IMPACT LOAD SYMMETRY FOLLOWING ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION AFTER RETURN TO SPORT IN COLLEGIATE ATHLETES

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ABSTRACT

Tyler Marie Hill: Impact Load Symmetry Following Anterior Cruciate Ligament Reconstruction After Return to Sport in Collegiate Athletes
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Anterior cruciate ligament injury and surgical reconstruction (ACLR) increases the risk of sustaining secondary injury in athletes returning to cutting and pivoting field sports. Changes in how an athlete loads each limb during sport-specific movements is thought to be a risk factor for sustaining secondary injury. It remains unclear as to how the ACLR population differs from healthy teammates in load symmetry during high-intensity running, cutting, pivoting, and jumping tasks as demanded on the field. Furthermore, little research has focused attention on the effects of muscular fatigue on field-based biomechanics such as load symmetry. The purpose of this research study is to find out if there are differences in load symmetry between collegiate athletes with a history of ACL reconstruction and healthy collegiate athletes without ACL injuries during sport-specific tasks. We will also investigate the effects of fatigue on load symmetry between ACLR individuals and determine the within-day reliability of measuring impact load symmetry during the designed test battery.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1:

INTRODUCTION

Injuries to the anterior cruciate ligament (ACL) affect 80,000 to 250,000 Americans each year.[1-3] At higher risk for rupturing the ACL are young athletes participating in cutting and pivoting sports.[4] Not only costly to an athlete financially, ACL injuries are time-loss injuries that result in an end to an athlete's season, and potentially, an athlete's career.[2-3,5] Although an athlete may successfully return to sport (RTS) following ACL reconstruction, his or her risk for sustaining secondary injury dramatically increases.[6,7] Although initial ACL injury prevalence is around 1.25-2.0%, almost one-third of athletes returning to high-risk, cutting and pivoting sports sustain secondary injury within 24 months.[7,8] Thus, there is a need to explore factors that may play a role in the high risk of secondary injury following return to sport following ACL reconstruction (ACLR).

Clinicians widely base return to sport criteria on time, strength, and functional tests following injury to determine an athlete's readiness to return to play.[9,10] However, given the high secondary ACL injury rates following return to sport, there may be other important factors not being considered in the return to sport determination and management process. A growing body of research advocates for clinicians to incorporate multiple factors into a return to sport decision, emphasizing that certain field-based components related to secondary injury may be often overlooked.[10,11]

An additional field-based component of return to sport is consideration of the loading symmetry between the involved and uninvolved limbs during sport-specific tasks and training. During rehabilitation, clinicians often use the athlete's uninvolved limb as a reference during functional testing by relying on Limb Symmetry Index (LSI) measures to determine readiness to return to sport.[12-14] LSI's are widely used as a measure of symmetrical performance, with an LSI of 100% representing complete symmetry between limbs. For an athlete to return to sport, meeting appropriate LSI thresholds often makeup a component of return to sport criteria.[13] For example, following ACLR, a treatment goal is for the athlete to achieve at least 90% LSI of quadriceps strength to demonstrate the functional performance similar to that of an un-injured athlete.[13-15] Research has supported that achieving load symmetry in a controlled setting is important for facilitating a successful return to sport with a reduced risk of secondary injury.[13-16]

Likewise, laboratory-based studies have analyzed biomechanical measures during specific functional tasks such as squatting, jump landing, or cutting.[15,17] In athletes following ACLR, decreases in measures such as postural stability of the involved limb indicating altered neuromuscular control, are associated with an increased risk for secondary ACL injury.[14] Laboratory studies have also demonstrated that the involved limb is often significantly under-loaded, by as much as 23%, in comparison to the uninvolved limb during stop-jump and side-to-side tasks when measuring ground reaction force.[17] Under-loading the injured limb following return to sport may indicate that athlete lacks the functional capabilities to withstand potential high joint forces and torques.

Though most functional testing completed in the laboratory or clinical setting is done in a rested state, different patterns of load symmetry have been seen in response to fatigue. The involved limb has been shown to be more resistant to fatigue than the un-involved limb during a single-task performance test following a laboratory-based generalized fatigue protocol.[18] This may suggest that the unaffected limb can only sustain the additional load for so long before weight must be distributed to the involved limb.[18-20] However, others have postulated that the altered neuromuscular response in the reconstructed limb following fatigue could be due to a shift in fiber type in the quadriceps.[18,21] This may warrant further investigation as to how sport-specific demands, more complex than completing a single task in a state of fatigue, could result in a change in loading symmetry. Similarly, how might this affect an athlete's risk of sustaining secondary ACL injury?

As previously mentioned, it is not clear if laboratory-based measures of load symmetry translate to real-world settings. While an athlete may match the profile of an uninjured athlete in quadriceps strength LSI in a controlled setting, he or she may fail to maintain the same pattern of load symmetry during on-field, sport-specific tasks, especially in a state of fatigue. As such, it may be important to quantify load symmetry during real-world training to ensure that load symmetry is transferred and maintained upon return to sport.

Quantifying load symmetry on-field is now possible through the use of inertial measurement units (IMU). IMUs consist of an accelerometer, gyroscope, and a magnetometer. IMUs placed on an athlete's distal tibias during sports-specific tasks can provide insight into impact load and symmetry between limbs. Furthermore, IMU software capabilities can be used to analyze an athlete's impact load from limb to limb and across various step acceleration intensities (low, medium, and high) required of an athlete during sport-specific tasks. Through the use of IMUs, quantifying and comparing the impact load symmetry of athletes following ACLR to athletes with no history of ACLR could serve as an essential component in understanding how load symmetry may relate to secondary injury.

Clinical Significance

This study, to our knowledge, will be one of the first to analyze load symmetry and the effects of fatigue within the ACLR population returning to collegiate, field-sports.

Through gaining an understanding of an athlete's field-based biomechanics related to secondary injury such as load symmetry, it may be possible to more safely return athletes to sport following ACL reconstruction. In turn, addressing these components may assist in reducing the high rate of re-rupture that exists in the ACLR population.

Research Questions and Hypotheses

RQ 1: Does the designed test battery, consisting of plyometric and unanticipated agility tasks, demonstrate acceptable within-day reliability for measuring impact load magnitude and symmetry in healthy collegiate athletes with no history of ACL reconstruction (ACLR)?

Hypothesis 1: The impact load magnitude and symmetry of healthy collegiate athletes during the designed test battery will have high within-day reliability with an ICC of 0.8 or greater.

RQ 2: Is there a change in impact load magnitude and symmetry post-fatigue compared to pre-fatigue in collegiate athletes who have returned to sport following ACL reconstruction (ACLR).

Hypothesis 2: Collegiate athletes with ACLR will demonstrate an increase in impact load magnitude and asymmetry following fatigue.

RQ 3: Are there differences in impact load magnitude and symmetry in college-aged athletes who have returned to sport following ACL reconstruction (ACLR) compared to those with no history of ACL injury (healthy, matched teammates)?

Hypothesis 3: Collegiate athletes with ACLR will demonstrate a greater impact load magnitude and asymmetry compared to healthy athletes with no history of ACLR.

CHAPTER 2:

LITERATURE REVIEW

Epidemiology

Injuries to the anterior cruciate ligament (ACL) remain a problematic and widespread injury facing young athletes. Epidemiological studies have shown that the rate of ACL injuries is 1 in 2500 in the United States alone.[2] The rate of ACL injuries in younger men and women, ages 15 to 24, is as high as 1 in 1100.[2] Injury to the ACL can be devastating to young athletes as many of these injuries are career-threatening, and sometimes career-ending. While most athletes choose to undergo reconstruction, recovery time following surgical intervention averages 6 to 9 months and can be longer depending on other injuries involved and the rehabilitation process.[22] Following surgery, it is estimated that 82% of athletes return to sport, however, only 63% of athletes return to their pre-injury level of participation in sport, and 44% of athletes are able to return to competitive sport.[23]

Consequences of ACL injuries not only contribute to a high level of short-term disability, but these injuries are also a burden on the health care system, with surgical cases costing almost $3 billion annually.[24] Recent literature has explored the long-term consequences of ACL injury as well, particularly the development of osteoarthritis (OA). Several studies have demonstrated that injury to the knee can be a predictor of osteoarthritis, especially when the injury is sustained in adolescence or young adulthood.[25-28] In a study by Salmon, within 13 years of ACL reconstruction, 79% of patients had radiographic changes and 50% of those that had sustained an isolated ACL injury with no damage to the meniscus had signs of OA development.[27]

Equally alarming, rates of OA after ACL injury has been seen from 10% to 90% within the first 10 to 20 years.[29] With such significant short-term and long-term consequences, researchers have focused attention on understanding injury rates and risk factors that can help clinicians minimize the costly effects of ACL injuries.

Injuries to the ACL are generally classified as contact or non-contact. Approximately 70% of ACL injuries are non-contact in nature and are more prevalent than contact ACL injuries.[30] Non-contact ACL injuries do not involve a blow to the knee by another object or athlete, and instead result from forces applied to the knee by the athlete's own movements and uncontrolled lower extremity biomechanics.[3] Contact injuries occur when the athlete sustains an impact to the knee, and most often occur during on-field collisions. Many researchers have also explained a third classification of ACL injury: indirect contact.[3] Injuries falling under this category occur when forces applied at the knee are due to perturbation that was caused by another athlete or object but did not directly contact the knee.[3] Since most of the ACL injuries that occur during sport are non-contact in nature, attention has been focused on what interventions may prevent these injuries and enhance understanding the associated risk factors.

Certain sports have been shown to have higher non-contact ACL injury rates than others. Participation in cutting and pivoting sports that require quick changes of direction have been linked to higher rates of non-contact ACL injuries.[31-34] The National Collegiate Athletic Association (NCAA) revealed through the Injury Surveillance System (ISS) that soccer, basketball, lacrosse, men's football and women's gymnastics have been associated with high rates of non-contact ACL injuries.[31-34] This is likely due to the high number of sport-specific movements that require cutting and pivoting. These sports also require plyometric activities such as landing from jumps, and quick, explosive, multidirectional movements that have been seen at the time of injury.[30]

The association of gender with ACL injury rates has also received attention. Several studies have demonstrated that females are at a greater risk for sustaining non-contact ACL injuries than males.[31,32,34] Specifically, women participating in high-risk, cutting and pivoting sports are at a risk 1.5 to 4.6 times greater than males.[3] Men's and women's sports such as soccer and basketball have shown the greatest disparity between injury rates.[3,31,35] Literature has explored various risk factors for ACL injuries that females may display in comparison to men, but of equal concern is the rapidly rising rates of ACL injury overall.[36,37] Such statistics have influenced a growing body of research advocating for ACL injury prevention efforts aimed at targeting and identifying populations more at risk.

Mechanism of Injury

For many years, researchers have investigated a number of proposed risk factors that occur during the exact moment of ACL injury. However, despite the large body of research that has accumulated, a precise mechanism of injury remains unknown. Recent studies using video analysis and computer simulation have attempted to confirm potential predictive risk factors, several common kinematics, forces, and biomechanics occurring at the moment of injury have been advanced understanding of the injury mechanism.

Anatomically, the ACL serves many functions to maintain knee stability. The ACL is crucial in preventing anterior translation of the tibia on the femur, providing rotary, valgus, and varus stability, preventing hyperextension, and guiding tibial motion through the screw-home mechanism.[1] Understanding the biomechanics and forces that act on dynamic and stabilizing structures of the knee may be important during the time of injury.[1,16,30] For example, the amount of knee flexion and tibial internal rotation can increase the load placed on the ACL.[1] Likewise, surrounding musculature such as the quadriceps, hamstrings, gastrocnemius and soleus all play significant roles in increasing or decreasing the load on the ACL making the ligament more susceptible to failure when not protected.[38]

Several researchers have investigated sagittal plane biomechanics and neuromuscular factors to understand how an athlete's joint kinematics may predispose an athlete to overload the ACL.[38-40] Early cadaveric studies have shown the most direct way to strain the ACL is through applying force in the anterior direction causing excessive translation of the tibia on the femur.[41] Both tibial slope and anterior tibial shear force (ATSF) have been thought to be possible risk factors that can contribute to ACL injury.[42,43] ATSF is believed to increase when excessive ground reaction force combines with quadriceps force when the knee is nearest full extension.[42,43] Females, particularly, have displayed less knee and hip flexion, more knee valgus, higher ATSF, greater quadriceps muscle activation during landing, and less hamstring strength when compared to males.[38-40,44-46,49-51] This movement profile, in combination with unanticipated movements required in high-risk sports, puts an athlete at greater risk for ACL failure.

Research studies have also focused on ATSF in combination with external forces that are transmitted up the kinetic chain. Several ground reaction forces such as knee flexion and extension moments have strong influences on kinetics and biomechanics of the lower extremity. Researchers have recently demonstrated correlations between ATSF and posterior and vertical ground reaction forces during jump landing maneuvers.[52,53] However, it is unclear whether ATSF alone is capable of rupturing the ACL. Using computer simulation, Mclean et al.[47] and Simenson et al.[48] found that during athletic movements such as side-stepping or cutting tasks, the ATSF values ranged from 520N to 900N, which is well below the theoretical threshold of 2000N for injury.[54]

Because an exact mechanism for injury is unknown, several ACL injury prevention strategies aim to re-train an athlete's mechanics of jump-landing to increase the knee flexion angle and protect the ACL from being overloaded.[28] Teaching an athlete to land from a jump with a larger knee flexion angle during initial contact with ground, and to sustain an increased knee flexion angle following through the landing, could prevent loading of the ACL.[28] In addition to a decreased knee flexion angle, other risk factors for ACL injury are identified during jump-landing tasks such as increased hip adduction angles, large knee internal rotation angles, and significant ground-reaction forces that increase ATSF.[26,29]

The exact combination of environmental, anatomical, hormonal, biomechanical and neuromuscular risk factors that occur at the moment of ACL injury remains elusive.[1] Implementing injury prevention programs to identify and correct lower extremity movement patterns while showing promise, have not fully accounted for the multitude of factors that can occur simultaneously.[54] Non-contact ACL injury scenarios vary greatly, partly due to the wide variety of on-field maneuvers required from sport to sport. Outside of the laboratory setting, athletes may be subjected to different movement patterns and forces when distracted or attempting to dodge defenders, judge distances, keep their footing or brace themselves for contact with an opponent. Though it is not likely feasible to accurately analyze biomechanics and neuromuscular risk factors on the field using current marker-based motion analysis systems, researchers are continuing to develop methodologies to more definitively study the mechanism of ACL injury.

Rate of Secondary Injury

Following ACLR, an athlete's chance of sustaining a secondary injury following return to sport (RTS) increases dramatically. Although an athlete's chance of sustaining a primary ACL injury is 1 in 2500,[2] Wiggins et al. found that in a group of young individuals returning to high-risk sport, the rate of re-injury was 23%.[56] These findings indicate that nearly 1 in 4 athletes sustaining an ACL injury that return to high risk sport go on to sustain another ACL injury at some point in their career. Equally as alarming, in a 2016 study of

100 athletes, Grindem et al. found that 24 athletes that returned to level one sport sustained re-injury, and 7 of these athletes reinjured despite waiting more than 9 months before returning to sport.[57] In Paterno's study following athletes for 12 months post-ACL reconstruction and return to sport, athletes were 15 times more likely to sustain a second ACL injury when compared to a healthy control group.[6] Similarly, in an extension study by Paterno et al, 29.5% of athletes returning to cutting and pivoting sports suffered a second ACL injury in 24 months following ACL RTS.[7] When following patients for a longer window of time, secondary injury rates continue to remain high. Webster et al reported a 29% re-rupture rate in patients younger than 20 years old at a minimum of 3 years follow up.[8] Re-rupture rates as high as 30% in the young, active population emphasize the need for a better understanding of risk factors that still remain once an athlete has been cleared for participation.[8]

Focus on female athletes returning to cutting and pivoting sports has shown that young females are at a greater risk for re-injury than males. In Paterno's extension study following athletes 24 months after initial ACL injury, 23 athletes sustained a subsequent injury.[7] Of the 23 athletes that suffered a secondary ACL rupture, 82.6% were female compared the 17.4 % that were males.[7] Furthermore, females with a history of ACL injury were almost 5 times more likely to sustain an ACL injury than females with no history of ACL injury.[7] Re-rupture rates continue to climb higher in female athletes continuing participation at the collegiate level. Stanley et al. reported that overall, females at the high school level are 2.30 times more likely to sustain ACL injuries, while at the collegiate level their chances increase to 2.49 times more likely.[58]

Interestingly, not all secondary ACL injuries occur in the previously injured limb. Kamath et al. reported findings in a group of athletes who sustained an initial ACL injury in high school, returned to sport, and suffered a secondary ACL injury during their collegiate career.[59] In a group of 35 athletes who ruptured their ACL before enrollment in college, 13 athletes sustained a secondary ACL injury at the collegiate level. Of the 13 athletes, 17% suffered graft failures, while 20% sustained contralateral ACL tears.[59] In a group of 54 athletes who sustained an initial ACL tear in college, only 7 athletes re-injured. Of the 7 athletes, 1.9% sustained ipsilateral graft failure, while 11.1% sustained contralateral tears.[59] Similarly, Paterno et al. reported that of the 29.5% of athletes that sustained a secondary ACL injury 24 months post-ACLR RTS, 20.5% sustained injury to the contralateral ACL, while 9% suffered ipsilateral injury (graft failure).[7] A high incidence of secondary injury to both the ipsilateral and contralateral ACL's indicates that while athletes may be able to return to sport, returning to the demands of higher level and high-risk sports may make it difficult for athletes to sustain good outcomes.

Risk Factors for Secondary Injury

Several risk factors have been shown to contribute to the high incidence of secondary ACL injuries. As mentioned, the young, athletic population participating in high-risk, cutting and pivoting sports is at an increased risk for sustaining both an initial ACL injury, as well as a secondary injury.[31-34] Though a previous history of ACL injury is the main predictor of secondary injury, environmental, anatomical, hormonal, biomechanical and neuromuscular risk factors that contributed to an athlete's primary ACL injury often remain problematic.[1] Recent research has identified the amount of time that an athlete waits before returning to sport as a potential risk factor as well.[57] Though it is common for clinicians to base return to sport decisions off of strength and performance criteria thought to facilitate a safer return, many athletes return to sport despite failing to meet these measures.[9] In addition, research has investigated whether or not an athlete's load symmetry may be overlooked as an important risk factor for on-field performance.[17,18]

Discrepancies exist regarding how long an athlete should wait before returning to sport following ACL reconstruction. In a systematic review by Barber-Westin, most clinicians' return to sport decisions are time-based.[60] Of the 158 studies reviewed, the majority of clinicians allowed athletes to return to sport at 6 months following reconstruction.[32] This is similar to a systematic review of 88 studies by Abrams and colleagues who also revealed that six months was the most common time point for RTS testing.[61] However, Grindem et al. reported that for every one-month delay in return to sport (up to 9 months), the risk of further knee injury was reduced by 51%.[57] Following return to sport, approximately half of all graft ruptures have been shown to occur within the first post-operative year in younger athletes.[64] Similarly, Paterno et al. reported that as opposed to secondary injury occurring in the first 24 months, the greatest risk of re-injury occurs within the first 12 months post-ACLR.[6,7] Stares et al. noted that because ACL injuries are time-loss injuries, return to sport should not be synonymous with the injury being "completely healed", but merely a stepping stone in an athlete's injury timeline.[62] Careful management and navigation of the time-line must include a multidimensional approach toward the return to sport criteria, instead of basing a decision solely on time.[62,63]

Another problematic risk factor contributing to the high rate of re-injury is the number of athletes that return to sport despite failing to meet return to sport criteria.[9] Grindem et al. reported in a study that up to 75% of athletes failed return to sport criteria but participated in sport anyway. Furthermore, 38% of these athletes went on to sustain re-injury compared to 5.6% of the athletes re-injured with passing RTP criteria.[57] In study of a six-part test battery consisting of isokinetic strength testing, on-field agility, and hop performance testing, Kyritsis et al. found that athletes that did not pass criteria for each of six tests had a 4 times greater risk for sustaining secondary ACL injury compared with those who successfully passed all six.[9] Despite the commonality of ACL injury, no single test battery or criteria has been accepted as an adequate measure of an athlete's readiness to return to sport. To reduce the risk of secondary injury, recent emphasis has been placed on incorporating additional RTS criteria that will better ensure safety, but may prolong an athlete's time away from sport.[9,63] While extending return to sport time frames may result in more games missed, these decisions remain complex. More games missed must be considered against increasing the athlete's risk for secondary injury, which may in turn increase the number of potential future games lost.[62,64,65]

Following an athlete's return to participation, risk factors exist in the form of deficits from his or her initial ACL injury. Strength and range of motion deficits, as well as decreased power, altered biomechanics, and poor movement quality have influenced the design of return to sport criteria.[9,61,63] Most clinicians use a combination of tests assessing quadriceps strength, hop tests to analyze performance, as well as the incorporation of balance, and proprioception measurements.[61,63] When comparing performance of the injured limb versus the uninjured limb, it has been common for clinicians to measure limb symmetry index (LSI).[13-15,61,63] Ideally, the athlete strives to achieve 100% LSI (perfect symmetry), however, clinicians widely accept ranges in LSI's from 80-90% depending on the measure being assessed. Despite the commonality, recent literature has highlighted that RTS criteria solely consisting of quadriceps LSI and hop-test performance may not be sufficient for safely returning athletes to sport.[18,61,63] Grindem et al. reported that those that did not meet an LSI equal to or greater than 90% on quadriceps strength testing increased their re-injury risk by 2.3 times.[57] However, a 12.5% re-injury rate was seen even in those who did.[57] Lautamies et al. reported that ACLR subjects can show weaker quadriceps muscle strength when compared to the uninvolved limb even 5 years after reconstruction.[66] Though an athlete may match the strength profile of an injured athlete during a single, controlled testing session, it remains to be determined whether or not athletes can maintain quadriceps strength on the field.

In addition to strength deficits, is also hypothesized that poor biomechanical and neuromuscular patterns contribute to a higher risk of secondary injury. Paterno and colleagues prospectively investigated how neuromuscular control and postural stability effected an athlete's chances of sustaining secondary injury.[16] Of 56 athletes studied, 13 suffered a secondary ACL injury.[16] During a drop vertical jump assessment, findings revealed increased knee valgus in the involved limb, hip internal rotation impulse in the uninvolved limb, and knee extension moment asymmetry at initial contact increased an athlete's odds of sustaining secondary ACL injury.[16] Similarly, single leg balance deficits on the involved limb using the Biodex SD Stability System increased an athlete's risk by 2.3 times.[16] Recently, it has been shown that following ACLR, athletes display a pattern of underloading that could affect secondary injury risk.[17,18,20] In a 2015 study, Webster et al. aimed to analyze weight bearing symmetry along with knee and hip joint symmetry during a double-leg squat. ACL athletes preferentially unloaded the reconstructed limb at baseline at both the knee and hip joints.[20] This study's findings are similar to others that have noted ACLR subjects' tendency to unload the involved limb when standing on a force plate or wearing in-shoe sensors.[67,68] Salem et al. described that during a squatting task, ACLR patients redistributed load from the targeted muscle group (the knee extensors) to a different muscle group (the hip extensors) to complete the multiple joint exercise.[69] In a group of 8 ACLR patients, the adopted strategy increased demand for muscular effort at the hip, while reducing the effort at the knee on the involved limb.[69] This altered pattern of loading symmetry may suggest that certain muscular imbalances exist after ACLR despite a clinician's best efforts in rehabilitation.[69] In addition to analyzing single joints in the lab-setting, investigating overall load symmetry in athletes returning to sport may help clinicians identify weight-distribution compensations that could contribute to secondary injury risk.

Load Symmetry

Following ACLR, an athlete may demonstrate deficits between the injured and un-injured limb that could limit his or her safe integration into the full demands of high-risk sport. Objective measurements of an athlete's load symmetry may assist clinicians in addressing any lasting impairments that may be related to an athlete's initial injury.[17,18,20] Though an athlete may surpass return to sport criteria set by a clinician in range of motion, strength, performance, and functional testing, it remains uncertain if an athlete displays sufficient load symmetry to safely return to sport. Although motion analysis systems have demonstrated accuracy in detecting asymmetrical loading patterns, the time for set-up, expense of equipment, and expertise required for use present difficulties for clinicians to repeatedly test athletes following ACLR.[70] Advances in wearable technology, specifically inertial sensors, have advantages such as portability, high capture rates, ease of use, cost-efficiency, and wireless capabilities that show promise in improving clinicians' convenience and ability to quantify load from limb to limb.[70]

Inertial sensors have the capabilities to directly output information from accelerometers and gyroscopes to bring load impact analysis outside of the laboratory setting. A growing body of research has recently emerged involving the use inertial sensors in non-controlled settings, but has been limited to investigating traditional measures of pathological gait patterns such as temporal, spatial, and kinematic data.[70,71,72] Sigward and colleagues explored the use of inertial sensors to detect spatiotemporal differences during early rehabilitation in the ACLR population attempting to restore gait.[70] Though the subjects studied following ACLR had no obvious patterns of pathological gait visible to the naked eye, the loading response while walking a 10-meter path in a laboratory setting showed that the surgical limb exhibited significantly smaller knee extensor moments and shank angular velocities compared to the un-involved limb.[70] However, no differences in stance or swing times were detected.[70] While it would appear that the ACLR subjects did not lack functional capabilities during gait observation, this did not translate into all knee loading mechanics analyzed through technology. In a 2016 longitudinal study, Sigward and colleagues demonstrated similar patterns of involved limb underloading during walking and running tasks.[71] Data revealed that ACLR subjects displayed less flexion, a 35% smaller knee extensor moment, and 47% less work on the surgical limb during walking. On the non-surgical limb, knee extensor moment and work were 1.7 and 1.6 greater compared to the surgical limb during running.[71]

Thomson and colleagues showed similar patterns of unloading.[73] A group of 16 soccer players that had completed the functional criteria required to return to sport, demonstrated significantly less maximum plantar force on the involved limb compared to the uninvolved limb.[73] Data measured through an in-shoe pressure system revealed a relatively large unloading of the involved ACLR limb across all running speeds in athletes less than 9 months post ACLR compared to those that were greater than 9 months post-ACLR.[73] This pattern of underloading seen in the lab setting warrants investigation as to whether patients following ACLR lack the functional capabilities to demonstrate symmetry from limb to limb, or if they are simply choosing to offload it. While comparison to the uninvolved limb is only assumed to demonstrate normal mechanics and may not be accurate, it likely provides the best frame of reference for interpreting load symmetry.[70] Athletes demonstrating underloading patterns in a lab setting despite having passed strength and functional testing may be unprepared to safely respond to high joint forces and torques generated during on-field movements required of high-risk sports.

While research using inertial sensors has primarily focused on gait analysis in the lab setting, there is a need for research on the error associated with using inertial sensors on the field. Many have debated whether or not the process of using inertial sensors in innovative ways, such as outside of the lab to produce clinically meaningful metrics could compromise validity and reliability.[72,74,75] Though motion analysis systems in controlled laboratory settings have continuously demonstrated accuracy in biomechanical measurements, in this setting it is difficult to replicate the sport-specific and real-world biomechanics that are demanded of athletes on the field. The feasibility of inertial sensors shows promise for clinicians hoping to develop innovative methodologies to incorporate field-based load symmetry into a RTS decision.[72]

New methods of technology have been designed to further improve the use of inertial sensors outside the lab. Inertial measurement units (IMUs) have recently emerged in various forms of sport tracking technologies. An IMU consists of sensors including an accelerometer, gyroscope, and a magnometer. One IMU sensor (Blue Trident Sensors, IMeasureU, Vicon; Oxford, UK) can be applied athlete's distal tibia in order to extract real-time data related to biomechanics, sport movement analysis, and gait analysis between limbs. IMeasureU has developed software capabilities to produce sensible metrics for clinical use such as step count, step intensity, bone load, and impact load. Though no peer-reviewed literature to date has validated the use of the Blue Trident Sensor specifically, this technology may serve as a practical instrument for clinicians to quantify load symmetry in athletes following ACLR during a training session or competition.

Muscular Fatigue

As previously described, current functional testing carried out by clinicians before making a RTS decision is often completed when an ACLR athlete is in a rested state. However, previous epidemiological data has revealed that athletes following ACLR who participate in high-risk sports are often at an increased risk for sustaining secondary injury in latter portions of activity, when a state of neuromuscular fatigue has been induced.[76, 77] "Muscular fatigue" is when a muscle loses peak force production as a result of physical exertion.[78] The resulting impairments following muscular fatigue within the neuromuscular system are generally categorized as factors of central fatigue (loss of a voluntary action) or peripheral fatigue (originating at or distal to the neuromuscular junction).[79] Athletic activity can produce a combination of central and peripheral fatigue, therefore, an understanding of the many physiological responses involved may be considered a potential risk factor for secondary injury.

Several researchers have found evidence of central fatigue during full-body functional fatigue protocols. To replicate the exercise an athlete experiences during a training session, Theurel suggested comparing exercise at varying intensities to a continuous bout of steady-state cardio.[80] When compared to continuous cycling, athletes that completed varying intensity exercise demonstrated a substantial decrease in levels of voluntary activation post-fatigue as well as higher levels of perceived exertion.[80] This study suggests that intermittent activity, similar to that required in collegiate field sports, induces higher amounts of central fatigue involving both increased physiological and perceptual changes. Furthermore, Theurel hypothesized that peripheral fatigue may play a role in the development of central fatigue.[80] This hypothesis was similar to other's postulations that the relationship between central and peripheral fatigue might occur through modulation of spinal reflexes and inhibition of the alpha motor neuron.[80]

Researchers have gathered similar conclusions from fatigue studies using stretch-shortening cycle (SSC) exercise.[81] SSC exercise often involves quick, powerful, repetitive jumps using an eccentric contraction to facilitate force development for concentric contraction in a small amount of time. In a study by Bookbinder et al. a group of 52 athletes completed a fatigue protocol consisting of treadmill running and unanticipated agility tasks, then completed a 4-jump test and a single leg hop for distance.[18] The ACLR group demonstrated a longer ground contact time on the reconstructed limb after exercise compared the uninvolved limb.[18] ACLR subjects also demonstrated different loading patterns following fatigue.[18] Before exercise, the ACLR group was 4% less symmetric compared with the healthy group.[18] However, this difference decreased to 1.5% after exercise.[18] Longer ground contact time as well as a shift in loading symmetry may suggest that SSC exercise induces fatigue responses changing movement efficiency.

McLean and colleagues designed a fatigue protocol to investigate the effects of fatigue on joint kinetics and kinematics of NCAA athletes.[82] A repetitive protocol of 20 step-up and step-downs followed by bounding strides with a deep-flexion landing position was repeated for 4 minutes.[82] Ankle, knee and hip moments were calculated through the use of a force plate upon landing. Following fatigue, both males and females demonstrated higher peak knee abduction, knee internal rotation angles, and peak internal rotation moments post-fatigue.[82] These findings suggest that in both genders, fatigue influences biomechanics that have been associated with placing increasing strain on the ACL.[38-40]

In a study exclusively analyzing female NCAA athletes, Borotikar et al. utilized a fatigue protocol consisting of double-leg squats, and double and single-leg landings, as well as unanticipated agility cutting tasks cued by a light system.[83] A flashing light system indicated not only which direction to cut, but also which foot to plant on the force plate to mimic decision-making skills required of an athlete on the field.[83] Following fatigue, ankle, knee, and hip joint kinematics were analyzed during initial contact and during peak stance phase. Findings revealed that in the 24 females, peak knee abduction angle was enhanced during unanticipated cutting, as well as peak internal rotation angles following fatigue.[83] During initial contact, these athletes had decreased hip flexion, increased hip internal rotation, and ankle supination following muscular fatigue.[83] While this study was not specific to the ACLR population, the study is useful in understanding neuromuscular response challenges during a fatigue protocol including components of both physical exertion and cognitive processing.[83]

Both Borotikar and McLean's findings suggest that changes in joint kinematics following muscular fatigue can influence movement patterns in potentially harmful ways, increasing load and strain on the ACL.[82,83] While both studies were conducted in lab settings, it can be assumed that on the field an athlete experiences external obstacles in addition to muscular fatigue that could further increase risk for secondary injury. Though prior fatigue protocols have used a wide variety of functional activities such as repetitive squatting, treadmill tests, jumping and bounding, repetitive sprinting, step-ups/step-downs, intermittent shuttle runs, and unanticipated agility drills, there remains discrepancy regarding which protocol best replicates the fatigue and an athlete experiences on the field. High-risk sports for secondary ACL injury often demand both aerobic and anaerobic systems, SSC exercise inducing both central and peripheral fatigue, as well as high cardiovascular endurance. In addition, athletes may have to perform intermittent sprints, jump landings, unanticipated agility tasks, and quick decision-making. Therefore, the protocol used in our study will be a modified version of a fatigue protocol used by McGrath and colleagues which has been validated and shown to produce substantial muscular fatigue.[84] The modification has been designed to incorporate many of the demands athletes experience on the field as listed above.

Within the limitations of time, the fatigue protocol used in this study will use metrics most similar to field-sport athletes. In a systematic review of the activity demands during multidirectional team sports by Taylor et al., authors found that soccer and field hockey demand the highest volume of running distances.[85] On average, male elite soccer players travelled between 9000 and 12,000 meters but spent more time and distance (222-1900 meters) in high-speed/intensity running than sprinting.[85] During a single game, soccer players cut at angles less than 90 degrees over 300 times to the right and left and were reported to travel laterally between 217 to 549 meters.[85] Though only two studies detail characteristics of jumping, male soccer players were found, on average, to jump 10.4 ± 5.4 times per game.[85] For our research study, each repetition a participant completes of the anticipated agility task (fatigue protocol), will cover 120 meters total in high-speed/intensity running and he or she will be required to travel laterally 30 meters. A total of 96 meters of distance will be covered during the unanticipated agility task which will involve equal cuts to both the right and left directions. During the plyometric tasks, participants will complete 6 different jumps for a total of 10 repetitions, performing 60 foot touches per leg. Our modified version of McGrath et al.'s fatigue protocol will ensure that participants are experiencing demands similar to those required of a typical game or practice session. In addition, an eleven-point scale for determining subjective fatigue through a rating of perceived exertion (RPE) will be derived from Micklewright and colleagues.[86] Through this protocol and a practical methodology for analyzing the effects of fatigue on loading symmetry, clinicians may be able to implement on-field load symmetry into a RTS decision in hopes of reducing high rates of secondary ACL injury.

CHAPTER 3:

METHODOLOGY

Design

This research was non-experimental, exploratory where we utilized a cohort design of male and female cutting and pivoting sport athletes at the University of North Carolina at Chapel Hill that had undergone anterior cruciate ligament reconstruction (ACLR) and returned to sport. In addition, a control group of healthy collegiate athletes participating in cutting and pivoting sports with no history of ACLR was recruited. Once informed consent was obtained, participants meeting inclusion/exclusion criteria, as well as the matched participants, were scheduled for a single test session where we examined impact load symmetry through a calculated limb symmetry index (LSI) value (involved limb Impact Load / uninvolved limb Impact Load x 100) during various functional tasks (unanticipated agility drill, plyometric assessment battery, and an anticipated agility task (fatigue protocol). We also compared how fatigue alters the impact load LSI values of ACLR participants during the anticipated agility task (fatigue protocol). The functional tasks incorporated multidirectional running, accelerations, decelerations, unanticipated movements, and plyometrics similar to the demands the participant experiences during his or her sport. The healthy controls with no history of ACLR were tested to measure the within-day reliability of the test battery.

Participants

Subjects were recruited from The University of North Carolina at Chapel Hill's cutting and pivoting field-sport teams including women's field hockey, and men's and women's lacrosse. An equal number of participants were recruited for the ACLR group and the healthy control group with no history of ACLR. The participants recruited were a convenience sample of athletes, both male and female, that meet inclusion and exclusion criteria. A participant was included if he or she has torn the ACL of one knee, undergone reconstruction, and returned to sport (RTS) within two and a half years of being tested. RTS was defined as clearance by both the participant's team physician and certified athletic trainer to return to his or her pre-injury participation level in a cutting or pivoting field sport. This participant also must have also had no history of time-loss injury to the lower body of opposite leg within 6 months of being tested. A participant was excluded if he or she had undergone surgery on the uninvolved knee or suffered a time loss injury to the opposite leg within 6 months of being tested (including MCL, LCL, PCL, etc.). Participants were not selected if they were restricted in participation on the field during team practices due to injury. He or she must have participated in at least 30 minutes of moderate to high-intensity physical activity a minimum of three days a week. Participants must have had no history of systemic or cardiorespiratory conditions that would prevent participation in high-intensity, fatiguing exercise. Matching criteria was based on the participant's sport, sex, position, and playing time. Informed consent was obtained prior to testing.

ACLR Inclusion Criteria

·Between the ages of 18 and 35

·History of primary, unilateral ACL rupture and reconstruction

·Clearance from team physician and certified athletic trainer for unrestricted RTS in cutting/pivoting field sport within 2.5 years of being tested

·Must participate in at least 30 minutes of moderate to high-intensity physical activity a minimum of 3 days a week

ACLR Exclusion Criteria

·Any additional ACL injuries other than the primary ACL tear

·Any additional procedure performed on other knee ligaments or articular cartilage (meniscectomy/meniscal repair will be included) either at time of ACLR or separately

·Any time-loss injury of either lower extremity within 6 months of testing

·Knowingly pregnant

·History of systemic or cardiorespiratory conditions that would prevent participation in high-intensity, fatiguing exercise

Heathy Participant Criteria

·Between the ages of 18 and 35

·No history of ACLR

·No history of any time-loss injury of either lower extremity within 6 months of testing that remains symptomatic

·Must participate in at least 30 minutes of moderate to high-intensity physical activity a minimum of 3 days a week

· No history of systemic or cardiorespiratory conditions that would prevent participation in high-intensity, fatiguing exercise

Instrumentation

Impact LSI was assessed using an inertial measurement unit device (Blue Trident Sensors, IMeasureU, Vicon; Oxford, UK). The IMUs contained low-g and high-g triaxial accelerometers. The low-g accelerometer had a range of ±16 g and sampling frequency of 1125 Hz, and the high-g accelerometer had a range of ± 200 g and sampling frequency of 1600 Hz. The IMUs also contained a triaxial gyroscope with a range of ± 2000 deg/sec and sampling frequency of 1125 Hz, and a triaxial magnetometer with a range of ± 4900 μT and sampling frequency of 100 Hz. Data was collected onboard the sensors then uploaded after the collection session.

Procedures

Participants that met inclusion criteria as well as the healthy participants were scheduled to participate in an on-field protocol designed to analyze load symmetry. Participants each underwent one individual testing session lasting approximately 45 minutes. Participants were instructed to wear athletic attire (shorts and a t-shirt) and appropriate running shoes. Each participant was required to complete an electronic informed consent form. Participants also completed an electronic health history form, an activity survey, and a series of outcome measure surveys relating to knee function prior to arriving at the location of testing. The participant was screened for COVID-19 24 hours before testing. If the participant was symptom-free and had not been in contact with an individual testing positive for COVID-19, the participant reported for his or her testing session. Upon arriving on campus, the participant had their temperature taken and verbally answered symptom screening questions. The participant was required to wear a face mask until the start of the testing session and comply with social distancing ordinances on campus. All testing sessions took place on a standard turf-field where the various functional tasks were mapped using a series of numbered cones (Figure 1.1). IMU sensors were placed directly over the distal tibia of both legs, just proximal to the medial malleolus, using a rubber strap with Velcro attachments.

ACLR Participants:

While the sensors were being applied, ACLR participants were read a script of instructions with a detailed explanation of how to complete the anticipated agility task (fatigue protocol). A visual representation of the anticipated agility task (fatigue protocol) is provided in Figure 1.2. The participant began by participating in 2 practice trials of each task (unanticipated agility drill, plyometric assessment battery, and anticipated agility task (fatigue protocol) at 50-75% of maximal effort. This served as the participant’s warm-up and was followed by 5 minutes of self-directed stretching prior to beginning the first task. Participants were able to ask questions to confirm understanding. Each participant was also given instructions on rating his or her perceived exertion (RPE). The eleven-point RPE scale derived from Micklewright and colleagues is provided in Figure 1.3.[86] Testing began with the participant first completing the plyometric assessment battery, which was followed by the unanticipated agility drill. Next, the participant completed the anticipated agility task (fatigue protocol) until his or her performance decreased by 25% (as determined by a 25% increase in the participant's initial trial time) and the participant's rating of perceived exertion (RPE) was above an 8 for three consecutive trials. The ACLR participant was automatically declared fatigued following 30 repetitions of the fatigue protocol regardless of RPE or performance decrease. Immediately after the final anticipated agility task (fatigue protocol) trial, the ACLR participant gave his or her RPE and was asked to repeat the unanticipated agility drill, followed by the plyometric assessment battery. Bilateral average impact load measures for each step taken were recorded across all tasks. The participant was encouraged to perform at maximal effort during each of the functional tasks. Detailed descriptions of each functional task are provided below.

Plyometric Tasks

The participant first performed a randomized series of six plyometric tasks. The investigator tagged each jumping task separately in the IMU software and indicated pre-fatigue or post-fatigue prior to the participant beginning and checked that the IMU sensors were properly positioned around the distal tibias. The plyometric tasks were performed in a random order, predetermined prior to testing so that each participant performed 60 foot touches per leg. These tasks consisted of 1) ten forward two-legged hops, 2) ten forward single leg bounding off each leg, 3) ten two-legged tuck jumps, 4) ten single leg jumps in place for each leg, 5) ten side-to-side two-legged hops, and 6) ten ice skater jumps per leg. The ten forward two-legged hops, as well as the forward single leg bounding jumps off each leg were measured for distance to ensure that the participant was exerting maximal effort. The participant also had to clear a distance (determined on the basis of his or her height) for the side-to-side two-legged hops and the ice skater jumps. The participant followed the command of the investigator and performed each of the six plyometrics tasks consecutively.

Unanticipated Agility Task

The participant then completed the unanticipated agility drill. A 10 meter by 10 meter box was setup on the turf field with eight cones equidistant from one another along the perimeter of the box (Figure 1.1) The participant stood in the center of the box facing the investigator. Cone one was be labeled as the cone in the back right corner of the box; cone two was 5 meters to the right of the participant; cone three was in the front right corner of the box; cone four was 5 meters in front of the participant; cone five was in the front left corner of the box; cone six was 5 meters to the left of the participant; cone seven was in the back left corner of the box; and cone eight was 5 meters behind the participant (Figure 1.1). Before beginning, the investigator tagged the task in the IMU software as “Unanticipated Agility: Pre-Fatigue”. The participant faced the investigator who, in a random and pre-determined order, held up a piece of paper with the number of the cone the athlete was to run to. The participant ran to the cone, touched the cone with their hand, cut off the respective foot, and returned to the center of the box. For cones 2, 4, 6, and 8, the participant ran a total of 10 meters (5 meters to the cone, 5 meters back to the center). For cones 1, 3, 5, 7, the participant ran a distance of 14 meters (7 meters to the cone, 7 meters back to the center). The random order of cones assigned to the participant ensured that he or she had equal opportunity to display symmetry by cutting off of both their right and left limbs for the same number of repetitions. Once the participant had finished the unanticipated agility tasks, they had touched all eight cones and had run a total of 96 meters. The participant quickly made his or her way to cone 1 to begin the fatigue protocol and was asked to give a rating of perceived exertion (RPE).

Anticipated Agility Task / Fatigue Protocol

To assess the participant's load symmetry in both a fatigued and non-fatigued state, all ACLR participants underwent a fatigue protocol. As previously used by researchers, the fatigue protocol had been shown to effectively induce fatigue through continuous repetitions of multidirectional movements.[83] Participants traveled a total distance of 120 meters around the same 10 by 10 meter boxed used for the unanticipated agility tasks. Prior to beginning, investigators had a stopwatch accessible, the activity was tagged in the IMU software as "Fatigue 1", and the IMU sensors were checked for proper positioning around the participant's distal tibias. The participant began at cone 1 and sprint around the perimeter of the box, passing cones 3 and 5 and changing direction at cone 7. From cone 7 the participant sprinted back around the perimeter the same way until they arrived back at cone 1. The participant side shuffled to their right past cone 2 and 3 until they reached cone 4. At cone 4, he or she sprinted forward to cone 8 and then on to cone 7. At cone 7 the participant side shuffled to their left past cones 5 and 6 until arriving at cone 4. Once arriving at cone 4 the participant sprinted forward to cone 8 and ended at cone 1 (Figure 1.2). The participant performed one additional practice trial prior to his or her first trial in order to ensure the participant understood the order of the task. He or she was reminded to give all-out, maximal effort for each trial and was timed with a stopwatch by the investigator. 125% of the participant's first trial time was calculated and noted. The participant had 25 seconds to rest in place at cone 1 between each trial. During the rest time, the participant was asked to give a rating of his or her perceived exertion. The rating of perceived exertion (RPE) was recorded between each trial. Each trial was timed, and a new activity was tagged in the IMU software for each repetition using the footnote "Fatigue 2", "Fatigue 3", etc. When the participant’s time met 125% of the first trial (as previously calculated) the participant had two remaining trials to improve. However, once the participant had reached the 125% time mark, meaning his or her performance had decreased by 25%, for two additional trials (for a total of 3 trials above 125% and reported a rating of 8 or higher on the RPE scale) the participant had met the operational definition of fatigue. Participants were declared fatigued after completing a maximum number of 30 trials regardless of RPE or performance decrease. Once fatigued, the participant moved to the center of the box to complete the unanticipated agility tasks once again, in randomized order in a fatigued state. Prior to the participant’s start, he or she had 20-30 seconds to rest, the task was tagged as “Unanticipated agility: Post-fatigue”, and the IMU sensors were properly positioned. The last activity the participant performed was the plyometric battery in a fatigued state. The order was randomized once again, and each jumping task was individually tagged prior to the participant’s start and indicated “Plyometrics: Post Fatigue”.

Within-Day Reliability Testing Procedures:

To assess within-day reliability of Impact Load magnitude and LSI as measured through IMU sensors, the healthy participants followed a modified version of the testing protocol that excluded the anticipated agility (fatigue protocol). Healthy participants reported for testing and the sensors were applied as described above. The participant began by participating in 2 practice trials of each task (unanticipated agility drill, plyometric assessment battery, and anticipated agility (fatigue protocol) at 50-75% of maximal effort. The participant was able to ask questions to confirm understanding. This served as the participant’s warm-up and was followed by 5 minutes of self-directed stretching prior to beginning the plyometric battery. Following the completion of the plyometric battery, the participant completed the unanticipated agility task. He or she completed only 1 trial of the anticipated agility (fatigue protocol) at maximal effort.

Immediately following, the participant was seated and was instructed to rest for a 10 minute period. Following the 10 minutes, the participant completed the unanticipated agility task once again finished by completing the plyometric battery.

Measures

The IMU sensor software algorithm detects steps and intensities based on data from the accelerometers, ranging from 1 to 200 g for each limb. For all participants, the average intensity (average impact load) was determined through the IMeasureU software dashboard that displays each participant's session asymmetry by grouping left limb and right limb step counts into intensity bins. The IMU software calculates an average intensity (or average impact load) based on the number of steps at each intensity on both the right limb and left limb. The average impact load for each limb was recorded from the IMU dashboard during each of the tasks that were tagged as footnotes during data collection. Average Impact Load Limb Symmetry Index (LSI) values were calculated as the involved limb average impact load / the uninvolved limb average impact load x 100. To determine the "involved" limb for healthy participants, each healthy participant was matched with an ACLR participant. If the matched ACLR participant tore the ACL of his or her dominant limb, the healthy participant's dominant limb was considered his or her "involved" limb. If the matched ACLR participant tore the ACL of his or her non-dominant limb, the healthy participant's non-dominant limb was considered his or her "involved" limb. Average Impact Load LSI calculations were repeated for each set of tasks. In the ACLR group, included the pre-fatigue plyometric battery, the pre-fatigue unanticipated agility task, the first three anticipated agility (fatigue protocol) trials, the last three anticipated agility (fatigue protocol) trials, the post-fatigue unanticipated agility task, and the post-fatigue plyometric battery. In the healthy participants this included the first plyometric battery, the first unanticipated agility task, the second unanticipated agility task, and the second plyometric battery based on the tagged footnotes used during data collection. In the ACLR participants, we analyzed both limb to limb differences pre-fatigue and post-fatigue as well as LSI values across tasks. To compare groups, we analyzed limb to limb values and LSI values in the pre-fatigue condition only.

Statistical Analysis

Descriptive characteristics for ACLR and healthy groups were reported along with the characteristics of the fatigue task. All statistical analyses were completed using SPSS software version 26.0 (IBM Corp., Armonk, NY, USA) and statistical analysis was set at $\alpha < .05$ for all analyses.

For healthy participants, within-day reliability was assessed using Intra-class correlation coefficient (ICC) values (ICC 3,k). For the reliability analysis, the average impact loads of the healthy participants' dominant and non-dominant limbs were used. We compared the average impact load of the first testing session (prior to the athlete's 10-minute rest period) to the second testing session (following the 10-minute rest period) between tasks and between limbs. We reported the standard error of the measurement (SEM), minimal detectable change (MDC), and associated confidence intervals values during the designed test battery.

To determine the effects of fatigue in ACLR participants, we used a repeated measures ANOVA to compare limb impact load magnitude and LSI values pre-fatigue and post-fatigue in the ACLR participants for each task and reported observed power. For impact load magnitude analyses, the within-subject's factors were the fatigue condition and limb. To compare the LSI values, we used a one-way ANOVA with the fatigue condition as a within-subject's factor.

Next, we used a mixed-model ANOVA to compare the impact load magnitude values between the ACLR group and the healthy participants. Our within subject's factor was limb and the between subject's factor was group (ACLR vs healthy). We used a one-way ANOVA to compare LSI values between groups.

CHAPTER 4:

RESULTS

Within-Day Reliability in Healthy Participants

A total of 10 participants were tested for this study. For the ACLR group, 5 participants were tested (3 females, 2 males). For the healthy group, 5 participants were tested (3 females, 2 males). Demographic information including age, height, weight, and sport is provided in Table 1.1. All participants met inclusion criteria and exclusion criteria as defined with the exception of one ACLR participant who was slightly outside of the 2.5-year window from the time of ACL reconstruction to testing (a5). This participant was included despite being 33 months out from ACL reconstruction. Information on each ACLR participant's demographics, injury, and involved limb is provided in Tables 1.2 and 1.3. Matching criteria to determine the involved limb of healthy participants when comparing between groups was determined on the basis of sport, gender, height and weight. Demographic information relating to healthy (control) participants is provided in Table 1.4.

To determine if the designed test battery demonstrated acceptable within-day reliability (ICC > .80) for measuring impact load in healthy collegiate athletes with no history of ACL reconstruction (ACLR), $ICC_{3,k}$ values were calculated for each task. The plyometrics battery demonstrated good within-day reliability for measuring average impact load with ICC values greater than 0.8 for both the dominant and non-dominant limbs. Session 1 and session 2 average impact load values for each participant's plyometrics task are provided for both the dominant, non-dominant limb in Figures 2.1

and 2.2. For the dominant limb, the ICC value was 0.947. For the non-dominant limb, the ICC value was 0.969. The calculated average impact load LSI values for each participant during the plyometrics task during session 1 and 2 are shown in Figure 2.3. The plyometrics battery demonstrated moderate within-day reliability for measuring average impact load LSI with an ICC value of 0.624.

Each participant's average impact load magnitude on the dominant limb from session 1 and session 2 during the unanticipated agility task is shown in Figure 3.1. The unanticipated agility task demonstrated poor within-day reliability for measuring average impact load for the dominant limb with an ICC value of 0.231. Good within-day reliability was demonstrated for average impact load of the non-dominant limb during the unanticipated agility task, with an ICC value of 0.824 (as seen in Figure 3.2). However, the calculated average impact load LSI values from sessions 1 and 2 of the unanticipated agility task demonstrated poor reliability with an ICC of 0.245 (Figure 3.3). SEM and MDC values were calculated for both the plyometrics and unanticipated agility tasks and are provided in Table 2.1.

Fatigue Effects in ACLR Participants

There were no significant changes in impact load magnitude post-fatigue compared to pre-fatigue in collegiate athletes who had returned to sport following ACL reconstruction (ACLR) for the plyometrics battery and unanticipated agility tasks. Figure 4.1 shows the average impact load magnitude of both the dominant and non-dominant limbs during the plyometrics task pre-fatigue and post-fatigue. The repeated measures ANOVA for the plyometrics battery pre-fatigue and post-fatigue revealed a nonsignificant main effect for fatigue ($F_{1,4}$=0.005, p=0.948), limb ($F_{1,4}$=0.090, p=0.779), and a nonsignificant fatigue x limb interaction ($F_{1,4}$=0.964, p=0.382). For the calculated plyometrics impact load LSI values, a one-way ANOVA (as seen in Figure 4.2) revealed that the main effect for fatigue was nonsignificant ($F_{1,4}$=0.777, p=0.428). Observed power for each task is provided in Tables 3.1-3.3.

Figure 5.1 shows the average impact load magnitude of both the dominant and non-dominant limbs during the unanticipated agility task pre-fatigue and post-fatigue. The repeated measures ANOVA for the unanticipated agility task revealed a nonsignificant main effect for fatigue ($F_{1,4}$=2.440, p=0.193), limb ($F_{1,4}$=5.359, p=0.082), and fatigue x limb interaction ($F_{1,4}$=0.186, p=0.063). For the calculated unanticipated agility impact load LSI values (Figure 5.2), the main effect for fatigue was nonsignificant ($F_{1,4}$=0.142, p=0.725).

Completion times for the anticipated agility task (fatigue protocol) are provided in Table 4.1 including the ACLR group participants' initial trial completion times, the total number of trials completed, the average time of each participant's first three trials and last three trials, and the average RPE (rating of perceived exertion) for the first three trials and last three trials. As seen in Table 4.2, the ACLR participants decreased in performance (as indicated by higher average completion times) from the first 3 trials to the last 3 trials. Similarly, the ACLR participants reported a higher RPE during the last 3 trials compared to the first three trials. Each ACLR participant's completion times pre- and post-fatigue were compared using dependent samples T-Tests. The designed fatigue protocol showed a significant decrease in completion time (t_4=-4.067, p=0.015) demonstrating that the protocol was successful in eliciting objective fatigue. The mean values and standard deviations are provided in Table 4.2. For the RPE values, the designed fatigue protocol showed a significant increase in RPE values (t_4=-4.333, p=0.012), demonstrating that the designed protocol was successful in eliciting subjective fatigue. The mean values and standard deviations are provided in Table 4.2.

The healthy participants each completed one trial of the anticipated agility task (fatigue protocol). The trial completion times of the healthy (controls) are provided in

Table 4.3. Figures 6.1-6.5 demonstrate each ACLR participant's average impact load for both the involved and uninvolved limbs during the initial 3 trials, compared to the participant's last 3 trials. The repeated measures ANOVA for the anticipated agility task (fatigue protocol) revealed a significant main effect for fatigue ($F_{1,4}$=14.571, p=0.019). However, both the main effect for limb ($F_{1,4}$=0.014, p=0.912), and the fatigue x limb interaction ($F_{1,4}$=0.001, p=0.979) were nonsignificant for the anticipated agility task (fatigue protocol).

Comparisons Between ACLR and Healthy Participants

When comparing average impact load in the pre-fatigue condition between the ACLR group and those with no history of ACL injury (healthy participants), a repeated measures ANOVA revealed that only the unanticipated agility task demonstrated a significant main effect for group ($F_{1,8}$=7.822, p=0.023). During the unanticipated agility task, the healthy (control) participants displayed a higher average impact load than the ACLR participants for both the involved and uninvolved limbs. Specific mean values and standard deviations are provided in Table 5.1. Findings were nonsignificant for the main effect for limb ($F_{1,8}$=0.144, p=0.714) and group x limb interaction ($F_{1,8}$=0.958, p=0.356). Additionally, the calculated impact load LSI values for the unanticipated agility task showed a nonsignificant main effect for group ($F_{1,8}$=1.258, p=0.294).

For the plyometrics battery, the main effect for limb was nonsignificant ($F_{1,8}$=1.274, p=0.292), as well as the main effect for group ($F_{1,8}$=2.705, p=0.139), and group x limb interaction ($F_{1,8}$=0.070, p=0.798). The one-way ANOVA of the calculated impact load LSI values for the plyometrics battery showed a nonsignificant main effect for group ($F_{1,8}$=0.170, p=0.691). These values are provided in Table 5.2.

Each participant included in the study completed at least one trial of the anticipated agility task. The initial trial of each ACLR participant was compared to the trial completed by each healthy participant. A repeated measures ANOVA for the anticipated agility (fatigue protocol) revealed no significant findings for the main effect for limb ($F_{1,8}$=0.238, p=0.639), no significant main effect for group ($F_{1,8}$=0.179, p=0.684), and no significant group x limb interaction ($F_{1,8}$=0.049, p=0.830). The calculated impact load LSI values for the initial trial of the anticipated agility task (fatigue protocol) showed a nonsignificant main effect for group ($F_{1,8}$=0.320, p=0.587). Figures 7.1 and 7.2 show the average impact load for each group, task, and limb in the pre-fatigue condition. Figure 7.3 compares the calculated impact load LSI values between groups and by task.

CHAPTER 5:

DISCUSSION

The purpose of this study was to determine if there are differences in load symmetry between collegiate athletes with a history of ACL reconstruction and healthy collegiate athletes with no history of ACL injury during sport-specific tasks. Another aim of the study was to investigate the effects of fatigue on impact load symmetry in athletes with a history of ACLR. Additionally, we analyzed whether the designed test battery demonstrated within-day reliability for assessing impact load symmetry in healthy (control) participants. Using the results of this study, we can draw several conclusions.

First, the designed test battery was reliable for measuring impact load symmetry in collegiate athletes for the plyometrics task in both limbs with ICC values greater than 0.8. Although the unanticipated agility task showed a lower ICC value of 0.247 for the dominant limb, one participant's high average impact load (33.13 g's) in session 1 could be an outlier potentially skewing the data. When analyzing the raw data of participant c5 during this task, it was unclear whether the high average impact load displayed during session 1 was attributed to error during testing or if this participant truly overloaded the dominant limb much greater than other participants. Because participant c5 was at an average impact load more similar to other participants in session 2 (23.26 g's), it is likely that the session 1 value was attributed to error. The unanticipated agility task demonstrated good reliability for the non-dominant limb during the unanticipated agility tasks with an ICC value of 0.824. However, the calculated LSI values for each task were not as reliable, likely due to the lack of participants and fluctuation of the LSI scores. Overall, our hypothesis that the designed test battery would demonstrate good reliability for measuring average impact load in healthy participants with no history of ACLR is supported for the plyometrics task. Additional research should focus on analyzing the within-day reliability of the unanticipated agility task.

Although there is no previous research on the reliability of using wearable inertial measurements units (IMUs) to measure average impact load symmetry during our specifically designed test battery, the results of our within-day reliability analysis indicate that wearable IMU sensors are highly reliable for the specific plyometrics tasks we designed. These findings are similar to findings in previous studies that have shown the reliability of IMUs outside the laboratory setting during planting/cutting, change of direction, and acceleration/deceleration tasks. In a reliability study by Burland and colleagues using the same Vicon Blue Trident IMU sensors used our study, on-field cumulative impact load during soccer-specific planting/cutting maneuvers demonstrated good to excellent reliability across three testing sessions with ICC values between 0.75 and 0.89.[87] Burland's study also found good to excellent reliability for change of direction, and acceleration/deceleration tasks.[87] The reliability analysis provided in our study aligns with previous research on the reliability of IMU sensors, and could be beneficial for clinicians searching for a reliable, feasible, and convenient option for analyzing on-field load symmetry during sport-specific tasks within the athletic population.

When looking for significant changes in impact load post-fatigue compared to pre-fatigue in collegiate athletes who had returned to sport following ACL reconstruction, the repeated-measures ANOVA for the anticipated agility task (fatigue protocol) found a significant main effect for fatigue ($F_{1,4}$=14.571, p=0.019). This finding indicates that ACLR participants displayed a significant difference in average impact load post-fatigue (in the last 3 trials) compared to pre-fatigue (first 3 trials) during the anticipated agility task. This is likely due to the decrease in performance as indicated in the slower trial completion times between the first 3 trials and last 3 trials (demonstrated in Table 4.2). During the last 3 trials of the fatigue protocol, the ACLR participants were both objectively fatigued (as indicated by slower trial completion times) and subjectively fatigued (reporting a higher average RPE) during the last 3 trials of the protocol. The significant main effect of fatigue is similar to previous research studies demonstrating that decreases in speed lead to decreases in impact load.[88] Although this pattern of both limbs loading less following fatigue may be a product of fatigue, it also may mean that these athletes are less likely to experience high impacts with the ground associated with injurious moments. Since there was not a significant main effect for limb or a fatigue x limb interaction, the limbs did not load differently as they fatigued, both limbs simply decreased the magnitude of impact. This important finding demonstrates that the previously injured limb displayed a pattern similar to the uninjured limb instead of behaving differently as hypothesized.

When comparing the impact load symmetry of ACLR participants and healthy participants in the pre-fatigue condition, the unanticipated agility task was the only task that displayed a main effect for group. During the unanticipated agility task, the healthy (control) participants displayed higher average impact load for both the involved and uninvolved limbs in the pre-fatigue condition than healthy participants. This finding may be clinically meaningful, as this shows that athletes with a history of ACL reconstruction may not be exerting as much force as healthy participants during cutting and pivoting tasks when the next movement is unknown. Less impact load could mean that ACLR participants were less explosive in movements, lacked the confidence to load when the next movement was unknown, etc. Although there may be several explanations for this pattern, exerting less force during unanticipated agility tasks could contribute to injury, as many mechanisms of ACLR injury occur as a result of non-contact, cutting/pivoting movements. This should be considered by clinicians when returning athletes to sport following ACL reconstruction, as it is important to incorporate unanticipated agility tasks that require cutting and pivoting. Future research may benefit from gathering baseline impact load symmetry data prior to injury to determine if the lower average impact load displayed by ACLR participants in this study was due to lack of power, or if ACLR athletes display lower average impact load during anticipated agility tasks due to their previous history of injury.

Limitations

The main limitation of this study was due to lack of power due to difficulty recruiting participants that met inclusion/criteria. Based on the calculated effect sizes, Tables 6.1-6.3 show the estimated sample sizes that would be required to achieve a statistical power of .80 or greater for each task and for each limb. Results of the study were likely influenced due to being underpowered. As many athletes did not have a true off-season due to the COVID-19 pandemic, some athletes were included despite having to undergo testing while in-season for their specific sport and could have displayed bias in performance due to their higher volume of activity, higher associated fitness levels, and lack of recovery.

Another limitation lies within the demographics of the ACLR participant pool. Athletes varied in the amount of time between ACL reconstruction and testing. As previous research indicates, athletes are more likely to sustain secondary injury within 24 months after ACL reconstruction. Some participants included in the ACLR group had exceeded the 24-month window, while some athletes were well under. Similarly, not all ACLR participants had the same access to rehabilitation following reconstruction, not all athletes had the same graft type, and not all athletes tore the ACL of the dominant limb versus non-dominant limb. Though matching criteria was determined on the basis of sport, gender, position, and limb dominance, the matches between ACLR participants and athletes were not perfect matches.

Although efforts were made to enhance external validity, the designed test battery (including a fatigue protocol requiring aspects of sport-specific movements including unanticipated changes of directions on a single foot), may not be completely applicable to the on-field situations or injurious movements required of each participant's competitions and training sessions. Instead, the results point to areas where differences in impact load symmetry may be associated with situations that may place an athlete a higher risk for injury.

Future Research Directions

There are a variety of areas that warrant future research when analyzing impact load symmetry. While our study assessed the within-day reliability of measuring impact load during the designed test battery in both ACLR and healthy athletes, future research would benefit from analyzing reliability with more time between sessions (several days or weeks). Additional research addressing the reliability of using wearable IMU sensors to assess impact load symmetry should also focus on increasing statistical power by including a higher number of participants in each group based on the estimated sample sizes provided in Tables 6.1-6.3.

While our results showed statistical significance for the main effect of fatigue in ACLR participants during the first 3 and last 3 trials of the anticipated agility task (fatigue protocol), further research should address the impact load of healthy participants following the designed fatigue protocol to determine whether the lower average impact loads seen following fatigue could be due to a history of ACL injury.

Similarly, clinicians could benefit from research that tests an athlete's impact load prior to injury as a "baseline" for comparison following ACL reconstruction and rehabilitation in order to use impact load as a tool for RTS decision-making. This would allow clinicians to compare load symmetry in ACLR athletes on an individual basis rather than generalizing findings based on group analysis.

Conclusions

This study examined differences in load symmetry between collegiate athletes with a history of ACL reconstruction and healthy collegiate athletes without ACL injuries during sport-specific tasks, the effects of fatigue on load symmetry within ACLR participants and assessed the within-day reliability of measuring on-field average impact load through inertial measurement units. The results demonstrate that wearable IMU sensors have good reliability for measuring the on-field average impact load of heathy athletes with no history of ACL reconstruction during the designed plyometrics battery. ACLR participants demonstrated a statistically significant main effect for fatigue on average impact load during the first 3 trials of the anticipated agility task (fatigue protocol) compared to the last 3. This finding aligns with previous research indicating that decreases in speed lead to decreases in impact load. Lastly, the unanticipated agility task demonstrated a significant main effect for group when comparing the average impact load of the ACLR group and healthy participants in the pre-fatigue condition. This suggests that measuring average impact load during unanticipated agility tasks may be important for clinicians to consider when making a return to sport decision. As displayed in the ACLR participants tested in our study, significantly lower average impact loads compared to athletes with no history of ACL injury during unanticipated movements may mean that ACLR athletes are less likely to experience high impacts with the ground associated with injurious moments. Although ACL re-injuries remain a major health problem affecting collegiate athletes, our study provides useful evidence that measuring on-field impact load symmetry is highly reliable and may be an important step in safely returning an athlete to sport following ACL injury. This study provides useful information on impact load symmetry that could be helpful in injury prevention strategies to reduce the high rates of ACL re-injury, and the long-term sequelae, in the physically active population.

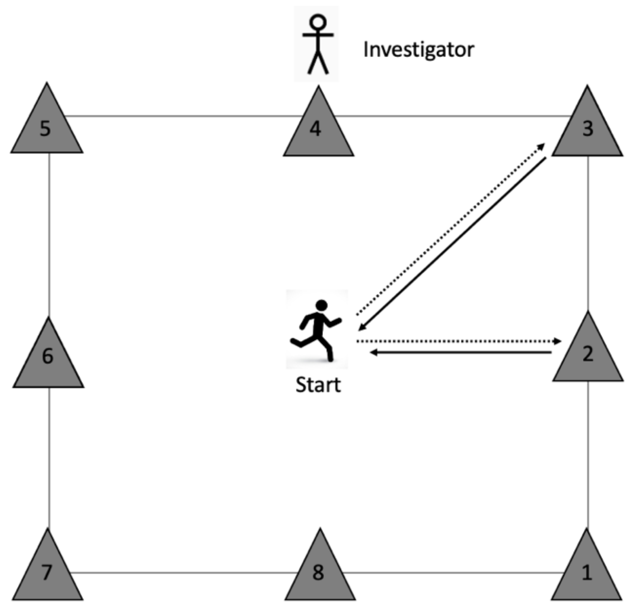

Figure 1.1. *Cone set-up for the unanticipated agility task and anticipated agility task (fatigue protocol)*

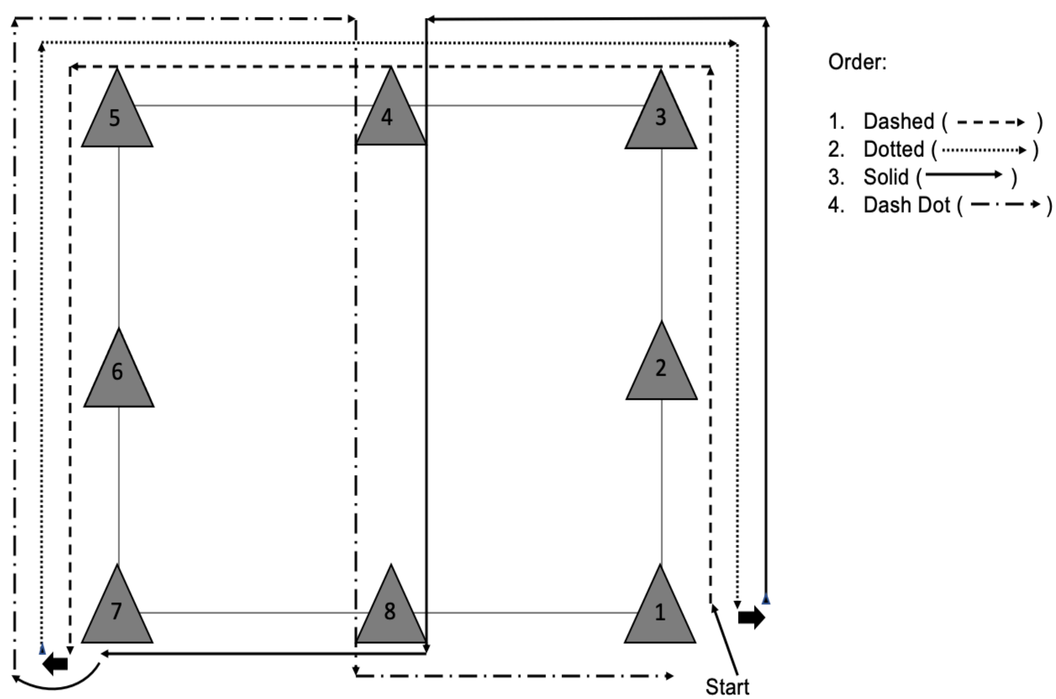

Figure 1.2. *Anticipated agility task (fatigue protocol) order.. Athletes will begin by following the dashed line (beside cone 1) and follow the lines in the appropriate order (1, 2, 3, 4)*

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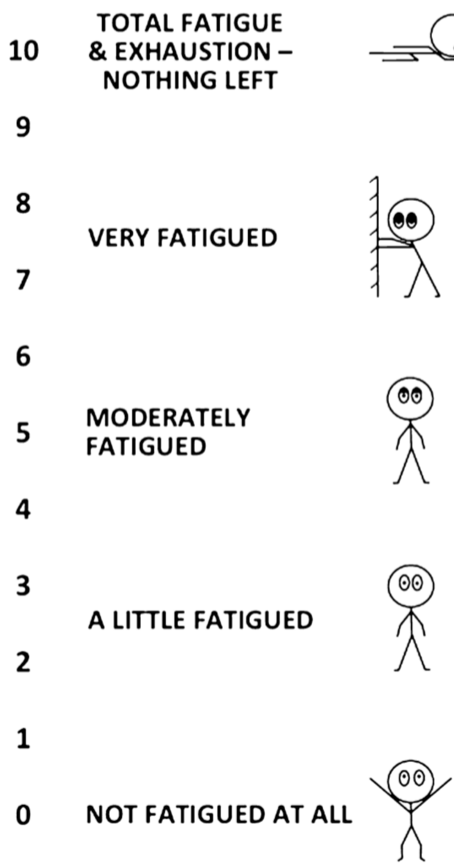

Figure 1.3. *Rating of Perceived Exertion (RPE) scale derived from Micklewright et al.*

	Healthy	ACLR
Age	18.80	19.60
Height (cm)	174.24	173.37
Mass (kg)	72.12	73.0
Gender	-	-
Male	2	2
Female	3	3
Sport	-	-
Women's Lacrosse	1	2
Men's Lacrosse	2	2
Women's Field Hockey	2	1

Table 1.1. *Participant Demographics*

	Age	Height (cm)	Weight (kg)	Gender	Limb Dominance
a1	21	190.50	99.79	Male	Right
a2	20	175.96	77.11	Male	Right
a3	18	165.10	62.14	Female	Right
a4	20	177.80	70.76	Female	Right
a5	19	157.48	55.34	Female	Right

Table 1.2 *ACLR Participant Demographics*

	Graft Type	Time to RTS	Time from Reconstruction to Testing	MOI	Involved Limb
a1	Patellar tendon	12 months	24 months	Non-Contact	Left
a2	Patellar tendon	8 months	15 months	Non-Contact	Right
a3	Patellar tendon	9 months	19 months	Non-Contact	Left
a4	Quadriceps tendon	11 months	18 months	Contact	Right
a5	Patellar tendon	9 months	33 months	Non-Contact	Right

Table 1.3 *ACLR Participant Injury Information*
RTS- Return to Sport
MOI- Mechanism of Injury

	Age	Height (cm)	Weight (kg)	Gender	Limb Dominance
c1	18	195.58	90.72	Male	Left
c2	18	162.56	60.78	Female	Right
c3	19	162.56	58.06	Female	Right
c4	19	167.64	64.86	Female	Right
c5	20	182.88	86.18	Male	Right

Table 1.4. *Healthy (control) Participant Information*

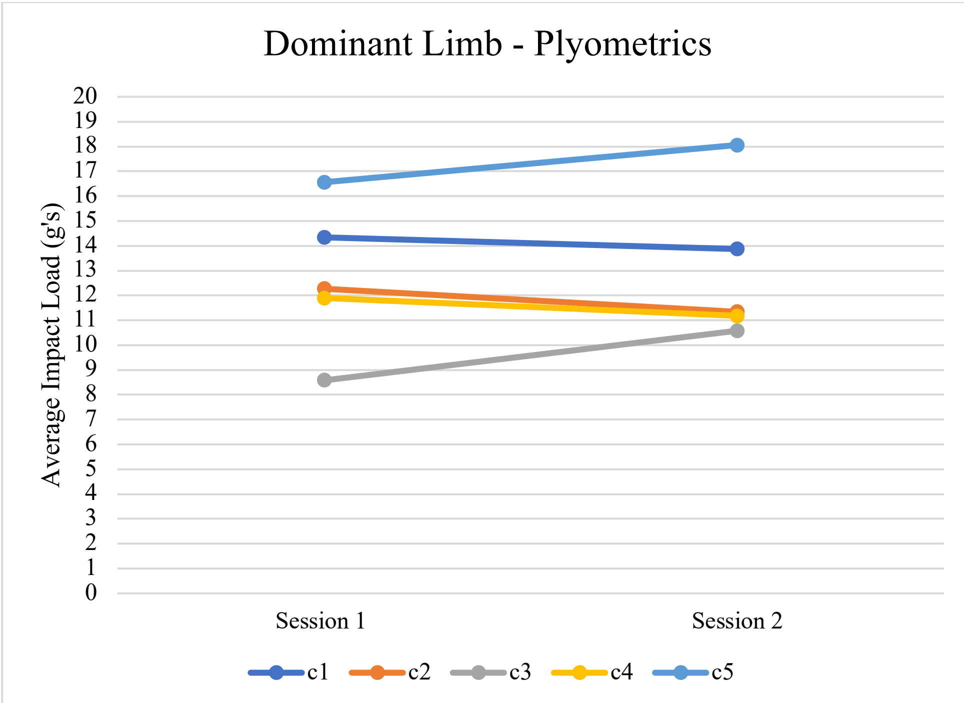

Figure 2.1. *Healthy participants' average impact loads of the dominant limb during the plyometrics task demonstrated good within-day reliability.* $ICC_{3,k} = 0.947$*.

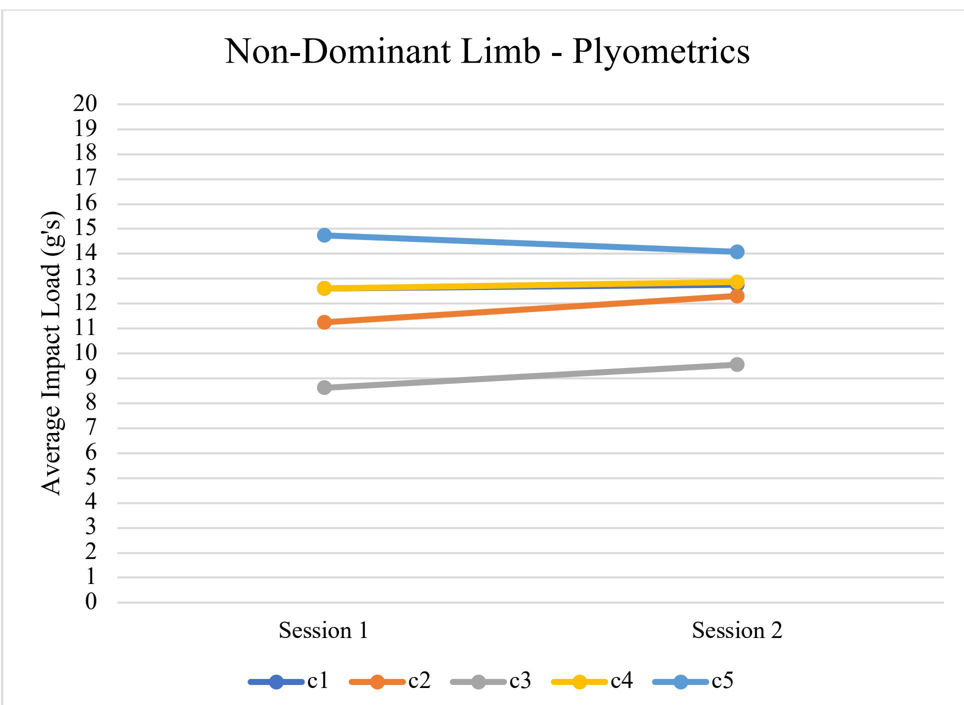

Figure 2.2. *Healthy participants' average impact loads of the non-dominant limb during the plyometrics task demonstrated good within-day reliability.* $ICC_{3,k} = 0.969$*.

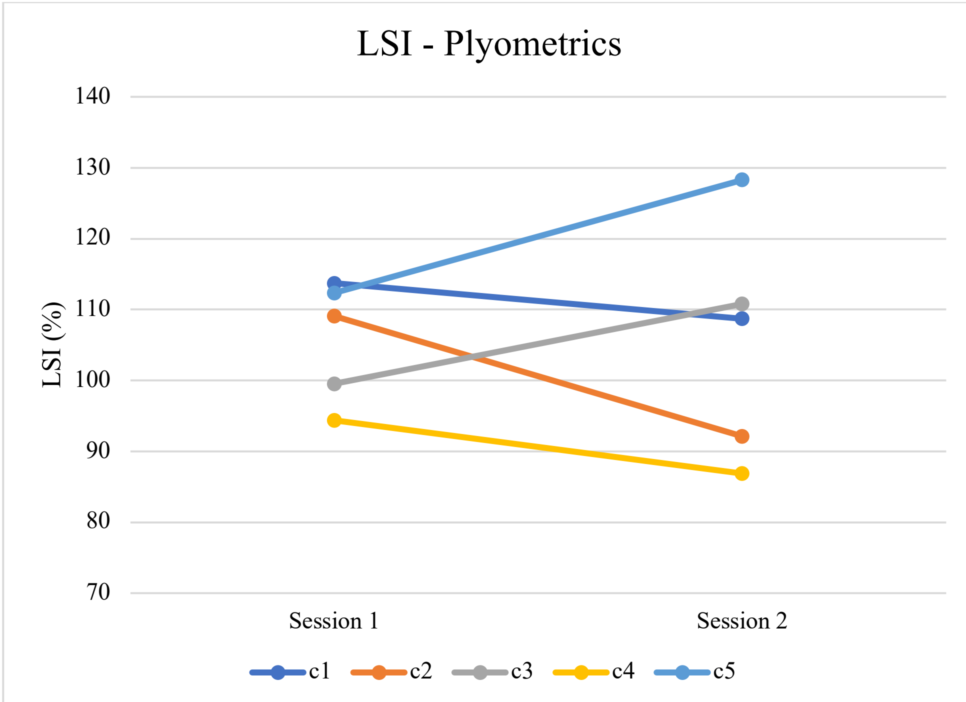

Figure 2.3. *The calculated LSI values for healthy participants during the plyometrics task demonstrated moderate within-day reliability.* $ICC_{3,k}$*= 0.624.*

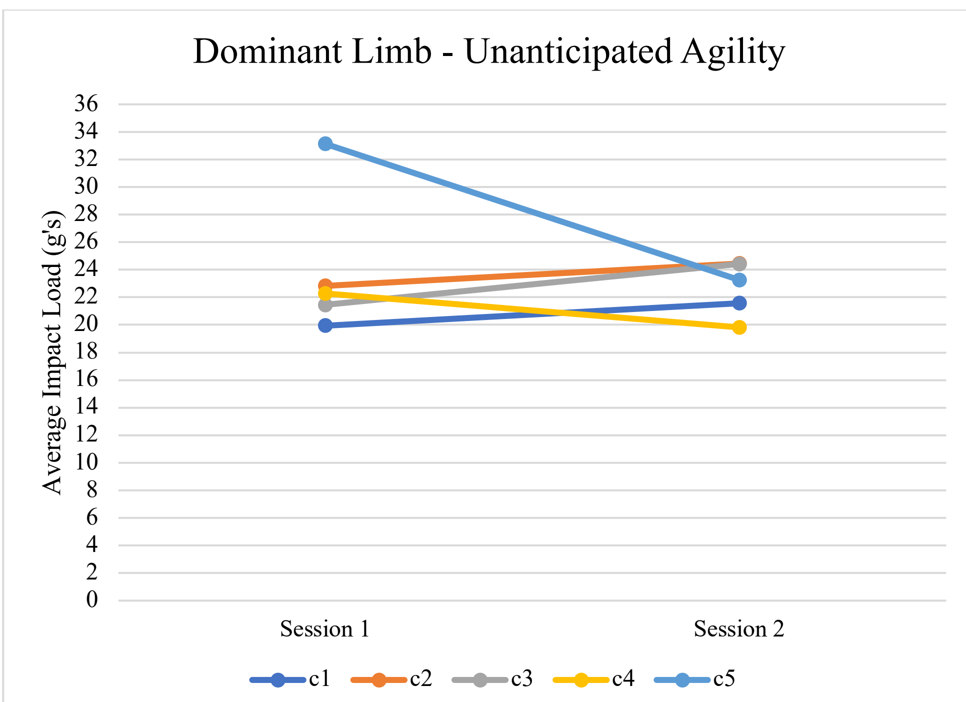

Figure 3.1. *The unanticipated agility task demonstrated poor within-day reliability for measuring average impact load in the dominant limb.* $ICC_{3,k}$*= 0.231.*

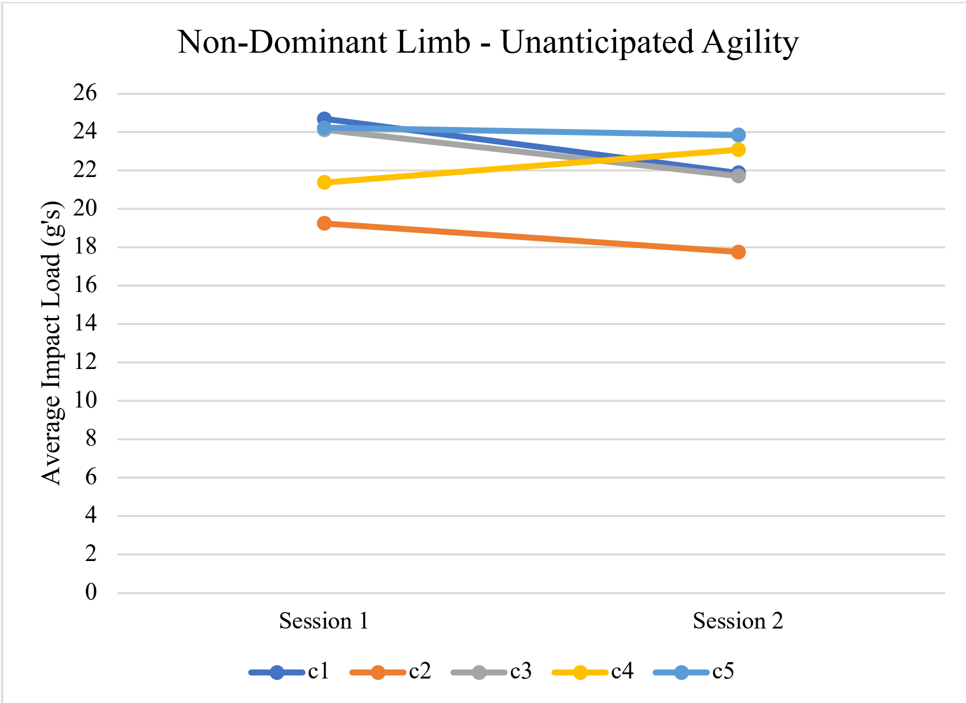

Figure 3.2. *The unanticipated agility task demonstrated good within-day reliability for measuring average impact load in the non-dominant limb.* $ICC_{3,k}$*= 0.824**.

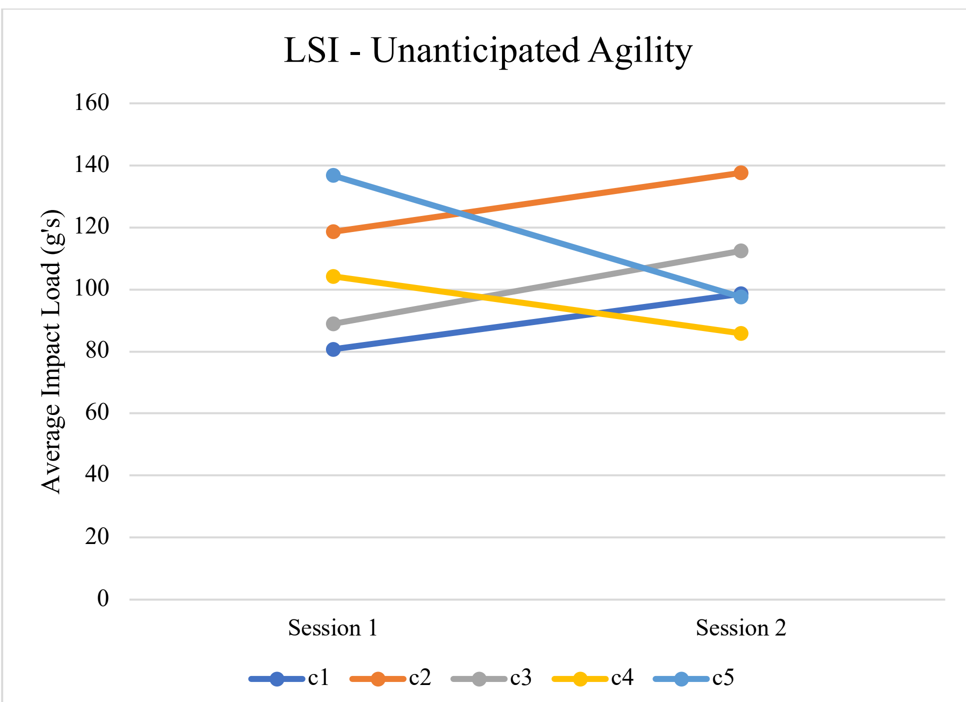

Figure 3.3. *The calculated LSI values for healthy participants during the unanticipated agility task demonstrated poor within-day reliability.* $ICC_{3,k}$*= 0.245.*

Variable	$ICC_{(3,k)}$	Standard Error of Measurement (SEM)	Minimal Detectable Change (MDC)
Plyometrics:	-	-	-
Dominant Limb	0.947*	0.712	1.972
Non-Dominant Limb	0.969*	0.396	1.097
LSI	0.624	10.088	27.944
Unanticipated Agility:	-	-	-
Dominant Limb	0.231	4.611	12.773
Non-dominant Limb	0.824*	0.985	2.728
LSI	0.245	19.587	54.256

Table 2.1. *Within-day reliability of measuring average impact load in healthy participants by task and limb.*

Plyometrics	
	Observed Power
Limb	0.056
Fatigue	0.050
Fatigue * Limb	0.120
LSI	
Fatigue	0.106

Table 3.1. *Plyometrics task observed power.*

Unanticipated Agility Task	
	Observed Power
Limb	0.424
Fatigue	0.227
Fatigue * Limb	0.063
LSI	
Fatigue	0.060

Table 3.2. *Unanticipated agility task observed power.*

Anticipated Agility Task	
	Observed Power
Limb	0.051
Fatigue	0.811
Fatigue * Limb	0.050
LSI	
Fatigue	0.055

Table 3.3. *Anticipated agility task observed power.*

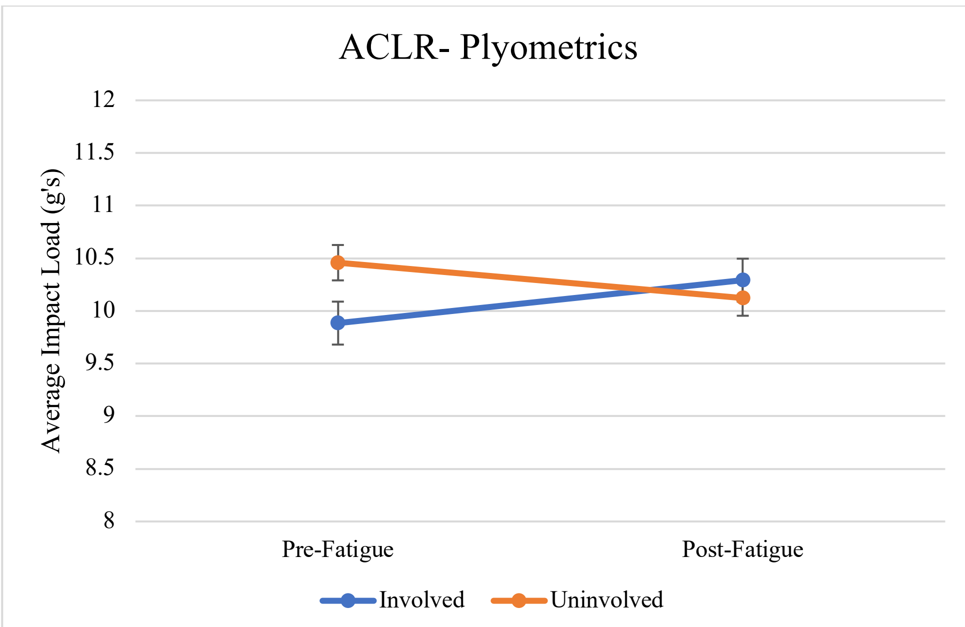

Figure 4.1 *represents the average impact load during the plyometrics task pre-fatigue and post-fatigue in ACLR group's involved vs uninvolved limbs. Error bars represent standard error.*
Main effect for fatigue: $F_{1,4}=0.005$, $p=0.948$
Main effect for limb: $F_{1,4}=0.090$, $p=0.779$
Fatigue x limb interaction: $F_{1,4}=0.964$, $p=0.382$

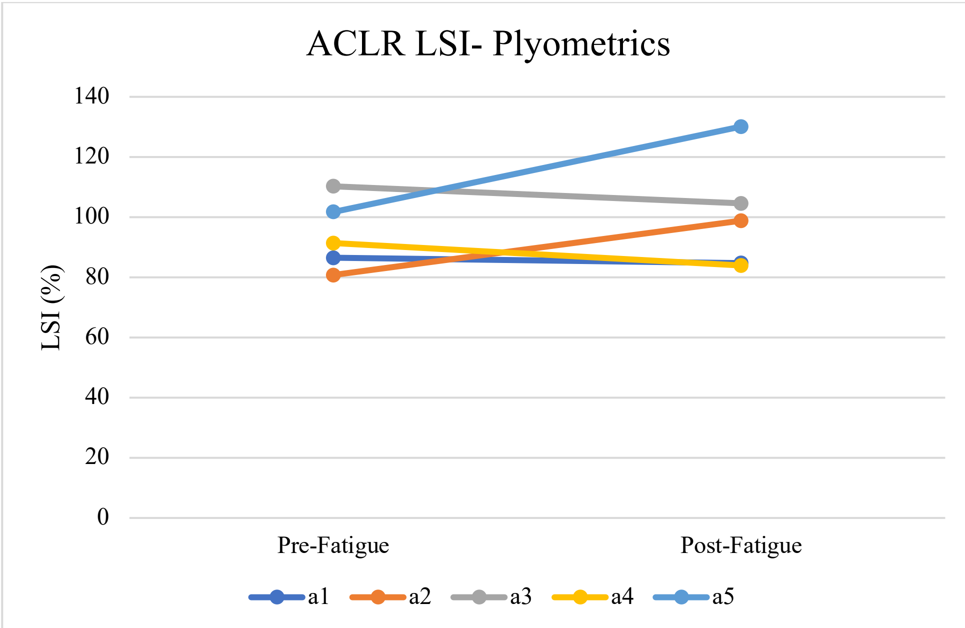

Figure 4.2 *represents the calculated LSI values for the plyometrics group pre-fatigue and post-fatigue for each ACLR participant.*
Main effect for fatigue: $F_{1,4}=0.777$, $p=0.428$

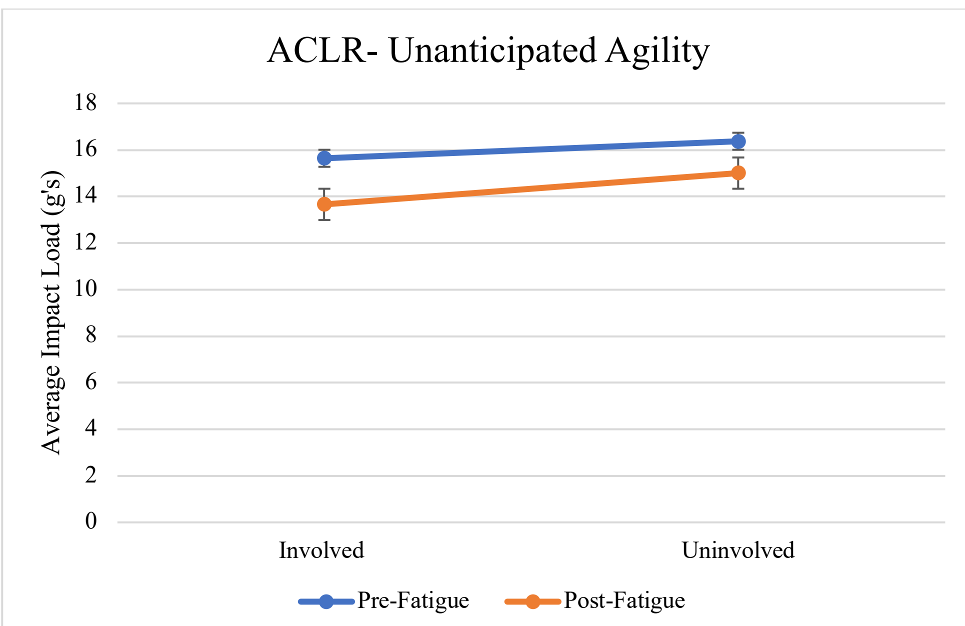

Figure 5.1 *represents the average impact load during the unanticipated agility tasks pre-fatigue and post-fatigue in ACLR group's involved vs uninvolved limbs. Error bars represent standard error.*
Main effect for fatigue: $F_{1,4}=2.440$, $p=0.193$
Main effect for limb: $F_{1,4}=5.359$, $p=0.082$
Fatigue x limb interaction: $F_{1,4}=0.186$, $p=0.063$

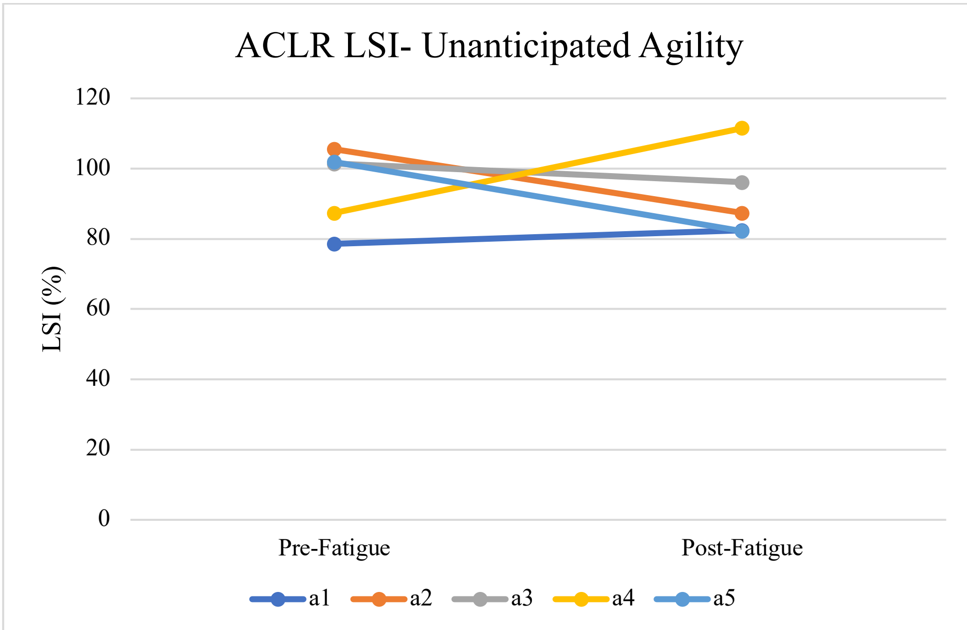

Figure 5.2 *represents each ACLR participant's average impact load LSI values during the unanticipated agility task pre-fatigue and post-fatigue.*
Main effect for fatigue: $F_{1,4}=0.142$, $p=0.725$

Anticipated Agility Task (Fatigue Protocol)	a1	a2	a3	a4	a5
Initial completion time (seconds)	33.3	32.2	32.2	33.1	36.1
Number of trials completed	10	26	14	10	6
Average Completion Time: First 3 Trials	35.5	34.1	33.8	35.4	39.1
Average Completion Time: Last 3 Trials	37.5	35.8	38.9	41.2	46.2
RPE average: First 3 Trials	6	7	5	8	6
RPE average: Last 3 Trials	8	9	9	9	10

Table 4.1. *Anticipated agility task (fatigue protocol) trial times for ACLR participants.*

Anticipated Agility Task (Fatigue Protocol)	Mean Value	Standard Deviation
Mean Completion Time: First 3 Trials	35.58	2.109
Mean Completion Time: Last 3 Trials	39.92	4.030
Mean RPE: First 3 Trials	6.40	1.140
Mean RPE: Last 3 Trials	9.00	0.707

Table 4.2. *Anticipated agility task mean completion times and RPE's for the ACLR participant's first 3 trials compared to the last 3 trials.*

Anticipated Agility Task (Fatigue Protocol)	Trial completion time (seconds)
c1	35.5
c2	32.0
c3	35.0
c4	32.4
c5	35.8

Table 4.3. *Anticipated agility task (fatigue protocol) trial times for healthy (control) participants.*

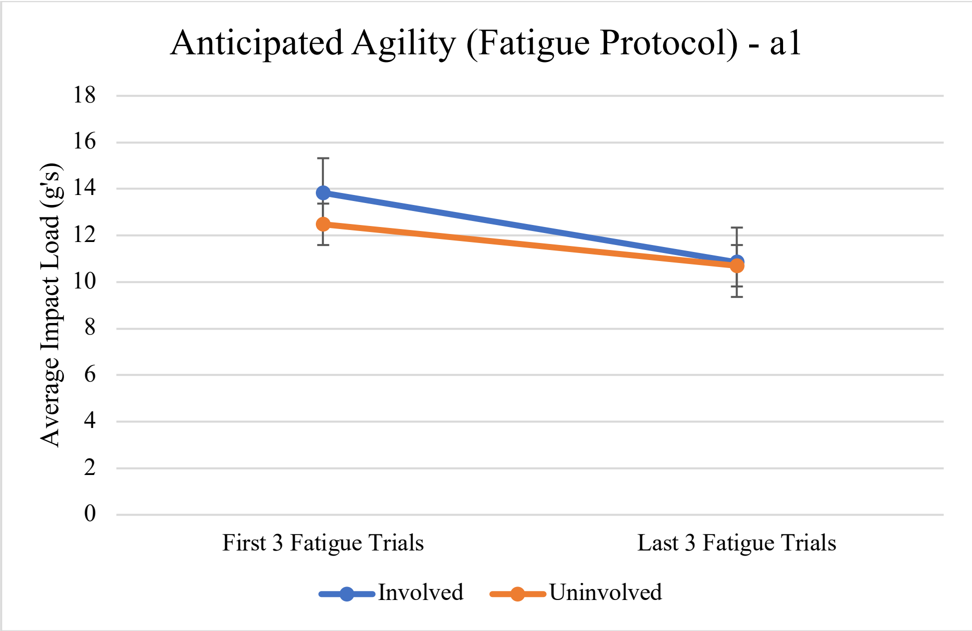

Figure 6.1 *shows ACLR participant a1's average impact load for the involved and uninvolved limb during the first 3 and last 3 trials of anticipated agility (fatigue protocol). Error bars represent standard error.*

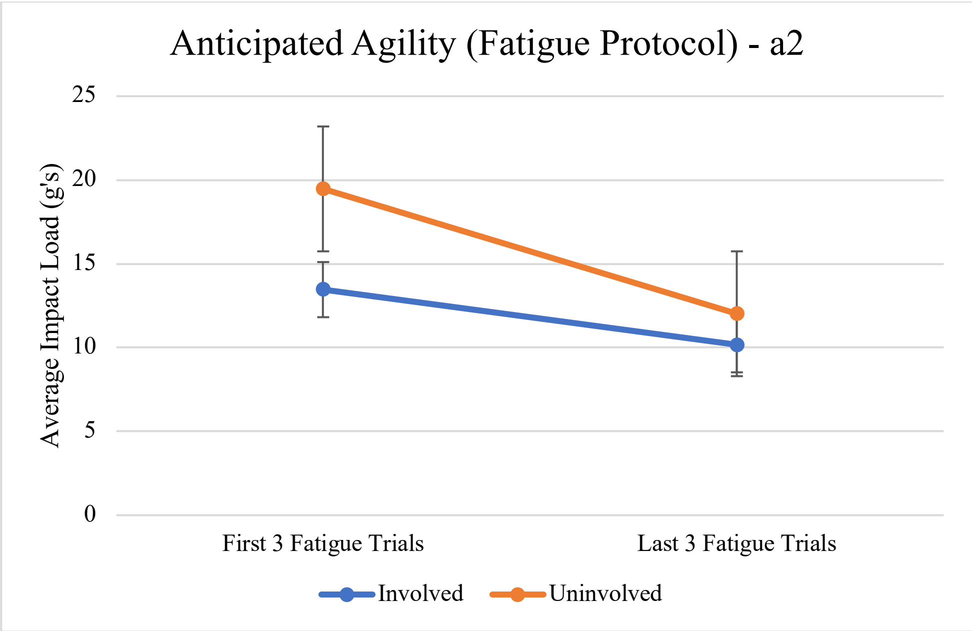

Figure 6.2 *shows ACLR participant a2's average impact load for the involved and uninvolved limb during the first 3 and last 3 trials of the anticipated agility (fatigue protocol). Error bars represent standard error.*

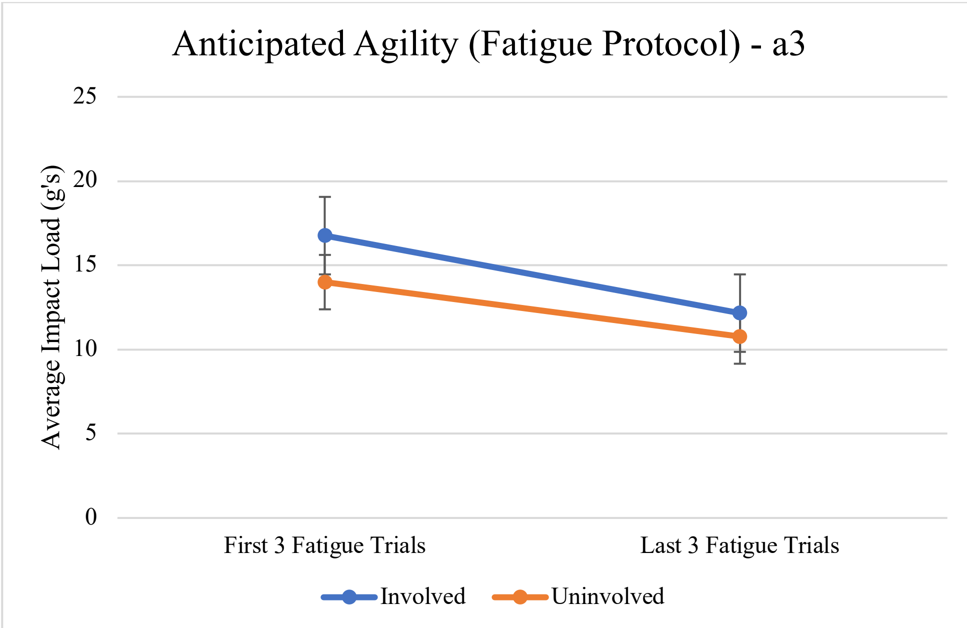

Figure 6.3 *shows ACLR participant a3's average impact load for the involved and uninvolved limb during the first 3 and last 3 trials of the anticipated agility (fatigue protocol). Error bars represent standard error.*

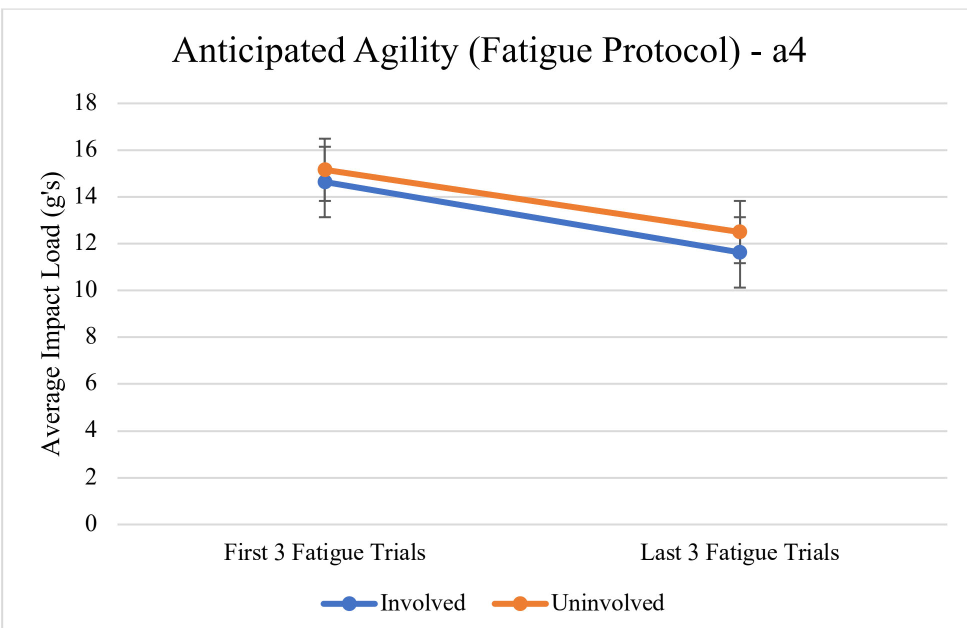

Figure 6.4 *shows ACLR participant a4's average impact load for the involved and uninvolved limb during the first 3 and last 3 trials of the anticipated agility (fatigue protocol)). Error bars represent standard error.*

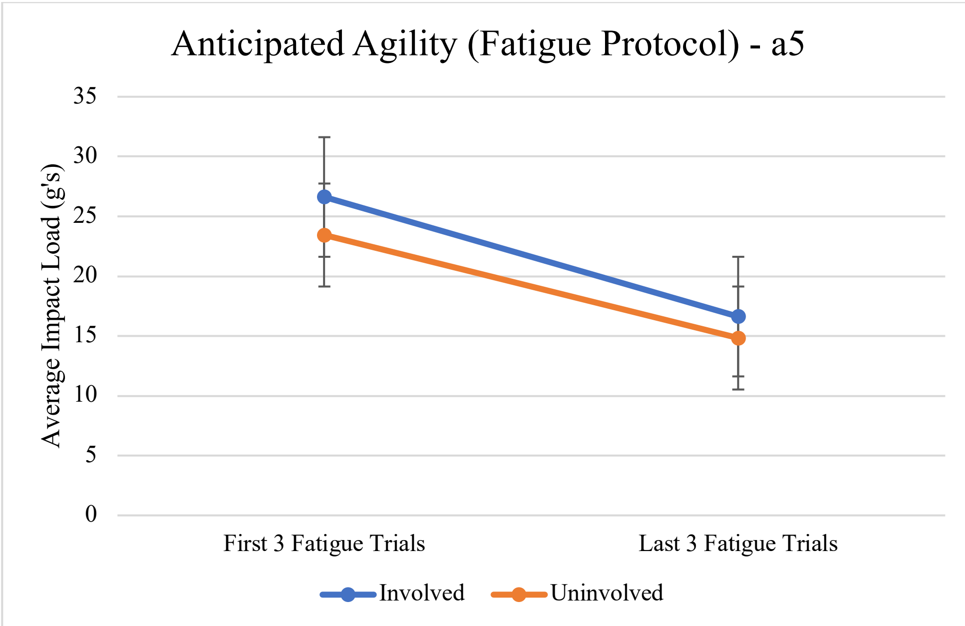

Figure 6.5 *shows ACLR participant a5's average impact load for the involved and uninvolved limb during the first 3 and last 3 trials of the anticipated agility (fatigue protocol). Error bars represent standard error.*
Together, figures 6.1-6.5 represent each ACLR participant's average impact load during the anticipated agility (fatigue protocol).
Main effect for fatigue: $F_{1,4}=14.571$, $p=0.019$*
Main effect for limb: $F_{1,4}=0.014$, $p=0.912$
Fatigue x limb interaction: $F_{1,4}=0.001$, $p=0.979$

	Involved Limb		Uninvolved Limb	
	Mean	Standard Deviation	Mean	Standard Deviation
ACLR Participants	15.640	5.259	16.372	4.859
Healthy Controls	24.164	5.378	22.504	1.844

Table 5.1. *Specific means and standard deviations of ACLR and Healthy Participants during the unanticipated agility task in the pre-fatigue condition*

	Plyometrics	Unanticipated Agility	Anticipated Agility
Main Effect for Limb	$F_{1,8}=1.274$, $p=0.292$	$F_{1,8}=0.144$, $p=0.714$	$F_{1,8}=0.238$, $p=0.639$
Main Effect for Group	$F_{1,8}=2.705$, $p=0.139$	$F_{1,8}=7.822$, $p=0.023$*	$F_{1,8}=0.179$, $p=0.684$
Group x Limb interaction	$F_{1,8}=0.070$, $p=0.798$	$F_{1,8}=0.958$, $p=0.356$	$F_{1,8}=0.049$, $p=0.830$
LSI			
Main Effect for Group	$F_{1,8}=0.170$, $p=0.691$	$F_{1,8}=1.258$, $p=0.294$	$F_{1,8}=0.320$, $p=0.587$

Table 5.2. *Comparison of ACLR group to healthy control group in the pre-fatigue condition by task.*

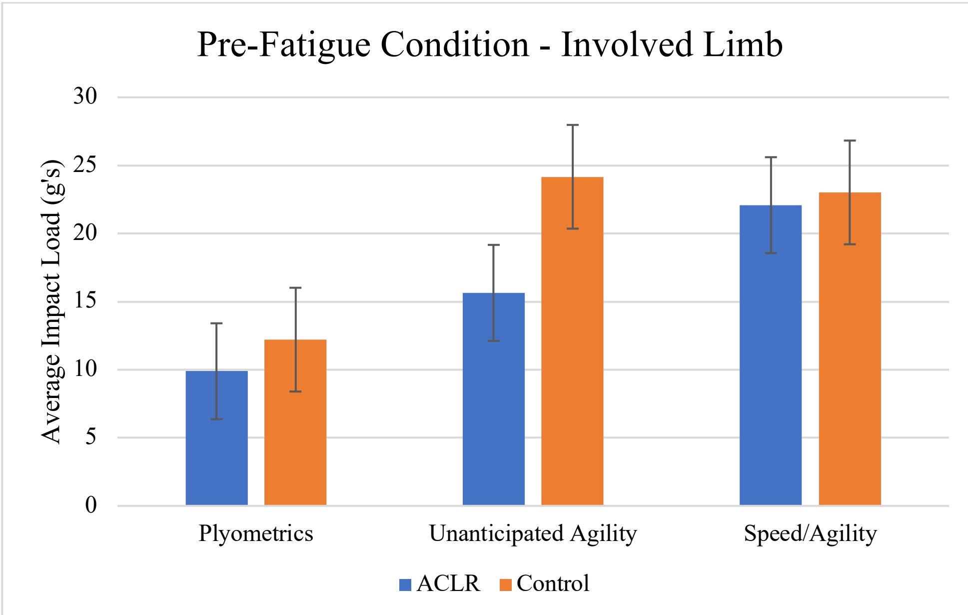

Figure 7.1 *represents the average impact load of the involved limb in the pre-fatigue condition in the ACLR group compared to the healthy (control) group between each task. Error bars represent standard error.*

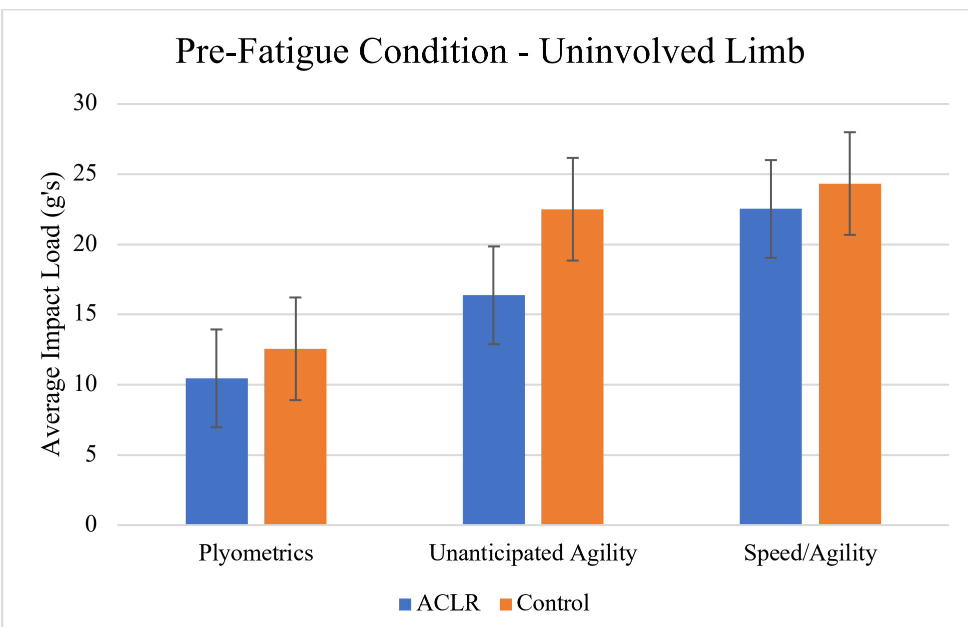

Figure 7.2 *represents the average impact load of the uninvolved limb in the pre-fatigue condition in the ACLR group compared to the healthy (control) group between each task. Error bars represent standard error.*

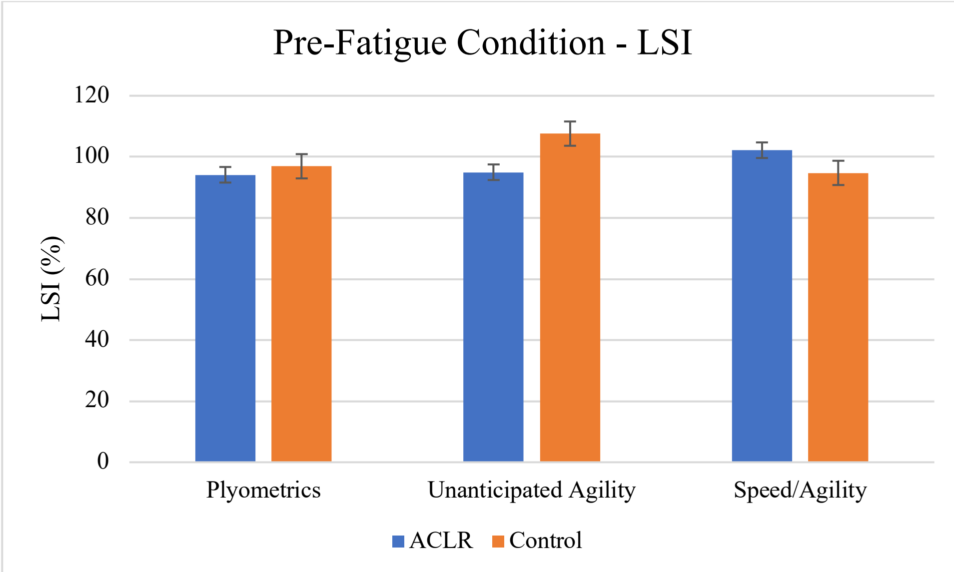

Figure 7.3 *represents the calculated impact load LSI values in the pre-fatigue condition in the ACLR group compared to the healthy (control) group between each task. Error bars represent standard error.*

ACLR Participants	Plyometrics		
	Involved	Uninvolved	LSI
Observed Effect Size	0.168948	0.235668	0.400906
Estimated Sample Size	277	144	51

Table 6.1 *demonstrates that based on the observed effect sizes for the plyometric task, the required sample size would range from 51-277 to achieve a statistical power of 0.8 or greater.*

ACLR Participants	Unanticipated Agility		
	Involved	Uninvolved	LSI
Observed Effect Size	0.459563	0.314591	0.254701
Estimated Sample Size	41	82	123

Table 6.2 *shows that based on the observed effect sizes for this task, the required sample size would range from 41-123 to achieve a statistical power of 0.8 or greater.*

ACLR Participants	Anticipated Agility (First 3/Last 3 Trials)		
	Involved	Uninvolved	LSI
Observed Effect Size	1.116059	1.401977	0.069133
Estimated Sample Size	10	7	1604

Table 6.3 *demonstrates that based on the observed effect sizes for this task, the required sample size would range from 7-1604 to achieve a statistical power of 0.8 or greater.*

REFERENCES

1. Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: Risk factors and prevention strategies. *J Am Acad Orthop Surg*. 2000;8(3):141-150.

2. Marshall SW, Padua DA, McGrath ML. Incidence of cruciate ligament (CL) injury in the United States, 1997-2004. *J Athl Train*. 2007;42:S-54.

3. Marshall SW, Padua DA, McGrath ML. Incidence of ACL injury. In: Hewett TE, Shultz SJ, Griffin LY, ed. *Understanding and Preventing Noncontact ACL Injuries*. Champaign, IL: Human Kinetics; 2007.

4. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: A systematic review and meta-analysis. *Am J Sports Med*. 2016;44(7):1861-1876.

5. Myklebust G, Bahr R. Return to play guidelines after anterior cruciate ligament surgery. *Br J Sports Med*. 2005;39:127-131.

6. Paterno M, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of contralateral and ipsilateral Anterior Cruciate Ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clin J Sports Med*. 2012;22(2):116-121.

7. Paterno M, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of second ACL injuries 2 years after primary ACL reconstruction and return to sport. *Am J Sports Med*. 2014;42(7):1567-1573.

8. Webster KE, Feller JA, Leigh WB, Richmond AK. Younger patients are at increased risk for graft rupture and contralateral injury after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2014;42(3):641-647.

9. Kyritsis P, Bahr R, Landreau P, Miladi R, Witvrouw E. Likelihood of ACL graft rupture: Not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. *Br J Sports Med*. 2016;50(15):946-951.

10. Rohman E, Steubs JT, Tompkins M. Changes in involved and uninvolved limb function during rehabilitation after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2015;43(6):1391-1398.

11. Bizzini M, Hancock D, Impellizzeri F. Suggestions from the field for return to sports participation following anterior cruciate ligament reconstruction: soccer. *J Orthop Sports Phys Ther*. 2012;42(4):304–312.

12. Paterno MV, 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.

13. Reid A, Birmingham TB, Stratford PW, Alcock GK, Giffin JR. Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. *Phys Ther*. 2007;87(3):337–349.

14. Schmitt LC, Paterno MV, 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.

15. Thomee R, Kaplan Y, Kvist J, Myklebust G, Risberg MA, Theisen D, Tsepis E, Werner S, Wondrasch B, Witvrouw E. Muscle strength and hop performance criteria prior to return to sports after ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2011;19(11):1798–1805.

16. Paterno MV, 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.

17. Dai B, Garrett W, Butler RJ, Queen RM. Using ground reaction force to predict knee kinetic asymmetry following anterior cruciate ligament reconstruction. *Scand J Med Sci Sports*. 2013;24(6):974-981.

18. Bookbinder H, Slater LV, Simpson A, Hertel J, Hart JM. Single-leg jump performance before and after exercise in healthy and anterior cruciate ligament reconstructed individuals. *J Sport Rehab*. 2019;(ahead of print).

19. Kuenze C, Hertel J, Hart JM. Effects of exercise on lower extremity muscle function after anterior cruciate ligament reconstruction. *J Sport Rehab*. 2013;22(1):33–40.

20. Webster KE, Austin DC, Feller JA, Clark RA, McClelland JA. Symmetry of squatting and the effect of fatigue following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(11):3208–3213.

21. McHugh MP, Tyler TF, Nicholas SJ, Browne MG, Gleim GW. Electromyographic analysis of quadriceps fatigue after anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 2001;31(1):25–32.

22. Cascio BM, Culp L, Cosgarea AJ. Return to play after anterior cruciate ligament reconstruction. *Clin Sports Med*. 2004;23:395-408.

23. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to the preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery: two-thirds of patients have not returned by 12 months after surgery. *Am J Sports Med.* 2011;39(3):538–543.

24. Mather RC III, Koenig L, Kocher MS, et al. Societal and economic impact of anterior cruciate ligament tears. *J Bone Joint Surg*. 2013;95:1751-1759.

25. Gelber AC, Hochberg MC, Mead LA, Wang NY, Wigley FM, Klag MJ. Joint injury in young adults and risk for subsequent knee and hip osteoarthritis. *Ann Intern Med*. 2000;133:321-328.

26. Roos EM. Joint injury causes knee osteoarthritis in young adults. *Curr Opin Rheumatol*. 2005;17:195-200.

27. Salmon LJ, Russell VJ, Refshauge K, Kader D, Connolly C, Linklater J, Pinczewski LA. Long-term outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft: minimum 13-year review. *Am J Sports Med*. 2006;34:721-732.

28. Thelin N, Holmberg S, Thelin A. Knee injuries account for the sports-related increased risk of knee osteoarthritis. *Scand J Med Sci Sports*. 2006;16:329-333.

29. 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.

30. Boden BP, Dean GS, Feagin JA, Jr., Garrett WE, Jr. Mechanisms of anterior cruciate ligament injury. *Orthopedics*. 2000;23:573-578.

31. Agel J, Arendt EA, Bershadsky B. Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review. *Am J Sports Med*. 2005;33:524-530.

32. Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J Athl Train*. 2007;42:311-319.

33. Arendt EA, Agel J, Dick R. Anterior Cruciate Ligament Injury Patterns Among Collegiate Men and Women. *J Athl Train*. 1999;34:86-92.

34. 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*. 1995;23:694-701.

35. Mihata LC, 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;34:899-904.

36. Lyman S, Koulouvaris P, Sherman S, Do H, Mandl LA, Marx RG. Epidemiology of anterior cruciate ligament reconstruction: trends, readmissions, and subsequent knee surgery. *J Bone Joint Surg Am*. 2009;91(10):2321–2328.

37. Dodwell ER, Lamont LE, Green DW, Pan TJ, Marx RG, Lyman S. 20 years of pediatric anterior cruciate ligament reconstruction in New York State. *Am J Sports Med*. 2014;42(3):675–680.

38. Sigward SM, Powers CM. The influence of gender on knee kinematics, kinetics and muscle activation patterns during side-step cutting. *Clin Biomech*. 2006;21:41-48.

39. McLean SG, Neal RJ, Myers PT, Walters MR. Knee joint kinematics during the sidestep cutting maneuver: potential for injury in women. *Med Sci Sports Exerc*. 1999;31:959-968.

40. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc*. 2003;35:1745-1750.

41. 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;13:930-935.

42. 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;32:477-483.

43. Withrow TJ, Huston LJ, Wojtys EM, Ashton-Miller JA. The relationship between quadriceps muscle force, knee flexion, and anterior cruciate ligament strain in an in vitro simulated jump landing. *Am J Sports Med*. 2006;34:269-274.

44. Lephart SM, Ferris CM, Riemann BL, Myers JB, Fu FH. Gender differences in strength and lower extremity kinematics during landing. *Clin Orthop Relat Res*. 2002:162-169.

45. Hewett TE, Zazulak BT, Myer GD, Ford KR. A review of electromyographic activation levels, timing differences, and increased anterior cruciate ligament injury incidence in female athletes. *Br J Sports Med*. 2005;39:347-350.

46. Pollard CD, Davis IM, Hamill J. Influence of gender on hip and knee mechanics during a randomly cued cutting maneuver. *Clin Biomech*. 2004;19:1022-1031.

47. McLean SG, Huang X, Su A, Van Den Bogert AJ. Sagittal plane biomechanics cannot injure the ACL during sidestep cutting. *Clin Biomech*. 2004;19:828-838.

48. Simonsen EB, Magnusson SP, Bencke J, Naesborg H, Havkrog M, Ebstrup JF, Sorensen H. Can the hamstring muscles protect the anterior cruciate ligament during a side-cutting maneuver? *Scand J Med Sci Sports*. 2000;10:78-84.

49. Ford KR, Myer GD, Toms HE, Hewett TE. Gender differences in the kinematics of unanticipated cutting in young athletes. *Med Sci Sports Exerc*. 2005;37:124-129.

50. Hewett TE, Myer GD, Ford KR. Anterior cruciate ligament injuries in female athletes: Part 1, mechanisms and risk factors. *Am J Sports Med*. 2006;34:299-311.

51. Barber-Westin SD, Noyes FR, Galloway M. Jump-land characteristics and muscle strength development in young athletes: a gender comparison of 1140 athletes 9 to 17 years of age. *Am J Sports Med*. 2006;34:375-384.

52. Yu B, Lin CF, Garrett WE. Lower extremity biomechanics during the landing of a stop-jump task. *Clin Biomech*. 2006;21:297-305.

53. Sell TC, Ferris CM, Abt JP, Tsai YS, Myers JB, Fu FH, Lephart SM. The effect of direction and reaction on the neuromuscular and biomechanical characteristics of the knee during tasks that simulate the noncontact anterior cruciate ligament injury mechanism. *Am J Sports Med.* 2006;34:43-54.

54. Woo SL, Hollis JM, Adams DJ, Lyon RM, Takai S. Tensile properties of the human femur-anterior cruciate ligament-tibia complex. The effects of specimen age and orientation. *Am J Sports Med*. 1991;19:217-225.

55. Padua DA, Frank B, Donaldson A, et al. Seven steps for developing and implementing a preventive training program: lessons learned from JUMP-ACL and beyond. *Clin Sports Med*. 2014;33(4):615– 632.

56. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: A systematic review and meta-analysis. *Am J Sports Med.* 2016;44(7):1861-1876.

57. Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: The Delaware-Oslo ACL cohort study. *Br J Sports Med*. 2016;50(13):804-808.

58. Stanley LE, Kerr ZY, Dompier TP, Padua DA. Sex differences in the incidence of anterior cruciate ligament, medial collateral ligament, and meniscal injuries in collegiate and high school sports. *Am J Sports Med.* 2016;44(6):1565-1572.

59. Kamath G, Murphy T, Creighton RA, Viradia N, Taft TN, Spang JT. Anterior cruciate ligament injury, return to play, and reinjury in the elite collegiate athlete. *Am J Sports Med*. 2014;42(7):1638-1643.

60. Barber-Westin SD, Noyes FR (2011) Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. *Arthroscopy*. 2011;27(12):1697–1705.

61. Abrams GD, Harris JD, Gupta AK, McCormick FM, Bush- Joseph CA, Verma NN, Cole BJ, Bach BR (2014) Functional performance testing after anterior cruciate ligament reconstruction: a systematic review. *Orthop J Sports Med*. 2014;2(1):1–10.

62. Stares JJ, Dawson B, Peeling P, et al. Subsequent injury risk is elevated above baseline after return to play: A 5-year prospective study in elite australian football. *Am J Sports Med*. 2019;47(9):2225-2231.

63. Gokeler A, Welling W, Zaffagnini S, Seil R, Padua D. Development of a test battery to enhance safe return to sports after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2017;25(1):192-199.

64. Drew MK, Raysmith BP, Charlton PC. Injuries impair the chance of successful performance by sportspeople: a systematic review. *Br J Sports Med*. 2017; 51:1209–1214.

65. Hägglund M, Waldén M, Magnusson H et al. Injuries affect team performance negatively in professional football: an 11-year follow-up of the UEFA Champions League injury study. *Br J Sports Med*. 2013;47(12):738–742.

66. Lautamies R, Harilainen A, Kettunen J, Sandelin J, Kujala UM. Isokinetic quadriceps and hamstring muscle strength and knee function 5 years after anterior cruciate ligament reconstruction: comparison between bone-patellar tendon-bone and hamstring tendon autografts. *Knee Surg Sports Traumatol Arthrosc*. 2008;16:1009–1016.

67. Neitzel JA, Kernozek TW, Davies GJ. Loading response following anterior cruciate ligament reconstruction during the parallel squat exercise. *Clin Biomech*. 2002;17(7):551–554.

68. Chmielewski TL, Wilk KE, Snyder-Mackler L. Changes in weight-bearing following injury or surgical reconstruction of the ACL: relationship to quadriceps strength and function. *Gait Posture*. 2002;16(1):87–95.

69. Salem GJ, Salinas R, Harding FV. Bilateral kinematic and kinetic analysis of the squat exercise after anterior cruciate ligament reconstruction. *Arch Phys Med Rehabil*. 2003;84(8):1211–1216.

70. Sigward SM, Chan MSM, Lin PE. Characterizing knee loading asymmetry in individuals following anterior cruciate ligament reconstruction using inertial sensors. *Gait Posture*. 2016;49:114-119.

71. Sigward SM, Lin P, Pratt K. Knee loading asymmetries during gait and running in early rehabilitation following anterior cruciate ligament reconstruction: A longitudinal study. *Clin Biomech*. 2016; 32:249–54.

72. Patterson M, Delahunt E, Sweeney K, Caulfield B. An ambulatory method of identifying anterior cruciate ligament reconstructed gait patterns. Sensors. 2014; 14:887–99.

73. Thomson A, Whiteley R, Einarsson E, et al. Peak plantar force in elite soccer players following ACL reconstruction: Greater symmetry after 9 months when running. *Br J Sports Med*. 2017;51(4):395.

74. Corke P., Lobo J., Dias J. An introduction to inertial and visual sensing. *Int. J Robot Res*. 2007;26:519–535.

75. Tao Y., Hu H., Zhou H. Integration of vision and inertial sensors for 3D arm motion tracking in home-based rehabilitation. *Int J Robot Res*. 2007;26:607–624.

76. Gabbett TJ. Incidence of injury in junior and senior rugby league players. *Sports Med*. 2004;34:849-859.

77. Waldén M, Hägglund M, Magnusson H, Ekstrand J. Anterior cruciate ligament injury in elite football: a prospective three-cohort study. *Knee Surg Sports Traumatol Arthrosc*. 2011;19:11-19.

78. Enoka RM. *Neuromechanics of Human Movement*. 3rd ed. Champaign, IL: Human Kinetics; 2002.

79. Gandevia SC. Spinal and supraspinal factors in human muscle fatigue. *Physiol Rev*. 2001;81:1725-1789.

80. Theurel J, Lepers R. Neuromuscular fatigue is greater following highly variable versus constant intensity endurance cycling. *Eur J Appl Physiol*. 2008;103:461-468.

81. Nicol C, Avela J, Komi PV. The stretch-shortening cycle: a model to study naturally occurring neuromuscular fatigue. *Sports Med*. 2006;36:977-999.

82. McLean SG, Felin RE, Suedekum N, Calabrese G, Passerallo A, Joy S. Impact of fatigue on gender-based high-risk landing strategies. *Med Sci Sports Exerc*. 2007;39:502-514.

83. 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*. 2008;23:81-92.

84. McGrath ML. Changes in lower extremity movement patterns following exercise-induced fatigue and verbal feedback [dissertation]. Chapel Hill: University of North Carolina; 2009.

85. Taylor JB, Wright AA, Dischiavi SL, Townsend MA, Marmom AR. Activity demands during multi-direction team sports: A systematic review. *Sports Med*. 2017;47:2533-2551.

86. Micklewright D, St. Clair Gibson A, Gladwell V, Al Salman A. Developments and validity of the rating of fatigue scale. *Sports Med*. 2017;47:2375-2393.

87. Burland JP, Outerleys JB, Lattermann C, Davis IS. Reliability of wearable sensors to assess impact metrics during sport-specific tasks. *J Sports Sci.* 2021;39(4):406-411.

88. Sheerin KR, Besier TF, Reid D, Hume PA. The one-week and six-month reliability and variability of three-dimensional tibial acceleration in runners. *Sports Biomechanics.* 2018;17(4):531-540.