematics and kinetics during soccer-specific planned and unplanned landing maneuvers in order to determine the minimum number of trials needed to achieve acceptable reliability (ICC $\geq$ 0.75). The second purpose was to determine between-session reliability (day-to-day) of kinematics, kinetics, and foot pressure profile during the 2 landing maneuvers performed by healthy soccer players. The third purpose was to evaluate the criterion-related validity (concurrent validity) of the peak plantar pressure measured by the F-Scan system in relation to the peak vertical ground reaction forces obtained using a platform system as a criterion reference during both landing maneuvers. The purpose of the second study was to compare kinematics, kinetics, and neuromuscular performance between soccer players with an ACLR and healthy non-injured soccer players during planned and unplanned landing maneuvers. The third study was aimed to compare kinematics, kinetics, and neuromuscular performance between soccer players with an ACLR and healthy non-injured soccer players during soccer-specific unplanned non-fatigue and fatigue landings.

The first study showed that good trial-to-trial reliability could be obtained for both landing maneuvers in a population of recreational soccer players if 4 trials of each landing are used. Additionally, F-Scan and 3D motion analysis systems are reliable during planned and unplanned landing maneuvers in healthy soccer players. Moreover, the F-Scan system is a valid instrument to measure ground reaction forces during planned and unplanned landing maneuvers and therefore may be a useful tool for field and laboratory assessment since it does not restrict participants to land on force plates and thus allowing them to perform a more natural landing pattern.

The findings of the second study showed that unplanned landing (heading a soccer ball) demonstrated greater injury predisposing factors compared with planned landing by exhibiting a stiff landing technique characterized by decreased hip and knee flexion. Soccer players should be trained to increase hip and knee flexion during unplanned landing to decrease the risk of ACL injury. Generally, soccer players with ACLR showed nearly similar landing mechanics and neuromuscular strategies to healthy non-injured soccer players during both planned and unplanned landing maneuvers. However, soccer players with ACLR appear to utilize a protective landing strategy by decreasing activation of the gastrocnemius muscle to reduce strain on the ACL, when averaged across both landing tasks.

The results of the third study indicated that fatigue caused changes in landing biomechanics such as decreased quadriceps activity and increased hip and knee flexion and ankle dorsiflexion angles; however, these changes were not significantly different when the groups were compared. Furthermore, these results indicated that having an ACLR (at least 1 year post-surgery) does not appear to lead to sustained changes in landing biomechanics induced by fatigue.

SUGGESTIONS FOR FUTURE STUDIES

Several researchers have reported that trunk motion greatly influences hip and knee joints kinematics and kinetics and consequently contribute to the mechanism of ACL injury.[1-5] For instance, increased trunk flexion during landing may decrease knee extension moments and consequently reduce loading to the ACL.[2] Therefore, research to evaluate trunk kinematics during landing maneuvers in soccer players with an ACLR is indicated. A better understanding of trunk motion during landing tasks may help clinicians and researchers implement trunk-focused training programs for those who have altered trunk kinematics in order to decrease the risk of ACL injury.

Moreover, investigators have reported that some impairments such as muscle weakness and impaired postural control are still observed in individuals with ACL reconstruction for up to 2 years following the surgery.[6-10] Therefore, additional research is indicated to evaluate landing mechanics and neuromuscular performance in soccer players following ACLR with an emphasis on classifying participants based on the time of surgery. For example, dividing participants into 3 different groups: ACLR-A (1-2 years post-surgery), ACLR-B (more than 2 years post-surgery) and healthy non-injured. This would help recognize early those who have abnormal landing mechanics and neuromuscular performance and determine if rehabilitation following ACLR may need to involve specific interventions to address these deficits in order to insure successful return of sports participation and reduce the risk of sustaining future injuries.

Furthermore, the fatigue protocol used in this investigation might not imitate the prolonged physiological demands that soccer players usually experience during a soccer game. Therefore, a future study may utilize a soccer-specific fatigue protocol to closely simulate fatigue to which soccer players are usually subjected during a match in order to gain a greater understanding of the biomechanical alterations induced by the fatigue in this particular population and subsequently develop injury prevention and training programs to decrease the risk of future injuries.

REFERENCES

Chapter I

1. Yu B, Garrett WE. Mechanisms of non-contact ACL injuries. *Br. J. Sports Med.* 2007;41 Suppl 1:i47-51. doi:10.1136/bjsm.2007.037192.
2. Childs SG. Pathogenesis of anterior cruciate ligament injury. *Orthop. Nurs.* 21(4):35-40. Available at: http://www.ncbi.nlm.nih.gov/pubmed/12224184. Accessed May 23, 2014.
3. Prodromos CC, Han Y, Rogowski J, Joyce B, Shi K. A meta-analysis of the incidence of anterior cruciate ligament tears as a function of gender, sport, and a knee injury-reduction regimen. *Arthroscopy* 2007;23(12):1320-1325.e6. doi:10.1016/j.arthro.2007.07.003.
4. Lohmander LS, Englund PM, Dahl LL, Roos EM. The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. *Am. J. Sports Med.* 2007;35(10):1756-69. doi:10.1177/0363546507307396.
5. Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J. Am. Acad. Orthop. Surg.* 8(3):141-50. Available at: http://www.ncbi.nlm.nih.gov/pubmed/10874221. Accessed April 28, 2014.
6. Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. *Am. J. Sports Med.* 23(6):694-701. Available at: http://www.ncbi.nlm.nih.gov/pubmed/8600737. Accessed May 9, 2014.
7. Viola RW, Steadman JR, Mair SD, Briggs KK, Sterett WI. Anterior cruciate ligament injury incidence among male and female professional alpine skiers. *Am. J. Sports Med.* 27(6):792-5. Available at: http://www.ncbi.nlm.nih.gov/pubmed/10569367. Accessed May 18, 2014.

8. Bjordal JM, Arnły F, Hannestad B, Strand T. Epidemiology of anterior cruciate ligament injuries in soccer. *Am. J. Sports Med.* 25(3):341-5. Available at: http://www.ncbi.nlm.nih.gov/pubmed/9167814. Accessed May 18, 2014.

9. Gwinn DE, Wilckens JH, McDevitt ER, Ross G, Kao TC. The relative incidence of anterior cruciate ligament injury in men and women at the United States Naval Academy. *Am. J. Sports Med.* 28(1):98-102. Available at: http://www.ncbi.nlm.nih.gov/pubmed/10653551. Accessed May 18, 2014.

10. Powell JW, Barber-Foss KD. Sex-related injury patterns among selected high school sports. *Am. J. Sports Med.* 28(3):385-91. Available at: http://www.ncbi.nlm.nih.gov/pubmed/10843133. Accessed May 18, 2014.

11. Inklaar H. Soccer injuries. I: Incidence and severity. *Sports Med.* 1994;18(1):55-73. Available at: http://www.ncbi.nlm.nih.gov/pubmed/7939040. Accessed May 18, 2014.

12. Oberländer KD, Brüggemann G-P, Höher J, Karamanidis K. Altered landing mechanics in ACL-reconstructed patients. *Med. Sci. Sports Exerc.* 2013;45(3):506-13. doi:10.1249/MSS.0b013e3182752ae3.

13. Kanisawa I, Banks AZ, Banks SA, Moriya H, Tsuchiya A. Weight-bearing knee kinematics in subjects with two types of anterior cruciate ligament reconstructions. *Knee Surg. Sports Traumatol. Arthrosc.* 2003;11(1):16-22. doi:10.1007/s00167-002-0330-y.

14. Keays SL, Bullock-Saxton J, Keays AC. Strength and function before and after anterior cruciate ligament reconstruction. *Clin. Orthop. Relat. Res.* 2000;(373):174-83. Available at: http://www.ncbi.nlm.nih.gov/pubmed/10810475. Accessed May 18, 2014.

15. Ageberg E. Consequences of a ligament injury on neuromuscular function and relevance to rehabilitation - using the anterior cruciate ligament-injured knee as model. *J. Electromyogr. Kinesiol.* 2002;12(3):205-12. Available at: http://www.ncbi.nlm.nih.gov/pubmed/12086815. Accessed July 25, 2014.

16. Fridén T, Roberts D, Ageberg E, Waldén M, Zätterström R. Review of knee proprioception and the relation to extremity function after an anterior cruciate ligament rupture. *J. Orthop. Sports Phys. Ther.* 2001;31(10):567-76. doi:10.2519/jospt.2001.31.10.567.

17. Ristanis S, Stergiou N, Patras K, Vasiliadis HS, Giakas G, Georgoulis AD. Excessive tibial rotation during high-demand activities is not restored by anterior cruciate ligament reconstruction. *Arthroscopy* 2005;21(11):1323-9. doi:10.1016/j.arthro.2005.08.032.

18. Webster KE, Santamaria LJ, McClelland J a, Feller J a. Effect of fatigue on landing biomechanics after anterior cruciate ligament reconstruction surgery. *Med. Sci. Sports Exerc.* 2012;44(5):910-6. doi:10.1249/MSS.0b013e31823fe28d.

19. Ristanis S, Stergiou N, Patras K, Tsepis E, Moraiti C, Georgoulis AD. Follow-up evaluation 2 years after ACL reconstruction with bone-patellar tendon-bone graft shows that excessive tibial rotation persists. *Clin. J. Sport Med.* 2006;16(2):111-6. Available at: http://www.ncbi.nlm.nih.gov/pubmed/16603879. Accessed July 25, 2014.

20. Schmitt LC, Paterno M V, Hewett TE. The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. *J. Orthop. Sports Phys. Ther.* 2012;42(9):750-9. doi:10.2519/jospt.2012.4194.

21. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. *Br. J. Sports Med.* 2011;45(7):596-606. doi:10.1136/bjsm.2010.076364.

22. Boden BP, Dean GS, Feagin JA, Garrett WE. Mechanisms of anterior cruciate ligament injury. *Orthopedics* 2000;23(6):573-8. Available at: http://www.ncbi.nlm.nih.gov/pubmed/10875418. Accessed May 18, 2014.

23. Hewett TE, Lindenfeld TN, Riccobene J V, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *Am. J. Sports Med.* 27(6):699-706. Available at: http://www.ncbi.nlm.nih.gov/pubmed/10569353. Accessed May 18, 2014.

24. Kirkendall DT, Garrett WE. The anterior cruciate ligament enigma. Injury mechanisms and prevention. *Clin. Orthop. Relat. Res.* 2000;(372):64-8. Available at: http://www.ncbi.nlm.nih.gov/pubmed/10738415. Accessed May 18, 2014.

25. Kirialanis P, Malliou P, Beneka A, Giannakopoulos K. Occurrence of acute lower limb injuries in artistic gymnasts in relation to event and exercise phase. *Br. J. Sports Med.* 2003;37(2):137-9. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1724619&tool=pmcentrez&rendertype=abstract. Accessed May 18, 2014.

26. Gray J, Taunton JE, McKenzie DC, Clement DB, McConkey JP, Davidson RG. A survey of injuries to the anterior cruciate ligament of the knee in female basketball players. *Int. J. Sports Med.* 1985;6(6):314-6. doi:10.1055/s-2008-1025861.

27. Decker MJ, Torry MR, Noonan TJ, Riviere A, Sterett WI. Landing adaptations after ACL reconstruction. *Med. Sci. Sports Exerc.* 2002;34(9):1408-13. doi:10.1249/01.MSS.0000027627.82650.1F.

28. Decker MJ, Torry MR, Wyland DJ, Sterett WI, Richard Steadman J. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clin. Biomech. (Bristol, Avon)* 2003;18(7):662-9. Available at: http://www.ncbi.nlm.nih.gov/pubmed/12880714. Accessed August 4, 2014.

29. Gokeler a, Hof a L, Arnold MP, Dijkstra PU, Postema K, Otten E. Abnormal landing strategies after ACL reconstruction. *Scand. J. Med. Sci. Sports* 2010;20(1):e12-9. doi:10.1111/j.1600-0838.2008.00873.x.

30. Paterno M V, Ford KR, Myer GD, Heyl R, Hewett TE. Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. *Clin. J. Sport Med.* 2007;17(4):258-62. doi:10.1097/JSM.0b013e31804c77ea.

31. Dufek JS, Bates BT. The evaluation and prediction of impact forces during landings. *Med. Sci. Sports Exerc.* 1990;22(3):370-7. Available at: http://www.ncbi.nlm.nih.gov/pubmed/2381305. Accessed August 1, 2014.

32. Pappas E, Sheikhzadeh A, Hagins M, Nordin M. The effect of gender and fatigue on the biomechanics of bilateral landings from a jump: peak values. *J. Sports Sci. Med.* 2007;6(1):77-84. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3778703&tool=pmcentrez&rendertype=abstract.

33. Borotikar BS, Newcomer R, Koppes R, McLean SG. Combined effects of fatigue and decision making on female lower limb landing postures: central and peripheral contributions to ACL injury risk. *Clin. Biomech. (Bristol, Avon)* 2008;23(1):81-92. doi:10.1016/j.clinbiomech.2007.08.008.

34. Gabbett TJ. Incidence, site, and nature of injuries in amateur rugby league over three consecutive seasons. *Br. J. Sports Med.* 2000;34(2):98-103. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1724194&tool=pmcentrez&rendertype=abstract. Accessed May 18, 2014.

35. Gabbett TJ. Incidence of injury in amateur rugby league sevens. *Br. J. Sports Med.* 2002;36(1):23-6. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1724444&tool=pmcentrez&rendertype=abstract. Accessed May 18, 2014.

36. Gabbett TJ. Influence of training and match intensity on injuries in rugby league. *J. Sports Sci.* 2004;22(5):409-17. doi:10.1080/02640410310001641638.

37. Hawkins RD, Hulse MA, Wilkinson C, Hodson A, Gibson M. The association football medical research programme: an audit of injuries in professional football. *Br. J. Sports Med.* 2001;35(1):43-7. Available at:

http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1724279&tool=pmcentrez&rendertype=abstract. Accessed May 18, 2014.

38. Kersey RD, Rowan L. Injury account during the 1980 NCAA wrestling championships. *Am. J. Sports Med.* 11(3):147-51. Available at: http://www.ncbi.nlm.nih.gov/pubmed/6869655. Accessed May 18, 2014.

39. Rahnama N, Reilly T, Lees A. Injury risk associated with playing actions during competitive soccer. *Br. J. Sports Med.* 2002;36(5):354-9. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1724551&tool=pmcentrez&rendertype=abstract. Accessed May 18, 2014.

40. Benjaminse A, Habu A, Sell TC, et al. Fatigue alters lower extremity kinematics during a single-leg stop-jump task. *Knee Surg. Sports Traumatol. Arthrosc.* 2008;16(4):400-7. doi:10.1007/s00167-007-0432-7.

41. Kernozek TW, Torry MR, Iwasaki M. Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue. *Am. J. Sports Med.* 2008;36(3):554-65. doi:10.1177/0363546507308934.

42. McLean SG, Fellin RE, Felin RE, et al. Impact of fatigue on gender-based high-risk landing strategies. *Med. Sci. Sports Exerc.* 2007;39(3):502-14. doi:10.1249/mss.0b013e3180d47f0.

43. Sparto PJ, Parnianpour M, Reinsel TE, Simon S. The effect of fatigue on multijoint kinematics, coordination, and postural stability during a repetitive lifting test. *J. Orthop. Sports Phys. Ther.* 1997;25(1):3-12. doi:10.2519/jospt.1997.25.1.3.

44. Parnianpour M, Nordin M, Kahanovitz N, Frankel V. 1988 Volvo award in biomechanics. The triaxial coupling of torque generation of trunk muscles during isometric exertions and the effect of fatiguing isoinertial movements on the motor output and movement patterns. *Spine (Phila. Pa. 1976).* 1988;13(9):982-92. Available at: http://www.ncbi.nlm.nih.gov/pubmed/3206305. Accessed May 17, 2014.

45. McLean SG, Samorezov JE. Fatigue-induced ACL injury risk stems from a degradation in central control. *Med. Sci. Sports Exerc.* 2009;41(8):1661-72. doi:10.1249/MSS.0b013e31819ca07b.

46. Rodacki ALF, Fowler NE, Bennett SJ. Vertical jump coordination: fatigue effects. *Med. Sci. Sports Exerc.* 2002;34(1):105-16. Available at: http://www.ncbi.nlm.nih.gov/pubmed/11782655. Accessed May 17, 2014.

47. Barfield J-P, Sells PD, Rowe DA, Hannigan-Downs K. Practice effect of the Wingate anaerobic test. *J. Strength Cond. Res.* 2002;16(3):472-3. Available at: http://www.ncbi.nlm.nih.gov/pubmed/12173966. Accessed May 17, 2014.

48. Chappell JD, Yu B, Kirkendall DT, Garrett WE. A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *Am. J. Sports Med.* 30(2):261-7. Available at: http://www.ncbi.nlm.nih.gov/pubmed/11912098. Accessed May 17, 2014.

49. Ronglan LT, Raastad T, Børgesen A. Neuromuscular fatigue and recovery in elite female handball players. *Scand. J. Med. Sci. Sports* 2006;16(4):267-73. doi:10.1111/j.1600-0838.2005.00474.x.

50. Greig M, Walker-Johnson C. The influence of soccer-specific fatigue on functional stability. *Phys. Ther. Sport* 2007;8(4):185-190. doi:10.1016/j.ptsp.2007.03.001.

51. Wilkins JC, Valovich McLeod TC, Perrin DH, Gansneder BM. Performance on the Balance Error Scoring System Decreases After Fatigue. *J. Athl. Train.* 2004;39(2):156-161. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=419510&tool=pmcentrez&rendertype=abstract. Accessed May 17, 2014.

52. Orishimo KF, Kremenic IJ. Effect of fatigue on single-leg hop landing biomechanics. *J. Appl. Biomech.* 2006;22(4):245-54. Available at: http://www.ncbi.nlm.nih.gov/pubmed/17293621. Accessed May 17, 2014.

53. Augustsson J, Thomeé R, Lindén C, Folkesson M, Tranberg R, Karlsson J. Single-leg hop testing following fatiguing exercise: reliability and biomechanical analysis. *Scand. J. Med. Sci. Sports* 2006;16(2):111-20. doi:10.1111/j.1600-0838.2005.00446.x.

54. Fagenbaum R, Darling WG. Jump landing strategies in male and female college athletes and the implications of such strategies for anterior cruciate ligament injury. *Am. J. Sports Med.* 31(2):233-40. Available at: http://www.ncbi.nlm.nih.gov/pubmed/12642258. Accessed May 17, 2014.

55. Coventry E, O'Connor KM, Hart BA, Earl JE, Ebersole KT. The effect of lower extremity fatigue on shock attenuation during single-leg landing. *Clin. Biomech. (Bristol, Avon)* 2006;21(10):1090-7. doi:10.1016/j.clinbiomech.2006.07.004.

56. Madigan ML, Pidcoe PE. Changes in landing biomechanics during a fatiguing landing activity. *J. Electromyogr. Kinesiol.* 2003;13(5):491-8. Available at: http://www.ncbi.nlm.nih.gov/pubmed/12932423. Accessed May 17, 2014.

57. Markolf KL, Gorek JF, Kabo JM, Shapiro MS. Direct measurement of resultant forces in the anterior cruciate ligament. An in vitro study performed with a new experimental technique. *J. Bone Joint Surg. Am.* 1990;72(4):557-67. Available at: http://www.ncbi.nlm.nih.gov/pubmed/2324143. Accessed July 25, 2014.

58. Wascher DC, Markolf KL, Shapiro MS, Finerman GA. Direct in vitro measurement of forces in the cruciate ligaments. Part I: The effect of multiplane loading in the intact knee. *J. Bone Joint Surg. Am.* 1993;75(3):377-86. Available at: http://www.ncbi.nlm.nih.gov/pubmed/8444916. Accessed August 2, 2014.

59. Wojtys EM, Wylie BB, Huston LJ. The effects of muscle fatigue on neuromuscular function and anterior tibial translation in healthy knees. *Am. J. Sports Med.* 24(5):615-21. Available at: http://www.ncbi.nlm.nih.gov/pubmed/8883681. Accessed May 17, 2014.

60. *Cram's Introduction To Surface Electromyography [Paperback]*. Jones & Bartlett Learning; 2 edition; 2010:412. Available at: http://www.amazon.com/Crams-Introduction-To-Surface-Electromyography/dp/0763732745. Accessed August 4, 2014.

61. Kindermann W, Simon G, Keul J. The significance of the aerobic-anaerobic transition for the determination of work load intensities during endurance training. *Eur. J. Appl. Physiol. Occup. Physiol.* 1979;42(1):25-34. Available at: http://www.ncbi.nlm.nih.gov/pubmed/499194. Accessed August 12, 2014.

62. Pugh L, Mascarenhas R, Arneja S, Chin PYK, Leith JM. Current concepts in instrumented knee-laxity testing. *Am. J. Sports Med.* 2009;37(1):199-210. doi:10.1177/0363546508323746.

63. Daniel DM, Stone ML, Sachs R, Malcom L. Instrumented measurement of anterior knee laxity in patients with acute anterior cruciate ligament disruption. *Am. J. Sports Med.* 13(6):401-7. Available at: http://www.ncbi.nlm.nih.gov/pubmed/4073348. Accessed October 6, 2014.

64. Daniel DM, Stone ML, Dobson BE, Fithian DC, Rossman DJ, Kaufman KR. Fate of the ACL-injured patient. A prospective outcome study. *Am. J. Sports Med.* 22(5):632-44. Available at: http://www.ncbi.nlm.nih.gov/pubmed/7810787. Accessed October 6, 2014.

65. Daniel DM, Malcom LL, Losse G, Stone ML, Sachs R, Burks R. Instrumented measurement of anterior laxity of the knee. *J. Bone Joint Surg. Am.* 1985;67(5):720-6. Available at: http://www.ncbi.nlm.nih.gov/pubmed/3997924. Accessed October 6, 2014.

66. Ahldén M, Kartus J, Ejerhed L, Karlsson J, Sernert N. Knee laxity measurements after anterior cruciate ligament reconstruction, using either bone-patellar-tendon-bone or hamstring tendon autografts, with special emphasis on comparison over time. *Knee Surg. Sports Traumatol. Arthrosc.* 2009;17(9):1117-24. doi:10.1007/s00167-009-0846-5.

67. Anderson AF, Lipscomb AB. Preoperative instrumented testing of anterior and posterior knee laxity. *Am. J. Sports Med.* 17(3):387-92. Available at: http://www.ncbi.nlm.nih.gov/pubmed/2729489. Accessed October 6, 2014.

68. Hanten WP, Pace MB. Reliability of measuring anterior laxity of the knee joint using a knee ligament arthrometer. *Phys. Ther.* 1987;67(3):357-9. Available at: http://www.ncbi.nlm.nih.gov/pubmed/3823149. Accessed October 6, 2014.

69. Highgenboten CL, Jackson A, Meske NB. Genucom, KT-1000, and Stryker knee laxity measuring device comparisons. Device reproducibility and interdevice comparison in asymptomatic subjects. *Am. J. Sports Med.* 17(6):743-6. Available at: http://www.ncbi.nlm.nih.gov/pubmed/2624283. Accessed October 6, 2014.

70. Wroble RR, Van Ginkel LA, Grood ES, Noyes FR, Shaffer BL. Repeatability of the KT-1000 arthrometer in a normal population. *Am. J. Sports Med.* 18(4):396-9. Available at: http://www.ncbi.nlm.nih.gov/pubmed/2403189. Accessed October 6, 2014.

71. Nagai T, Sell TC, House AJ, Abt JP, Lephart SM. Knee proprioception and strength and landing kinematics during a single-leg stop-jump task. *J. Athl. Train.* 48(1):31-8. doi:10.4085/1062-6050-48.1.14.

72. Ortiz A, Olson SL, Roddey TS, Morales J. Reliability of selected physical performance tests in young adult women. *J. Strength Cond. Res.* 2005;19(1):39-44. doi:10.1519/14163.1.

73. McBride JM, Triplett-McBride T, Davie A, Newton RU. The effect of heavy- vs. light-load jump squats on the development of strength, power, and speed. *J. Strength Cond. Res.* 2002;16(1):75-82. Available at: http://www.ncbi.nlm.nih.gov/pubmed/11834109. Accessed August 15, 2014.

74. Portney LG, Watkins MP. *Foundations of Clinical Research: Applications to Practice*. Pearson/Prentice Hall; 2009:892. Available at: http://books.google.com/books?id=apNJPgAACAAJ&pgis=1. Accessed May 20, 2014.

75. Salci Y, Kentel BB, Heycan C, Akin S, Korkusuz F. Comparison of landing maneuvers between male and female college volleyball players. *Clin. Biomech. (Bristol, Avon)* 2004;19(6):622-8. doi:10.1016/j.clinbiomech.2004.03.006.

76. Inbar O, Bar-Or O, Skinner JS. *The Wingate Anaerobic Test*.; 1996. Available at: http://books.google.com.sa/books/about/The_Wingate_Anaerobic_Test.html?id=f2h3hWiNOOkC&pgis=1. Accessed May 18, 2014.

77. Ortiz A, Olson SL, Etnyre B, Trudelle-Jackson EE, Bartlett W, Venegas-Rios HL. Fatigue effects on knee joint stability during two jump tasks in women. *J. Strength Cond. Res.* 2010;24(4):1019-27. doi:10.1519/JSC.0b013e3181c7c5d4.

Chapter II

1. Hewett TE, Di Stasi SL, Myer GD. Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2013;41(1):216-224. doi:10.1177/0363546512459638.

2. Cimino F. Anterior Cruciate Ligament Injury: Diagnosis, Management, and Prevention. 2010;82(8). www.aafp.org/afp. Accessed August 5, 2016.

3. Childs SG. Pathogenesis of anterior cruciate ligament injury. *Orthop Nurs*. 21(4):35-40. http://www.ncbi.nlm.nih.gov/pubmed/12224184. Accessed May 23, 2014.

4. Prodromos CC, Han Y, Rogowski J, Joyce B, Shi K. A meta-analysis of the incidence of anterior cruciate ligament tears as a function of gender, sport, and a knee injury-reduction regimen. *Arthroscopy*. 2007;23(12):1320-1325.e6. doi:10.1016/j.arthro.2007.07.003.

5. Lohmander LS, Englund PM, Dahl LL, Roos EM. The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. *Am J Sports Med*. 2007;35(10):1756-1769. doi:10.1177/0363546507307396.

6. Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg*. 8(3):141-150. http://www.ncbi.nlm.nih.gov/pubmed/10874221. Accessed April 28, 2014.

7. Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and

soccer. NCAA data and review of literature. *Am J Sports Med*. 23(6):694-701. http://www.ncbi.nlm.nih.gov/pubmed/8600737. Accessed May 9, 2014.

8. Viola RW, Steadman JR, Mair SD, Briggs KK, Sterett WI. Anterior cruciate ligament injury incidence among male and female professional alpine skiers. *Am J Sports Med*. 27(6):792-795. http://www.ncbi.nlm.nih.gov/pubmed/10569367. Accessed May 18, 2014.

9. Frobell RB, Lohmander LS, Roos HP. Acute rotational trauma to the knee: poor agreement between clinical assessment and magnetic resonance imaging findings. *Scand J Med Sci Sports*. 2007;17(2):109-114. doi:10.1111/j.1600-0838.2006.00559.x.

10. Roos H, Ornell M, Gärdsell P, Lohmander LS, Lindstrand A. Soccer after anterior cruciate ligament injury--an incompatible combination? A national survey of incidence and risk factors and a 7-year follow-up of 310 players. *Acta Orthop Scand*. 1995;66(2):107-112. http://www.ncbi.nlm.nih.gov/pubmed/7740937. Accessed January 13, 2016.

11. Bjordal JM, Arnły F, Hannestad B, Strand T. Epidemiology of anterior cruciate ligament injuries in soccer. *Am J Sports Med*. 25(3):341-345. http://www.ncbi.nlm.nih.gov/pubmed/9167814. Accessed May 18, 2014.

12. Gwinn DE, Wilckens JH, McDevitt ER, Ross G, Kao TC. The relative incidence of anterior cruciate ligament injury in men and women at the United States Naval Academy. *Am J Sports Med*. 28(1):98-102. http://www.ncbi.nlm.nih.gov/pubmed/10653551. Accessed May 18, 2014.

13. Powell JW, Barber-Foss KD. Sex-related injury patterns among selected high school sports. *Am J Sports Med*. 28(3):385-391. http://www.ncbi.nlm.nih.gov/pubmed/10843133. Accessed May 18, 2014.

14. Waldén M, Hägglund M, Magnusson H, Ekstrand J. Anterior cruciate ligament injury in elite football: a prospective three-cohort study. *Knee Surgery, Sport Traumatol Arthrosc*. 2011;19(1):11-19. doi:10.1007/s00167-010-1170-9.

15. Amis AA, Dawkins GP. Functional anatomy of the anterior cruciate ligament. Fibre bundle

actions related to ligament replacements and injuries. *J Bone Joint Surg Br*. 1991;73(2):260-267. http://www.ncbi.nlm.nih.gov/pubmed/2005151. Accessed August 8, 2016.

16. Petersen W, Zantop T. Anatomy of the anterior cruciate ligament with regard to its two bundles. *Clin Orthop Relat Res*. 2007;454:35-47. doi:10.1097/BLO.0b013e31802b4a59.

17. Woo SL-Y, Wu C, Dede O, Vercillo F, Noorani S. Biomechanics and anterior cruciate ligament reconstruction. *J Orthop Surg Res*. 2006;1:2. doi:10.1186/1749-799X-1-2.

18. Giuliani JR, Kilcoyne KG, Rue J-PH. Anterior cruciate ligament anatomy: a review of the anteromedial and posterolateral bundles. *J Knee Surg*. 2009;22(2):148-154. http://www.ncbi.nlm.nih.gov/pubmed/19476182. Accessed August 5, 2016.

19. Buoncristiani AM, Tjoumakaris FP, Starman JS, et al. Anatomic Double-Bundle Anterior Cruciate Ligament Reconstruction. *Arthrosc J Arthrosc Relat Surg*. 2006;22(9):1000-1006. doi:10.1016/j.arthro.2006.06.005.

20. Li G, DeFrate LE, Sun H, Gill TJ. In vivo elongation of the anterior cruciate ligament and posterior cruciate ligament during knee flexion. *Am J Sports Med*. 2004;32(6):1415-1420. doi:10.1177/0363546503262175.

21. Sidles JA, Larson R V, Garbini JL, Downey DJ, Matsen FA. Ligament length relationships in the moving knee. *J Orthop Res*. 1988;6(4):593-610. doi:10.1002/jor.1100060418.

22. Odensten M, Gillquist J. Functional anatomy of the anterior cruciate ligament and a rationale for reconstruction. *J Bone Joint Surg Am*. 1985;67(2):257-262. http://www.ncbi.nlm.nih.gov/pubmed/3968118. Accessed August 5, 2016.

23. Anderson AF, Dome DC, Gautam S, Awh MH, Rennirt GW. Correlation of anthropometric measurements, strength, anterior cruciate ligament size, and intercondylar notch characteristics to sex differences in anterior cruciate ligament tear rates. *Am J Sports Med*. 29(1):58-66. http://www.ncbi.nlm.nih.gov/pubmed/11206258. Accessed August 5, 2016.

24. Georgoulis AD, Pappa L, Moebius U, et al. The presence of proprioceptive mechanoreceptors in the remnants of the ruptured ACL as a possible source of re-innervation of the ACL

autograft. *Knee Surg Sports Traumatol Arthrosc*. 2001;9(6):364-368. doi:10.1007/s001670100240.

25. Kennedy JC, Alexander IJ, Hayes KC. Nerve supply of the human knee and its functional importance. *Am J Sports Med*. 10(6):329-335. http://www.ncbi.nlm.nih.gov/pubmed/6897495. Accessed August 6, 2016.

26. Butler DL, Noyes FR, Grood ES. Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. *J Bone Joint Surg Am*. 1980;62(2):259-270. http://www.ncbi.nlm.nih.gov/pubmed/7358757. Accessed August 8, 2016.

27. Lipke JM, Janecki CJ, Nelson CL, et al. The role of incompetence of the anterior cruciate and lateral ligaments in anterolateral and anteromedial instability. A biomechanical study of cadaver knees. *J Bone Joint Surg Am*. 1981;63(6):954-960. http://www.ncbi.nlm.nih.gov/pubmed/7240336. Accessed August 8, 2016.

28. Chen L, Kim PD, Ahmad CS, Levine WN. Medial collateral ligament injuries of the knee: current treatment concepts. *Curr Rev Musculoskelet Med*. 2008;1(2):108-113. doi:10.1007/s12178-007-9016-x.

29. Mazzocca AD, Nissen CW, Geary M, Adams DJ. Valgus medial collateral ligament rupture causes concomitant loading and damage of the anterior cruciate ligament. *J Knee Surg*. 2003;16(3):148-151. http://www.ncbi.nlm.nih.gov/pubmed/12943283. Accessed August 8, 2016.

30. Shimokochi Y, Shultz SJ. Mechanisms of noncontact anterior cruciate ligament injury. *J Athl Train*. 2008;43(4):396-408. doi:10.4085/1062-6050-43.4.396.

31. Murphy DF, Connolly DAJ, Beynnon BD. Risk factors for lower extremity injury: a review of the literature. *Br J Sports Med*. 2003;37(1):13-29. http://www.ncbi.nlm.nih.gov/pubmed/12547739. Accessed August 8, 2016.

32. Griffin LY, Albohm MJ, Arendt EA, et al. Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. *Am J Sports*

Med. 2006;34(9):1512-1532. doi:10.1177/0363546506286866.

33. Orchard JW, Chivers I, Aldous D, Bennell K, Seward H. Rye grass is associated with fewer non-contact anterior cruciate ligament injuries than bermuda grass. *Br J Sports Med*. 2005;39(10):704-709. doi:10.1136/bjsm.2004.017756.

34. Orchard JW, Powell JW. Risk of knee and ankle sprains under various weather conditions in American football. *Med Sci Sports Exerc*. 2003;35(7):1118-1123. doi:10.1249/01.MSS.0000074563.61975.9B.

35. Orchard JW, Chivers I, Aldous D, Bennell K, Seward H. Rye grass is associated with fewer non-contact anterior cruciate ligament injuries than bermuda grass. *Br J Sports Med*. 2005;39(10):704-709. doi:10.1136/bjsm.2004.017756.

36. Lambson RB, Barnhill BS, Higgins RW. Football cleat design and its effect on anterior cruciate ligament injuries. A three-year prospective study. *Am J Sports Med*. 24(2):155-159. http://www.ncbi.nlm.nih.gov/pubmed/8775112. Accessed August 9, 2016.

37. Yu B, Herman D, Preston J, Lu W, Kirkendall DT, Garrett WE. Immediate effects of a knee brace with a constraint to knee extension on knee kinematics and ground reaction forces in a stop-jump task. *Am J Sports Med*. 32(5):1136-1143. doi:10.1177/0363546503262204.

38. Vailas JC, Pink M. Biomechanical Effects of Functional Knee Bracing. *Sport Med*. 1993;15(3):210-218. doi:10.2165/00007256-199315030-00006.

39. Sitler M, Ryan J, Hopkinson W, et al. The efficacy of a prophylactic knee brace to reduce knee injuries in football. A prospective, randomized study at West Point. *Am J Sports Med*. 18(3):310-315. http://www.ncbi.nlm.nih.gov/pubmed/2372083. Accessed August 10, 2016.

40. Hutchinson MR, Ireland ML. Knee injuries in female athletes. *Sports Med*. 1995;19(4):288-302. http://www.ncbi.nlm.nih.gov/pubmed/7604201. Accessed August 10, 2016.

41. Ireland ML. Anterior cruciate ligament injury in female athletes: epidemiology. *J Athl Train*. 1999;34(2):150-154. http://www.ncbi.nlm.nih.gov/pubmed/16558558. Accessed August 10, 2016.

42. Heiderscheit BC, Hamill J, Caldwell GE. Influence of Q-angle on lower-extremity running kinematics. *J Orthop Sports Phys Ther*. 2000;30(5):271-278. doi:10.2519/jospt.2000.30.5.271.

43. Livingston LA, Mandigo JL. Bilateral within-subject Q angle asymmetry in young adult females and males. *Biomed Sci Instrum*. 1997;33:112-117. http://www.ncbi.nlm.nih.gov/pubmed/9731345. Accessed August 10, 2016.

44. Nguyen A-D, Boling MC, Levine B, Shultz SJ. Relationships between lower extremity alignment and the quadriceps angle. *Clin J Sport Med*. 2009;19(3):201-206. doi:10.1097/JSM.0b013e3181a38fb1.

45. Allen MK, Glasoe WM. Metrecom measurement of navicular drop in subjects with anterior cruciate ligament injury. *J Athl Train*. 2000;35(4):403-406. http://www.ncbi.nlm.nih.gov/pubmed/16558652. Accessed August 11, 2016.

46. Bonci CM. Assessment and evaluation of predisposing factors to anterior cruciate ligament injury. *J Athl Train*. 1999;34(2):155-164. http://www.ncbi.nlm.nih.gov/pubmed/16558559. Accessed August 11, 2016.

47. Loudon JK, Jenkins W, Loudon KL. The relationship between static posture and ACL injury in female athletes. *J Orthop Sports Phys Ther*. 1996;24(2):91-97. doi:10.2519/jospt.1996.24.2.91.

48. Uhorchak JM, Scoville CR, Williams GN, Arciero RA, St Pierre P, Taylor DC. Risk factors associated with noncontact injury of the anterior cruciate ligament: a prospective four-year evaluation of 859 West Point cadets. *Am J Sports Med*. 31(6):831-842. http://www.ncbi.nlm.nih.gov/pubmed/14623646. Accessed August 10, 2016.

49. Shelbourne KD, Davis TJ, Klootwyk TE. The relationship between intercondylar notch width of the femur and the incidence of anterior cruciate ligament tears. A prospective study. *Am J Sports Med*. 26(3):402-408. http://www.ncbi.nlm.nih.gov/pubmed/9617403. Accessed August 10, 2016.

50. McClay Davis I, Ireland ML. ACL injuries--the gender bias. *J Orthop Sports Phys Ther*. 2003;33(8):A2-A8. http://www.ncbi.nlm.nih.gov/pubmed/12968861. Accessed August 11, 2016.

51. Brown CN, Yu B KD. Effects of increased body mass index on lower extremity motion patterns in a stop-jump task: National Athletic Trainers Association annual meeting. In: *J Athl Train*. Indianapolis, IN; 2005:404.

52. Renstrom P, Ljungqvist A, Arendt E, et al. Non-contact ACL injuries in female athletes: An International Olympic Committee current concepts statement - Deel 2. *Sport en Geneeskd*. 2008;41(4):20-30. doi:10.1136/bjsm.2008.048934.

53. Hewett TE, Zazulak BT, Myer GD. Effects of the menstrual cycle on anterior cruciate ligament injury risk: a systematic review. *Am J Sports Med*. 2007;35(4):659-668. doi:10.1177/0363546506295699.

54. Yu WD, Liu SH, Hatch JD, Panossian V, Finerman G a. Effect of estrogen on cellular metabolism of the human anterior cruciate ligament. *Clin Orthop Relat Res*. 1999;(366):229-238. http://www.ncbi.nlm.nih.gov/pubmed/10627740.

55. Zazulak BT, Paterno M, Myer GD, Romani WA, Hewett TE. The effects of the menstrual cycle on anterior knee laxity: a systematic review. *Sports Med*. 2006;36(10):847-862. doi:10.1177/0363546506297909.

56. Besier TF, Lloyd DG, Cochrane JL, Ackland TR. External loading of the knee joint during. *Med Sci Sport Exerc*. 2001;01(May 2000):1168-1175. doi:10.1097/00005768-200107000-00014.

57. Chappell JD, Yu B, Kirkendall DT, Garrett WE. A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *Am J Sports Med*. 30(2):261-267. http://www.ncbi.nlm.nih.gov/pubmed/11912098. Accessed May 17, 2014.

58. Colby S, Francisco A, Yu B, Kirkendall D, Finch M, Garrett W. Electromyographic and Kinematic Analysis of Cutting Maneuvers Implications for Anterior Cruciate Ligament

Injury. *Am J Sports Med*. 2000;28(2):234-240. doi:10.1016/S1440-2440(99)80066-8.

59. Decker MJ, Torry MR, Wyland DJ, Sterett WI, Richard Steadman J. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clin Biomech (Bristol, Avon)*. 2003;18(7):662-669. http://www.ncbi.nlm.nih.gov/pubmed/12880714. Accessed August 4, 2014.

60. Huston LJ, Vibert B, Ashton-Miller JA, Wojtys EM. Gender differences in knee angle when landing from a drop-jump. *Am J Knee Surg*. 2001;14:215-219; discussion 219-220.

61. Huston LJ, Wojtys EM. Neuromuscular performance characteristics in elite female athletes. *Am J Sports Med*. 1996;24(4):427-436. doi:10.1177/036354659602400405.

62. Lephart SM, Ferris CM, Riemann BL, Myers JB, Fu FH. Gender differences in strength and lower extremity kinematics during landing. *Clin Orthop Relat Res*. 2002;(401):162-169. doi:10.1097/00003086-200208000-00019.

63. Aune AK, Cawley PW, Ekeland A. Quadriceps muscle contraction protects the anterior cruciate ligament during anterior tibial translation. *Am J Sports Med*. 25(2):187-190. http://www.ncbi.nlm.nih.gov/pubmed/9079171. Accessed August 18, 2016.

64. DeMorat G, Weinhold P, Blackburn T, Chudik S, Garrett W. Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. *Am J Sports Med*. 2004;32(2):477-483. http://www.ncbi.nlm.nih.gov/pubmed/14977677. Accessed August 18, 2016.

65. Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE. A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech (Bristol, Avon)*. 2001;16(5):438-445. http://www.ncbi.nlm.nih.gov/pubmed/11390052. Accessed August 18, 2016.

66. Granata KP, Padua DA, Wilson SE. Gender differences in active musculoskeletal stiffness. Part II. Quantification of leg stiffness during functional hopping tasks. *J Electromyogr Kinesiol*. 2002;12(2):127-135. http://www.ncbi.nlm.nih.gov/pubmed/11955985. Accessed August 18, 2016.

67. Granata KP, Wilson SE, Padua DA. Gender differences in active musculoskeletal stiffness. Part I. Quantification in controlled measurements of knee joint dynamics. *J Electromyogr Kinesiol*. 2002;12(2):119-126. http://www.ncbi.nlm.nih.gov/pubmed/11955984. Accessed August 18, 2016.

68. Kibler WB, Livingston B. Closed-chain rehabilitation for upper and lower extremities. *J Am Acad Orthop Surg*. 9(6):412-421. http://www.ncbi.nlm.nih.gov/pubmed/11730332. Accessed August 18, 2016.

69. Wojtys EM, Ashton-Miller JA, Huston LJ. A gender-related difference in the contribution of the knee musculature to sagittal-plane shear stiffness in subjects with similar knee laxity. *J Bone Joint Surg Am*. 2002;84-A(1):10-16. http://www.ncbi.nlm.nih.gov/pubmed/11792773. Accessed August 18, 2016.

70. Wojtys EM, Huston LJ, Schock HJ, Boylan JP, Ashton-Miller JA. Gender differences in muscular protection of the knee in torsion in size-matched athletes. *J Bone Joint Surg Am*. 2003;85-A(5):782-789. http://www.ncbi.nlm.nih.gov/pubmed/12728025. Accessed August 18, 2016.

71. Yang C-S, Lee G-S, Kim J-G, et al. The Anterior Cruciate Ligament Inury Prevention Program: A Meta-Analysis. *Biomech Sport Port J Sport Sci*. 29(11).

72. Boden BP, Dean GS, Feagin JA, Garrett WE. Mechanisms of anterior cruciate ligament injury. *Orthopedics*. 2000;23(6):573-578. http://www.ncbi.nlm.nih.gov/pubmed/10875418. Accessed May 18, 2014.

73. Faunø P, Wulff Jakobsen B. Mechanism of anterior cruciate ligament injuries in soccer. *Int J Sports Med*. 2006;27(1):75-79. doi:10.1055/s-2005-837485.

74. McNair PJ, Marshall RN, Matheson JA. Important features associated with acute anterior cruciate ligament injury. *N Z Med J*. 1990;103(901):537-539. http://www.ncbi.nlm.nih.gov/pubmed/2243642. Accessed August 19, 2016.

75. Noyes FR, Matthews DS, Mooar PA, Grood ES. The symptomatic anterior cruciate-deficient

knee. Part II: the results of rehabilitation, activity modification, and counseling on functional disability. *J Bone Joint Surg Am*. 1983;65(2):163-174. http://www.ncbi.nlm.nih.gov/pubmed/6822580. Accessed August 19, 2016.

76. Noyes FR, Mooar PA, Matthews DS, Butler DL. The symptomatic anterior cruciate-deficient knee. Part I: the long-term functional disability in athletically active individuals. *J Bone Joint Surg Am*. 1983;65(2):154-162. http://www.ncbi.nlm.nih.gov/pubmed/6687391. Accessed August 19, 2016.

77. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc*. 2009;17(7):705-729. doi:10.1007/s00167-009-0813-1.

78. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slauterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res*. 1995;13(6):930-935. doi:10.1002/jor.1100130618.

79. Markolf KL, Gorek JF, Kabo JM, Shapiro MS. Direct measurement of resultant forces in the anterior cruciate ligament. An in vitro study performed with a new experimental technique. *J Bone Joint Surg Am*. 1990;72(4):557-567. http://www.ncbi.nlm.nih.gov/pubmed/2324143. Accessed July 25, 2014.

80. Wascher DC, Markolf KL, Shapiro MS, Finerman GA. Direct in vitro measurement of forces in the cruciate ligaments. Part I: The effect of multiplane loading in the intact knee. *J Bone Joint Surg Am*. 1993;75(3):377-386. http://www.ncbi.nlm.nih.gov/pubmed/8444916. Accessed August 2, 2014.

81. Fornalski S, McGarry MH, Csintalan RP, Fithian DC, Lee TQ. Biomechanical and anatomical assessment after knee hyperextension injury. *Am J Sports Med*. 2008;36(1):80-84. doi:10.1177/0363546507308189.

82. Hame SL, Oakes DA, Markolf KL. Injury to the anterior cruciate ligament during alpine skiing: a biomechanical analysis of tibial torque and knee flexion angle. *Am J Sports Med*.

30(4):537-540. http://www.ncbi.nlm.nih.gov/pubmed/12130408. Accessed August 19, 2016.

83. Swenson TM, Harner CD. Knee ligament and meniscal injuries. Current concepts. *Orthop Clin North Am*. 1995;26(3):529-546. http://www.ncbi.nlm.nih.gov/pubmed/7609964. Accessed August 19, 2016.

84. Berns GS, Hull ML, Patterson HA. Strain in the anteromedial bundle of the anterior cruciate ligament under combination loading. *J Orthop Res*. 1992;10(2):167-176. doi:10.1002/jor.1100100203.

85. Dick R, Putukian M, Agel J, Evans TA, Marshall SW. Descriptive epidemiology of collegiate women's soccer injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2002-2003. *J Athl Train*. 42(2):278-285. http://www.ncbi.nlm.nih.gov/pubmed/17710177. Accessed August 5, 2016.

86. Agel J, Olson DE, Dick R, Arendt EA, Marshall SW, Sikka RS. Descriptive epidemiology of collegiate women's basketball injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2003-2004. *J Athl Train*. 42(2):202-210. http://www.ncbi.nlm.nih.gov/pubmed/17710168. Accessed September 2, 2016.

87. Arendt EA, Agel J, Dick R. Anterior cruciate ligament injury patterns among collegiate men and women. *J Athl Train*. 1999;34(2):86-92. http://www.ncbi.nlm.nih.gov/pubmed/16558564. Accessed September 2, 2016.

88. Mihata LCS, Beutler AI, Boden BP. Comparing the incidence of anterior cruciate ligament injury in collegiate lacrosse, soccer, and basketball players: implications for anterior cruciate ligament mechanism and prevention. *Am J Sports Med*. 2006;34(6):899-904. doi:10.1177/0363546505285582.

89. Lohmander LS, Ostenberg A, Englund M, Roos H. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum*. 2004;50(10):3145-3152. doi:10.1002/art.20589.

90. Mather RC, Koenig L, Kocher MS, et al. Societal and economic impact of anterior cruciate

ligament tears. *J Bone Joint Surg Am*. 2013;95(19):1751-1759. doi:10.2106/JBJS.L.01705.

91. Kiapour AM, Murray MM. Basic science of anterior cruciate ligament injury and repair. *Bone Joint Res*. 2014;3(2):20-31. doi:10.1302/2046-3758.32.2000241.

92. Levine JW, Kiapour AM, Quatman CE, et al. Clinically relevant injury patterns after an anterior cruciate ligament injury provide insight into injury mechanisms. *Am J Sports Med*. 2013;41(2):385-395. doi:10.1177/0363546512465167.

93. Chu CR, Beynnon BD, Buckwalter JA, et al. Closing the gap between bench and bedside research for early arthritis therapies (EARTH): report from the AOSSM/NIH U-13 Post-Joint Injury Osteoarthritis Conference II. *Am J Sports Med*. 2011;39(7):1569-1578. doi:10.1177/0363546511411654.

94. Nebelung W, Wuschech H. Thirty-five years of follow-up of anterior cruciate ligament-deficient knees in high-level athletes. *Arthroscopy*. 2005;21(6):696-702. doi:10.1016/j.arthro.2005.03.010.

95. von Porat A, Roos EM, Roos H. High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. *Ann Rheum Dis*. 2004;63(3):269-273. http://www.ncbi.nlm.nih.gov/pubmed/14962961. Accessed September 3, 2016.

96. Quatman CE, Kiapour A, Myer GD, et al. Cartilage pressure distributions provide a footprint to define female anterior cruciate ligament injury mechanisms. *Am J Sports Med*. 2011;39(8):1706-1713. doi:10.1177/0363546511400980.

97. Siegel L, Vandenakker-Albanese C, Siegel D. Anterior cruciate ligament injuries: anatomy, physiology, biomechanics, and management. *Clin J Sport Med*. 2012;22(4):349-355. doi:10.1097/JSM.0b013e3182580cd0.

98. Carmichael JR, Cross MJ. Why bone-patella tendon-bone grafts should still be considered the gold standard for anterior cruciate ligament reconstruction. *Br J Sports Med*. 2009;43(5):323-325. doi:10.1136/bjsm.2009.058024.

99. Chang SKY, Egami DK, Shaieb MD, Kan DM, Richardson AB. Anterior cruciate ligament reconstruction: allograft versus autograft. *Arthroscopy*. 19(5):453-462. doi:10.1053/jars.2003.50103.

100. Hospodar SJ, Miller MD. Controversies in ACL reconstruction: bone-patellar tendon-bone anterior cruciate ligament reconstruction remains the gold standard. *Sports Med Arthrosc*. 2009;17(4):242-246. doi:10.1097/JSA.0b013e3181c14841.

101. Kleipool AE, van Loon T, Marti RK. Pain after use of the central third of the patellar tendon for cruciate ligament reconstruction. 33 patients followed 2-3 years. *Acta Orthop Scand*. 1994;65(1):62-66. http://www.ncbi.nlm.nih.gov/pubmed/8154286. Accessed August 20, 2016.

102. Forssblad M, Valentin A, Engström B, Werner S. ACL reconstruction: patellar tendon versus hamstring grafts--economical aspects. *Knee Surg Sports Traumatol Arthrosc*. 2006;14(6):536-541. doi:10.1007/s00167-006-0064-3.

103. Freedman KB, D'Amato MJ, Nedeff DD, Kaz A, Bach BR. Arthroscopic anterior cruciate ligament reconstruction: a metaanalysis comparing patellar tendon and hamstring tendon autografts. *Am J Sports Med*. 31(1):2-11. http://www.ncbi.nlm.nih.gov/pubmed/12531750. Accessed August 20, 2016.

104. Li S, Chen Y, Lin Z, Cui W, Zhao J, Su W. A systematic review of randomized controlled clinical trials comparing hamstring autografts versus bone-patellar tendon-bone autografts for the reconstruction of the anterior cruciate ligament. *Arch Orthop Trauma Surg*. 2012;132(9):1287-1297. doi:10.1007/s00402-012-1532-5.

105. Xie X, Liu X, Chen Z, Yu Y, Peng S, Li Q. A meta-analysis of bone-patellar tendon-bone autograft versus four-strand hamstring tendon autograft for anterior cruciate ligament reconstruction. *Knee*. 2015;22(2):100-110. doi:10.1016/j.knee.2014.11.014.

106. Beynnon BD, Johnson RJ, Abate JA, Fleming BC, Nichols CE. Treatment of anterior cruciate ligament injuries, part I. *Am J Sports Med*. 2005;33(10):1579-1602.

doi:10.1177/0363546505279913.

107. Brandsson S, Karlsson J, Swärd L, Kartus J, Eriksson BI, Kärrholm J. Kinematics and laxity of the knee joint after anterior cruciate ligament reconstruction: pre- and postoperative radiostereometric studies. *Am J Sports Med*. 30(3):361-367. http://www.ncbi.nlm.nih.gov/pubmed/12016076. Accessed August 20, 2016.

108. Papannagari R, Gill TJ, Defrate LE, Moses JM, Petruska AJ, Li G. In vivo kinematics of the knee after anterior cruciate ligament reconstruction: a clinical and functional evaluation. *Am J Sports Med*. 2006;34(12):2006-2012. doi:10.1177/0363546506290403.

109. Scarvell JM, Smith PN, Refshauge KM, Galloway HR, Woods KR. Does anterior cruciate ligament reconstruction restore normal knee kinematics?: A prospective MRI analysis over two years. *J Bone Joint Surg Br*. 2006;88(3):324-330. doi:10.1302/0301-620X.88B3.16787.

110. Tashman S, Collon D, Anderson K, Kolowich P, Anderst W. Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2004;32(4):975-983. http://www.ncbi.nlm.nih.gov/pubmed/15150046. Accessed August 20, 2016.

111. Yoo JD, Papannagari R, Park SE, DeFrate LE, Gill TJ, Li G. The effect of anterior cruciate ligament reconstruction on knee joint kinematics under simulated muscle loads. *Am J Sports Med*. 2005;33(2):240-246. http://www.ncbi.nlm.nih.gov/pubmed/15701610. Accessed August 20, 2016.

112. Kanisawa I, Banks AZ, Banks SA, Moriya H, Tsuchiya A. Weight-bearing knee kinematics in subjects with two types of anterior cruciate ligament reconstructions. *Knee Surg Sports Traumatol Arthrosc*. 2003;11(1):16-22. doi:10.1007/s00167-002-0330-y.

113. Keays SL, Bullock-Saxton J, Keays AC. Strength and function before and after anterior cruciate ligament reconstruction. *Clin Orthop Relat Res*. 2000;(373):174-183. http://www.ncbi.nlm.nih.gov/pubmed/10810475. Accessed May 18, 2014.

114. Ageberg E. Consequences of a ligament injury on neuromuscular function and relevance to

rehabilitation - using the anterior cruciate ligament-injured knee as model. *J Electromyogr Kinesiol*. 2002;12(3):205-212. http://www.ncbi.nlm.nih.gov/pubmed/12086815. Accessed July 25, 2014.

115. Fridén T, Roberts D, Ageberg E, Waldén M, Zätterström R. Review of knee proprioception and the relation to extremity function after an anterior cruciate ligament rupture. *J Orthop Sports Phys Ther*. 2001;31(10):567-576. doi:10.2519/jospt.2001.31.10.567.

116. Ristanis S, Stergiou N, Patras K, Vasiliadis HS, Giakas G, Georgoulis AD. Excessive tibial rotation during high-demand activities is not restored by anterior cruciate ligament reconstruction. *Arthroscopy*. 2005;21(11):1323-1329. doi:10.1016/j.arthro.2005.08.032.

117. Webster KE, Santamaria LJ, McClelland J a, Feller J a. Effect of fatigue on landing biomechanics after anterior cruciate ligament reconstruction surgery. *Med Sci Sports Exerc*. 2012;44(5):910-916. doi:10.1249/MSS.0b013e31823fe28d.

118. Ristanis S, Stergiou N, Patras K, Tsepis E, Moraiti C, Georgoulis AD. Follow-up evaluation 2 years after ACL reconstruction with bone-patellar tendon-bone graft shows that excessive tibial rotation persists. *Clin J Sport Med*. 2006;16(2):111-116. http://www.ncbi.nlm.nih.gov/pubmed/16603879. Accessed July 25, 2014.

119. Schmitt LC, Paterno M V, Hewett TE. The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 2012;42(9):750-759. doi:10.2519/jospt.2012.4194.

120. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. *Br J Sports Med*. 2011;45(7):596-606. doi:10.1136/bjsm.2010.076364.

121. Chaves SF, Marques NP, Silva RLE, et al. Neuromuscular efficiency of the vastus medialis obliquus and postural balance in professional soccer athletes after anterior cruciate ligament reconstruction. *Muscles Ligaments Tendons J*. 2012;2(2):121-126. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3666503&tool=pmcentrez&rende

rtype=abstract. Accessed November 26, 2015.

122. Mouzopoulos G, Siebold R, Tzurbakis M. Hip flexion strength remains decreased in anterior cruciate ligament reconstructed patients at one-year follow up compared to healthy controls. *Int Orthop*. 2015;39(7):1427-1432. doi:10.1007/s00264-014-2662-x.

123. Cordeiro N, Cortes N, Fernandes O, Diniz A, Pezarat-Correia P. Dynamic knee stability and ballistic knee movement after ACL reconstruction: an application on instep soccer kick. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(4):1100-1106. doi:10.1007/s00167-014-2894-8.

124. Stearns KM, Pollard CD. Abnormal frontal plane knee mechanics during sidestep cutting in female soccer athletes after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med*. 2013;41(4):918-923. doi:10.1177/0363546513476853.

125. Pollard CD, Stearns KM, Hayes AT, Heiderscheit BC. Altered lower extremity movement variability in female soccer players during side-step cutting after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2015;43(2):460-465. doi:10.1177/0363546514560153.

126. Alvarez-Diaz P, Alentorn-Geli E, Ramon S, et al. Effects of anterior cruciate ligament reconstruction on neuromuscular tensiomyographic characteristics of the lower extremity in competitive male soccer players. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(11):3407-3413. doi:10.1007/s00167-014-3165-4.

127. Allen DG, Lamb GD, Westerblad H. Skeletal muscle fatigue: cellular mechanisms. *Physiol Rev*. 2008;88(1):287-332. doi:10.1152/physrev.00015.2007.

128. Gandevia SC. Spinal and supraspinal factors in human muscle fatigue. *Physiol Rev*. 2001;81(4):1725-1789. http://www.ncbi.nlm.nih.gov/pubmed/11581501. Accessed August 20, 2016.

129. Taylor JL, Gandevia SC. A comparison of central aspects of fatigue in submaximal and maximal voluntary contractions. *J Appl Physiol*. 2008;104(2):542-550. doi:10.1152/japplphysiol.01053.2007.

130. Davis MP, Walsh D. Mechanisms of fatigue. *J Support Oncol*. 8(4):164-174.

http://www.ncbi.nlm.nih.gov/pubmed/20822034. Accessed November 4, 2016.

131. Borotikar BS, Newcomer R, Koppes R, McLean SG. Combined effects of fatigue and decision making on female lower limb landing postures: central and peripheral contributions to ACL injury risk. *Clin Biomech (Bristol, Avon)*. 2008;23(1):81-92. doi:10.1016/j.clinbiomech.2007.08.008.

132. Gabbett TJ. Incidence, site, and nature of injuries in amateur rugby league over three consecutive seasons. *Br J Sports Med*. 2000;34(2):98-103. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1724194&tool=pmcentrez&rendertype=abstract. Accessed May 18, 2014.

133. Gabbett TJ. Incidence of injury in amateur rugby league sevens. *Br J Sports Med*. 2002;36(1):23-26. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1724444&tool=pmcentrez&rendertype=abstract. Accessed May 18, 2014.

134. Gabbett TJ. Influence of training and match intensity on injuries in rugby league. *J Sports Sci*. 2004;22(5):409-417. doi:10.1080/02640410310001641638.

135. Hawkins RD, Hulse MA, Wilkinson C, Hodson A, Gibson M. The association football medical research programme: an audit of injuries in professional football. *Br J Sports Med*. 2001;35(1):43-47. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1724279&tool=pmcentrez&rendertype=abstract. Accessed May 18, 2014.

136. Kersey RD, Rowan L. Injury account during the 1980 NCAA wrestling championships. *Am J Sports Med*. 11(3):147-151. http://www.ncbi.nlm.nih.gov/pubmed/6869655. Accessed May 18, 2014.

137. Rahnama N, Reilly T, Lees A. Injury risk associated with playing actions during competitive soccer. *Br J Sports Med*. 2002;36(5):354-359. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1724551&tool=pmcentrez&rende

rtype=abstract. Accessed May 18, 2014.

138. Benjaminse A, Habu A, Sell TC, et al. Fatigue alters lower extremity kinematics during a single-leg stop-jump task. *Knee Surg Sports Traumatol Arthrosc*. 2008;16(4):400-407. doi:10.1007/s00167-007-0432-7.

139. Kernozek TW, Torry MR, Iwasaki M. Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue. *Am J Sports Med*. 2008;36(3):554-565. doi:10.1177/0363546507308934.

140. McLean SG, Fellin RE, Felin RE, et al. Impact of fatigue on gender-based high-risk landing strategies. *Med Sci Sports Exerc*. 2007;39(3):502-514. doi:10.1249/mss.0b013e3180d47f0.

141. Sparto PJ, Parnianpour M, Reinsel TE, Simon S. The effect of fatigue on multijoint kinematics, coordination, and postural stability during a repetitive lifting test. *J Orthop Sports Phys Ther*. 1997;25(1):3-12. doi:10.2519/jospt.1997.25.1.3.

142. Parnianpour M, Nordin M, Kahanovitz N, Frankel V. 1988 Volvo award in biomechanics. The triaxial coupling of torque generation of trunk muscles during isometric exertions and the effect of fatiguing isoinertial movements on the motor output and movement patterns. *Spine (Phila Pa 1976)*. 1988;13(9):982-992. http://www.ncbi.nlm.nih.gov/pubmed/3206305. Accessed May 17, 2014.

143. McLean SG, Samorezov JE. Fatigue-induced ACL injury risk stems from a degradation in central control. *Med Sci Sports Exerc*. 2009;41(8):1661-1672. doi:10.1249/MSS.0b013e31819ca07b.

144. Rodacki ALF, Fowler NE, Bennett SJ. Vertical jump coordination: fatigue effects. *Med Sci Sports Exerc*. 2002;34(1):105-116. http://www.ncbi.nlm.nih.gov/pubmed/11782655. Accessed May 17, 2014.

145. Barfield J-P, Sells PD, Rowe DA, Hannigan-Downs K. Practice effect of the Wingate anaerobic test. *J Strength Cond Res*. 2002;16(3):472-473. http://www.ncbi.nlm.nih.gov/pubmed/12173966. Accessed May 17, 2014.

146. Ronglan LT, Raastad T, Børgesen A. Neuromuscular fatigue and recovery in elite female handball players. *Scand J Med Sci Sports*. 2006;16(4):267-273. doi:10.1111/j.1600-0838.2005.00474.x.

147. Greig M, Walker-Johnson C. The influence of soccer-specific fatigue on functional stability. *Phys Ther Sport*. 2007;8(4):185-190. doi:10.1016/j.ptsp.2007.03.001.

148. Wilkins JC, Valovich McLeod TC, Perrin DH, Gansneder BM. Performance on the Balance Error Scoring System Decreases After Fatigue. *J Athl Train*. 2004;39(2):156-161. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=419510&tool=pmcentrez&rendertype=abstract. Accessed May 17, 2014.

149. Orishimo KF, Kremenic IJ. Effect of fatigue on single-leg hop landing biomechanics. *J Appl Biomech*. 2006;22(4):245-254. http://www.ncbi.nlm.nih.gov/pubmed/17293621. Accessed May 17, 2014.

150. Augustsson J, Thomeé R, Lindén C, Folkesson M, Tranberg R, Karlsson J. Single-leg hop testing following fatiguing exercise: reliability and biomechanical analysis. *Scand J Med Sci Sports*. 2006;16(2):111-120. doi:10.1111/j.1600-0838.2005.00446.x.

151. Fagenbaum R, Darling WG. Jump landing strategies in male and female college athletes and the implications of such strategies for anterior cruciate ligament injury. *Am J Sports Med*. 31(2):233-240. http://www.ncbi.nlm.nih.gov/pubmed/12642258. Accessed May 17, 2014.

152. Coventry E, O'Connor KM, Hart BA, Earl JE, Ebersole KT. The effect of lower extremity fatigue on shock attenuation during single-leg landing. *Clin Biomech (Bristol, Avon)*. 2006;21(10):1090-1097. doi:10.1016/j.clinbiomech.2006.07.004.

153. Madigan ML, Pidcoe PE. Changes in landing biomechanics during a fatiguing landing activity. *J Electromyogr Kinesiol*. 2003;13(5):491-498. http://www.ncbi.nlm.nih.gov/pubmed/12932423. Accessed May 17, 2014.

154. Gokeler A, Eppinga P, Dijkstra PU, et al. Effect of fatigue on landing performance assessed with the landing error scoring system (less) in patients after ACL reconstruction. A pilot

study. *Int J Sports Phys Ther*. 2014;9(3):302-311. http://www.ncbi.nlm.nih.gov/pubmed/24944848. Accessed December 4, 2016.

155. Kuenze C, Hertel J, Hart JM. Effects of exercise on lower extremity muscle function after anterior cruciate ligament reconstruction. *J Sport Rehabil*. 2013;22(1):33-40. http://www.ncbi.nlm.nih.gov/pubmed/23307572. Accessed December 4, 2016.

156. Lepley LK, Thomas AC, McLean SG, Palmieri-Smith RM. Fatigue's lack of effect on thigh-muscle activity in anterior cruciate ligament-reconstructed patients during a dynamic-landing task. *J Sport Rehabil*. 2013;22(2):83-92. http://www.ncbi.nlm.nih.gov/pubmed/23069653. Accessed December 4, 2016.

157. Dalton EC, Pfile KR, Weniger GR, Ingersoll CD, Herman D, Hart JM. Neuromuscular changes after aerobic exercise in people with anterior cruciate ligament-reconstructed knees. *J Athl Train*. 46(5):476-483. http://www.ncbi.nlm.nih.gov/pubmed/22488134. Accessed November 3, 2016.

158. Robertson DGE, Caldwell GE, Hamill J, Kamen G, Whittlesey SN. *Research Methods in Biomechanics*.

159. Soderberg GL, Knutson LM. A guide for use and interpretation of kinesiologic electromyographic data. *Phys Ther*. 2000;80(5):485-498. http://www.ncbi.nlm.nih.gov/pubmed/10792859. Accessed September 4, 2016.

160. Zatsiorsky VM. *Kinematics of Human Motion*. Human Kinetics; 1998.

161. Zatsiorsky VM. *Kinetics of Human Motion*. Human Kinetics; 2002.

162. Fleming BC, Renstrom PA, Ohlen G, et al. The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. *J Orthop Res*. 2001;19(6):1178-1184. doi:10.1016/S0736-0266(01)00057-2.

163. Levangie PK, Norkin CC, Levangie PK. *Joint Structure and Function : A Comprehensive Analysis*. F.A. Davis Co; 2011.

164. Yu B, Garrett WE. Mechanisms of non-contact ACL injuries. *Br J Sports Med*. 2007;41 Suppl

1:i47-i51. doi:10.1136/bjsm.2007.037192.

165. Criswell E, Cram JR. *Cram's Introduction to Surface Electromyography*. Jones and Bartlett; 2011.

166. Papadonikolakis A, Cooper L, Stergiou N, Georgoulis AD, Soucacos PN. Compensatory mechanisms in anterior cruciate ligament deficiency. *Knee Surg Sports Traumatol Arthrosc*. 2003;11(4):235-243. doi:10.1007/s00167-003-0367-6.

167. Moore KL, Dalley AF, Agur AMR. *Clinically Oriented Anatomy*.

168. Myer GD, Ford KR, Brent JL, Hewett TE. The effects of plyometric vs. dynamic stabilization and balance training on power, balance, and landing force in female athletes. *J Strength Cond Res*. 2006;20(2):345-353. doi:10.1519/R-17955.1.

169. Myer GD, Ford KR, Barber Foss KD, Liu C, Nick TG, Hewett TE. The Relationship of Hamstrings and Quadriceps Strength to Anterior Cruciate Ligament Injury in Female Athletes. *Clin J Sport Med*. 2009;19(1):3-8. doi:10.1097/JSM.0b013e318190bddb.

170. Withrow TJ, Huston LJ, Wojtys EM, Ashton-Miller JA. Effect of Varying Hamstring Tension on Anterior Cruciate Ligament Strain During in Vitro Impulsive Knee Flexion and Compression Loading. *J Bone Jt Surgery-American Vol*. 2008;90(4):815-823. doi:10.2106/JBJS.F.01352.

171. Devita P, Skelly WA. Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Med Sci Sports Exerc*. 1992;24(1):108-115. http://www.ncbi.nlm.nih.gov/pubmed/1548984. Accessed April 6, 2015.

172. Chevalier TL, Hodgins H, Chockalingam N. Plantar pressure measurements using an in-shoe system and a pressure platform: a comparison. *Gait Posture*. 2010;31(3):397-399. doi:10.1016/j.gaitpost.2009.11.016.

173. Chen B, Bates BT. Comparison of F-Scan in-sole and AMTI forceplate system in measuring vertical ground reaction force during gait. *Physiother Theory Pract*. 2009. http://www.tandfonline.com/doi/abs/10.1080/095939800307601. Accessed February 9, 2016.

174. Billing DC, Hayes JP, Harvey EC, Baker J. Measurement of ground reaction forces using unobtrusive, on-athlete instrumentation. In: *International Conference on Intelligent Sensing and Information Processing, 2004. Proceedings of*. IEEE; 2004:218-221. doi:10.1109/ICISIP.2004.1287655.

175. Hurkmans HLP, Bussmann JBJ, Selles RW, et al. Validity of the Pedar Mobile system for vertical force measurement during a seven-hour period. *J Biomech*. 2006;39(1):110-118. doi:10.1016/j.jbiomech.2004.10.028.

176. Ahroni JH, Boyko EJ, Forsberg R. Reliability of F-scan in-shoe measurements of plantar pressure. *Foot ankle Int*. 1998;19(10):668-673. http://www.ncbi.nlm.nih.gov/pubmed/9801080. Accessed October 13, 2015.

177. Vidmar G, Novak P. Reliability of in-shoe plantar pressure measurements in rheumatoid arthritis patients. *Int J Rehabil Res Int Zeitschrift für Rehabil Rev Int Rech réadaptation*. 2009;32(1):36-40. doi:10.1097/MRR.0b013e328307bdc2.

178. Leitch KM, Birmingham TB, Jones IC, Giffin JR, Jenkyn TR. In-shoe plantar pressure measurements for patients with knee osteoarthritis: Reliability and effects of lateral heel wedges. *Gait Posture*. 2011;34(3):391-396. doi:10.1016/j.gaitpost.2011.06.008.

179. Mueller MJ, Strube MJ. Generalizability of in-shoe peak pressure measures using the F-scan system. *Clin Biomech (Bristol, Avon)*. 1996;11(3):159-164. http://www.ncbi.nlm.nih.gov/pubmed/11415614. Accessed January 2, 2016.

180. Mueller MJ, Sinacore DR, Hoogstrate S, Daly L. Hip and ankle walking strategies: effect on peak plantar pressures and implications for neuropathic ulceration. *Arch Phys Med Rehabil*. 1994;75(11):1196-1200. http://www.ncbi.nlm.nih.gov/pubmed/7979928. Accessed January 2, 2016.

Chapter III

1. Ford KR, Myer GD, Hewett TE. Reliability of landing 3D motion analysis: implications for longitudinal analyses. *Med Sci Sports Exerc*. 2007;39(11):2021-2028. doi:10.1249/mss.0b013e318149332d.
2. Milner CE, Westlake CG, Tate JJ. Test-retest reliability of knee biomechanics during stop jump landings. *J Biomech*. 2011;44(9):1814-1816. doi:10.1016/j.jbiomech.2011.04.005.
3. Ahroni JH, Boyko EJ, Forsberg R. Reliability of F-scan in-shoe measurements of plantar pressure. *Foot ankle Int*. 1998;19(10):668-673. http://www.ncbi.nlm.nih.gov/pubmed/9801080. Accessed October 13, 2015.
4. Vidmar G, Novak P. Reliability of in-shoe plantar pressure measurements in rheumatoid arthritis patients. *Int J Rehabil Res Int Zeitschrift für Rehabil Rev Int Rech réadaptation*. 2009;32(1):36-40. doi:10.1097/MRR.0b013e328307bdc2.
5. Chappell JD, Limpisvasti O. Effect of a neuromuscular training program on the kinetics and kinematics of jumping tasks. *Am J Sports Med*. 2008;36(6):1081-1086. doi:10.1177/0363546508314425.
6. Lephart SM, Abt JP, Ferris CM, et al. Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance program. *Br J Sports Med*. 2005;39(12):932-938. doi:10.1136/bjsm.2005.019083.
7. Pollard CD, Sigward SM, Ota S, Langford K, Powers CM. The influence of in-season injury prevention training on lower-extremity kinematics during landing in female soccer players. *Clin J Sport Med*. 2006;16(3):223-227. http://www.ncbi.nlm.nih.gov/pubmed/16778542. Accessed September 16, 2015.
8. Leitch KM, Birmingham TB, Jones IC, Giffin JR, Jenkyn TR. In-shoe plantar pressure measurements for patients with knee osteoarthritis: Reliability and effects of lateral heel wedges. *Gait Posture*. 2011;34(3):391-396. doi:10.1016/j.gaitpost.2011.06.008.

9. Chevalier TL, Hodgins H, Chockalingam N. Plantar pressure measurements using an in-shoe system and a pressure platform: a comparison. *Gait Posture*. 2010;31(3):397-399. doi:10.1016/j.gaitpost.2009.11.016.

10. Chesnin KJ, Selby-Silverstein L, Besser MP. Comparison of an in-shoe pressure measurement device to a force plate: concurrent validity of center of pressure measurements. *Gait Posture*. 2000;12(2):128-133. http://www.ncbi.nlm.nih.gov/pubmed/10998609. Accessed January 4, 2016.

11. Barnett S, Cunningham JL, West S. A comparison of vertical force and temporal parameters produced by an in-shoe pressure measuring system and a force platform. *Clin Biomech (Bristol, Avon)*. 2000;15(10):781-785. http://www.ncbi.nlm.nih.gov/pubmed/11050363. Accessed February 9, 2016.

12. Chen B, Bates BT. Comparison of F-Scan in-sole and AMTI forceplate system in measuring vertical ground reaction force during gait. *Physiother Theory Pract*. 2009. http://www.tandfonline.com/doi/abs/10.1080/095939800307601. Accessed February 9, 2016.

13. Billing DC, Hayes JP, Harvey EC, Baker J. Measurement of ground reaction forces using unobtrusive, on-athlete instrumentation. In: *International Conference on Intelligent Sensing and Information Processing, 2004. Proceedings of*. IEEE; 2004:218-221. doi:10.1109/ICISIP.2004.1287655.

14. Hurkmans HLP, Bussmann JBJ, Selles RW, et al. Validity of the Pedar Mobile system for vertical force measurement during a seven-hour period. *J Biomech*. 2006;39(1):110-118. doi:10.1016/j.jbiomech.2004.10.028.

15. Mueller MJ, Strube MJ. Generalizability of in-shoe peak pressure measures using the F-scan system. *Clin Biomech (Bristol, Avon)*. 1996;11(3):159-164. http://www.ncbi.nlm.nih.gov/pubmed/11415614. Accessed January 2, 2016.

16. Mueller MJ, Sinacore DR, Hoogstrate S, Daly L. Hip and ankle walking strategies: effect on peak plantar pressures and implications for neuropathic ulceration. *Arch Phys Med Rehabil*.

1994;75(11):1196-1200. http://www.ncbi.nlm.nih.gov/pubmed/7979928. Accessed January 2, 2016.

17. Ortiz A, Olson SL, Roddey TS, Morales J. Reliability of selected physical performance tests in young adult women. *J Strength Cond Res*. 2005;19(1):39-44. doi:10.1519/14163.1.

18. Perry MC, Morrissey MC, Jones JS, et al. Number of repetitions to maximum in hop tests in patients with anterior cruciate ligament injury. *Int J Sports Med*. 2005;26(8):688-692. doi:10.1055/s-2004-830494.

19. Church JB, Wiggins MS, Moode FM, Crist R. Effect of warm-up and flexibility treatments on vertical jump performance. *J Strength Cond Res*. 2001;15(3):332-336. http://www.ncbi.nlm.nih.gov/pubmed/11710660. Accessed February 7, 2016.

20. Vescovi JD, McGuigan MR. Relationships between sprinting, agility, and jump ability in female athletes. *J Sports Sci*. 2008;26(1):97-107. doi:10.1080/02640410701348644.

21. Isaacs LD. Comparison of the vertec and Just Jump Systems for measuring height of vertical jump by young children. *Percept Mot Skills*. 1998;86(2):659-663. doi:10.2466/pms.1998.86.2.659.

22. Leard JS, Cirillo MA, Katsnelson E, et al. Validity of two alternative systems for measuring vertical jump height. *J Strength Cond Res*. 2007;21(4):1296-1299. doi:10.1519/R-21536.1.

23. Moir G, Shastri P, Connaboy C. Intersession reliability of vertical jump height in women and men. *J Strength Cond Res*. 2008;22(6):1779-1784. doi:10.1519/JSC.0b013e318185f0df.

24. McBride JM, Triplett-McBride T, Davie A, Newton RU. The effect of heavy- vs. light-load jump squats on the development of strength, power, and speed. *J Strength Cond Res*. 2002;16(1):75-82. http://www.ncbi.nlm.nih.gov/pubmed/11834109. Accessed August 15, 2014.

25. Portney LG, Watkins MP. *Foundations of Clinical Research: Applications to Practice*. Pearson/Prentice Hall; 2009. http://books.google.com/books?id=apNJPgAACAAJ&pgis=1. Accessed May 20, 2014.

26. Hunter JP, Marshall RN, McNair P. Reliability of biomechanical variables of sprint running. *Med Sci Sports Exerc*. 2004;36(5):850-861. http://www.ncbi.nlm.nih.gov/pubmed/15126721. Accessed November 5, 2015.

27. Hopper DM, Goh SC, Wentworth LA, et al. Test–retest reliability of knee rating scales and functional hop tests one year following anterior cruciate ligament reconstruction. *Phys Ther Sport*. 2002;3(1):10-18. doi:10.1054/ptsp.2001.0094.

28. Augustsson J, Thomeé R, Lindén C, Folkesson M, Tranberg R, Karlsson J. Single-leg hop testing following fatiguing exercise: reliability and biomechanical analysis. *Scand J Med Sci Sports*. 2006;16(2):111-120. doi:10.1111/j.1600-0838.2005.00446.x.

29. Batterham AM, George KP. Reliability in evidence-based clinical practice: a primer for allied health professionals☆. *Phys Ther Sport*. 2003;4(3):122-128. doi:10.1016/S1466-853X(03)00076-2.

30. Ortiz A, Olson S, Libby CL, Kwon Y-H, Trudelle-Jackson E. Kinematic and kinetic reliability of two jumping and landing physical performance tasks in young adult women. *N Am J Sports Phys Ther*. 2007;2(2):104-112. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2953289&tool=pmcentrez&rendertype=abstract.

31. España-Romero V, Artero EG, Jimenez-Pavón D, et al. Assessing health-related fitness tests in the school setting: reliability, feasibility and safety; the ALPHA Study. *Int J Sports Med*. 2010;31(7):490-497. doi:10.1055/s-0030-1251990.

32. Kadaba MP, Ramakrishnan HK, Wootten ME, Gainey J, Gorton G, Cochran G V. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *J Orthop Res*. 1989;7(6):849-860. doi:10.1002/jor.1100070611.

33. Winter DA. Kinematic and kinetic patterns in human gait: Variability and compensating effects. *Hum Mov Sci*. 1984;3(1-2):51-76. doi:10.1016/0167-9457(84)90005-8.

34. Alenezi F, Herrington L, Jones P, Jones R. The reliability of biomechanical variables collected during single leg squat and landing tasks. *J Electromyogr Kinesiol*. 2014;24(5):718-721. doi:10.1016/j.jelekin.2014.07.007.

35. Hay JG, Miller JA, Canterna RW. The techniques of elite male long jumpers. *J Biomech*. 1986;19(10):855-866. doi:10.1016/0021-9290(86)90136-3.

Chapter IV

1. Yu B, Garrett WE. Mechanisms of non-contact ACL injuries. *Br J Sports Med*. 2007;41 Suppl 1:i47-i51. doi:10.1136/bjsm.2007.037192.

2. Childs SG. Pathogenesis of anterior cruciate ligament injury. *Orthop Nurs*. 21(4):35-40. http://www.ncbi.nlm.nih.gov/pubmed/12224184. Accessed May 23, 2014.

3. Prodromos CC, Han Y, Rogowski J, Joyce B, Shi K. A meta-analysis of the incidence of anterior cruciate ligament tears as a function of gender, sport, and a knee injury-reduction regimen. *Arthroscopy*. 2007;23(12):1320-1325.e6. doi:10.1016/j.arthro.2007.07.003.

4. Lohmander LS, Englund PM, Dahl LL, Roos EM. The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. *Am J Sports Med*. 2007;35(10):1756-1769. doi:10.1177/0363546507307396.

5. Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg*. 8(3):141-150. http://www.ncbi.nlm.nih.gov/pubmed/10874221. Accessed August 10, 2016.

6. Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. *Am J Sports Med*. 23(6):694-701. http://www.ncbi.nlm.nih.gov/pubmed/8600737. Accessed May 9, 2014.

7. Viola RW, Steadman JR, Mair SD, Briggs KK, Sterett WI. Anterior cruciate ligament injury incidence among male and female professional alpine skiers. *Am J Sports Med*. 27(6):792-

795. http://www.ncbi.nlm.nih.gov/pubmed/10569367. Accessed May 18, 2014.

8. Bjordal JM, Arnły F, Hannestad B, Strand T. Epidemiology of anterior cruciate ligament injuries in soccer. *Am J Sports Med*. 25(3):341-345. http://www.ncbi.nlm.nih.gov/pubmed/9167814. Accessed May 18, 2014.

9. Gwinn DE, Wilckens JH, McDevitt ER, Ross G, Kao TC. The relative incidence of anterior cruciate ligament injury in men and women at the United States Naval Academy. *Am J Sports Med*. 28(1):98-102. http://www.ncbi.nlm.nih.gov/pubmed/10653551. Accessed May 18, 2014.

10. Powell JW, Barber-Foss KD. Sex-related injury patterns among selected high school sports. *Am J Sports Med*. 28(3):385-391. http://www.ncbi.nlm.nih.gov/pubmed/10843133. Accessed May 18, 2014.

11. Inklaar H. Soccer injuries. I: Incidence and severity. *Sports Med*. 1994;18(1):55-73. http://www.ncbi.nlm.nih.gov/pubmed/7939040. Accessed May 18, 2014.

12. Oberländer KD, Brüggemann G-P, Höher J, Karamanidis K. Altered landing mechanics in ACL-reconstructed patients. *Med Sci Sports Exerc*. 2013;45(3):506-513. doi:10.1249/MSS.0b013e3182752ae3.

13. Kanisawa I, Banks AZ, Banks SA, Moriya H, Tsuchiya A. Weight-bearing knee kinematics in subjects with two types of anterior cruciate ligament reconstructions. *Knee Surg Sports Traumatol Arthrosc*. 2003;11(1):16-22. doi:10.1007/s00167-002-0330-y.

14. Keays SL, Bullock-Saxton J, Keays AC. Strength and function before and after anterior cruciate ligament reconstruction. *Clin Orthop Relat Res*. 2000;(373):174-183. http://www.ncbi.nlm.nih.gov/pubmed/10810475. Accessed May 18, 2014.

15. Ageberg E. Consequences of a ligament injury on neuromuscular function and relevance to rehabilitation - using the anterior cruciate ligament-injured knee as model. *J Electromyogr Kinesiol*. 2002;12(3):205-212. http://www.ncbi.nlm.nih.gov/pubmed/12086815. Accessed July 25, 2014.

16. Fridén T, Roberts D, Ageberg E, Waldén M, Zätterström R. Review of knee proprioception and the relation to extremity function after an anterior cruciate ligament rupture. *J Orthop Sports Phys Ther*. 2001;31(10):567-576. doi:10.2519/jospt.2001.31.10.567.

17. Ristanis S, Stergiou N, Patras K, Vasiliadis HS, Giakas G, Georgoulis AD. Excessive tibial rotation during high-demand activities is not restored by anterior cruciate ligament reconstruction. *Arthroscopy*. 2005;21(11):1323-1329. doi:10.1016/j.arthro.2005.08.032.

18. Webster KE, Santamaria LJ, McClelland J a, Feller J a. Effect of fatigue on landing biomechanics after anterior cruciate ligament reconstruction surgery. *Med Sci Sports Exerc*. 2012;44(5):910-916. doi:10.1249/MSS.0b013e31823fe28d.

19. Ristanis S, Stergiou N, Patras K, Tsepis E, Moraiti C, Georgoulis AD. Follow-up evaluation 2 years after ACL reconstruction with bone-patellar tendon-bone graft shows that excessive tibial rotation persists. *Clin J Sport Med*. 2006;16(2):111-116. http://www.ncbi.nlm.nih.gov/pubmed/16603879. Accessed July 25, 2014.

20. Schmitt LC, Paterno M V, Hewett TE. The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 2012;42(9):750-759. doi:10.2519/jospt.2012.4194.

21. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. *Br J Sports Med*. 2011;45(7):596-606. doi:10.1136/bjsm.2010.076364.

22. Boden BP, Dean GS, Feagin JA, Garrett WE. Mechanisms of anterior cruciate ligament injury. *Orthopedics*. 2000;23(6):573-578. http://www.ncbi.nlm.nih.gov/pubmed/10875418. Accessed May 18, 2014.

23. Hewett TE, Lindenfeld TN, Riccobene J V, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *Am J Sports Med*. 27(6):699-706. http://www.ncbi.nlm.nih.gov/pubmed/10569353. Accessed May 18, 2014.

24. Kirkendall DT, Garrett WE. The anterior cruciate ligament enigma. Injury mechanisms and

prevention. *Clin Orthop Relat Res*. 2000;(372):64-68. http://www.ncbi.nlm.nih.gov/pubmed/10738415. Accessed May 18, 2014.

25. Kirialanis P, Malliou P, Beneka A, Giannakopoulos K. Occurrence of acute lower limb injuries in artistic gymnasts in relation to event and exercise phase. *Br J Sports Med*. 2003;37(2):137-139. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1724619&tool=pmcentrez&rendertype=abstract. Accessed May 18, 2014.

26. Gray J, Taunton JE, McKenzie DC, Clement DB, McConkey JP, Davidson RG. A survey of injuries to the anterior cruciate ligament of the knee in female basketball players. *Int J Sports Med*. 1985;6(6):314-316. doi:10.1055/s-2008-1025861.

27. Decker MJ, Torry MR, Noonan TJ, Riviere A, Sterett WI. Landing adaptations after ACL reconstruction. *Med Sci Sports Exerc*. 2002;34(9):1408-1413. doi:10.1249/01.MSS.0000027627.82650.1F.

28. Decker MJ, Torry MR, Wyland DJ, Sterett WI, Richard Steadman J. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clin Biomech (Bristol, Avon)*. 2003;18(7):662-669. http://www.ncbi.nlm.nih.gov/pubmed/12880714. Accessed August 4, 2014.

29. Gokeler a, Hof a L, Arnold MP, Dijkstra PU, Postema K, Otten E. Abnormal landing strategies after ACL reconstruction. *Scand J Med Sci Sports*. 2010;20(1):e12-e19. doi:10.1111/j.1600-0838.2008.00873.x.

30. Paterno M V, Ford KR, Myer GD, Heyl R, Hewett TE. Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. *Clin J Sport Med*. 2007;17(4):258-262. doi:10.1097/JSM.0b013e31804c77ea.

31. Dufek JS, Bates BT. The evaluation and prediction of impact forces during landings. *Med Sci Sports Exerc*. 1990;22(3):370-377. http://www.ncbi.nlm.nih.gov/pubmed/2381305. Accessed August 1, 2014.

32. Pappas E, Sheikhzadeh A, Hagins M, Nordin M. The effect of gender and fatigue on the biomechanics of bilateral landings from a jump: peak values. *J Sports Sci Med*. 2007;6(1):77-84. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3778703&tool=pmcentrez&rendertype=abstract.
33. Salci Y, Kentel BB, Heycan C, Akin S, Korkusuz F. Comparison of landing maneuvers between male and female college volleyball players. *Clin Biomech (Bristol, Avon)*. 2004;19(6):622-628. doi:10.1016/j.clinbiomech.2004.03.006.
34. Church JB, Wiggins MS, Moode FM, Crist R. Effect of warm-up and flexibility treatments on vertical jump performance. *J Strength Cond Res*. 2001;15(3):332-336. http://www.ncbi.nlm.nih.gov/pubmed/11710660. Accessed February 7, 2016.
35. Vescovi JD, McGuigan MR. Relationships between sprinting, agility, and jump ability in female athletes. *J Sports Sci*. 2008;26(1):97-107. doi:10.1080/02640410701348644.
36. Isaacs LD. Comparison of the vertec and Just Jump Systems for measuring height of vertical jump by young children. *Percept Mot Skills*. 1998;86(2):659-663. doi:10.2466/pms.1998.86.2.659.
37. Leard JS, Cirillo MA, Katsnelson E, et al. Validity of two alternative systems for measuring vertical jump height. *J Strength Cond Res*. 2007;21(4):1296-1299. doi:10.1519/R-21536.1.
38. Moir G, Shastri P, Connaboy C. Intersession reliability of vertical jump height in women and men. *J Strength Cond Res*. 2008;22(6):1779-1784. doi:10.1519/JSC.0b013e318185f0df.
39. Pugh L, Mascarenhas R, Arneja S, Chin PYK, Leith JM. Current concepts in instrumented knee-laxity testing. *Am J Sports Med*. 2009;37(1):199-210. doi:10.1177/0363546508323746.
40. Daniel DM, Stone ML, Sachs R, Malcom L. Instrumented measurement of anterior knee laxity in patients with acute anterior cruciate ligament disruption. *Am J Sports Med*. 13(6):401-407. http://www.ncbi.nlm.nih.gov/pubmed/4073348. Accessed October 6, 2014.
41. Daniel DM, Stone ML, Dobson BE, Fithian DC, Rossman DJ, Kaufman KR. Fate of the

ACL-injured patient. A prospective outcome study. *Am J Sports Med*. 22(5):632-644. http://www.ncbi.nlm.nih.gov/pubmed/7810787. Accessed October 6, 2014.

42. Daniel DM, Malcom LL, Losse G, Stone ML, Sachs R, Burks R. Instrumented measurement of anterior laxity of the knee. *J Bone Joint Surg Am*. 1985;67(5):720-726. http://www.ncbi.nlm.nih.gov/pubmed/3997924. Accessed October 6, 2014.

43. Hanten WP, Pace MB. Reliability of measuring anterior laxity of the knee joint using a knee ligament arthrometer. *Phys Ther*. 1987;67(3):357-359. http://www.ncbi.nlm.nih.gov/pubmed/3823149. Accessed October 6, 2014.

44. Bach BR, Warren RF, Flynn WM, Kroll M, Wickiewiecz TL. Arthrometric evaluation of knees that have a torn anterior cruciate ligament. *J Bone Joint Surg Am*. 1990;72(9):1299-1306. http://www.ncbi.nlm.nih.gov/pubmed/2229104. Accessed September 17, 2016.

45. *Cram's Introduction To Surface Electromyography [Paperback]*. Jones & Bartlett Learning; 2 edition; 2010. http://www.amazon.com/Crams-Introduction-To-Surface-Electromyography/dp/0763732745. Accessed August 4, 2014.

46. Ortiz A, Olson SL, Roddey TS, Morales J. Reliability of selected physical performance tests in young adult women. *J Strength Cond Res*. 2005;19(1):39-44. doi:10.1519/14163.1.

47. Besier TF, Lloyd DG, Ackland TR. Muscle activation strategies at the knee during running and cutting maneuvers. *Med Sci Sports Exerc*. 2003;35(1):119-127. doi:10.1249/01.MSS.0000043608.79537.AB.

48. Croce R V, Russell PJ, Swartz EE, Decoster LC. Knee muscular response strategies differ by developmental level but not gender during jump landing. *Electromyogr Clin Neurophysiol*. 2004;44(6):339-348. http://www.ncbi.nlm.nih.gov/pubmed/15473345. Accessed September 17, 2016.

49. Lloyd DG, Buchanan TS. Strategies of muscular support of varus and valgus isometric loads at the human knee. *J Biomech*. 2001;34(10):1257-1267. http://www.ncbi.nlm.nih.gov/pubmed/11522305. Accessed September 17, 2016.

50. Manolopoulos E, Papadopoulos C, Kellis E. Effects of combined strength and kick coordination training on soccer kick biomechanics in amateur players. *Scand J Med Sci Sports*. 2006;16(2):102-110. doi:10.1111/j.1600-0838.2005.00447.x.

51. Rodacki AL, Fowler NE, Bennett SJ. Multi-segment coordination: fatigue effects. *Med Sci Sports Exerc*. 2001;33(7):1157-1167. http://www.ncbi.nlm.nih.gov/pubmed/11445763. Accessed September 17, 2016.

52. Rodacki ALF, Fowler NE, Bennett SJ. Vertical jump coordination: fatigue effects. *Med Sci Sports Exerc*. 2002;34(1):105-116. http://www.ncbi.nlm.nih.gov/pubmed/11782655. Accessed May 17, 2014.

53. Soderberg GL, Knutson LM. A guide for use and interpretation of kinesiologic electromyographic data. *Phys Ther*. 2000;80(5):485-498. http://www.ncbi.nlm.nih.gov/pubmed/10792859. Accessed September 4, 2016.

54. Wang L-I. The lower extremity biomechanics of single- and double-leg stop-jump tasks. *J Sports Sci Med*. 2011;10(1):151-156. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3737885&tool=pmcentrez&rendertype=abstract.

55. Bressel E, Cronin J. The Landing Phase of a Jump Strategies to Minimize Injuries. *J Phys Educ Recreat Danc*. 2005;76(2):30-35. doi:10.1080/07303084.2005.10607332.

56. Irmischer BS, Harris C, Pfeiffer RP, DeBeliso MA, Adams KJ, Shea KG. Effects of a knee ligament injury prevention exercise program on impact forces in women. *J Strength Cond Res*. 2004;18(4):703-707. doi:10.1519/R-13473.1.

57. Levangie PK, Norkin CC, Levangie PK. *Joint Structure and Function : A Comprehensive Analysis*. F.A. Davis Co; 2011.

58. McNitt-Gray JL. Kinetics of the lower extremities during drop landings from three heights. *J Biomech*. 1993;26(9):1037-1046. http://www.ncbi.nlm.nih.gov/pubmed/8408086. Accessed September 17, 2016.

59. Ortiz A, Olson S, Libby CL, et al. Landing mechanics between noninjured women and women with anterior cruciate ligament reconstruction during 2 jump tasks. *Am J Sports Med*. 2008;36(1):149-157. doi:10.1177/0363546507307758.

60. Papadonikolakis A, Cooper L, Stergiou N, Georgoulis AD, Soucacos PN. Compensatory mechanisms in anterior cruciate ligament deficiency. *Knee Surg Sports Traumatol Arthrosc*. 2003;11(4):235-243. doi:10.1007/s00167-003-0367-6.

61. Fleming BC, Renstrom PA, Ohlen G, et al. The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. *J Orthop Res*. 2001;19(6):1178-1184. doi:10.1016/S0736-0266(01)00057-2.

62. Limbird TJ, Shiavi R, Frazer M, Borra H. EMG profiles of knee joint musculature during walking: changes induced by anterior cruciate ligament deficiency. *J Orthop Res*. 1988;6(5):630-638. doi:10.1002/jor.1100060503.

63. Thomas AC, Villwock M, Wojtys EM, Palmieri-Smith RM. Lower extremity muscle strength after anterior cruciate ligament injury and reconstruction. *J Athl Train*. 2013;48(5):610-620. doi:10.4085/1062-6050-48.3.23.

64. de Jong SN, van Caspel DR, van Haeff MJ, Saris DBF. Functional assessment and muscle strength before and after reconstruction of chronic anterior cruciate ligament lesions. *Arthroscopy*. 2007;23(1):21-28, 28.e1-e3. doi:10.1016/j.arthro.2006.08.024.

65. Yasuda K, Ohkoshi Y, Tanabe Y, Kaneda K. Muscle weakness after anterior cruciate ligament reconstruction using patellar and quadriceps tendons. *Bull Hosp Jt Dis Orthop Inst*. 1991;51(2):175-185. http://www.ncbi.nlm.nih.gov/pubmed/1666006. Accessed September 24, 2016.

66. Malfait B, Dingenen B, Smeets A, et al. Knee and Hip Joint Kinematics Predict Quadriceps and Hamstrings Neuromuscular Activation Patterns in Drop Jump Landings. *PLoS One*. 2016;11(4):e0153737. doi:10.1371/journal.pone.0153737.

67. Moore KL, Dalley AF, Agur AMR. *Clinically Oriented Anatomy*.

68. Myer GD, Ford KR, Brent JL, Hewett TE. The effects of plyometric vs. dynamic stabilization and balance training on power, balance, and landing force in female athletes. *J Strength Cond Res*. 2006;20(2):345-353. doi:10.1519/R-17955.1.

69. Clarke SB, Kenny IC, Harrison AJ. Dynamic knee joint mechanics after anterior cruciate ligament reconstruction. *Med Sci Sports Exerc*. 2015;47(1):120-127. doi:10.1249/MSS.0000000000000389.

70. Blackburn JT, Padua DA. Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Clin Biomech (Bristol, Avon)*. 2008;23(3):313-319. doi:10.1016/j.clinbiomech.2007.10.003.

71. Hewett TE, Torg JS, Boden BP. Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. *Br J Sports Med*. 2009;43(6):417-422. doi:10.1136/bjsm.2009.059162.

72. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J Sports Med*. 2007;35(7):1123-1130. doi:10.1177/0363546507301585.

73. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. *Am J Sports Med*. 2007;35(3):368-373. doi:10.1177/0363546506297909.

74. Bangsbo J. Energy demands in competitive soccer. *J Sports Sci*. 1994;12 Spec No:S5-S12. http://www.ncbi.nlm.nih.gov/pubmed/8072065. Accessed September 24, 2016.

75. Bloomfield J, Polman R, O'Donoghue P. Physical Demands of Different Positions in FA Premier League Soccer. *J Sports Sci Med*. 2007;6(1):63-70. http://www.ncbi.nlm.nih.gov/pubmed/24149226. Accessed September 24, 2016.

Chapter V

1. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. *J Sports Sci*. 2003;21(7):519-528. doi:10.1080/0264041031000071182.

2. Robineau J, Jouaux T, Lacroix M, Babault N. Neuromuscular fatigue induced by a 90-minute soccer game modeling. *J Strength Cond Res*. 2012;26(2):555-562. doi:10.1519/JSC.0b013e318220dda0.

3. Rampinini E, Coutts AJ, Castagna C, Sassi R, Impellizzeri FM. Variation in top level soccer match performance. *Int J Sports Med*. 2007;28(12):1018-1024. doi:10.1055/s-2007-965158.

4. Magalhães J, Rebelo A, Oliveira E, Silva JR, Marques F, Ascensão A. Impact of Loughborough Intermittent Shuttle Test versus soccer match on physiological, biochemical and neuromuscular parameters. *Eur J Appl Physiol*. 2010;108(1):39-48. doi:10.1007/s00421-009-1161-z.

5. Krustrup P, Zebis M, Jensen JM, Mohr M. Game-Induced Fatigue Patterns in Elite Female Soccer. *J Strength Cond Res*. 2010;24(2):437-441. doi:10.1519/JSC.0b013e3181c09b79.

6. Mohr M, Krustrup P, Bangsbo J. Fatigue in soccer: A brief review. *J Sports Sci*. 2005;23(6):593-599. doi:10.1080/02640410400021286.

7. Borotikar BS, Newcomer R, Koppes R, McLean SG. Combined effects of fatigue and decision making on female lower limb landing postures: central and peripheral contributions to ACL injury risk. *Clin Biomech (Bristol, Avon)*. 2008;23(1):81-92. doi:10.1016/j.clinbiomech.2007.08.008.

8. Rahnama N, Reilly T, Lees A. Injury risk associated with playing actions during competitive soccer. *Br J Sports Med*. 2002;36(5):354-359. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1724551&tool=pmcentrez&rendertype=abstract. Accessed May 18, 2014.

9. Benjaminse A, Habu A, Sell TC, et al. Fatigue alters lower extremity kinematics during a single-leg stop-jump task. *Knee Surg Sports Traumatol Arthrosc*. 2008;16(4):400-407. doi:10.1007/s00167-007-0432-7.

10. Kernozek TW, Torry MR, Iwasaki M. Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue. *Am J Sports Med*. 2008;36(3):554-565. doi:10.1177/0363546507308934.

11. McLean SG, Fellin RE, Felin RE, et al. Impact of fatigue on gender-based high-risk landing strategies. *Med Sci Sports Exerc*. 2007;39(3):502-514. doi:10.1249/mss.0b013e3180d47f0.

12. Sparto PJ, Parnianpour M, Reinsel TE, Simon S. The effect of fatigue on multijoint kinematics, coordination, and postural stability during a repetitive lifting test. *J Orthop Sports Phys Ther*. 1997;25(1):3-12. doi:10.2519/jospt.1997.25.1.3.

13. Parnianpour M, Nordin M, Kahanovitz N, Frankel V. 1988 Volvo award in biomechanics. The triaxial coupling of torque generation of trunk muscles during isometric exertions and the effect of fatiguing isoinertial movements on the motor output and movement patterns. *Spine (Phila Pa 1976)*. 1988;13(9):982-992. http://www.ncbi.nlm.nih.gov/pubmed/3206305. Accessed May 17, 2014.

14. McLean SG, Samorezov JE. Fatigue-induced ACL injury risk stems from a degradation in central control. *Med Sci Sports Exerc*. 2009;41(8):1661-1672. doi:10.1249/MSS.0b013e31819ca07b.

15. Rodacki ALF, Fowler NE, Bennett SJ. Vertical jump coordination: fatigue effects. *Med Sci Sports Exerc*. 2002;34(1):105-116. http://www.ncbi.nlm.nih.gov/pubmed/11782655. Accessed May 17, 2014.

16. Barfield J-P, Sells PD, Rowe DA, Hannigan-Downs K. Practice effect of the Wingate anaerobic test. *J Strength Cond Res*. 2002;16(3):472-473. http://www.ncbi.nlm.nih.gov/pubmed/12173966. Accessed May 17, 2014.

17. Ronglan LT, Raastad T, Børgesen A. Neuromuscular fatigue and recovery in elite female handball players. *Scand J Med Sci Sports*. 2006;16(4):267-273. doi:10.1111/j.1600-0838.2005.00474.x.

18. Greig M, Walker-Johnson C. The influence of soccer-specific fatigue on functional stability. *Phys Ther Sport*. 2007;8(4):185-190. doi:10.1016/j.ptsp.2007.03.001.

19. Wilkins JC, Valovich McLeod TC, Perrin DH, Gansneder BM. Performance on the Balance Error Scoring System Decreases After Fatigue. *J Athl Train*. 2004;39(2):156-161. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=419510&tool=pmcentrez&rendertype=abstract. Accessed May 17, 2014.

20. Orishimo KF, Kremenic IJ. Effect of fatigue on single-leg hop landing biomechanics. *J Appl Biomech*. 2006;22(4):245-254. http://www.ncbi.nlm.nih.gov/pubmed/17293621. Accessed May 17, 2014.

21. Augustsson J, Thomeé R, Lindén C, Folkesson M, Tranberg R, Karlsson J. Single-leg hop testing following fatiguing exercise: reliability and biomechanical analysis. *Scand J Med Sci Sports*. 2006;16(2):111-120. doi:10.1111/j.1600-0838.2005.00446.x.

22. Fagenbaum R, Darling WG. Jump landing strategies in male and female college athletes and the implications of such strategies for anterior cruciate ligament injury. *Am J Sports Med*. 31(2):233-240. http://www.ncbi.nlm.nih.gov/pubmed/12642258. Accessed May 17, 2014.

23. Coventry E, O'Connor KM, Hart BA, Earl JE, Ebersole KT. The effect of lower extremity fatigue on shock attenuation during single-leg landing. *Clin Biomech (Bristol, Avon)*. 2006;21(10):1090-1097. doi:10.1016/j.clinbiomech.2006.07.004.

24. Madigan ML, Pidcoe PE. Changes in landing biomechanics during a fatiguing landing activity. *J Electromyogr Kinesiol*. 2003;13(5):491-498. http://www.ncbi.nlm.nih.gov/pubmed/12932423. Accessed May 17, 2014.

25. Markolf KL, Gorek JF, Kabo JM, Shapiro MS. Direct measurement of resultant forces in the anterior cruciate ligament. An in vitro study performed with a new experimental technique. *J*

Bone Joint Surg Am. 1990;72(4):557-567. http://www.ncbi.nlm.nih.gov/pubmed/2324143. Accessed July 25, 2014.

26. Wascher DC, Markolf KL, Shapiro MS, Finerman GA. Direct in vitro measurement of forces in the cruciate ligaments. Part I: The effect of multiplane loading in the intact knee. *J Bone Joint Surg Am*. 1993;75(3):377-386. http://www.ncbi.nlm.nih.gov/pubmed/8444916. Accessed August 2, 2014.

27. Ageberg E. Consequences of a ligament injury on neuromuscular function and relevance to rehabilitation - using the anterior cruciate ligament-injured knee as model. *J Electromyogr Kinesiol*. 2002;12(3):205-212. http://www.ncbi.nlm.nih.gov/pubmed/12086815. Accessed July 25, 2014.

28. Ristanis S, Stergiou N, Patras K, Tsepis E, Moraiti C, Georgoulis AD. Follow-up evaluation 2 years after ACL reconstruction with bone-patellar tendon-bone graft shows that excessive tibial rotation persists. *Clin J Sport Med*. 2006;16(2):111-116. http://www.ncbi.nlm.nih.gov/pubmed/16603879. Accessed July 25, 2014.

29. Webster KE, Santamaria LJ, McClelland J a, Feller J a. Effect of fatigue on landing biomechanics after anterior cruciate ligament reconstruction surgery. *Med Sci Sports Exerc*. 2012;44(5):910-916. doi:10.1249/MSS.0b013e31823fe28d.

30. Dalton EC, Pfile KR, Weniger GR, Ingersoll CD, Herman D, Hart JM. Neuromuscular changes after aerobic exercise in people with anterior cruciate ligament-reconstructed knees. *J Athl Train*. 46(5):476-483. http://www.ncbi.nlm.nih.gov/pubmed/22488134. Accessed November 3, 2016.

31. *Cram's Introduction To Surface Electromyography [Paperback]*. Jones & Bartlett Learning; 2 edition; 2010. http://www.amazon.com/Crams-Introduction-To-Surface-Electromyography/dp/0763732745. Accessed August 4, 2014.

32. Kindermann W, Simon G, Keul J. The significance of the aerobic-anaerobic transition for the determination of work load intensities during endurance training. *Eur J Appl Physiol Occup*

Physiol. 1979;42(1):25-34. http://www.ncbi.nlm.nih.gov/pubmed/499194. Accessed August 12, 2014.

33. Kulandaivelan, Verma S, Mukhopadhyay SK, Vignesh S. Test Retest Reproducibility of a Hand-Held Lactate Analyzer in Healthy Men. *J Exerc Sci Physiother*. 2009;5(1):30-33.

34. Hart S, Drevets K, Alford M, Salacinski A, Hunt BE. A method-comparison study regarding the validity and reliability of the Lactate Plus analyzer. *BMJ Open*. 2013;3(2):e001899. doi:10.1136/bmjopen-2012-001899.

35. Church JB, Wiggins MS, Moode FM, Crist R. Effect of warm-up and flexibility treatments on vertical jump performance. *J Strength Cond Res*. 2001;15(3):332-336. http://www.ncbi.nlm.nih.gov/pubmed/11710660. Accessed February 7, 2016.

36. Vescovi JD, McGuigan MR. Relationships between sprinting, agility, and jump ability in female athletes. *J Sports Sci*. 2008;26(1):97-107. doi:10.1080/02640410701348644.

37. Isaacs LD. Comparison of the vertec and Just Jump Systems for measuring height of vertical jump by young children. *Percept Mot Skills*. 1998;86(2):659-663. doi:10.2466/pms.1998.86.2.659.

38. Leard JS, Cirillo MA, Katsnelson E, et al. Validity of two alternative systems for measuring vertical jump height. *J Strength Cond Res*. 2007;21(4):1296-1299. doi:10.1519/R-21536.1.

39. Moir G, Shastri P, Connaboy C. Intersession reliability of vertical jump height in women and men. *J Strength Cond Res*. 2008;22(6):1779-1784. doi:10.1519/JSC.0b013e318185f0df.

40. Pugh L, Mascarenhas R, Arneja S, Chin PYK, Leith JM. Current concepts in instrumented knee-laxity testing. *Am J Sports Med*. 2009;37(1):199-210. doi:10.1177/0363546508323746.

41. Daniel DM, Malcom LL, Losse G, Stone ML, Sachs R, Burks R. Instrumented measurement of anterior laxity of the knee. *J Bone Joint Surg Am*. 1985;67(5):720-726. http://www.ncbi.nlm.nih.gov/pubmed/3997924. Accessed October 6, 2014.

42. Wroble RR, Van Ginkel LA, Grood ES, Noyes FR, Shaffer BL. Repeatability of the KT-1000 arthrometer in a normal population. *Am J Sports Med*. 18(4):396-399. http://www.ncbi.nlm.nih.gov/pubmed/2403189. Accessed October 6, 2014.

43. Hanten WP, Pace MB. Reliability of measuring anterior laxity of the knee joint using a knee ligament arthrometer. *Phys Ther*. 1987;67(3):357-359. http://www.ncbi.nlm.nih.gov/pubmed/3823149. Accessed October 6, 2014.

44. Bach BR, Warren RF, Flynn WM, Kroll M, Wickiewiecz TL. Arthrometric evaluation of knees that have a torn anterior cruciate ligament. *J Bone Joint Surg Am*. 1990;72(9):1299-1306. http://www.ncbi.nlm.nih.gov/pubmed/2229104. Accessed September 17, 2016.

45. Nagai T, Sell TC, House AJ, Abt JP, Lephart SM. Knee proprioception and strength and landing kinematics during a single-leg stop-jump task. *J Athl Train*. 48(1):31-38. doi:10.4085/1062-6050-48.1.14.

46. Ortiz A, Olson SL, Roddey TS, Morales J. Reliability of selected physical performance tests in young adult women. *J Strength Cond Res*. 2005;19(1):39-44. doi:10.1519/14163.1.

47. Inbar O, Bar-Or O, Skinner JS. *The Wingate Anaerobic Test*.; 1996. http://books.google.com.sa/books/about/The_Wingate_Anaerobic_Test.html?id=f2h3hWiNOOkC&pgis=1. Accessed May 18, 2014.

48. Ortiz A, Olson SL, Etnyre B, Trudelle-Jackson EE, Bartlett W, Venegas-Rios HL. Fatigue effects on knee joint stability during two jump tasks in women. *J Strength Cond Res*. 2010;24(4):1019-1027. doi:10.1519/JSC.0b013e3181c7c5d4.

49. Besier TF, Lloyd DG, Ackland TR. Muscle activation strategies at the knee during running and cutting maneuvers. *Med Sci Sports Exerc*. 2003;35(1):119-127. doi:10.1249/01.MSS.0000043608.79537.AB.

50. Croce R V, Russell PJ, Swartz EE, Decoster LC. Knee muscular response strategies differ by developmental level but not gender during jump landing. *Electromyogr Clin Neurophysiol*.

2004;44(6):339-348. http://www.ncbi.nlm.nih.gov/pubmed/15473345. Accessed September 17, 2016.

51. Lloyd DG, Buchanan TS. Strategies of muscular support of varus and valgus isometric loads at the human knee. *J Biomech*. 2001;34(10):1257-1267. http://www.ncbi.nlm.nih.gov/pubmed/11522305. Accessed September 17, 2016.

52. Manolopoulos E, Papadopoulos C, Kellis E. Effects of combined strength and kick coordination training on soccer kick biomechanics in amateur players. *Scand J Med Sci Sports*. 2006;16(2):102-110. doi:10.1111/j.1600-0838.2005.00447.x.

53. Rodacki AL, Fowler NE, Bennett SJ. Multi-segment coordination: fatigue effects. *Med Sci Sports Exerc*. 2001;33(7):1157-1167. http://www.ncbi.nlm.nih.gov/pubmed/11445763. Accessed September 17, 2016.

54. Soderberg GL, Knutson LM. A guide for use and interpretation of kinesiologic electromyographic data. *Phys Ther*. 2000;80(5):485-498. http://www.ncbi.nlm.nih.gov/pubmed/10792859. Accessed September 4, 2016.

55. Brazen DM, Todd MK, Ambegaonkar JP, Wunderlich R, Peterson C. The effect of fatigue on landing biomechanics in single-leg drop landings. *Clin J Sport Med*. 2010;20(4):286-292. doi:10.1097/JSM.0b013e3181e8f7dc.

56. Decker MJ, Torry MR, Wyland DJ, Sterett WI, Richard Steadman J. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clin Biomech (Bristol, Avon)*. 2003;18(7):662-669. http://www.ncbi.nlm.nih.gov/pubmed/12880714. Accessed August 4, 2014.

57. Moore KL, Dalley AF, Agur AMR. *Clinically Oriented Anatomy*.

58. Myer GD, Ford KR, Brent JL, Hewett TE. The effects of plyometric vs. dynamic stabilization and balance training on power, balance, and landing force in female athletes. *J Strength Cond Res*. 2006;20(2):345-353. doi:10.1519/R-17955.1.

59. Malfait B, Dingenen B, Smeets A, et al. Knee and Hip Joint Kinematics Predict Quadriceps and Hamstrings Neuromuscular Activation Patterns in Drop Jump Landings. *PLoS One*. 2016;11(4):e0153737. doi:10.1371/journal.pone.0153737.

60. Devita P, Skelly WA. Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Med Sci Sports Exerc*. 1992;24(1):108-115. http://www.ncbi.nlm.nih.gov/pubmed/1548984. Accessed April 6, 2015.

61. Blackburn JT, Padua DA. Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Clin Biomech (Bristol, Avon)*. 2008;23(3):313-319. doi:10.1016/j.clinbiomech.2007.10.003.

62. Levangie PK, Norkin CC, Levangie PK. *Joint Structure and Function : A Comprehensive Analysis*. F.A. Davis Co; 2011.

Chapter VI

1. Blackburn JT, Padua DA. Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Clin Biomech*. 2008;23(3):313-319. doi:10.1016/j.clinbiomech.2007.10.003.

2. Blackburn JT, Padua DA. Sagittal-Plane Trunk Position, Landing Forces, and Quadriceps Electromyographic Activity. *J Athl Train*. 2009;44(2):174-179. doi:10.4085/1062-6050-44.2.174.

3. Oberländer KD, Brüggemann G-P, Höher J, Karamanidis K. Reduced knee joint moment in ACL deficient patients at a cost of dynamic stability during landing. *J Biomech*. 2012;45(8):1387-1392. doi:10.1016/j.jbiomech.2012.02.029.

4. Shimokochi Y, Ambegaonkar JP, Meyer EG, Lee SY, Shultz SJ. Changing sagittal plane body position during single-leg landings influences the risk of non-contact anterior cruciate ligament injury. *Knee Surgery, Sport Traumatol Arthrosc*. 2013;21(4):888-897.

doi:10.1007/s00167-012-2011-9.

5. Shimokochi Y, Yong Lee S, Shultz SJ, Schmitz RJ. The Relationships Among Sagittal-Plane Lower Extremity Moments: Implications for Landing Strategy in Anterior Cruciate Ligament Injury Prevention. *J Athl Train*. 2009;44(1):33-38. doi:10.4085/1062-6050-44.1.33.

6. Castanharo R, da Luz BS, Duarte M, Bitar AC, D'Elia CO, Castropil W. Males still have limb asymmetries in multijoint movement tasks more than 2 years following anterior cruciate ligament reconstruction. *J Orthop Sci*. 2011;16(5):531-535. doi:10.1007/s00776-011-0118-3.

7. Neitzel JA, Kernozek TW, Davies GJ. Loading response following anterior cruciate ligament reconstruction during the parallel squat exercise. *Clin Biomech (Bristol, Avon)*. 2002;17(7):551-554. http://www.ncbi.nlm.nih.gov/pubmed/12206949. Accessed November 23, 2016.

8. Paterno M V, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med*. 2010;38(10):1968-1978. doi:10.1177/0363546510376053.

9. Mattacola CG, Perrin DH, Gansneder BM, Gieck JH, Saliba EN, McCue FC. Strength, Functional Outcome, and Postural Stability After Anterior Cruciate Ligament Reconstruction. *J Athl Train*. 2002;37(3):262-268. http://www.ncbi.nlm.nih.gov/pubmed/12937583. Accessed November 23, 2016.

10. Paterno M V., Schmitt LC, Ford KR, Rauh MJ, Myer GD, Hewett TE. Effects of Sex on Compensatory Landing Strategies Upon Return to Sport After Anterior Cruciate Ligament Reconstruction. *J Orthop Sport Phys Ther*. 2011;41(8):553-559. doi:10.2519/jospt.2011.3591.

Appendix A

Institutional Review Board Approval Letters

TWU
TEXAS WOMAN'S UNIVERSITY
DENTON DALLAS HOUSTON

Institutional Review Board
Office of Research
6700 Fannin, Houston, TX 77030
713-794-2480
mjackson3@twu.edu
http://www.twu.edu/irb.html

DATE: December 4, 2014

TO: Mr. Ahmad Alanazi
Physical Therapy - Houston

FROM: Institutional Review Board - Houston

Re: Approval for Biomechanical Evaluation during Unplanned and Planned Landing Maneuvers in Soccer Players with an Anterior Cruciate Ligament Reconstruction (Protocol #: 17902)

The above referenced study has been reviewed and approved by the Houston Institutional Review Board (IRB) on 12/3/2014 using an expedited review procedure. This approval is valid for one year and expires on 12/3/2015. The IRB will send an email notification 45 days prior to the expiration date with instructions to extend or close the study. It is your responsibility to request an extension for the study if it is not yet complete, to close the protocol file when the study is complete, and to make certain that the study is not conducted beyond the expiration date.

If applicable, agency approval letters must be submitted to the IRB upon receipt prior to any data collection at that agency. A copy of the approved consent form with the IRB approval stamp is enclosed. Please use the consent form with the most recent approval date stamp when obtaining consent from your participants. A copy of the signed consent forms must be submitted with the request to close the study file at the completion of the study.

Any modifications to this study must be submitted for review to the IRB using the Modification Request Form. Additionally, the IRB must be notified immediately of any adverse events or unanticipated problems. All forms are located on the IRB website. If you have any questions, please contact the TWU IRB.

cc. Dr. Peggy Gleeson, Physical Therapy - Houston
Alexis Ortiz, PT, PhD, Physical Therapy - Houston
Graduate School

Institutional Review Board
Office of Research
6700 Fannin, Houston, TX 77030
713-794-2480
irb-houston@twu.edu
http://www.twu.edu/irb.html

DATE: November 19, 2015

TO: Mr. Ahmad Alanazi
Physical Therapy - Houston

FROM: Institutional Review Board (IRB) - Houston

Re: Extension for Biomechanical Evaluation during Unplanned and Planned Landing Maneuvers in Soccer Players with an Anterior Cruciate Ligament Reconstruction (Protocol #: 17902)

The request for an extension of your IRB approval for the above referenced study has been reviewed by the TWU IRB (operating under FWA00000178) and appears to meet our requirements for the protection of individuals' rights.

If applicable, agency approval letters must be submitted to the IRB upon receipt PRIOR to any data collection at that agency. If subject recruitment is on-going, a copy of the approved consent form with the IRB approval stamp is enclosed. Please use the consent form with the most recent approval date stamp when obtaining consent from your participants. A copy of the signed consent forms must be submitted with the request to close the study file at the completion of the study.

This extension is valid one year from December 3, 2015. Any modifications to this study must be submitted for review to the IRB using the Modification Request Form. Additionally, the IRB must be notified immediately of any unanticipated incidents. All forms are located on the IRB website. If you have any questions, please contact the TWU IRB.

cc. Dr. Peggy Gleeson, Physical Therapy - Houston
Dr. Alexis Ortiz, Physical Therapy - Houston
Graduate School