DETERMINING THE EFFECTS OF FATIGUE ON ANTERIOR KNEE LAXITY

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Taliah Jo Carlson
August 2024

ABSTRACT

There is a high incidence rate of ACL injuries in the United States, and it has been previously found that increasing anterior knee laxity (AKL) is a risk factor for ACL injuries. Therefore, this study aimed to examine if there is a relationship between muscular fatigue and AKL as the relationship is not currently well understood. The primary purpose was to examine how muscular fatigue influences AKL in the preferred kicking leg from baseline to post-warm-up and throughout a fatigue protocol that simulates game or practice situations. Additionally, the secondary purpose of the study was to investigate the impact of fatigue on vertical ground reaction forces and muscle activity in the quadriceps and hamstrings using electromyography. By recruiting recreationally active female young adults from the local community, the research sought to provide insights into how fatigue affects anterior knee laxity and exploratory vertical ground reaction forces and muscle activity variables, aiming to improve injury prevention and rehabilitation programs. The methodology included a dynamic warm-up, a fatigue protocol using the Yo-Yo Intermittent Recovery Test Level 1, jumping and cutting tasks, and measurements of AKL using a GNRB® arthrometer, aiming to improve our understanding of muscular fatigue as an injury mechanism for ACL injury and determine if there is a link between muscle fatigue and AKL. For the drop jump task, the peak loading and average loading rate significantly increased. The jump height from the countermovement jumps significantly decreased. For the drop cut task, the pre-activation vastus medialis median frequency significantly increased. Despite the fatigue protocol eliciting some significant changes, the study concludes that the fatigue protocol did not induce the level of muscular fatigue necessary to induce significant changes in AKL for all participants. Further research with tailored fatigue protocols that investigate intersubject variability in AKL, in terms of magnitude and type of responders, and its underlying causes is needed to better understand the dynamics between muscular fatigue, AKL, and ACL injury risk.

TABLE OF CONTENTS

Chapter 1: Development of the Problem 1
Background and Rationale 1
Statement of the Problem 3
Statement of Purpose 3
Research Hypotheses 3
Limitations of the Study 5
Delimitations of the Study 5
Assumptions of the Study 5
Significance of the Study 6
Operational Definition of Terms 6

Chapter 2: Review of the Literature 7
Introduction 7
Laxity and Injuries 8
Fatigue Effects 11
Definition of Fatigue 11
Performance Metrics 14
Biomechanics Metrics 16
Fatigue Effects on Laxity 18
General Laxity 18
Knee Laxity 21
Fatigue Effects on Supporting Variables 23
Fatigue Effects on vGRF 23
Fatigue Effects on EMG 24
Whole Body vs. Local Fatigue 26
Warm-Up 31
Effects of a Warm-Up 31
Laxity and Warm-Up Relationship 34
Role of Sex Differences 35
Sex Differences in ACL Injuries 35
Sex Differences in Anterior Knee Laxity During Fatigue 37
Conclusion 37

Chapter 3: Methods 39
Participants 39
Participant Preparation 40
Experimental Protocol 41
Instrumentation 44
Data Reduction and Analysis 45
Statistical Analysis 47

Chapter 4: Results 49
Anterior Knee Laxity 49

Vertical Ground Reaction Forces 49
Drop Cut Task 49
Drop Jump Task 50
Jump Height from Countermovement Jump 51
Electromyography 51
Drop Cut Task 51
Drop Jump Task 52

Chapter 5: Discussion 54
Co-Contraction Ratio 54
Median Frequency 55
Peak vGRF and Average vGRF Loading Rate 57
AKL 60
Considerations for Comparison with Previous Research 64
Future Considerations 66
Conclusions 67

References 69

Appendices 74
Appendix A. Participant Demographics 74
Appendix B. Chapter 3 Tables 75
Appendix C. Chapter 3 Figures 76
Appendix D. Chapter 4 Tables 81
Appendix E. Chapter 4 Figures 87
Appendix F. Chapter 5 Tables 91
Appendix G. Chapter 5 Figures 93
Appendix H. Informed Consent 94
Appendix I. Lower Extremity Functional Scale 99
Appendix J. Musculoskeletal Questionnaire 101
Appendix K. Fitness Activity Questionnaire 110
Appendix L. Recruitment Flyer 111
Appendix M. IRB Approval Letter 112
Appendix N. Individual Participant Demographics and Results 114
Appendix O. Within-Subjects ANOVA Tables 125

Vita 130

LIST OF TABLES

Table 1: Mean participant demographics. 74

Table 2: The running speed increment schedule for the Yo-Yo Test. After stage 5 the speed continued to incrementally increase by 0.5 km/hour every 8 shuttles until a speed of 19 km/hour. 75

Table 3: Anterior knee laxity across the time points of the study protocol and the p-value. 81

Table 4: Peak impact loading and average loading rate for drop cut task. Normalized to body weight. 82

Table 5: Peak impact loading and average loading rate for drop cut task. Normalized to body weight. 83

Table 6: Jump height calculated from the vGRF data from the countermovement jump, which is used to assess fatigue. 84

Table 7: Median frequency and co-contraction ratio from EMG data for the pre-activation and landing phases of the drop cut task. 85

Table 8: Median frequency and co-contraction ratio from EMG data for the pre-activation and landing phases of the drop jump task. 86

Table 9: Anterior knee laxity displacement with the criteria of 10% difference between the baseline (Pre Warm-Up) measurements and the Yo-Yo Round 3. 91

Table 10: Two-tailed t-tests comparing the positive and negative AKL responders. 92

Table 11: Demographic information for the individual participants. 114

Table 12: Individual participant AKL average displacements (mm) of the three trials at each time point. 115

*Table 13: Individual participant co-contraction ratios for the pre-activation and landing phases of the drop cut task. *Subjects 1 and 21 were not utilized because they had incomplete datasets.* 116

*Table 14: Individual participant pre-activation phase median frequencies for the drop cut task. *Subjects 1 and 21 were not utilized because they had incomplete datasets.* 117

*Table 15: Individual participant landing phase median frequencies for the drop cut task. *Subjects 1 and 21 were not utilized because they had incomplete datasets.* 118

Table 16: Individual participant means for peak loading and average loading rate for the drop cut task. 119

*Table 17: Individual participant co-contraction ratios for the pre-activation and landing phases of the drop jump task. *Subjects 1 and 21 were not utilized because they had incomplete datasets.* 120

*Table 18: Individual participant pre-activation phase median frequencies for the drop jump task. *Subjects 1 and 21 were not utilized because they had incomplete datasets.* 121

*Table 19: Individual participant landing phase median frequencies for the drop jump task. *Subjects 1 and 21 were not utilized because they had incomplete datasets.* 122

Table 20: Individual participant means for peak loading and average loading rate for the drop jump task. 123

Table 21:Individual participant jump height calculated from the countermovement jump. 124

Table 22: Within-Subjects 1x4 ANOVA Tables for the vGRF and EMG variables during the drop cut task. 125

Table 23: Within-Subjects 1x4 ANOVA Tables for the vGRF and EMG variables during the drop jump task. 126

Table 24: Within-Subjects 1x4 ANOVA Tables for the jump height calculated from the countermovement jump. 127

Table 25: Within-Subjects 1x6 ANOVA Tables for the anterior knee laxity. 128

Table 26: Within-Subjects 1x6 ANOVA Tables for the anterior knee laxity for the comparison of positive and negative responders. 129

LIST OF FIGURES

Figure 1: The arthrometer setup utilized to assess anterior knee laxity (AKL). 76

Figure 2: Visual Aid of the Landing Tasks and the Countermovement Jump: A) The 45-degree cut for a participant with a preferred right side kicking leg, B) The bilateral drop jump landing task, C) The countermovement jump to assess fatigue through jump height. ... 77

Figure 3: A visual aid of the experimental protocol the participant engaged in where the participant engaged in 3 rounds of the Yo-Yo Test, countermovement jump (CMJ), laxity tests, and then landing tasks. 78

Figure 4: A visual aid of the modified Yo-Yo Test set up for the fatigue protocol. 79

Figure 5: Vertical ground reaction force (vGRF) curve of the countermovement jump (CMJ) with the defined start and takeoff points. 80

Figure 6: Median frequency of the vastus medialis and medial hamstrings muscles in the drop cut task. 87

Figure 7: Co-Contraction Ratio of quadriceps (VM) to hamstrings (MH) muscle force for the pre-activation and landing phases of the drop cut task. 88

Figure 8: Median frequency of the vastus medialis and medial hamstrings muscles in the drop jump task. 89

Figure 9: Co-Contraction Ratio of quadriceps (VM) to hamstrings (MH) muscle force for the pre-activation and landing phases of the drop jump task. 90

Figure 10: Comparison of AKL positive, negative, and none responders to the fatigue protocol. 93

NOMENCLATURE

ACL	Anterior cruciate ligament
AKL	Anterior knee laxity
CMJ	Countermovement jump
EMG	Electromyography
GJL	Generalized joint laxity
IRS	Intermittent shuttle run
LSD	Least significant difference
MH	Medial hamstring muscle
MVIC	Maximum voluntary isometric contraction
OA	Osteoarthritis
PAP	Post-activation potentiation
PSD	Power spectral density
RPE	Rating of perceived exertion
SAFT45	Soccer-specific match simulation
vGRF	Vertical ground reaction forces
VM	Vastus medialis muscle
ANOVA	Analysis of Variance

Chapter 1: Development of the Problem

Background and Rationale

It has been previously estimated that more than 120,000 anterior cruciate ligament (ACL) injuries happen each year (Gornitzky et al., 2016), typically because of rapid and sudden accelerations, decelerations, and changes in direction (De Ste Croix et al., 2015). For collision sports, such as football, ACL injury incidence rate is reportedly 1.29 injuries per 10,000 exposures, whereas for contact sports, such as basketball and soccer, it has been found to be 1.51 injuries per 10,000 exposures (Montalvo et al., 2019).

ACL injuries result in a significant burden in terms of treatment costs and missing matches (Webster et al., 2021). Sustaining an ACL injury can also leave the athlete vulnerable to subsequent re-injury and development of other knee diseases. ACL tears in individuals younger than 30 years old can result in early onset knee osteoarthritis (OA), which is associated with pain, limitations to knee function, and a decreased quality of life (Friel & Chu, 2013). After an ACL injury, the goal of ACL reconstruction is to reduce knee instability, but the incidence of post-traumatic knee OA after an ACL injury is as high as 87% (Friel & Chu, 2013). Therefore, gaining a better understanding of the injury mechanisms is an important step in reducing ACL injury incidence rates.

Sports such as football, basketball, and soccer are weightbearing sports that include rapid and sudden accelerations, decelerations, and changes in direction, which is when non-contact ACL tears tend to occur (De Ste Croix et al., 2015). The ligaments and tendons surrounding the knee joint need to be sufficiently taut enough to stabilize the knee joint (Myer et al., 2008), so increasing the anterior knee laxity (AKL) is a risk factor for ACL injury (Shultz et al., 2009).

However, joint stability is rarely included in the pre-participation physical examinations (Myer et al., 2008). AKL is the anterior displacement of the tibia relative to the femur (Shultz et al., 2009). Since previous research has found that AKL is a risk factor for ACL injuries, it is important to examine how AKL changes throughout a practice or game situation to work towards developing training interventions for injury prevention.

Athletes are consistently enduring the demands of intense training and competitive games and practices. Therefore, athletes regularly experience muscle fatigue, which begins to develop shortly after initiating physical activity and can be defined as a reduced force producing capability of the involved muscles (Enoka & Duchateau, 2008). Fatigue is often considered a risk factor for ACL injury because it is thought to lead to temporary reductions in muscle strength, and harmful alterations in lower extremity kinematics and kinetics during potentially risky tasks such as landing and cutting (Bourne et al., 2019). For example, anterior knee laxity (AKL), another ACL injury risk factor (Shultz et al., 2009), has been shown to increase as a result of fatiguing exercise (Shultz et al., 2013). Shultz et al. (2013) examined changes in anterior knee laxity during an intermittent exercise protocol that simulated the intensity and duration of a soccer match. They reported more pronounced exercise-related knee laxity changes in females. However, Shultz et al. (2013) examined only the left leg, stating it is typically the dominant stance leg when an individual kicks a ball. Since leg dominance has also been linked to ACL injury risk (Brophy et al., 2010) it is imperative to determine if the relationship between fatigue and anterior knee laxity also exists in the preferred kicking leg as well. A thorough understanding of individual risk factors, and potential interrelationship between risk factors, could aid in injury prevention and rehabilitation strategies.

Statement of the Problem

The high incidence of ACL injuries and subsequent injuries and knee tissue damage, such as knee OA, shows the importance of preventing ACL injuries from occurring. To do so, research must first understand the injury mechanisms for ACL injury. This study aimed to provide insight on AKL as a risk factor for ACL injuries. Specifically, this study aimed to examine if there was a relationship between muscular fatigue and lower extremity kinematics and kinetics. Previous research has identified exercise-related increases in AKL, but utilized different fatigue protocols, stance limb when kicking a ball instead of kicking leg, or examined a specific sport population (Shultz et al., 2013).

Statement of Purpose

The primary purpose was to examine the effects of fatigue on the preferred kicking leg, the testing limb, on anterior knee laxity from baseline to post warm-up and throughout a fatigue protocol that simulated a game or practice situation. The secondary purpose was to examine the influence of fatigue on vertical ground reaction forces, as well as quadriceps and hamstrings muscle activity, via electromyography (EMG).

Research Hypotheses

Based on previous research, we did not expect significant changes in anterior knee laxity from baseline to post dynamic warm-up (Shultz et al., 2013; Steele et al., 1999) but did expect anterior knee laxity to increase after completion of a fatigue protocol (Shultz et al., 2013). Therefore, it was hypothesized that from baseline measures to completion of the fatigue protocol the AKL would increase.

The supporting variables, vertical ground reaction forces (vGRF) and muscle activity, measured via electromyography (EMG), were exploratory elements of the analysis. They were intended to provide supplementary insight and help explore potential relationships as well as provide depth to the understanding of the results. For vGRF, the variables were peak impact and loading rate from initial contact to impact peak. A meta-analysis showed that results of impact peak and loading rate to impact peak vary between studies (Zadpoor & Nikooyan, 2012). Based on previous research utilizing a different fatigue protocol and task we expected vGRF to increase for both variables from baseline measures to completion of the fatigue protocol (James et al., 2006). Therefore, it was hypothesized for impact peak and loading rate from initial contact to impact peak that from baseline measures to completion of the fatigue protocol the vGRF would increase.

For EMG, the variables were median frequency and co-contraction ratio of the quadriceps to the hamstrings muscle. Previous research utilizing isometric, local muscle fatigue has found that median frequency decreases as muscle fatigues occurs (Allison & Fujiwara, 2002; Mannion & Dolan, 1996). Therefore, it was hypothesized that from baseline measurements to completion of the fatigue protocol the median frequency would decrease. Based on previous research, we expected that for both the pre-activation and landing phase that the co-contraction ratio would increase from baseline measurements to completion of a fatigue protocol (Padua et al., 2006). Therefore, it was hypothesized that from baseline measures to completion of the fatigue protocol the co-contraction ratio would increase, meaning it would become more quadriceps dominant, for both the pre-activation and landing phases.

Limitations of the Study

- The space constrictions of the UTK Biomechanics/Sports Medicine Laboratory required that the Yo-Yo Test setup for the fatigue protocol be slightly modified.

Delimitations of the Study

- Participants were between the ages of 18 and 35 years old.
- All participants were female due to previously reported differences in AKL response between sexes (Shultz et al., 2013).
- Participants were considered acceptable according to inclusion criteria and a healthy participant if they had no previous surgical intervention on their lower extremities as well as no injuries to their lower extremities in the past 6 months prior to testing.
- Participants wore the same footwear (Nike Pegasus, Nike Inc., Beaverton, OR, USA).
- The fatigue protocol, the Yo-Yo Intermittent Recovery Test Level 1, was a volitional fatigue protocol, meaning that it relies on the decisions and effort of the participant to continue each round of the fatigue protocol. This means the time spent in each round of fatigue protocol and effort levels were not standardized across participants.

Assumptions of the Study

- Participants were truthful when filing out all survey forms, including the Lower Extremity Functional Scale, Fitness Activity Questionnaire, and the modified-musculoskeletal health questionnaire.
- The instrumentation and equipment utilized in this study were operating as expected and accurately calibrated for each data collection throughout the study.

- The placement of the EMG surface sensors and the arthrometer were consistent across the participants.
- Participants were providing maximum effort throughout the fatigue protocol and experimental tasks.

Significance of the Study

The results of this project helped to improve our understanding of muscular fatigue as an injury mechanism for ACL injury. These results aided in determining if there was a link between muscle fatigue and anterior knee laxity, which could help improve injury prevention and rehabilitation programs. The relationship between muscle fatigue and anterior knee laxity is not well understood at this time. Thus, it was necessary to examine this potential relationship in a controlled, laboratory setting where high precision equipment (force plates, EMG, etc.) could be utilized. Once the relationship was established, future studies are needed to determine if it persists in an individual's natural environment as well as to develop screening tools that can be used by clinicians who may not have access to a full motion capture lab.

Operational Definition of Terms

Anterior knee laxity: The amount of anterior displacement of the tibia relative to the femur (Shultz et al., 2009).

Muscle fatigue: An exercise-induced reduction in the maximal force or power produced by the muscles (Enoka & Duchateau, 2008) and begins at the onset of muscle contraction and is progressive (Nigg, 2000).

Chapter 2: Review of the Literature

Introduction

It has been estimated that more than 120,000 anterior cruciate ligament (ACL) injuries happen each year (Gornitzky et al., 2016). For collision sports, such as football, the ACL injury incidence rate has been previously found to be 1.29 injuries per 10,000 exposures, whereas for contact sports, such as basketball and soccer, it has been found to be 1.51 injuries per 10,000 exposures (Montalvo et al., 2019). The most common mechanism of ACL injuries is non-contact, where the individual is twisting through the knee joint or in a cutting motion with the foot planted (Smith et al., 2014). Direct contact injuries do occur, and the mechanism of injury occurs when there is a direct blow to the knee joint, typically from the lateral or anterior direction (Smith et al., 2014). ACL injuries tend to occur because of rapid and sudden accelerations, decelerations, and changes in direction which occur in sports such as football, basketball, and soccer (De Ste Croix et al., 2015).

In 2019, ACL injuries cause 17.9 missed games per club per season in Australian Rules Football , showing that ACL injuries are resulting in a significant burden in terms of treatment costs and missing matches (Webster et al., 2021). From 1993 to 2013 the Australian Football League had a subsequent ACL injury rate after ACL reconstruction of 30% for either knee, with a rate of 50% for players that were less than 21 years old (Lai et al., 2018). The majority of individuals with acute ACL tears are younger than 30 years old when the injury occurs, which results in early onset knee OA (Friel & Chu, 2013). This is associated with pain, limitations to knee function, and a decreased quality of life (Friel & Chu, 2013). After an ACL injury, the goal of ACL reconstruction is to reduce knee instability, but the incidence of post-traumatic knee OA after an ACL injury is as high as 87% (Friel & Chu, 2013).

Athletes are consistently enduring the demands of intense training and competitive games and practices. Therefore, athletes regularly experience muscle fatigue, which starts to develop shortly after the beginning of physical activity and is a reduction in the maximal force or power that is produced by the muscles involved in the activity (Enoka & Duchateau, 2008). Whole-body fatigue is experienced during games and practices. Anterior knee laxity (AKL), which is a risk factor for ACL injury (Shultz et al., 2009), has previously been shown to change as a result of fatiguing exercise (Shultz et al., 2013).

Laxity and Injuries

Both passive (ligaments) and active (muscular) joint restraints affect dynamic knee stability (Myer et al., 2008). The ACL is the main restraint against AKL (Shultz et al., 2009). The amount of anterior displacement of the tibia in relation to the femur is known as an AKL (Shultz et al., 2009), which has also been referred to as anteroposterior tibiofemoral laxity. It has been previously identified that increased AKL is a risk factor for ACL injury and during weightbearing activities may disrupt normal joint neuromechanics (Shultz et al., 2009) and decrease dynamic knee stability during athletic tasks (Myer et al., 2008). Many sports, including football, basketball, and soccer, are weightbearing sports in which rapid and sudden accelerations, decelerations, and changes in direction occur, which is when ACL tears tend to occur (De Ste Croix et al., 2015). The increased ACL injury risk may be a result of the ligaments and tendons surrounding the knee joint not being sufficiently taut enough to stabilize the knee and absorb the ground reaction forces (Myer et al., 2008). Therefore, it is important to understand the role AKL plays in injuries. Joint stability is rarely included in the physical examinations prior to participation in physical activity and identifying and addressing a risk factor in preventative interventions may help reduce the risk of ACL injury (Myer et al., 2008).

Non-contact ACL injuries, which are ACL tears without physical contact with another player at the time of injury, make up 70-84% of all ACL tears in both male and female athletes (Alentorn-Geli et al., 2009). One study examined female soccer and basketball players and measured knee joint laxity as anterior-posterior tibiofemoral translation utilizing a CompuKT knee arthrometer and found that it was related to a higher risk of ACL injuries (Myer et al., 2008). Once athletes have been identified as at risk for ACL injuries, they can engage in neuromuscular training that is designed to increase the athletes' dynamic coronal plane knee stability (Myer et al., 2008). Preventing knee ligament injuries would allow for continued participation in sports and avoidance of long-term medical issues, such as disability and osteoarthritis that are estimated to be 10 times more likely following a knee ligament injury (Myer et al., 2008). Previous research has found that AKL is a risk factor for ACL injuries, which often occurs in sports situations, so it is important to examine how AKL, and therefore the potential risk for ACL injury, changes throughout a practice or game situation to work towards developing training interventions for injury prevention.

Laxity and Loading Relationship

One systematic review examining the biomechanics associated with ACL injuries found that one of the most common biomechanical variables associated with ACL injuries was increased abduction loading (Weiss & Whatman, 2015). During dynamic knee abduction the ACL is strained trying to prevent an excessive knee abduction moment (Weiss & Whatman, 2015). Weiss and Whatman (2015) suggested that a repetitive and increased knee abduction loading compared to a single bout of a large abduction load may lead to injury and therefore cumulative and chronic abnormal loading in the frontal plane may be a factor that leads to injury. An increased abduction moment can lead to disturbance of the normal tibiofemoral sagittal plane mechanics and increased anterior tibial translation, which can be contributing factors to the risk of ACL injuries (Weiss & Whatman, 2015). During dynamic sports-associated tasks, when the knee joint loading is occurring primarily in the frontal plane, this may alter the sagittal plane mechanics, which decreases the stability of the knee joint and loads the ACL (Weiss & Whatman, 2015).

Previous research has examined individuals diagnosed with an ACL injury for the effects of varying loads of seated knee extensor open kinetic chain resistance training on the participants AKL (Barcellona et al., 2015). These participants engaged in either a standardized rehabilitation program, standardized rehabilitation program and low loads of 2 sets of 20 maximum repetitions of resistance training, or standardized rehabilitation program and high loads of 20 sets of 2 maximum repetitions of resistance training (Barcellona et al., 2015). The group that engaged in the low load resistance training showed a decrease in AKL when comparing the baseline data to the data after 12 weeks of training, suggesting that resistance training of the thigh musculature can decrease AKL (Barcellona et al., 2015). This does conflict with previous research that found AKL does not change, but this may be explained by the different protocols utilized (Barcellona et al., 2015). Therefore, it appears that AKL, which has been specifically examined in the ACL-injured population, may be a factor that is modifiable by manipulating loading. This is an aspect that should be further examined in a healthy population, meaning no previous ACL injury, by investigating how the load of a practice or game-like situation affects the AKL. Developing this understanding and baseline knowledge will help further the development of training interventions to reduce the risk of injury.

Fatigue Effects

Definition of Fatigue

There have been many different definitions of fatigue from previous research studies, which also vary based on the way the researchers are examining fatigue. According to Gear (2011) fatigue is generally associated with failure of the involved muscle to sustain the action. Other researchers contradict this statement and say that muscle fatigue is not the point of failure of a task or when the muscle becomes exhausted (Enoka & Duchateau, 2008). Enoka and Duchateau (2008), state that this broad definition of fatigue is problematic because utilizing this fatigue definition there are several situations that can occur that are caused by different physiological mechanisms reducing the ability to identify the cause of muscle fatigue. Instead, a more specific definition has been developed to combat this limitation. Muscle fatigue is an exercise-induced, meaning it develops shortly after the onset of sustained physical activity, reduction in the maximal force or power produced by the involved muscles (Enoka & Duchateau, 2008). Other researchers have added to this more specified definition in that muscular fatigue is also characterized by local discomfort and pain, a subjective measurement (Rozzi et al., 1999). Muscle fatigue begins at the onset of muscle contraction and is progressive (Nigg, 2000). Changes in contractile response that are considered symptoms of fatigue include reduced force output, muscle relaxation slowing down, reduction in maximal velocity, and a reduction in economy and efficiency (Nigg, 2000).

When engaging in sports, both muscular and cardiovascular fatigue will occur as they engage in physical activity. The type of physical activity an individual regularly engages in can play a role in how the individual fatigues. According to Henneman's Size Principle, during physical activity Type I muscle fibers (slow-twitch), more specifically motor units, are recruited first as they are smaller and less fatigable, then the Type II muscle fibers (fast-twitch) that are larger in size and fatigue quicker are recruited as the intensity and frequency of the stimulus increases (Ehrman, 2018). Type I muscle fibers support endurance-type activities, while Type II fibers support activities that are high power and velocity and previous research has shown that the makeup of muscle fiber type can vary based on the activities an individual engage in (Ehrman, 2018). One study found that endurance athletes had 60-70% Type I muscle fibers, untrained controls showed a 50/50 ratio of Type I and Type II fibers, and sprinters showed about 80% Type II (Ehrman, 2018).

There are several contributors to the muscle fatigue process, central and peripheral control systems that cause time-related changes in the levels of recruitment and firing rate of motor units (Nigg, 2000). Central components of muscle fatigue refer to fatigue originating from the central nervous system, meaning it leads to decreases in neural signaling to the muscle, whereas peripheral components refers to fatigue caused by changes distal to or at the neuromuscular junction (Wan et al., 2017). There are several central or peripheral factors that may contribute to the reduction in muscle force that occurs during fatigue (Barber-Westin & Noyes, 2017). One central factor is the slowing or ceasing of motor unit firing contributes to the decrease in muscle force which indicates muscle fatigue (Wan et al., 2017). The activation of motor units, in order to achieve muscle force output, is accomplished by the central nervous system utilizing neurotransmitters to excite or inhibit inputs on the spinal motorneurons. Another central factor are central neurotransmitters, such as serotonin, dopamine, and norepinephrine, because they contribute whole-body exercise and fatigue. However, recent research on drug suggests that ambient temperatures may affect neutrotransmitters and examining the thermoregulatory system on exercise performance may be important, so further research is needed. One peripheral factor is calcium, an important component in cross-bridge cycling, which can contribute to fatigue in specific skeletal muscle fibers when its release from the sarcoplasmic reticulum is impaired. Impaired calcium release from the sarcoplasmic reticulum occurs at the skeletal muscle fiber level but is connected to central components of muscle fatigue. Calcium release from the sarcoplasmic reticulum to initiate cross-bridge cycling is a result of neural activation from the brain to the muscle's transverse tubules so fatigue of the central nervous system decreasing the neural drive to the muscle results in reduced force production. Blood flow and oxygen uptake is important for aerobic ATP production and providing the working muscles with oxygen, but this becomes a factor for fatigue at very high intensity, where the VO_{2max} has already been achieved, because the demands for ATP can no longer be met by increasing the oxygen delivery (Wan et al., 2017).

Within specific studies the researchers define fatigue according to the tasks being measured. Sanna and O'Connor (2008) observed fatigue as a broad reduction in the ability to express neuromuscular parameters, in this study specifically jumping performance in terms of power, at the same level. In another study, fatigue was observed as increases in the sprint time of participants shuttle run performance to then examine fatigue-related effects on multiplanar knee laxity and landing biomechanics (Shultz et al., 2015). Another study fatigued the thigh musculature utilizing a dynamometer and then examined the effects of fatigue from the baseline values of the landing tasks to the post-fatigue values (Fagenbaum & Darling, 2003). This study examined fatigue as the inability to consistently produce a knee extension torque 50% of their maximum extension torque or 60 repetitions and then also examined further fatigue as inability to produce a knee extension torque that was 25% of their maximum or until 60 repetitions (Fagenbaum & Darling, 2003). Utilizing maximal voluntary isometric contractions (MVIC) is a poor performance metric during dynamic exercises where there are submaximal contractions and less than 50% of the muscle mass activated at any time (Cairns et al., 2005). Muscle force during isometric contractions, such as those from a Biodex, underestimate functional impairments and in normal movements isokinetic contractions do not exist (Cairns et al., 2005). Therefore, to assess performance, meaning functional relevance, measuring power, determined utilizing force-velocity measures, is the more appropriate measure during dynamic exercises (Cairns et al., 2005).

Performance Metrics

There is a need for more quantification of fatigue within competitive sports (Cairns et al., 2005). There is limited research examining the effects of fatigue on technical skills while engaging in soccer-specific exercise (Russell et al., 2011). Performance metrics can be utilized as a measure of muscle fatigue. Power output, instead of isometric force, should be utilized as the performance measure of fatigue during dynamic exercises (Cairns et al., 2005).

Performance metrics can be utilized as a measurement tool for muscle fatigue. The results of Sanna and O’Connor (2008) suggested physiological fatigue decreased countermovement jump power output and the participant’s rating of perceived exertion (RPE). The results of the

RPE and jumping tasks due to the fatigue protocol of the intermittent shuttle run (IRS) indicated that there was a reduction in neuromuscular performance (Sanna & O'Connor, 2008). Another study utilizing US NCAA Division 1 collegiate female soccer players that completed one-legged countermovement jumps, run-and-cut tasks, the IRS fatigue protocol, and then the one-legged countermovement jumps again post-fatigue protocol (Collins et al., 2016). This study found that there was a significant decrease in the height of the one-legged countermovement jump after the IRS fatigue protocol (Collins et al., 2016).

Performance metrics can also be utilized to examine how the fatigue induced by the exercise across a game, or match simulation, affects the technical skills within the athlete's performance. One study on 15 youth soccer players involved a soccer match simulation in which the participants engaged in intermittent multi-directional activity for 90 minutes, which was separated into 45-minute halves with a 15-minute halftime recovery to replicate the demands of a soccer match (Russell et al., 2011). Throughout the protocol the participants engaged in assessments of technical skills, which were shooting, passing, and dribbling. This study found that the fatigue that was induced by the soccer match simulation decreased the athlete's performance in that the speed of passing and shooting decreased from the first half to the second half. Russell et al (2011) also found that the shooting precision decreased after exercise compared to before exercise. In this study dribbling performance was uninfluenced by exercise, suggesting it is more resilient to fatigue than the other skills that require a greater peak muscular activity. Therefore, assessing performance metrics provides a measurement of muscle fatigue and provides coaches and athletes with information on the effects of fatigue on sport-specific skills.

Biomechanics Metrics

The fatigue effects on biomechanics variables, specifically of the lower limbs, are one factor to consider when investigating sports-related tasks and injury risk. Previous studies have examined the effects of fatigue on biomechanical variables during various tasks.

Fagenbaum and Darling (2003) examined female and male college basketball players performing jump landings on their dominant leg from various heights while fatigued or not fatigued. The fatigue protocol involved isokinetic flexion and extension of the knee joint utilizing a isokinetic dynamometer until 50% of maximal extension torque, then the participant completed the jumping tasks, and then this was immediately repeated but until 25% of maximal extension torque. This study found that women had greater knee flexion angles when landing and greater knee flexion accelerations compared to men. It has been previously established that landing with the knee joint more extended increases ACL injury risk because the knee angle decreases the ability of the hamstring muscles to counteract tibial translation. Quickly accelerating into a knee flexion angle appears to be advantageous to prevent ACL injury, but the hamstring muscles must be activated to prevent excessive stress on the ACL. In terms of fatigue effects, as fatigue increased there was a decrease in the knee flexion acceleration for both men and women. Fagenbaum and Darling (2003) state this result suggests that the fatigued muscle still has a strong capability to resist forced lengthening, which may be an important factor to consider in ACL injury prevention in a fatigued state.

One systematic review, which included both general and peripheral fatigue protocols, found that there was no consistency between studies for the effects of the fatigue protocols on hip, knee, and ankle joint angles or moments or for muscle activation patterns (Barber-Westin &

Noyes, 2017). However, this study does conclude that the effect of fatigue protocols on ACL injury risk needs further investigation, especially to refine the fatigue protocols, protocol tasks, and methodology of the data analysis (Barber-Westin & Noyes, 2017). This systematic review shows that that there were so many variations in protocol, including general versus peripheral, single-leg versus double-leg tasks, planned versus reactive, that the review was unable to find consistency in results and therefore further research is needed.

Another study examined the interaction effects of anticipation and fatigue on knee joint biomechanics during a run-and-cut task in female athletes (Collins et al., 2016). Following the fatigue protocol, the participants had a significantly increased peak knee abduction angle. Anticipation significantly affected the participants, where the participants had a significantly increased peak knee flexion, peak knee abduction, and peak knee internal rotation angles as well significantly increased in peak knee adduction moments in the unanticipated trials. This study suggests that an increase in peak knee abduction angle would increase the athlete's ACL injury risk because previous studies have reported knee valgus collapse as a mechanism for ACL injury and an increased peak knee abduction angle as a significant predictor of ACL injury during tasks involving landing and jumping. Overall, the authors suggest that the results indicate there is a greater risk of ACL injury for athletes when they are fatigued (Collins et al., 2016).

This previous research demonstrates that depending on the methodology and fatigue protocol, there may be differences in the lower-limb biomechanical variables after fatigue and this is something future research should continue to investigate. Fagenbaum and Darling (2003) utilized an isokinetic dynamometer to induce fatigue and examined jump landing performance, whereas Collins et al (2016) utilized a motion capture system with retro-reflective markers and in-ground force plates to obtain the kinematics and kinetics. Logistically this equipment and technology is not available or realistic for field assessment studies of athletes. Therefore, the logistical issues of requiring a laboratory setting like these previous studies did shows a more realistic field-assessment protocol should be utilized for future research.

Fatigue Effects on Laxity

Steiner et al. (1986) was the first study to conclude that engaging in exercise, specifically in exercise that repetitively stresses the knee joint, increases anterior-posterior knee laxity. One study compared the fatigue protocol to a control condition, where the participants engaged in the dynamic warm up, but for the time exercise blocks of the fatigue protocol they spent the duration of that time sitting quietly, meaning they did not engage in exercise or experience fatigue (Shultz et al., 2013). This means they were able to examine with subjects the effects of fatigue on AKLand found that AKL increased when the participants engaged in the running fatigue protocol condition, but not when they were in the control condition, where they did not engage in exercise or experience fatigue (Shultz et al., 2013). This indicates that fatigue from exercise does affect knee laxity (Shultz et al., 2013). General laxity examines the laxity of multiple joints across the body, whereas knee laxity, specifically AKL, allows for a more in-depth examination of the ACL because increased AKL is a risk factor for ACL injuries because the ACL is the main restraint against AKL (Shultz et al., 2009).

General Laxity

Generalized joint laxity (GJL) is defined as the increase in range of motion in multiple joints in comparison to average range of motion in the normal population (Bin Abd Razak et al., 2014; Tingle et al., 2018). GJL does not have an internationally agreed definition and has also been referred to as generalized ligamentous laxity and generalized joint hypermobility (Tingle et al., 2018). The Beighton scoring method (Beighton et al., 1973) is a commonly used method for assessing the mobility of nine joints across the body, including bilateral assessment of thumb opposition, fifth finger extension. Knee extension, elbow extension, and lumbar spine and hip flexion while standing (Tingle et al., 2018). In this clinical tool, a goniometer is utilized and a score of greater than or equal to four out of nine is commonly used to indicate GJL (Tingle et al., 2018). The prevalence of GJL is between 5-15% in the general population (Bin Abd Razak et al., 2014). There are varying recommendations by clinicians and researchers for individuals with GJL when it comes to the risk of participating in sports and training (Bin Abd Razak et al., 2014).

One previous study examined if GJL was a risk factor for musculoskeletal injuries in males aged 18-25 years old in the military, comparing 100 males with previous musculoskeletal injuries of the upper or lower extremity that resulted from physical activity to 100 control males (Bin Abd Razak et al., 2014). GJL was present in 12% of the previously injured group and only 4% in the control group (Bin Abd Razak et al., 2014). This means GJL is more common in those with a musculoskeletal injury and therefore, GJL may be a risk factor for musculoskeletal injuries (Bin Abd Razak et al., 2014).

Another study examined the risk of ACL rupture in individuals with GJL, considering a Beighton score greater than 6 as GJL, by comparing individuals with an ACL injury prior to reconstruction, to a control group (Ramesh et al., 2005). In the injured group 42.6% of the individuals had GJL, whereas the control group had 21.5% GJL (Ramesh et al., 2005). More specifically, they examined knee hyperextension, an assessment in the Beighton score, and found that 78.7% of the ACL injured individuals had knee hyperextension, compared to the 37% of control individuals (Ramesh et al., 2005). The researchers therefore concluded that ACL injuries are more common in individuals with GJL, especially for those with knee hyperextension (Ramesh et al., 2005). The researchers state that the Beighton scoring method was utilized because it is well established in the literature and can be quickly performed, but that the literature is divided on the association between joint laxity and injuries, which can be partially attributed to the inconsistency in how laxity is assessed (Ramesh et al., 2005). This is one reason that utilizing an arthrometer to assess knee laxity is beneficial because it can produce the same amount of force with each testing. This study does not directly examine fatigue effects on GJL but did record the mechanism of injury for the ACL injured group and found that 75.4% of the injuries occurred due to a non-contact mechanism (Ramesh et al., 2005). A similar study examined GJL in female volleyball players comparing individuals with previous ligamentous injury(s) and no history of such injury and found that the GJL scores were higher in the previously injured group and the athletes therefore may be more prone to ligament injuries (Sueyoshi et al., 2016).

GJL is often used to examine material fatigue over the course of a season, where accumulation of microdamage to the tissue due to repeated bouts of exercise may reduce the material strength, thereby increasing injury risk. One study took pre-season assessments, including physical fatigue and GJL, and recorded football-related injuries throughout the season (Frisch et al., 2011). The results showed that utilizing a univariate model comparing those with an injury that lasted more than 3 days versus non-injured players, physical fatigue was significantly related to football injury, but GJL was not significantly different (Frisch et al., 2011).

These studies do not examine GJL during a fatigue protocol, but rather after injuries or throughout a season. Assessing laxity specifically at the knee with an arthrometer allows for assessment of laxity throughout a fatigue protocol, which may be more representative of laxity changes within a single game or practice. Utilizing an arthrometer allows for a consistent force to be applied, increasing intra-rater reliability compared to manual tests, such as the Beighton scoring method.

Knee Laxity

Previous research examined the change in AKL before and after respective exercise for each of the following groups of individuals, sedentary controls, squat power lifters, basketball players, and distance runners (Steiner et al., 1986). Steiner et al. (1986) suggests the differences in laxity changes between participant groups can be attributed to the different types of exercise the participants engage in. Distance running and basketball place repetitive stress on the knee joint and led to significant increases in AKL laxity after exercise. Whereas there were no significant changes for the sedentary controls or squat power lifters. For the squat power lifters, the exercise is a few high compressive knee joint loads and did not influence the AKL. This shows that the primary restraints of knee motion, such as the ACL, need to undergo sufficient loading intensity and frequency to stimulate increases in AKL (Steele et al., 1999). Steiner et al. (1986) did not collect laxity measurements post-exercise to examine the recovery of knee laxity, which can be an important aspect to consider for half-time recovery and after games and practices. Subsequent post-exercise laxity measurements were not a part of this study, but the authors note some previous research on recovery rates of connective tissues have been done on other areas of the body (Steiner et al., 1986).

A more recent study by Shultz et al. (2013), examined AKL before and after a warm-up and throughout and after an exercise protocol for intercollegiate and club sport athletes. Females demonstrated peak increased AKL values at halftime and the end of the second half of the fatigue protocol (Shultz et al., 2013). In terms of recovery for the females, the AKL did not return to baseline AKL values, meaning pre warm-up or post warm-up, but the AKL recovery values at 30, 45, and 60 minutes post-fatigue did decrease from the peak values that occurred at the end of each half of the fatigue protocol (Shultz et al., 2013). For males, the AKL values increased less than 5% and throughout the fatigue protocol and during recovery AKL did not significantly differ from the pre-warm-up value (Shultz et al., 2013). In terms of recovery for the males, AKL progressively decreased as recovery time increased (Shultz et al., 2013). In this study, there was individual variability in the amount of AKL change with more females showing a larger increase in AKL compared to males (Shultz et al., 2013). This shows that AKL changes as a result of fatiguing exercise, specifically this fatigue protocol designed to simulate the demands of intermittent endurance sports that involve 45 minutes halves and a 20-minute halftime, such as soccer. However, it is also important to examine the effects of fatigue protocols that are not as specific to a single sport in order to continue to examine how an individual's AKL is affected by fatiguing exercise. It is also vital to examine the more generalizable recreationally active adult population as compared to college-level or elite athletes. Shultz et al. (2013) stated that the more athletic participants may have different characteristics in terms of stiffness, meaning better equipped to resist joint displacement, and therefore result in lower knee laxity changes.

Previous retrospective and prospective studies have consistently found that higher levels of knee joint laxity are associated with an increased risk of ACL injury (Shultz et al., 2013). Additionally, it has been reported that knee joint laxity increases by 20-30% above baseline measurements after 20-30 minutes of exercise, aligning with the timing of the highest injury rates during games or practice sessions (Shultz et al., 2013). This shows the importance of research to continue examining for potential initial increased risk as well as if ACL injury risk changes as AKL changes during exercise.

Fatigue Effects on Supporting Variables

Not only is important to examine the muscular fatigue effects on knee laxity, but it crucial to examine how fatigue effects vertical ground reaction forces (vGRF) and EMG measures. vGRF measurements, such as impact peak and loading rate to impact peak, provide insight into the loading of the musculoskeletal system. EMG measurements, such as power spectral density, provide insight into muscle fatigue and the frequency of the signal.

Fatigue Effects on vGRF

It is important to examine how fatigue affects an individual’s landing performance, which can be examined through vGRF. Ground reaction force is a commonly used measure of the loading of the musculoskeletal system when in contact with the ground (Zadpoor & Nikooyan, 2012). The muscles are activated prior to, meaning as in anticipation of contact with the ground, and in response to contact with the ground to ensure there are no adverse effects of the contact (Zadpoor & Nikooyan, 2012). When the muscles are fatigued after prolonged physical activity the muscles may not have sufficient capacity to manage the contact with the ground and could play a role in a resulting injury (Zadpoor & Nikooyan, 2012). Therefore, it is vital that the external load that the body experiences in a task, measured via vGRF from the force plates, is examined when the muscles are fatigued.

Two common vGRF measurements examined are impact peak and loading rate to impact peak. The impact peak is the peak that occurs when the body makes contact with the ground. The loading rate from initial contact to the first peak shows how quickly the vGRF rises. These measures are important aspects as the amount of load and how quickly the loading occurs affects the loading on the musculoskeletal system and therefore can affect the loading on the ACL. Previous research has found that fatigue alters landing performance and produced results that are consistent with an increase in injury risk, such as increased external loading with repetitions and altered neuromuscular control (James et al., 2006). One study utilized drop landings as the tasks and maximum vertical countermovement jumps as the fatiguing protocol. This study found that the first peak in vGRF, the impact peak, was significantly higher in the fatigued condition compared to the control condition (James et al., 2006). While not statistically significant, this study also found that there was an increase in the vGRF loading rate from initial contact to peak vGRF in the fatigued condition compared to the control condition (James et al., 2006). A meta-analysis on the effects of muscular fatigue on vGRF showed that results of impact peak and loading rate to impact peak vary between studies (Zadpoor & Nikooyan, 2012). The varying results may be a result of the differences in fatigue protocol and the tasks examined. Therefore, it is important to continue to study the impacts of muscular fatigue on vGRF.

Fatigue Effects on EMG

It is also important to examine how fatigue influences muscle activity via EMG. The energy that comes from muscles has a frequency spectrum and the data collected by surface

EMG can be visualized to show the range of frequencies occurring (Criswell, 2010). A power spectral density (PSD) graph displays the different frequencies present from that EMG signal and indicates how likely each frequency is to occur within that signal (Criswell, 2010). When muscles are fatigued, the shape of the frequency spectrum changes as there is a reduction of the higher frequencies and increase of the lower frequencies. This shift in the frequency spectrum could be attributed to the shift in the dominance of fast-twitch muscle fibers to slow-twitch muscle fibers because fast-twitch fibers fatigue faster (Criswell, 2010). Therefore, because fatigue significantly alters the frequency spectrum of muscle activity, which indicates a shift from fast-twitch to slow-twitch muscle fiber dominance, it is crucial to utilize EMG to examine the changes in muscle activity as an individual fatigues.

One study utilized countermovement jumps to induce fatigue and examined pre-and post-fatigue performance in drop landings from an adjustable overhead bar and examined the EMG variables for a pre-activation phase and a landing phase (James et al., 2006). A pre-activation phase is considered 100 milliseconds prior to contact with the ground. The study reported average EMG values as the percent of the maximum values during the control, non-fatigued condition and found that during the landing phase there were not significant differences for the group of participants, but the vastus medialis and semitendinosus did decrease in the fatigued condition (James et al., 2006). For the pre-activation phase, there were no significant differences for the group of participants, but the vastus medialis increased and the semitendinosus decreased in the fatigued condition compared to the control (James et al., 2006). This shows that changes in vastus medialis and semitendinosus muscle activity due to fatigue may occur, suggesting that further research in this area is needed.

Whole Body vs. Local Fatigue

Not only is it important to consider how to examine the effects of fatigue on laxity, vGRF, and EMG, but it is also important to consider how to examine muscular fatigue. Fatigue can be examined on the local level or in terms of whole-body fatigue. Local fatigue is considered isolated muscle fatigue, which may not be representative of the fatigue occurring in real life situations, such as games and practices. Therefore, when conducting research on the recreationally-active population it is important to examine the fatigue effects from a whole-body approach as it is generally considered a better approach when compared to local fatigue (Barber-Westin & Noyes, 2017).

Local Fatigue

Local fatigue is the fatigue of a specific muscle group(s), such as hamstrings or hamstrings and quadriceps (Gear, 2011). Isokinetic muscle fatigue allows a researcher to isolate muscle groups and examine their function in different types of situations (Pincivero et al., 2001). Local muscle fatigue, also referred to as peripheral fatigue (muscle-specific) in previous research are short in duration and leads to a reduction in the capacity of the muscle to produce force at or distal to the neuromuscular junction level (Barber-Westin & Noyes, 2017). This fatigue is caused by metabolic factors or muscle damage if it is primarily eccentric contractions and there are no changes in overall neuromuscular control (Barber-Westin & Noyes, 2017).

Assessing muscle function through localized fatigue protocols does have limitations. For example, Pincivero et al. (2001) demonstrated a linear decrease in quadriceps work during 30 maximal, isokinetic repetitions. The decline in torque production was attributed to a rapid decrease in the firing rate of maximally recruited motor units during the exercise protocol, understood to be mainly driven by anaerobic glycolysis during the short bout of high-intensity exercise (Pincivero et al., 2001). Athletic activities, however, usually require multiple bouts of high-intensity muscle contractions, and aerobic metabolic processes increase in contribution during longer durations of exercise. Furthermore, muscles, such as the hamstrings, may consist of a higher percentage of fast twitch muscle fibers, which compared to slow twitch muscle fibers fatigue faster (Gear 2011). Suggesting, local muscle fatigue induced by isokinetic contractions may not be representative of the fatigue occurring throughout the body where fiber type distribution varies between muscles. Thus, isokinetic based protocols used to induce local muscle fatigue are limited as they do not replicate sport-specific activities and real-life daily activities (Pincivero et al., 2001).

Fatigue of the muscles surrounding the knee is assumed to occur during athletic activities. Fagenbaum & Darling (2003) investigated if local fatigue of the hamstring muscles reduces their ability to produce sufficient tension to protect the ACL against injury (Fagenbaum & Darling, 2003). During knee flexion the hamstring muscle contraction restricts anterior tibial translation but near full extension the hamstring muscle do not provide a large enough posterior force to protect the ACL (Fagenbaum & Darling, 2003). This localized fatigue utilizing a dynamometer on thigh musculature was unable to objectively measure the fatigue of the muscles and was limited in the fact that the fatigue protocol likely reduced the force output of the fast motor units, which are able to recover quickly (Fagenbaum & Darling, 2003). This is not representative of the fatigue an athlete would undergo in a game or practice. In another study an isokinetic dynamometer was utilized to fatigue the knee flexor and extensor muscles and the researchers found that this fatigue protocol did not significantly affect tibial translation (Rozzi et al., 1999).

Isokinetic exercise may be more compressive than shearing, which means that while the flexion and extension fatigue protocol does fatigue the musculature, it does not simulate the joint forces occurring during athletic events (Rozzi et al., 1999). Therefore, it seems that the joint forces in exercises like running and jumping are necessary to induce changes in the laxity of ligaments (Rozzi et al., 1999).

Whole Body Fatigue

Whole body fatigue, or general fatigue as referred to in previous research, utilizes a fatigue protocol with several bouts of sub-maximal tasks (Barber-Westin & Noyes, 2017). This is better when compared to local fatigue for simulating games or practice situations for athletes. Whole body fatigue causes a reduction in the amount of voluntary muscle activation and is generally considered better when compared to local fatigue for simulating games or practice situations for athletes (Barber-Westin & Noyes, 2017). Fatigue protocols that are designed to cause general fatigue involve both peripheral and central fatigue effects (Collins et al., 2016). When comparing local and whole body (general) fatigue mechanisms, it is difficult to counter peripheral fatigue because as the athlete increases effort, the increases in muscle fatigue resistance typically increases so this fatigue is inevitable (McLean & Samorezov, 2009). However, research has shown that targeting the central mechanisms of whole body fatigue, which has been demonstrated to enhance motor performance, may be effective towards negating the negative impacts of fatigue on the risk of ACL injuries (McLean & Samorezov, 2009). Central fatigue mechanisms may potentially be trainable, meaning it can be targeted to modify and counter the impact of fatigue on ACL injury risk (McLean & Samorezov, 2009). One study examined unilateral fatigue during single-leg landings and found that there was a crossover of the fatigue to the contralateral limb, which means that the biomechanical changes to the non-fatigued limb provide evidence that central fatigue appears to be an important component of landing strategies when fatigued (McLean & Samorezov, 2009). The large magnitude of this fatigue crossover also suggests that the isolated central fatigue mechanisms are potentially promoting hazardous adjustments to posture and it is therefore suggested that targeting supraspinal and spinal control may be effective for counteracting the effects of central fatigue in landing strategies (McLean & Samorezov, 2009). It is also suggested that techniques such as more complex, cognitively demanding tasks and mental imagery may be helpful for perception and decision making in sports environments where it is unanticipated tasks (McLean & Samorezov, 2009). Overall, whole body fatigue includes both central and peripheral fatigue, but central fatigue may be a mechanism that can be targeted and modified to reduce ACL injury risk and is it therefore important to examine the effects of whole body fatigue.

Previous research has utilized several different methods to measure fatigue levels, such as Borg's rating of perceived exertion (RPE) scale or measuring a task such as jump height or hop distance (Santamaria & Webster, 2010). In these studies, fatigue was defined as the inability to carry on the fatiguing task or a reduction in the performance metric, such as hop distance (Santamaria & Webster, 2010). However, the type of fatigue protocol chosen may substantially affect results, even when sample population and experimental task are similar. McLean and Samorezov (2009) utilized a fatigue protocol alternating bodyweight squats and cutting trials where maximal fatigue was defined as the inability to perform three unassisted single-leg squats whereas Collins et al. (2016) utilized an intermittent shuttle run (IRS) fatigue protocol to mimic the demands of a soccer match and the participants engaged in a run-and-cut task prior to and after the fatigue protocol. McLean and Samorezov (2009) found that fatigue induced statistically significant decreases in knee flexion angle at initial contact and at peak stance decreases in knee flexion moment and increases in knee abduction angles and moments. Collins et al. (2016) found that there was an 68% increase in peak knee abduction angles after the fatigue protocol and that fatigue therefore promoted knee mechanics, such as knee valgus, that are related to an increased risk of sustaining a knee injury. Collins et al. (2016) utilized a fatigue protocol that was less demanding than the McLean and Samorezov (2009) fatigue protocol. The McLean and Samorezov (2009) study were a generalized fatigue protocol inducing fatigue on a unilateral lower limb, whereas Collins et al. (2016) utilized a fatigue protocol that was more sport-specific and included a cardiovascular component. While both studies found that fatigue affected the knee joint mechanics, the utilization of different fatigue protocols showed varying results and effects.

It is important to examine fatigue through a whole-body fatigue protocol that simulates games or practice situations because that may help provide insight into the relationship between fatigue and AKL when individuals are engaging in games and practices. Previous research has examined biomechanical and performance changes that were fatigue related by examining differences in the activity movements of walking, jogging, cruising speed, and sprinting (Sanna & O'Connor, 2008). The goal is to reach a fatigued state that would be representative of the fatigue an athlete endures during a game or practice (Sanna & O'Connor, 2008). One of the previously validated whole body fatigue protocols is the intermittent shuttle run protocol (IRS), in which the athlete engages in periods of different intensities for a duration between 60 and 90 minutes to produce a soccer-like fatigue state (Sanna & O'Connor, 2008). This fatigue protocol has been found to decrease strength and joint laxity when compared to a fatigue state induced by steady state treadmill running (Sanna & O'Connor, 2008), which further shows the importance of fatigue protocol selection. Another fatigue protocol that has been previously utilized is a soccer-specific match simulation (SAFT45) to mimic the demands that occur during a soccer match (Nuccio et al., 2021). This protocol fatigues the entire body through multi-directional movements, accelerations, and decelerations at varying intensities in three sessions of 15 minutes for a total of 45 minutes (Nuccio et al., 2021). This study found that in healthy male soccer players AKL increased and anterior knee stiffness decreased from baseline after the fatigue protocol (Nuccio et al., 2021). Whole-body fatigue is better when compared to local fatigue for simulating games or practice situations for athletes, but it is vital to consider the impact of fatigue protocol selection, such as more generalized movements (McLean & Samorezov, 2009) or a more sport-specific protocol (Collins et al., 2016; Nuccio et al., 2021; Sanna & O'Connor, 2008), as it can affect the outcomes of knee mechanics and knee laxity.

Warm-Up

The warm-up utilized prior to engaging in physical activity can affect performance outcomes and injury risk. Therefore, it is important to understand the influence of a warm-up on knee laxity.

Effects of a Warm-Up

Athletes engage in a warm-up prior to engaging in sports situations to improve motor performance and prevent injuries (Gelen, 2010). Prior research studies suggest that engaging in warm-ups with voluntary muscle contractions of moderate-to-high intensity increases performance and power production through activating neuromuscular functions, which is known as post-activation potentiation (PAP) (Gelen, 2010). PAP occurs when there is a temporary increase in the muscles contractile ability following previous contractions (Gelen, 2010).

Gelen (2010) investigated the acute effects of various warm-up methods on soccer performance, specifically sprinting, slalom dribbling, and penalty kicks, of professional male soccer players. In this study the warm-up was a low-intensity jog followed by either nothing (no stretching), static stretching, dynamic stretching, or a combination of both static and dynamic stretching (Gelen, 2010). The warm-up consisting of static stretching decreased the performance of the sprints, slalom dribbling, and penalty kicks, while dynamic stretching increased the performance of the sprints, slalom dribbling, and penalty kicks (Gelen, 2010). The combination of static and dynamic stretching in a warm-up mitigated the negative effects of static stretching on the performance tasks (Gelen, 2010). The results of this study demonstrate that the type of warm-up the participants engage in affects performance, specifically performance in high-power production during soccer-specific tasks in this case.

Holt & Lambourne (2008) also examined the effect of warm-up selection on the performance of countermovement jumps (CMJ) in Division I college football players. The participants engaged in a pretest CMJ and then randomly assigned either general cardiovascular warm-up only, general warm-up and static stretching, general warm-up and dynamic warm-up, or general warm-up and dynamic flexibility, followed by the posttest CMJs (Holt & Lambourne, 2008). The participants engaged in the posttest CMJs until their jump height did not increase for two jumps in a row and the highest jump height was utilized (Holt & Lambourne, 2008). Holt and Lambourne (2008) found that there was a significant improvement in the participants vertical jump performance from pre-to-post testing for the general cardiovascular warm-up only, general warm-up and dynamic warm-up, and the general warm-up and dynamic flexibility conditions. The static stretching and general warm up condition had a significantly lower average improvement in jump performance in the posttest, showing that the static stretching had negative effects on performance (Holt & Lambourne, 2008). The acute negative effects of static stretching on power and speed performance is a mechanism that researchers are still trying to explain, specifically through the alterations in the biomechanical characteristics of muscle and in the neuromuscular transmission (Gelen, 2010).

A general cardiovascular warm-up is effective because it increases the temperature in the muscles (DeVries, 1980), which increases flexibility to prepare the individual for the physical activity demands. It also increases heart rate and blood flow (DeVries, 1980), which increases the delivery of oxygen and nutrients to the muscles (Baechle & Earle, 2000).

Previous research has shown that static stretching can have negative effects on performance (Gelen, 2010; Holt & Lambourne, 2008). Dynamic stretching however has been shown to improve performance (Gelen, 2010; Holt & Lambourne, 2008). A general cardiovascular warm-up has been previously found to improve vertical jump performance from baseline testing (Holt & Lambourne, 2008) and is utilized to prepare the individual for engaging in physical activity (Baechle & Earle, 2000). Therefore, engaging in a warm-up that includes a general cardiovascular warm-up and dynamic stretching appears to be appropriate for the recreationally active population prior to engaging in fatiguing physical activity as it has not previously shown to be negatively affect performance.

Laxity and Warm-Up Relationship

The warm-up chosen, meaning static versus dynamic influence the warm-up's relationship with knee laxity. In one study, knee laxity was examined prior to and after a warm-up, as well as during and after an intermittent exercise protocol (Shultz et al., 2013). The participants, intercollegiate and club sport female and male athletes, engaged in a standardized 12-minute dynamic warm-up prior to the fatigue protocol for the experimental session and for the control session engaged in the warm-up, but not the fatigue protocol (Shultz et al., 2013). While transverse plane knee laxity increased from pre-to-post warm-up, there were no significant changes in AKL from pre-to-post warm-up, but AKL increased within the first 15 minutes of the fatigue protocol (Shultz et al., 2013).

This research suggests that increases in knee laxity are more likely to be accredited to the viscoelastic response of the ligament structures due to the repetitive loading of the joint than the decrease of muscle tone that is caused by fatiguing the muscle (Shultz et al., 2013). The authors further suggest that the increases in knee joint laxity may be a physiological response to the tissue warming, which may help the movement efficiency in exercise but may also increase the risk of the joint displacing the loads, and therefore put the athlete as higher risk when fatigue and laxity are increased later in the exercise protocol (Shultz et al., 2013). Therefore, it is important to examine in further detail the effects of the warm-up prior to the fatigue protocol to gain insight into how the warm-up plays a role in AKL for athletes in game and practice situations.

The goal of a warm-up prior to exercise is to increase the temperature of the muscle tissue without causing fatigue and previous research has shown that increasing the tissue temperature increases the extensibility of the viscoelastic tissue (Steele et al., 1999). Another study on healthy individuals examined the effects of a warm-up on active and passive knee laxity utilizing an arthrometer with the aim to determine if a warm-up was necessary in a clinical setting prior to assessing knee laxity (Steele et al., 1999). This study found that there was no increase in passive knee laxity after the warm-up (Steele et al., 1999). Shultz et al. (2013) utilized a KT-2000 Knee Arthrometer with posterior-to-anterior forces from -90 to 133 N, but it is important to continue to examine the knee laxity and warm-up relationship utilizing other arthrometers that measure knee laxity at varying forces and directions of forces. Gaining insight into when the potential changes in AKL are occurring with the protocol simulating a game or practice situation will help provide information on when the athletes are most at risk of ACL injuries, since increases in AKL is a risk factor for ACL injuries (Shultz, Nguyen, and Levine, 2009).

Role of Sex Differences

Previous research shows that there are sex differences between females and males both in the incidence rates of ACL injuries and the changes in AKL throughout a fatigue protocol. It is therefore important to consider the role that sex differences play in ACL injury risk factors, such as increased AKL.

Sex Differences in ACL Injuries

One systematic review on the epidemiology of ACL injuries specifically in soccer stated that the majority of studies found that females are 2 to 3 times more likely to sustain an ACL injury compared to male players (Walden et al., 2011). This systematic review also found that females are more likely to sustain the ACL injury at a younger age compared to males. Previous research also indicates that in non-contact sports females exhibit a higher incidence of ACL injuries (Montalvo et al., 2019). For females, the sports that have the highest injury risk per season were found to be soccer, basketball, and lacrosse (Gornitzky et al., 2016). For males, football, lacrosse, and soccer are the sports that have the highest injury risk per season (Gornitzky et al., 2016). One common factor in these sports is the movement patterns they involve, including rapid changes of direction, which increases the load and loading rate on the ACL. Therefore, understanding how these movement patterns the individual is engaging in within their sport is crucial for assessing injury risk.

Another important factor to consider is that females have greater knee extension moments compared to males, which suggests a muscle force imbalance, meaning that female's quadriceps muscles produce a greater force relative to female's hamstrings force (quadriceps dominance), which increase the ACL strain in the sagittal plane (Hughes, 2014). This increases the ACL strain because it results in an anterior shear force on the proximal end of the tibia, causing anterior displacement of the tibia relative to the femur (Hughes, 2014). This muscle imbalance is a modifiable risk factor because it can be trained to re-balance the muscle strength to be better able to evenly distribute the load and absorb force to reduce the loading on the ACL. It is therefore, important to acknowledge this difference between females and males and examine the muscle imbalance through co-contraction ratio to gain a better understanding of this factor during fatigue. The higher incidence rate of ACL injuries in females can also be contributed to hormonal factors, jump-landing mechanics, gait, and musculoskeletal differences.(Smith et al., 2014) Some of these factors can be modified, which shows the importance of examining them, but it is important to take note of the varying factors and examine how they may play a role in

ACL injuries. This highlights the importance of acknowledging sex as a significant factor in examining risk factors for ACL injuries, as these factors may vary between females and males.

Sex Differences in Anterior Knee Laxity During Fatigue

One study compared male and female intercollegiate and club athletes that engaged in an intermittent exercise protocol that simulated the intensity and length of a soccer match (Shultz et al., 2013). This study found that there were sex differences in AKL in the fatigue protocol condition. In females, the AKL increased at 15 minutes, 30 minutes, 45 minutes, 60, minutes 75 minutes, and 90 minutes in comparison to the baseline pre warm-up AKL values (all $p < 0004$). Also, there were peak values at the end of the first half (45 minutes) and second half (90 minutes) of the protocol (10.1 ± 2.0 and 10.1 ± 2.1 mm, respectively) that were 12% greater than the pre warm-up AKL value (9.0 ± 1.8 mm). Females had greater AKL compared to males at 15 minutes, 30 minutes, 45 minutes, and 90 minutes during the fatigue protocol as well as at 15 minutes and 60 minutes during the recovery period following the fatigue protocol. There was intersubject variability for both sexes, with more females having considerable changes in AKL during the fatigue protocol. This study found that 33% of females and 10% of males had increases in AKL that were equal to or greater than 1.9 mm. Therefore, it is important to further examine the potential increases in AKL in females during fatigue protocols that applies to a more generalized athletic population to continue to gain a better understanding of the roles of fatigue on AKL.

Conclusions

In sports, such as football, basketball, and soccer, ACL tears tend to occur during the rapid and sudden accelerations, decelerations, and changes in direction (De Ste Croix et al., 2015). Muscle fatigue is induced by exercise and is a reduction in the maximal force or power that the involved muscles produce (Enoka & Duchateau, 2008) and considered a risk factor for ACL injury (Collins et al., 2016). Moreover, AKL is another risk factor for ACL injuries (Shultz et al., 2009) and reportedly increases as a result of fatigue (Shultz et al., 2013). However, joint stability is rarely included in the pre-participation physical examinations of athletes, and more work is needed to determine the relationship between physical activity and knee laxity. The previously reported differences in AKL between females and males (Shultz et al., 2013) and the higher ACL injury rates in females (Smith et al., 2014) show the importance of examining the effects of a fatigue protocol specifically on females.

Chapter 3: Methods

The primary purpose of this study was to examine the effects of fatigue on dominant leg anterior knee laxity utilizing a GNRB® arthrometer from baseline to post warm-up and throughout a fatigue protocol that simulated a game or practice situation. The secondary purpose of this study was to examine the influence of fatigue on vertical ground reaction forces, via force plates, as well as quadriceps and hamstrings muscle activity, via EMG.

Participants

Prior to data collection, experimental procedures received ethical approval from the university's Institutional Review Board. The female participants were recruited from the local community via word of mouth, flyer, or an email containing a pre-approved email script. Twenty-one recreationally active females (Age: 21.67 ± 2.22 years, Height: 1.66 ± 0.08 m, Mass: 65.13 ±11.62 kg) engaged in the data collection protocol (Table 1). All the figures and tables are in the appendices section. Inclusion criteria for participation included being 18 to 35 years old, recreationally engaging in physical activity, and have no history of lower extremity injury within the past six months prior to testing or no lower extremity surgeries ever. Participants also reported previous experience in sports, such as basketball and soccer, which was examined during data analysis to provide insight into the participant's familiarity with movement patterns similar to the landing and cutting tasks. For this research, recreationally active was defined as they engaged in physical activity at least three times per week for a minimum of 30 minutes each session, with activity being moderate to vigorous activity, such as running, weight training, elliptical, pick-up basketball, etc. Participants were excluded from this research if they 1) have a history of lower extremity injury within the past 6 months, 2) have had a lower extremity surgery ever, 3) had lower extremity pain on the day of testing, or 4) engaged in physical activity on the day of testing. For exclusion criteria 3 and 4, the participant's data collection was rescheduled for another day. For the power analysis the alpha level was set at 0.05 and the beta power level was set at 0.8. Based on an expected effect size of 0.28 (Shultz et al., 2013), the power analysis indicated that a sample size of 15 participants would be sufficient to detect the expected effect size in anterior knee laxity. Shultz et al. (2013) had 13 measurements of AKL from before, during, and after the fatigue protocol (2 before, 7 during, and 4 after), whereas the current study had 6 measurements of AKL total (2 before, 3 during, and 1 after for recovery). Based on the expected effect size of 0.39 (James et al., 2006), the power analysis indicated that a sample size of 11 would be sufficient to detect the expected effect size for peak vGRF. Based on the expected effect size of 0.30 (James et al., 2006), the power analysis indicated that a sample size of 17 would be sufficient to detect the expected effect size for vGRF loading rate. Therefore, a sample size of 21 participants was utilized so that the study was sufficiently powered.

Participant Preparation

Data collections were preceded by the informed consent form, Fitness Activity Questionnaire, modified-musculoskeletal questionnaire, and the Lower Extremity Functional Scale. Participant height and weight were measured with a stadiometer and force plate, respectively. The participants were fitted with a heart monitor. EMG electrode sites were identified and prepared for the vastus medialis and medial hamstrings of the preferred kicking leg. Electrodes were placed according to the SENIAM Guidelines (Hermens et al., 2000). Skin preparation consisted of shaving the hair, abrading the skin, and cleaning the skin with isopropyl alcohol. After EMG electrodes were placed, the inferior pole of the patella and the anterior tibial tuberosity were identified and marked to ensure consistent alignment in the arthrometer for all anterior knee laxity tests (Figure 1).

Experimental Protocol

Following participant preparation for the data collection, the participant engaged in the pre warm-up laxity test. The arthrometer mimics the position of the Lachman test, a clinical test to evaluate the ACL, at 20 degrees of knee flexion, but controls the pressure stabilizing the patella and is able to measure anterior tibial translation without the participant activating the hamstring muscles (Magdic et al., 2023). Utilizing the arthrometer over the clinical test has the advantage of greater objectivity (Magdic et al., 2023). The inter-rater reliability of the arthrometer in healthy, active participants has been previously found to be good for measurements of a force of 134 Newtons and 200 Newtons on the tibia (Magdic et al., 2023). Magdic et al. (2023) examined activation of the hamstring muscles during laxity test, as a contraction can reduce the displacement of the tibia, and showed the importance of informing the participant to relax their body during the laxity testing. The participant positioning is very important and even slight changes can influence the displacement measurements (Magdic et al., 2023), so the participants were positioned utilizing the markings made in participant preparation. The participant underwent 3 anteriorly direct forces of 134 Newtons to measure the anterior laxity of the knee.

After the pre warm-up laxity test, the participant put on the heart rate sensor and then engaged in the dynamic warm-up. The warm-up included the following: 3 minutes of forward and backwards joggings over 10 yards, 10 heel-toe walks on each leg, 10 heel kicks on each leg, 10 yard side shuffle in each direction, 10 walking lunges on each leg, 10 each of inward and outward walking hip rotations on each leg, and 10 high knees on each leg. Maximum voluntary isometric contraction (MVIC) for each of the EMG sensors were collected for normalization purposes. EMG data were collected while the participant is encouraged to perform a maximal isometric contraction for 5 seconds. The participant sat on a dynamometer with their hips flexed to 90 degrees and their knee flexed to 60 degrees for both the vastus medialis and medial hamstrings MVICs (Ebben et al., 2010). The 90 degree angle for the hip joint and the 60 degree angle for the knee joint were confirmed utilizing a goniometer measurement. Following the MVIC, the CMJ was utilized to assess fatigue through changes in jump height (Figure 2C). The participant stood with both feet on one force plate, then they squatted down, and with maximal effort vertically jumped and landed back on the force plate. The participant was allowed to freely move their arms as they preferred in the trials. The participant completed 3 successful trials. For the CMJ, the trial was deemed unsuccessful if the participant did not land fully and steadily with both feet on the force plate. If deemed unsuccessful, the trial was re-done. Following the CMJ trials, anterior knee laxity was measured again as previously described for the post warm-up measurement.

Next, the participant engaged in the baseline landing tasks: drop jump and drop cut (Figure 2). The participants were allowed to practice each task until they felt comfortable and then completed 5 successful trials of each. For the drop jump landing task, the participant began on a 30 cm box placed 10 cm behind the force plate. The drop jump landing task required the participants to drop from the box with both feet, and immediately perform a maximum effort vertical jump, landing back on force plates. For the drop cut task the 30 cm box was placed one half of their standing height away from the force plates (Padua et al., 2009). This utilized the

Landing Error Scoring System (LESS) methodology for a drop jump as it is a clinical assessment tool for non-contact ACL injuries. The drop cut task required the participants to perform a single leg forward jump with minimal upward displacement from box where the participant jumped from their non-testing limb and landed on the testing limb onto one force plate and immediately cut at 45 degrees to the opposite side. For example, a forward jump from the box from the left leg onto the right leg and cutting to the left. For all the landing tasks, the trial was deemed unsuccessful if any of the following occurred: the participant did not land with their testing limb foot completely on the force plate for the initial landing from the box, the participant dropped from the box instead of a forward jump, or if the participant jumped up rather than forward and out. If deemed unsuccessful, the trial was re-done.

The fatigue protocol, that simulated a game or practice situation, consisted of three rounds of a modified Yo-Yo Intermittent Recovery Test Level 1 (Yo-Yo Test). The Yo-Yo Test has been found to be significantly correlated with intermittent sports such as soccer (Schmitz et al., 2018). Following each round of the Yo-Yo Test, three CMJ trials were collected, anterior knee laxity was immediately measured following that, and then the participant engaged in five successful trials of each of the landing tasks. Borg's Rating of Perceived Exertion (RPE) Scale from 6-20 was used as a tool for monitoring exercise intensity and the participant's subjective perception of effort after each round of the Yo-Yo Test (Scherr et al., 2013). Heart rate was measured immediately prior to and upon completion of each round of the Yo-Yo Test. A visual aid of the overall experimental protocol is shown in Figure 3.

The Yo-Yo Test (Figure 4) consisted of a 20-meter runway where the participant began at the sound of the audio beep, had to reach the turn-around point before a second audio beep and returned to the starting position before a third audio beep. There was a 10 second active recovery period between every 40-meter run, during which the participant had to walk or jog and returned to the starting point. For rounds one and two of the Yo-Yo Test, the running speed increased at regular intervals (Table 2). Participants continued for as long as they could maintain the pace.

For all three rounds of the Yo-Yo Test, the participants ran until they received 2 infractions. Participants were given a warning when they started the run before the audio signal, did not reach either line before the audio signal, or turned before the 20-meter mark. Due to space limitations, the Yo-Yo Test was modified by placing a line 2 meters in front of the original start line as the start line was a wall and the participant needed space to decelerate to avoid hitting the wall, as well as the 5 meters of active recovery was in front of the start line. In round three of the Yo-Yo Test, the speed was set at the participant's average stage level from the maximum level achieved in the first and second rounds. Participants ran at that speed until they received two infractions which marked the end of the third round of the Yo-Yo Test.

Following the third round of the Yo-Yo Test the participant engaged in the three successful trials of CMJ, an immediate post-fatigue laxity test, and the final round of five successful trials of each of the landing tasks. 30 minutes following the end of the tasks the participant engaged in another final laxity test to examine the recovery rate of their AKL.

Instrumentation

A GNRB® arthrometer (Genourob, Lavel, France) was utilized to analyze ACL laxity, through displacement, via an automated Lachman test with a pre-determined force. A dynamometer (Biodex Medical Systems, System 4 Pro, NY, USA) was utilized for the MVIC for the EMG. The vertical ground reaction force (vGRF) data during the landing tasks was collected via AMTI force plates (2000 Hz, AMTI, Inc., Watertown, MA, USA). A Tringo™ Wireless EMG system (2000 Hz, Delsys, Inc., Natick, MA, USA) was utilized to measure muscle activity during the landing tasks. The vGRF force plate and EMG data was processed utilizing Matlab (R2022b, MathWorks Inc., USA). The statistical analysis was completed in SPSS (IBM SPSS Statistics, Version 29, Armonk, NY, USA). The Polar Verity Sense optical heart rate sensor was utilized to measure heart rate (Polar Electro, USA). G*Power Software (3.1.9.7, Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) was utilized to run a power analysis to determine a sufficient sample size.

Data Reduction and Analysis

The data for each trial was organized into two phases: pre-activation phase and landing phase. The pre-activation phase was defined as 100 milliseconds before the initial contact with the force plate (Kellis & Kouvelioti, 2009). The landing phase was defined as the time from initial contact with the force plate to the last contact with the force plate, meaning it includes both the eccentric and concentric phases.

The vGRF data was filtered with a 4th order low pass Butterworth filter with a cut-off frequency of 50 Hz. Then the vGRF data was trimmed to the landing phase by finding participant's first contact and last contact with the force plate. The vGRF data examined the peaking loading by finding the maximum vGRF. The loading rate of the landing phase of the tasks were found by calculating the rate of change over time (N/s). The average loading rate from initial contact with the force plate to peak vGRF was calculated. The vGRF data was normalized to body weight to compare the subjects. The vGRF variables were calculated for each of the five trials at a singular timepoint and then those values were averaged to one value.

The CMJ trials were conducted to assess fatigue by examining jump height. The vGRF collected during the countermovement jump trials were filtered with a 4th order low pass Butterworth filter with a cut-off frequency of 50 Hz. The start of the CMJ was defined as the instance the vGRF magnitude became less than the participants body weight (Figure 5). Then the takeoff was defined as first instance the vGRF was zero (Figure 5). The jump height was then calculated utilizing the impulse-momentum relationship from start of the CMJ to takeoff. The CMJ jump height was calculated for each of the three trials at a singular timepoint and then those values were averaged to one value.

Raw data was imported from the EMG sensors for muscle activity analysis. The raw data signal was processed with a 2nd order high pass Butterworth filter with a cut-frequency of 20 Hz. Then the data was full-wave rectified and followed by the application of a 2nd order low pass Butterworth filter with a cut-off frequency of 15 Hz. The MVIC data was then processed with a moving average filter with a window of 0.1 seconds. Finally, the trial EMG was normalized to the maximum of the MVIC moving average. The power spectral density for the EMG data was calculated utilizing the high pass filtered data to examine the frequency components for the probability of their occurrence. The median frequency was also calculated using the high pass filtered data to examine the muscular fatigue. Median frequency was calculated instead of mean frequency because it is less sensitive to noise and more sensitive to the biochemical and physiological processes occurring in the muscles during contractions (De Luca, 1997). Finally, the co-contraction ratio between the vastus medialis of the quadriceps and the medial hamstrings was calculated utilizing the average of the normalized data. The EMG variables were calculated for each of the five trials at a singular timepoint and then those values were averaged to one value.

The GNRB® arthrometer provided a knee displacement differential in millimeters for each of the three anterior pushes in one laxity testing session. These three displacements were averaged to create one displacement value in millimeters per testing time point. Shultz et al. (2013) utilized the average of the last two displacements at each time point, therefore that metric was also completed in the current study for comparison. The averaged AKL displacement from each time point was utilized in the 1x6 repeated measures ANOVA to examine the effects of fatigue.

Statistical Analysis

A 1x6 repeated measure ANOVA was used to examine the effects of fatigue on anterior knee laxity. The AKL measurements were at the following time points: 1) pre warm-up, 2) post warm-up, 3) post Yo-Yo test round 1, 4) post Yo-Yo test round 2, 5) immediate post fatigue after Yo-Yo round 3, and 6) 30 minutes post fatigue after completion of tasks. A 1x4 repeated measure ANOVA was used to examine the effects of fatigue on vGRF and EMG variables. The drop jump landing and drop cut tasks were completed at the following timepoint: 1) post warm-up, 2) post Yo-Yo test round 1, 3) post Yo-Yo test round 2 and 4) post fatigue after Yo-Yo test round 3. The significance level for all tests was set at $\alpha=0.05$. Mauchly's Test of Sphericity assessed sphericity. There was no confidence interval adjustment applied to the ANOVAs, the least significant difference (LSD) was utilized for the pairwise comparison. Cohen's d effect-sizes were calculated for statistically significant pairwise comparisons. The Greenhouse-Geisser correction was applied if Mauchly's Test of Sphericity was significant, indicating a violation of the sphericity assumption. Post-hoc analysis was completed with ANOVA's and t-tests as an exploratory analysis to provide insight on the results of the primary variables based on the criteria of positive and negative AKL responders that had a 10% difference from baseline measurement to the Yo-Yo Round 3 measurement. A 2x6 repeated measures ANOVA was completed with the criteria of positive and negative AKL responders over the time points.

Chapter 4: Results

Anterior Knee Laxity

A 1x6 repeated measures ANOVA determined Mauchly's Test of Sphericity was not significant so sphericity was assumed and there was no significant difference across the time points when averaging the three trials at each timepoint ($F_{5,100}$=1.714, *p*=0.138, η^2=0.079) (Table 3). A 1x6 repeated measures ANOVA determined Mauchly's Test of Sphericity was not significant so sphericity was assumed and there was no significant difference across the time points when averaging the last two trials at each timepoint ($F_{5,100}$=1.573, *p*=0.175, η^2=0.073) (Table 3). The AKL did show an increase from baseline measures to round three of the Yo-Yo Test for both the average of three trials and the last two trials, but it was not a statistically significant increase (Table 3). Shultz et al. (2013) utilized the average of the last two displacements at each time point for their analysis because they found in pilot testing the last two displacements were more stable measurements when compared to all three displacements. Therefore, for comparison the current study analyzed the data for all three displacement trials and for the last two displacements trials at each time point. There was also a decrease in AKL from round three of the Yo-Yo Test to the post fatigue measurement after 30 minutes of recovery.

Vertical Ground Reaction Forces

Drop Cut Task

For the normalized peak impact load, a 1x4 repeated measures ANOVA determined Mauchly's Test of Sphericity was significant so a Greenhouse-Geisser correction was applied, and no statistical significance was found across the time points ($F_{2.072,41.441}$=1.323, *p*=0.278,

η^2=0.062) (Table 4). For the normalized average loading rate, a 1x4 repeated measures ANOVA determined Mauchly's Test of Sphericity was significant so a Greenhouse-Geisser correction was applied, and no statistical significance was found across the time points ($F_{1.328,26.553}$=0.532, *p*=0.521, η^2=0.026) (Table 4).

Drop Jump Task

For the normalized peak impact loading, Mauchly's Test of Sphericity was violated so the Greenhouse-Geisser correction was applied and the 1x4 repeated measures ANOVA revealed there was a statistically significant difference across measures and large effect size ($F_{1.784,35.679}$=7.841, *p*=0.002, η^2=0.282) (Table 5). The pairwise comparison showed that there was a statistically significant increase from baseline measurement to rounds one, two, and three of the Yo-Yo Test (respectively, mean difference: +0.262 BW, *p*=0.001, d=0.58; mean difference: +0.194 BW, *p*=0.030, d=0.43; mean difference: +0.295 BW, *p*=0.004, d=0.61). There was a statistically significant increase from round two of the Yo-Yo Test to round three of the Yo-Yo Test (mean difference: +0.102 BW, *p*=0.043, d=0.20).

For the normalized average loading rate, Mauchly's Test of Sphericity was violated so the Greenhouse-Geisser correction was applied and the 1x4 repeated measures ANOVA revealed there was a statistical significance and large effect size ($F_{1.911,38.216}$=4.476, *p*=0.019, η^2=0.183) (Table 5). The pairwise comparison showed that there was a statistically significant increase from the baseline measurement to rounds one and two of the Yo-Yo Test (respectively, mean difference: +11.328 BW/s, *p*=0.002, d=0.22; mean difference: +8.482 BW/s, *p*=0.049, d=0.16).

Jump Height from Countermovement Jump

The vGRF from the countermovement jump was utilized to assess fatigue through jump height. A 1x4 repeated measures ANOVA determined that Mauchly's test of Sphericity was significant ($p<0.001$), so the Greenhouse-Geisser correction was utilized and there was statistically significant difference found across the time points as well as a large effect size ($F_{1.967,39.342}=5.324$, $p=0.009$, $\eta^2=0.210$). There was a statistically significant decrease from jump height at baseline to rounds two and three of the Yo-Yo Test (respectively, mean difference: -0.020 m, $p=0.042$, d=0.35; mean difference: -0.037 m, $p=0.009$, d=0.63). There was also a statistically significant decrease from jump height at round one of the Yo-Yo Test to round three of the Yo-Yo Test (mean difference: -0.022 m, $p=0.033$, d=0.39).

Electromyography

For the EMG variables, there were two participants that had technical issues with the EMG data during the data collection and therefore their EMG data was excluded from analysis, meaning that only 19 participants were included in these statistical tests.

Drop Cut Task

In the pre-activation phase, the 1x4 repeated measures ANOVA conducted on the median frequency for the vastus medialis (VM) demonstrated statistical significance and revealed a large effect size ($F_{3,54}=2.538$, $p=0.003$, $\eta^2=0.226$) (Table 7). The pairwise comparison revealed there was a statistically significant increase in VM median frequency from the baseline measurement to rounds two and three of the Yo-Yo Test (respectively, mean difference: +9.794 Hz, $p=0.008$, d=0.94; mean difference: +9.081 Hz, $p=0.004$, d=0.89). There was also a statistically significant increase from round one of the Yo-Yo Test to rounds two and three of the Yo-Yo Test (respectively, mean difference: +7.871 Hz, *p*=0.018, d=0.72; mean difference: +7.158 Hz, *p*=0.030, d=0.66) (Table 7, Figure 6). The median frequency for medial hamstrings (MH) in the pre-activation phase was not statistically significant ($F_{3,54}$=1.534, *p*=0.216, η^2=0.079) (Table 7). For the landing phase, the median frequency of VM violated the assumption of sphericity so the Greenhouse-Giesser correction was applied and the ANVOA revealed there was not statistically significant difference across the time points ($F_{1.941,34.939}$=0.054, *p*=0.944, η^2=0.003) (Table 7). The median frequency for MH in the landing phase was not statistically significant ($F_{3,54}$=0.561, *p*=0.643, η^2=0.030) (Table 7). The analyses for pre-activation and landing co-contraction ratio violated the assumption of sphericity so the Greenhouse-Geisser correction was applied. The co-contraction ratio of VM to MH was not statistically significant for the pre-activation phase ($F_{1.42,25.562}$=2.538, *p*=0.113, η^2=0.124). The co-contraction ratio was also not statistically significant for the landing phase ($F_{1.758,31.636}$=1.71, *p*=0.199, η^2=0.087). The co-contraction ratio was higher in the landing phase as compared to the pre-activation phase (Figure 7).

Drop Jump Task

For the pre-activation phase the median frequency for VM was not statistically significant and had a medium effect size ($F_{3,48.373}$=1.724, *p*=0.173, η^2=0.087) (Table 8, Figure 8). The median frequency for MH violated the assumption of sphericity so the Greenhouse-Geisser correction was applied, and it was not statistically significant ($F_{1.837,33.064}$=1.005, *p*=0.371, η^2=0.053) (Table 8). For the landing phase, the median frequency for VM and MH violated the assumption of sphericity, so the Greenhouse-Geisser correction was applied. The median frequency for VM was not statistically significant ($F_{1.965, 35.369}$=1.549, *p*=0.227, η^2=0.079) (Table 8). Also, the landing phase median frequency for MH was not statistically significant

($F_{1.921,34.569}$=0.658, p=0.518, η^2=0.0.35) (Table 8). For the pre-activation and landing phases, the co-contraction ratio violated the assumption of sphericity, so the Greenhouse-Geisser correction was applied. The co-contraction ratio of VM to MH was not statistically significant for the pre-activation phase ($F_{1.888,33.988}$=0.428, p=0.734, η^2=0.023) (Table 8). The co-contraction ratio was also not statistically significant for the landing phase ($F_{1.831.32.964}$=0.345, p=0.793, η^2=0.019) (Table 8). Throughout the protocol, the co-contraction ratio for both the pre-activation and landing phase of the drop jump task the co-contraction ratio was greater than one, indicating quadriceps dominance (Figure 9). The co-contraction ratio was higher in the landing phase as compared to the pre-activation phase.

Chapter 5: Discussion

The aim of this study was to examine if there is a relationship between muscular fatigue and AKL. The co-contraction ratio and median frequency from the EMG data as well as the impact peak load and average loading rate from the vGRF data were exploratory elements of the analysis to provide more insight.

Co-Contraction Ratio

Co-contraction ratio provides insight into muscle imbalance by examining if and by how much the magnitude of the quadriceps muscle force is greater than the hamstrings muscle force because it increases sagittal plane ACL strain (Hughes, 2014). The hypothesis that the co-contraction ratio would increase from baseline measures to completion of the fatigue protocol was not supported because the results were not statistically significant. A co-contraction ratio greater than one means the participant is more quadriceps muscle force dominant. Although the current study did not find significant differences in the co-contraction ratio, the results indicate quadriceps dominance during the landing phase. This quadriceps dominance can compromise knee joint stability and increases strain on the ACL (Padua et al., 2006). The averages for the participants showed quadriceps dominance, but the standard deviations show there were some participants that had co-contraction ratios less than one, meaning hamstring dominant during the pre-activation phase (Figure 7). These findings emphasize the need for further research on this variable.

Padua et al. (2006) suggests that a shift to a quadriceps dominance when fatigued is a compensatory mechanism to counteract quadriceps muscle fatigue and enhance the internal knee extension moment that is generated by the quadriceps muscles. Quadriceps dominance is considered bad for knee joint stability and increases strain on the ACL (Padua et al., 2006), suggesting that further research is still needed. Although the current study did not find a significant change in co-contraction ratio, the results show quadriceps dominance in the landing phase. Previous research has found that there are sex differences in co-contraction ratios of the quadriceps to hamstrings, where females had greater co-contraction ratios and therefore utilized a more quadriceps dominant strategy (Padua et al., 2006). Muscle imbalance, which is a modifiable risk factor for ACL injuries, can be addressed through targeted training to achieve a more balanced load distribution between the quadriceps and hamstrings muscles. This helps to more evenly distribute the load and absorb the force, thereby reducing the loading on the ACL. Therefore, this is a variable that should be continued to be researched for injury prevention strategies, especially for females.

Median Frequency

The hypothesis that median frequency would decrease from baseline to after completing the fatigue protocol was not supported for the drop jump task or drop cut task. The shift in median frequency from the surface EMG power spectrum density is one method of assessing muscular fatigue (Criswell, 2010). For the drop cut task, the median frequency significantly increased from baseline to completion of the fatigue protocol for the VM in the pre-activation phase, which conflicts with the direction of the hypothesis. The increase in median frequency could be attributed to the recruitment of specific motor units and a potential absence of the anticipated transition from fast twitch to slow twitch motor units. The Yo-Yo Intermittent Recovery Test Level 1 was designed for recreational level athletes, as it is the version that starts at a lower speed, but for this sample population appeared to be more of a cardiovascular exerting task than muscularly fatiguing. Therefore, during the fatigue protocol the participants might not have been recruiting the fast twitch motor units as expected, potentially fatiguing the slow twitch motor units more. In order to generate the force output required in the experimental tasks, the drop cut and drop jump, participants might not have required maximum activation of the muscle and potentially, based on Henneman's Size Principle, been able to accomplish the tasks without requiring the largest fast twitch motor units.

It is important to consider how long the participants were running for in each round of the Yo-Yo Test because this will affect the type and amount of motor units in our muscles of interest. Type I (slow twitch) muscle fiber motor units are utilized in aerobic and endurance activities, are smaller in size, and are more fatigue resistant. Type II (fast twitch) muscle fiber motor units are utilized in anaerobic, high-intensity explosive activities, are larger in size, and do not require oxygen so they produce energy quickly but fatigue quicker. As per Henneman's Size Principle, the smaller and less fatigable Type I motor units will be recruited first, followed by the recruitment of the Type II motor units as the intensity and frequency of the stimulus increases (Ehrman, 2018). Alterations in the recruitment and synchronization of motor units and muscle fiber type have been linked to changes in the frequency of the power spectral density (Allison & Fujiwara, 2002). Therefore, it was expected that median frequency would decrease because the Type II motor units would become fatigued. In fact, the opposite occurred as the VM median frequency increased during the pre-activation phase, indicating a shift from Type I to Type II motor units. For the expected decrease in median frequency to occur, future research should consider alternative fatigue protocols that would require more muscle force. One example would be to utilize the experimental task as the fatigue protocol. Cooper et al. (2020) utilized the Bosco fatigue protocol, in which participants engaged in continuous maximal-effort squat jumps until they did not touch an elastic band set at their 90-degree knee angle height. This study found that there was a significant decrease from pre- to post- fatigue in countermovement vertical jump height, peak power, peak force, impact force, and peak velocity potentially due to a decrease in the force generating capacity of the lower extremity muscles following the fatigue protocol (Cooper et al., 2020). Another example would be to utilize an isokinetic knee flexion and extension fatigue protocol, which would be a more localized fatigue protocol, such as the one utilized by Fagenbaum and Darling (2003).

Peak vGRF and Average vGRF Loading Rate

Peak vGRF and average vGRF loading rate were examined as indicators of magnitude of the external load applied and the rate at which it was applied to the musculoskeletal system (Xia et al., 2017) as it affects the loading on the ACL (Maniar et al., 2022). The hypothesis that peak impact load would increase from baseline measures to completion of the fatigue protocol was supported for the drop jump task, but the results were not statistically significant for the drop cut task. It has been found that the magnitude of peak impact load significantly increases when participants are fatigued (James et al., 2006), which aligns with the results of the drop jump task. James et al. (2006) reported an increase in peak impact load from 12.5 ± 4.76 N/kg (1.27 ± 0.46 BW) to 15.4 ± 4.83 N/kg (1.57 ± 0.49 BW), from the control condition to when fatigued, respectively. From baseline measurements to completion of the final round of the fatigue protocol, the current study found that peak loading increased from 1.81 ± 0.41 BW to 2.11 ± 0.55 BW (Table 5). James et al. (2006) consisted of five healthy male participants and the fatigue protocol consisted of countermovement jumps utilizing a jump-and-reach-protocol with the drop landing protocol occurring from a hanging overhead bar. Therefore, the differences in the magnitudes of peak load may be due to subtle methodological differences between the studies.

The hypothesis that average loading rate would increase from baseline measures to completion of the fatigue protocol was not supported for the drop cut task but was partially supported for the drop jump task. In the drop jump task, the average loading rate significantly increased from baseline to rounds one and two of the Yo-Yo Test, but was not significant for round three of the Yo-Yo Test. From baseline measurements to completion of the final round of the fatigue protocol, the current study found that average loading rate increased from 52.61 ± 49.41 BW/s to 61.95 ± 49.71 BW/s (Table 5), with significant increase from baseline measures to rounds one and two of the Yo-Yo Test. James et al. (2006) did not find a significant difference from the control to fatigue condition, but found an increase from 949.7 ± 345.52 N/(s·kg) (96.81 ± 35.22 BW/s) for the control condition to 1130.00 ± 260.45 N/(s·kg) (115.19 ± 26.55 BW/s) when fatigued. The differences in significance and magnitude of the loading rate again may be due to the differences in the sex of the participants, as there are anatomical differences between men and women, and protocols (James et al., 2006).

Zadpoor and Nikooyan (2012) explain that there are two predominant biomechanical theories on the effects of muscular fatigue regarding peak impact load and loading rate, with one expecting an increase and the other expecting a decrease with muscular fatigue. One line of reasoning, which aligns with the hypothesis of the current study, suggests that muscle fatigue impairs the body's ability to effectively absorb ground impact (Zadpoor & Nikooyan, 2012). Therefore, assuming that controlled joint movement is essential for maintaining a consistent GRF, it is expected that peak impact load and/or loading rate should increase (Zadpoor &

Nikooyan, 2012). The alternative biomechanical theory is the speculation that the body utilizes protective strategies, lowering the peak load and/or loading rate as muscle fatigue occurs to prevent the body from incurring injuries (Zadpoor & Nikooyan, 2012). For both the drop jump and drop cut task the peak load and loading rate increased from baseline to round three of the Yo-Yo Test, aligning with the first biomechanical line of reasoning. The drop cut potentially may not have shown significance due to differences in mechanisms between the tasks and it is possible that the participants did not achieve the level of muscular fatigue required to elicit the anticipated changes in the drop cut task. A meta-analysis by Zadpoor and Nikooyan (2012) states that many of the studies reviewed assumed that increased peak load or loading rate are associated with an increased risk of injuries during running and landing, but the validity of this assumption needs to be further researched to provide more insight into the relationship between peak load and/or loading rate and a higher risk of running and landing injuries. Additionally, given that previous literature indicates variations in vGRF responses, it has been proposed that the neuromuscular system may respond differently to various fatigue conditions or neuromuscular impairments, possibly optimizing the neuromuscular systems response to vGRF based on different performance factors (James et al., 2010). Two approaches that have been suggested are reduced vGRF and stiffness or increased vGRF and stiffness, but it is unknown what factors these changes are related to, such a type or severity of fatigue or type or intensity of exercise (James et al., 2010). This means that when comparing studies it is important to note the differences in fatigue protocols as that will result in different performance changes (James et al., 2010) and therefore highlights the importance of choosing a fatigue protocol that best reflects the activities of the sample population.

Anterior Knee Laxity

The hypothesis that AKL would increase from baseline measures to completion of round three of the Yo-Yo Test fatigue protocol was not supported by statistically significant findings. Shultz et al. (2013) found that AKL in females significantly increased during the sport-related intermittent exercise protocol at multiple time points compared to the pre warm-up displacement (p<0.004). For females, the AKL peaked at halftime and the end of the second half of the fatigue protocol (respectively, 10.1 ± 2.0 and 10.1 ± 2.1 mm), which were 12% higher than the pre warm-up displacement (9.0 ± 1.8 mm) (Shultz et al., 2013). In the current study, the AKL peaked following round one of the Yo-Yo Test (4.9 ± 1.23 mm) which was 12.9% higher than the pre warm-up displacement (4.34 ± 0.97 mm). The differences in magnitudes of the AKL displacements could be due to multiple factors that should be considered in future AKL fatigue protocol studies. One of the primary differences is the population of the current study was self-reported recreationally active females and the participants in Shultz et al. (2013) were intercollegiate and club sport athletes. Shultz et al. (2013) suggested that the participants in their study that were more athletic had different stiffness characteristics, meaning increased muscle strength that can resist joint displacement, which consequently resulted in diminished fatigue-induced changes in AKL. The athletic ability and previous sports participation for the participants in the current study has a larger variability as compared to Shultz et al. (2013), which may be one explanation for the differences in results. Shultz et al. (2013) were higher-level athletes that regularly engage in competitive sports that involve running, cutting, and landing movements, which is when ACL injuries tend to occur (De Ste Croix et al., 2015), whereas that was not a requirement for the current study and only one subject reported currently engaging in a recreational sport that involves these movement patterns. The daily loading of the ACL for participants in this previous study may vary from that of the current study, which may be a factor in the results. It is also important to note that there was a difference in the type of arthrometer utilized for AKL measurements. The current study used an GNRB® arthrometer with three anteriorly-directed forced at 134 N, whereas Shultz et al. (2013) utilized a KT-2000™ arthrometer that conducted three posterior-to-anterior directed forces at -90 to 133 N. The GNRB® arthrometer demonstrates more consistent intra-rater and inter-rater reliability as compared to the KT-1000™ arthrometer (Collette et al., 2012; Klasan et al., 2020). Since the components of the KT-2000™ arthrometer are the same as the KT-1000™ arthrometer (Collette et al., 2012), the GNRB® arthrometer proves to be a more reliable and consistent device than both the KT-1000 ™ and KT-2000 ™. This reliability is crucial for interpreting differences in study results and for guiding future research.

Shultz et al. (2013) also stated there was a notable variability in the magnitude of increases in AKL between individual participants. It is currently unknown what causes this intersubject variability, which is also seen in the current study. The intersubject variability could stem from a variety of factors such as variations in training impacts, alignment of the lower extremities, movement patterns, anthropometrics, or joint geometry, all of which may influence the multi-directional stresses that are placed on the soft tissues, such as the ACL, that surround the knee during sports activities (Shultz et al., 2013). The individual differences each participant has in lower extremity lean muscle mass and the mechanical properties of their knee ligaments, which influence knee joint behavior, could also be affected during exercise (Shultz et al., 2013). Shultz et al. (2013) concluded that additional research was warranted to investigate which factors promote larger increases in AKL during exercise as compared to those observed in other individuals.

Through post-hoc exploratory analysis this aspect was further examined with the AKL results from the current study. Although the AKL displacement was not statistically significant, post-hoc exploratory analysis was completed to provide insight into the differences in positive and negative responses to fatigue that the participants had. Participants were classified based on a 10% difference from baseline displacement values to the round three Yo-Yo Test values as positive responders (increased displacement), negative responders (decreased displacement), or non-responders (displacement variation within 10%). The results showed that 10 participants responded positively to fatigue, 3 negatively, and 8 showed no change in AKL. A 2x6 repeated measures ANOVA was then completed between the positive and negative responders. Mauchly's Test of Sphericity showed sphericity was assumed and there was statistically significant difference between the positive and negative responders when there is a 10% difference in displacement between the baseline measurement and the AKL following round 3 of the Yo-Yo Test ($F_{5,55}=50.31$, $p<0.001$, $\eta^2=0.314$) (Table 9). For the negative responders, there was a statistically significant decrease between the pre warm-up and round three of the Yo-Yo Test (Mean difference: -1.433 mm, $p=0.017$, d=1.42), post warm-up and round three of the Yo-Yo Test (Mean difference: -1.167 mm, $p=0.035$, d=12.78), and round one of the Yo-Yo Test and round three of the Yo-Yo Test (Mean difference: -1.343 mm, $p=0.008$, d=1.65) (Table 9). For the positive responders, there was a statistically significant increase between the pre warm-up and rounds one, two, and three of the Yo-Yo Test as well as the 30-minutes post fatigue recovery measurement (respectively, mean difference: +0.942 mm, $p<.001$, d=0.95; mean difference:

+1.298 mm, *p*=0.005, d=1.08; mean difference: +1.410 mm, *p*<.001, d=1.27; mean difference: +0.789 mm, *p*=.022, d=0.96) (Table 9). The positive responders had a statistically significant increase from post warm-up to rounds two and three of the Yo-Yo Test (respectively, mean difference: +0.818 mm, *p*=0.20, d=0.67; mean difference: +0.930 mm, *p*=.005, d=0.82) (Table 9, Figure 10).

This shows there may be other variables that need to be examined to explain why individuals have a positive, negative, or no response in AKL displacement to a fatigue protocol. Two-tailed t-tests were completed comparing the positive and negative AKL responders with the following variables: height, mass, Yo-Yo Test distances in each round, Yo-Yo Test total distance, RPE, self-reported fitness activity levels for aerobic and anaerobic frequency, duration, workout intensity, and workout length, as well as jump height from the countermovement jump. These demographic and other factors in the t-tests were not significant. The factors that revealed both a non-significance and a low effect size, such as height (d=0.08) and mass (d=0.19), could mean that they are not important factors in this scenario (Table 10). There were several variables that revealed a medium effect size such as, Yo-Yo Test round 3 CMJ jump height (d=0.66) and current aerobic exercise intensity (d=0.68). There were also eight variables that revealed a large effect size, such as baseline and Yo-Yo Test rounds 1 and 2 CMJ jump heights (respectively, d=0.93, d=1.33, and d=1.15), length of participation in aerobic activities (d=0.98), and Yo-Yo test rounds 1 and 3 and total distance (respectively, d=0.82, d=0.81, and d=0.91) (Table 10). While there was a lack of significance in the t-tests, these medium and large effect sizes could be due to low sample size, which shows the importance of future research on these factors with a larger sample size. This shows that there are other potential confounding explanatory variables for why some participants showed an increase or decrease in AKL or no change and indicates future research is needed with other exploratory variables to provide more insight.

Considerations for Comparison with Previous Research

When comparing the results of the current study with previous studies, it is important to consider how each study defines fatigue. James et al. (2006) defined fatigue as a 5-20% decrease in jump height, considering a minimal fatigue level at a 5% reduction in the performance of three consecutive jumps compared to the highest CMJ jump height, allowing for 15% recovery. This may also explain the differences in results for the vGRF and EMG variables because the previous study was conducted once fatigued was determined to be induced, whereas the fatigue protocol in the current study continued until participants could not keep pace with Yo-Yo Test. The degree to which fatigue was induced was assessed by examining jump height from the CMJ trials. The significant decrease in jumping performance from baseline to rounds two and three of the Yo-Yo Test and from round two to round three of the Yo-Yo test indicates physiological fatigue and decreased neuromuscular performance, which is similar to results from previous research with a different fatigue protocol (Sanna & O'Connor, 2008). From baseline to round three of the Yo-Yo Test there was a group average of 16% decrease in jump height, which depending on the referenced study, such as (James et al., 2006), may or may not fall within the definition of muscular fatigue.

One potential reason for these results could be the level and type of fatigue that occurred. The CMJ results indicate that while muscular fatigue may have occurred, it may not have occurred to the extent necessary for all participants to induce changes. The participants may have reached their cardiovascular thresholds before experiencing considerable muscular fatigue. The percent increase in heart rate, from the lowest heart rate in the first minute of wearing the heart rate sensor to the heart rate following round three of the Yo-Yo Test, is one way of examining the participants cardiovascular exertion. On average, the participant's heart rate increased by 116.76 ± 27.42%, which suggests that from the pre-warm-up to following the fatigue protocol the participants were experiencing high cardiovascular demands. If participants underwent high cardiovascular demands, they may not have been able to sustain the Yo-Yo Test pace for a sufficient duration to elicit the levels of muscular fatigue needed to induce changes in AKL. Additionally, in the first two rounds of the Yo-Yo Test the running speed increased at regular intervals (Table 2) and for round three of the Yo-Yo Test the speed was set at each participant's average stage level from the maximum level achieved in the first and second rounds. It is conceivable that due to their current fitness activities and level of activities, these participants might have been unable to sustain the pace at higher speeds. Consequently, even if they did not achieve the levels of muscular fatigue intended, the Yo-Yo Test rounds might have halted because the participants failed to maintain the required pace.

Another important factor to consider is that the Yo-Yo Test is volitional, meaning that it involves voluntary effort or decision to continue with the test. Therefore, this was a delimitation that the participant's time running in the fatigue protocol and effort was not standardized. RPE was collected as a subjective measure of physical exertion to examine the participants' feeling of how hard they worked in each round of the Yo-Yo Test. On average, the RPE increased from 14.42 ± 2.04 to 16.24 ± 2.23, indicating that participant's felt their effort increased as the fatigue protocol advanced. However, not every participant's RPE increased with each round of the Yo-

Yo Test. This individual variation could explain why not all participants experienced the necessary level of muscular fatigue.

The type of protocol utilized in this study may be another reason that more muscular fatigue was not induced to cause the expected changes. Previous studies have utilized a fatigue protocol that was more specific to their populations, such as Shultz et al. (2013) utilizing an intermittent exercise protocol that simulated the duration and intensity of a soccer match for intercollegiate and club-level athletes or Nuccio et al. (2021) utilizing SAFT45, a soccer-specific protocol mimicking the mechanical and physiological demands of soccer of male soccer players. The current study's protocol was chosen to be more generalized to match the broader sample population. However, this approach may have resulted in a fatigue protocol, specifically in terms of running pace, that was unfamiliar to the participants. According to Zadpoor and Nikooyan (2012), when running speed is not controlled for in running fatigue protocols, as fatigue occurs the participant's running speed decreases. Therefore, the participant's might have been trying to maintain the increasing speed in rounds one and two of the Yo-Yo Test or the higher set speed of round three of the Yo-Yo Test and were not able to maintain the pace, so they did not engage in the running protocol long enough to induce more muscular fatigue. In future research, it will be vital to consider the desired sample populations athletic activities and pick a protocol best suited for those individuals to induce the level of muscular fatigue desired.

Future Considerations

Certain future considerations based off the current study should be underlined. The volitional aspect of the fatigue protocol means that not every participant may have undergone the level of muscular fatigue necessary to induce changes. This was a delimitation and could be addressed in future research by setting tighter inclusion and exclusion criteria for the participants in terms of activity levels or considering the utilization of other fatigue protocols. One limitation of the current study that should be underlined is that the limited space in the UTK Biomechanics/Sports Medicine Laboratory led to a slight modification to the standard setup of the Yo-Yo Test for the fatigue protocol. As a result, participants may have begun decelerating prematurely to prevent colliding with the wall, which could have led to warnings that would not have occurred if they could accelerate through a line. This alteration might have influenced the duration that participants were able to continue with the fatigue protocol. Another aspect future research should consider is tracking the number of experimental task trials re-done throughout the fatigue protocol to provide more insight into if and how this impacts the fatigue participant's experience. Future research could track the time between Yo-Yo Test rounds and the number of experimental task trials re-done to provide insight on the in-between fatiguing running rounds recovery time. Although participants provided self-reported data on their menstrual cycles, as hormones are believed to influence laxity according to Shultz et al. (2009), future studies should also collect information on the use of birth control. Understanding whether and what type of birth control participants use could identify potential confounders and enhance insights into how fatigue affects AKL for each individual.

Conclusions

Three rounds of the Yo-Yo Intermittent Recovery Test Level 1 as a fatigue protocol to simulate a game or practice situation, did elicit some changes in ground reaction force metrics and muscle activations. For the drop jump task, the peak loading and average loading rate significantly increased. The jump height from the countermovement jumps significantly decreased, indicating muscular fatigue may have occurred. For the drop cut task, the pre-activation vastus medialis median frequency significantly increased. However, some of the changes expected did not occur. The differences in fatigue protocols between the current study and prior research may account for the discrepancies in results, which complicates direction comparison. Further investigation into intersubject variability in AKL, in terms of magnitude and positive, negative, and non-responders, and its underlying causes is imperative to enhance our understanding of muscular fatigue as a mechanism for ACL injuries. These research endeavors are pivotal for aiding in the comprehension of the intricate relationship between muscle fatigue and AKL.

References

Alentorn-Geli, E., Myer, G. D., Silvers, H. J., Samitier, G., Romero, D., Lazaro-Haro, C., & Cugat, R. (2009). Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc*, *17*(7), 705-729. https://doi.org/10.1007/s00167-009-0813-1

Allison, G. T., & Fujiwara, T. (2002). The relationship between EMG median frequency and low frequency band amplitude changes at different levels of muscle capacity. *Clin Biomech (Bristol, Avon)*, *17*(6), 464-469. https://doi.org/10.1016/s0268-0033(02)00033-5

Baechle, T., & Earle, R. (2000). *Essentials of Strength Training and Conditioning* (2 ed.). Human Kinetics

Barber-Westin, S. D., & Noyes, F. R. (2017). Effect of Fatigue Protocols on Lower Limb Neuromuscular Function and Implications for Anterior Cruciate Ligament Injury Prevention Training: A Systematic Review. *Am J Sports Med*, *45*(14), 3388-3396. https://doi.org/10.1177/0363546517693846

Barcellona, M. G., Morrissey, M. C., Milligan, P., Clinton, M., & Amis, A. A. (2015). The effect of knee extensor open kinetic chain resistance training in the ACL-injured knee. *Knee Surg Sports Traumatol Arthrosc*, *23*(11), 3168-3177. https://doi.org/10.1007/s00167-014-3110-6

Beighton, P., Solomon, L., & Soskolne, C. L. (1973). Articular mobility in an African population. *Ann Rheum Dis*, *32*(5), 413-418. https://doi.org/10.1136/ard.32.5.413

Bin Abd Razak, H. R., Bin Ali, N., & Howe, T. S. (2014). Generalized ligamentous laxity may be a predisposing factor for musculoskeletal injuries. *J Sci Med Sport*, *17*(5), 474-478. https://doi.org/10.1016/j.jsams.2013.11.001

Bourne, M. N., Webster, K. E., & Hewett, T. E. (2019). Is Fatigue a Risk Factor for Anterior Cruciate Ligament Rupture? *Sports Med*, *49*(11), 1629-1635. https://doi.org/10.1007/s40279-019-01134-5

Brophy, R., Silvers, H. J., Gonzales, T., & Mandelbaum, B. R. (2010). Gender influences: the role of leg dominance in ACL injury among soccer players. *British Journal of Sports Medicine*, *44*(10), 694-697. https://doi.org/10.1136/bjsm.2008.051243

Cairns, S. P., Knicker, A. J., Thompson, M. W., & Sjogaard, G. (2005). Evaluation of models used to study neuromuscular fatigue. *Exerc Sport Sci Rev*, *33*(1), 9-16. https://www.ncbi.nlm.nih.gov/pubmed/15640715

Collette, M., Courville, J., Forton, M., & Gagniere, B. (2012). Objective evaluation of anterior knee laxity; comparison of the KT-1000 and GNRB(R) arthrometers. *Knee Surg Sports Traumatol Arthrosc*, *20*(11), 2233-2238. https://doi.org/10.1007/s00167-011-1869-2

Collins, J. D., Almonroeder, T. G., Ebersole, K. T., & O'Connor, K. M. (2016). The effects of fatigue and anticipation on the mechanics of the knee during cutting in female athletes. *Clin Biomech (Bristol, Avon)*, *35*, 62-67. https://doi.org/10.1016/j.clinbiomech.2016.04.004

Cooper, C. N., Dabbs, N. C., Davis, J., & Sauls, N. M. (2020). Effects of Lower-Body Muscular Fatigue on Vertical Jump and Balance Performance. *J Strength Cond Res*, *34*(10), 2903-2910. https://doi.org/10.1519/JSC.0000000000002882

Criswell, E. (2010). *Cram's Introduction to Surface Electromyography* (2 ed.). Jones & Bartlett Learning.
De Luca, C. J. (1997). The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics*, *13*(2), 135-163. https://doi.org/DOI 10.1123/jab.13.2.135
De Ste Croix, M. B., Priestley, A. M., Lloyd, R. S., & Oliver, J. L. (2015). ACL injury risk in elite female youth soccer: Changes in neuromuscular control of the knee following soccer-specific fatigue. *Scand J Med Sci Sports*, *25*(5), e531-538. https://doi.org/10.1111/sms.12355
DeVries, H. A. (1980). *Physiology of Exercise for Physical Education and Athletics*. W. C. Brown Company.
Ebben, W. P., Fauth, M. L., Petushek, E. J., Garceau, L. R., Hsu, B. E., Lutsch, B. N., & Feldmann, C. R. (2010). Gender-based analysis of hamstring and quadriceps muscle activation during jump landings and cutting. *J Strength Cond Res*, *24*(2), 408-415. https://doi.org/10.1519/JSC.0b013e3181c509f4
Ehrman, J. K., Dennis; Keteyian, Steven. (2018). *Advanced Exercise Physiology* (1 ed.). Human Kinetics.
Enoka, R. M., & Duchateau, J. (2008). Muscle fatigue: what, why and how it influences muscle function. *J Physiol*, *586*(1), 11-23. https://doi.org/10.1113/jphysiol.2007.139477
Fagenbaum, R., & Darling, W. G. (2003). Jump landing strategies in male and female college athletes and the implications of such strategies for anterior cruciate ligament injury. *Am J Sports Med*, *31*(2), 233-240. https://doi.org/10.1177/03635465030310021301
Friel, N. A., & Chu, C. R. (2013). The role of ACL injury in the development of posttraumatic knee osteoarthritis. *Clin Sports Med*, *32*(1), 1-12. https://doi.org/10.1016/j.csm.2012.08.017
Frisch, A., Urhausen, A., Seil, R., Croisier, J. L., Windal, T., & Theisen, D. (2011). Association between preseason functional tests and injuries in youth football: a prospective follow-up. *Scand J Med Sci Sports*, *21*(6), e468-476. https://doi.org/10.1111/j.1600-0838.2011.01369.x
Gear, W. S. (2011). Effect of different levels of localized muscle fatigue on knee position sense. *J Sports Sci Med*, *10*(4), 725-730. https://www.ncbi.nlm.nih.gov/pubmed/24149565
Gelen, E. (2010). Acute effects of different warm-up methods on sprint, slalom dribbling, and penalty kick performance in soccer players. *J Strength Cond Res*, *24*(4), 950-956. https://doi.org/10.1519/JSC.0b013e3181cb703f
Gornitzky, A. L., Lott, A., Yellin, J. L., Fabricant, P. D., Lawrence, J. T., & Ganley, T. J. (2016). Sport-Specific Yearly Risk and Incidence of Anterior Cruciate Ligament Tears in High School Athletes: A Systematic Review and Meta-analysis. *Am J Sports Med*, *44*(10), 2716-2723. https://doi.org/10.1177/0363546515617742
Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol*, *10*(5), 361-374. https://doi.org/10.1016/s1050-6411(00)00027-4
Holt, B. W., & Lambourne, K. (2008). The impact of different warm-up protocols on vertical jump performance in male collegiate athletes. *J Strength Cond Res*, *22*(1), 226-229. https://doi.org/10.1519/JSC.0b013e31815f9d6a

Hughes, G. (2014). A review of recent perspectives on biomechanical risk factors associated with anterior cruciate ligament injury. *Res Sports Med*, *22*(2), 193-212. https://doi.org/10.1080/15438627.2014.881821

James, C. R., Dufek, J. S., & Bates, B. T. (2006). Effects of stretch shortening cycle exercise fatigue on stress fracture injury risk during landing. *Res Q Exerc Sport*, *77*(1), 1-13. https://doi.org/10.1080/02701367.2006.10599346

James, C. R., Scheuermann, B. W., & Smith, M. P. (2010). Effects of two neuromuscular fatigue protocols on landing performance. *J Electromyogr Kinesiol*, *20*(4), 667-675. https://doi.org/10.1016/j.jelekin.2009.10.007

Jonathan Ehrman, D. K., and Steven Keteyian. (2018). *Advanced Exercise Physiology* (1 ed.). Human Kinetics.

Kellis, E., & Kouvelioti, V. (2009). Agonist versus antagonist muscle fatigue effects on thigh muscle activity and vertical ground reaction during drop landing. *J Electromyogr Kinesiol*, *19*(1), 55-64. https://doi.org/10.1016/j.jelekin.2007.08.002

Klasan, A., Putnis, S. E., Kandhari, V., Oshima, T., & Parker, D. A. (2020). Anterior knee translation measurements after ACL reconstruction are influenced by the type of laximeter used. *Knee Surg Sports Traumatol Arthrosc*, *28*(11), 3639-3646. https://doi.org/10.1007/s00167-020-05950-5

Lai, C. C. H., Feller, J. A., & Webster, K. E. (2018). Fifteen-Year Audit of Anterior Cruciate Ligament Reconstructions in the Australian Football League From 1999 to 2013: Return to Play and Subsequent ACL Injury. *Am J Sports Med*, *46*(14), 3353-3360. https://doi.org/10.1177/0363546518803932

Magdic, M., Dahmane, R. G., & Vauhnik, R. (2023). Intra-rater reliability of the knee arthrometer GNRB(R) for measuring knee anterior laxity in healthy, active subjects. *J Orthop*, *39*, 7-10. https://doi.org/10.1016/j.jor.2023.03.016

Maniar, N., Cole, M. H., Bryant, A. L., & Opar, D. A. (2022). Muscle Force Contributions to Anterior Cruciate Ligament Loading. *Sports Med*, *52*(8), 1737-1750. https://doi.org/10.1007/s40279-022-01674-3

Mannion, A. F., & Dolan, P. (1996). Relationship between myoelectric and mechanical manifestations of fatigue in the quadriceps femoris muscle group. *Eur J Appl Physiol Occup Physiol*, *74*(5), 411-419. https://doi.org/10.1007/BF02337721

McLean, S. G., & Samorezov, J. E. (2009). Fatigue-induced ACL injury risk stems from a degradation in central control. *Med Sci Sports Exerc*, *41*(8), 1661-1672. https://doi.org/10.1249/MSS.0b013e31819ca07b

Montalvo, A. M., Schneider, D. K., Webster, K. E., Yut, L., Galloway, M. T., Heidt, R. S., Jr., Kaeding, C. C., Kremcheck, T. E., Magnussen, R. A., Parikh, S. N., Stanfield, D. T., Wall, E. J., & Myer, G. D. (2019). Anterior Cruciate Ligament Injury Risk in Sport: A Systematic Review and Meta-Analysis of Injury Incidence by Sex and Sport Classification. *J Athl Train*, *54*(5), 472-482. https://doi.org/10.4085/1062-6050-407-16

Myer, G. D., Ford, K. R., Paterno, M. V., Nick, T. G., & Hewett, T. E. (2008). The effects of generalized joint laxity on risk of anterior cruciate ligament injury in young female athletes. *Am J Sports Med*, *36*(6), 1073-1080. https://doi.org/10.1177/0363546507313572

Nigg, B. M., Brian; Mester, Joachim. (2000). *Biomechanics and Biology of Movement* (1 ed.). Human Kinetics.

Nuccio, S., Labanca, L., Rocchi, J. E., Mariani, P. P., Sbriccoli, P., & Macaluso, A. (2021). Altered Knee Laxity and Stiffness in Response to a Soccer Match Simulation in Players Returning to Sport Within 12 Months After Anterior Cruciate Ligament Reconstruction. *Am J Sports Med*, *49*(8), 2150-2158. https://doi.org/10.1177/03635465211013020

Padua, D. A., Arnold, B. L., Perrin, D. H., Gansneder, B. M., Carcia, C. R., & Granata, K. P. (2006). Fatigue, vertical leg stiffness, and stiffness control strategies in males and females. *J Athl Train*, *41*(3), 294-304. https://www.ncbi.nlm.nih.gov/pubmed/17043698

Padua, D. A., Marshall, S. W., Boling, M. C., Thigpen, C. A., Garrett, W. E., Jr., & Beutler, A. I. (2009). The Landing Error Scoring System (LESS) Is a valid and reliable clinical assessment tool of jump-landing biomechanics: The JUMP-ACL study. *Am J Sports Med*, *37*(10), 1996-2002. https://doi.org/10.1177/0363546509343200

Pincivero, D. M., Gear, W. S., & Sterner, R. L. (2001). Assessment of the reliability of high-intensity quadriceps femoris muscle fatigue. *Med Sci Sports Exerc*, *33*(2), 334-338. https://doi.org/10.1097/00005768-200102000-00025

Ramesh, R., Von Arx, O., Azzopardi, T., & Schranz, P. J. (2005). The risk of anterior cruciate ligament rupture with generalised joint laxity. *J Bone Joint Surg Br*, *87*(6), 800-803. https://doi.org/10.1302/0301-620X.87B6.15833

Rozzi, S. L., Lephart, S. M., & Fu, F. H. (1999). Effects of muscular fatigue on knee joint laxity and neuromuscular characteristics of male and female athletes. *J Athl Train*, *34*(2), 106-114. https://www.ncbi.nlm.nih.gov/pubmed/16558552

Russell, M., Benton, D., & Kingsley, M. (2011). The effects of fatigue on soccer skills performed during a soccer match simulation. *Int J Sports Physiol Perform*, *6*(2), 221-233. https://doi.org/10.1123/ijspp.6.2.221

Sanna, G., & O'Connor, K. M. (2008). Fatigue-related changes in stance leg mechanics during sidestep cutting maneuvers. *Clin Biomech (Bristol, Avon)*, *23*(7), 946-954. https://doi.org/10.1016/j.clinbiomech.2008.03.065

Santamaria, L. J., & Webster, K. E. (2010). The effect of fatigue on lower-limb biomechanics during single-limb landings: a systematic review. *J Orthop Sports Phys Ther*, *40*(8), 464-473. https://doi.org/10.2519/jospt.2010.3295

Scherr, J., Wolfarth, B., Christle, J. W., Pressler, A., Wagenpfeil, S., & Halle, M. (2013). Associations between Borg's rating of perceived exertion and physiological measures of exercise intensity. *European Journal of Applied Physiology*, *113*(1), 147-155. https://doi.org/10.1007/s00421-012-2421-x

Schmitz, B., Pfeifer, C., Kreitz, K., Borowski, M., Faldum, A., & Brand, S. M. (2018). The Yo-Yo Intermittent Tests: A Systematic Review and Structured Compendium of Test Results. *Front Physiol*, *9*, 870. https://doi.org/10.3389/fphys.2018.00870

Shultz, S. J., Nguyen, A. D., & Levine, B. J. (2009). The Relationship Between Lower Extremity Alignment Characteristics and Anterior Knee Joint Laxity. *Sports Health*, *1*(1), 54-60. https://doi.org/10.1177/1941738108326702

Shultz, S. J., Schmitz, R. J., Cone, J. R., Copple, T. J., Montgomery, M. M., Pye, M. L., & Tritsch, A. J. (2013). Multiplanar knee laxity increases during a 90-min intermittent exercise protocol. *Med Sci Sports Exerc*, *45*(8), 1553-1561. https://doi.org/10.1249/MSS.0b013e31828cb94e

Shultz, S. J., Schmitz, R. J., Cone, J. R., Henson, R. A., Montgomery, M. M., Pye, M. L., & Tritsch, A. J. (2015). Changes in fatigue, multiplanar knee laxity, and landing biomechanics during intermittent exercise. *J Athl Train*, *50*(5), 486-497. https://doi.org/10.4085/1062-6050-49.5.08

Smith, M. A., Smith, W. T., & Kosko, P. (2014). Anterior cruciate ligament tears: reconstruction and rehabilitation. *Orthop Nurs*, *33*(1), 14-24; quiz 25-16. https://doi.org/10.1097/NOR.0000000000000019

Steele, J. R., Milburn, P. D., & Roger, G. J. (1999). Warm-up effect on active and passive arthrometric assessment of knee laxity. *Arch Phys Med Rehabil*, *80*(7), 829-836. https://doi.org/10.1016/s0003-9993(99)90235-6

Steiner, M. E., Grana, W. A., Chillag, K., & Schelberg-Karnes, E. (1986). The effect of exercise on anterior-posterior knee laxity. *Am J Sports Med*, *14*(1), 24-29. https://doi.org/10.1177/036354658601400105

Sueyoshi, T., Emoto, G., & Yuasa, T. (2016). Generalized Joint Laxity and Ligament Injuries in High School-Aged Female Volleyball Players in Japan. *Orthop J Sports Med*, *4*(10), 2325967116667690. https://doi.org/10.1177/2325967116667690

Tingle, A., Bennett, O., Wallis, A., & Palmer, S. (2018). The links between Generalized Joint Laxity and the incidence, prevalence and severity of limb injuries related to physical exercise: a systematic literature review. *Physical Therapy Reviews*, *23*(4-5), 259-272. https://doi.org/10.1080/10833196.2018.1481626

Walden, M., Hagglund, M., Werner, J., & Ekstrand, J. (2011). The epidemiology of anterior cruciate ligament injury in football (soccer): a review of the literature from a gender-related perspective. *Knee Surg Sports Traumatol Arthrosc*, *19*(1), 3-10. https://doi.org/10.1007/s00167-010-1172-7

Wan, J. J., Qin, Z., Wang, P. Y., Sun, Y., & Liu, X. (2017). Muscle fatigue: general understanding and treatment. *Exp Mol Med*, *49*(10), e384. https://doi.org/10.1038/emm.2017.194

Webster, K. E., Hewett, T. E., & Feller, J. A. (2021). Anterior Cruciate Ligament Injuries in Australian Rules Football: Incidence, Prevention and Return to Play Outcomes. *Open Access J Sports Med*, *12*, 33-41. https://doi.org/10.2147/OAJSM.S250414

Weiss, K., & Whatman, C. (2015). Biomechanics Associated with Patellofemoral Pain and ACL Injuries in Sports. *Sports Med*, *45*(9), 1325-1337. https://doi.org/10.1007/s40279-015-0353-4

Xia, R., Zhang, X., Wang, X., Sun, X., & Fu, W. (2017). Effects of Two Fatigue Protocols on Impact Forces and Lower Extremity Kinematics during Drop Landings: Implications for Noncontact Anterior Cruciate Ligament Injury. *J Healthc Eng*, *2017*, 5690519. https://doi.org/10.1155/2017/5690519

Zadpoor, A. A., & Nikooyan, A. A. (2012). The effects of lower extremity muscle fatigue on the vertical ground reaction force: a meta-analysis. *Proc Inst Mech Eng H*, *226*(8), 579-588. https://doi.org/10.1177/0954411912447021

Appendices

Appendix A. Participant Demographics

Table 1: Mean participant demographics.

Table 1: Participant Demographics: Mean ± STD

Height (m)	Mass (kg)	Age (years)	LEFS
1.66 ± 0.08	65.13 ± 11.62	21.67 ± 2.22	79.38 ± 1.36

Appendix B. Chapter 3 Tables

Table 2: The running speed increment schedule for the Yo-Yo Test. After stage 5 the speed continued to incrementally increase by 0.5 km/hour every 8 shuttles until a speed of 19 km/hour.

Table 2: Yo-Yo Test Rounds 1 and 2 Running Speed Increments

Stage	Number of Shuttles (20m)	Speed (km/hr)	Accumulated Distance (m)
1	2	10	40
2	2	11.5	80
3	4	13	160
4	6	13.5	280
5	8	14	440
6	16	14.5	760
7	16	15	1080
8	16	15.5	1400
9	16	16	1720
10	16	16.5	2040
11	16	17	2360
12	16	17.5	2680
13	16	18	3000
14	16	18.5	3320
15	16	19	3640

Appendix C. Chapter 3 Figures

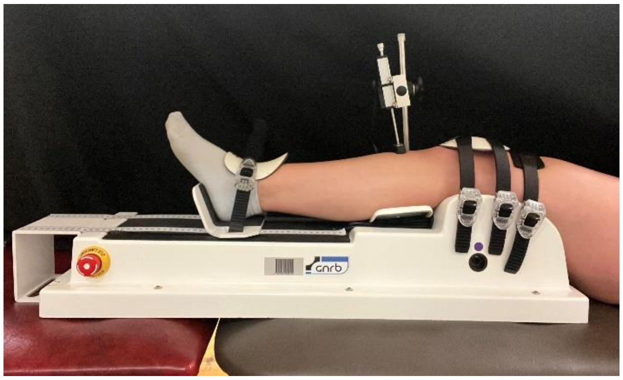

Figure 1: The arthrometer setup utilized to assess anterior knee laxity (AKL).

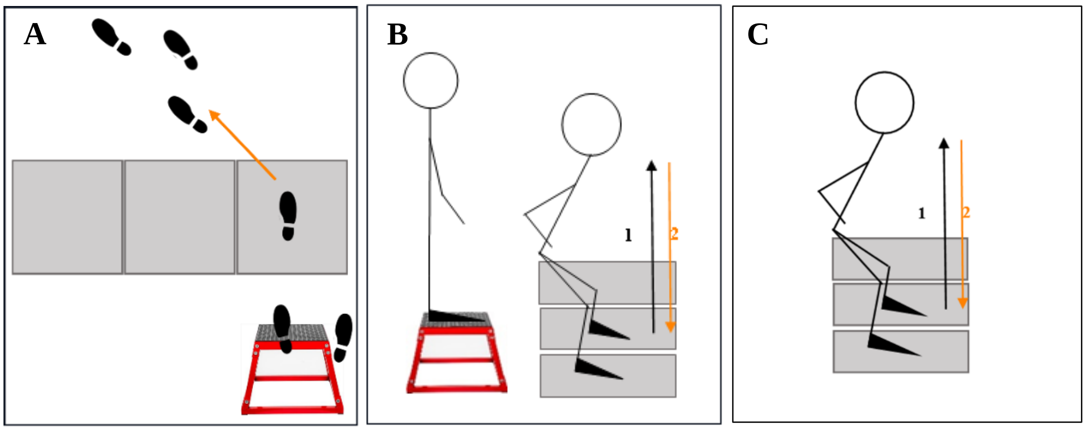

Figure 2: Visual Aid of the Landing Tasks and the Countermovement Jump: A) The 45-degree cut for a participant with a preferred right side kicking leg, B) The bilateral drop jump landing task, C) The countermovement jump to assess fatigue through jump height.

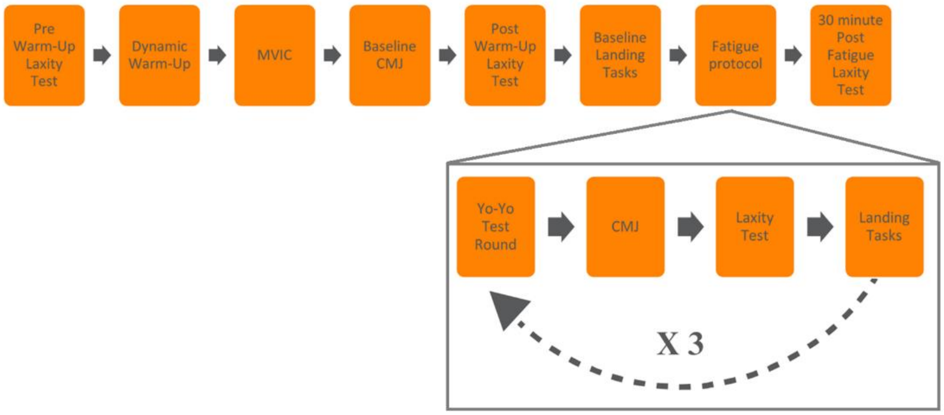

Figure 3: A visual aid of the experimental protocol the participant engaged in where the participant engaged in 3 rounds of the Yo-Yo Test, countermovement jump (CMJ), laxity tests, and then landing tasks.

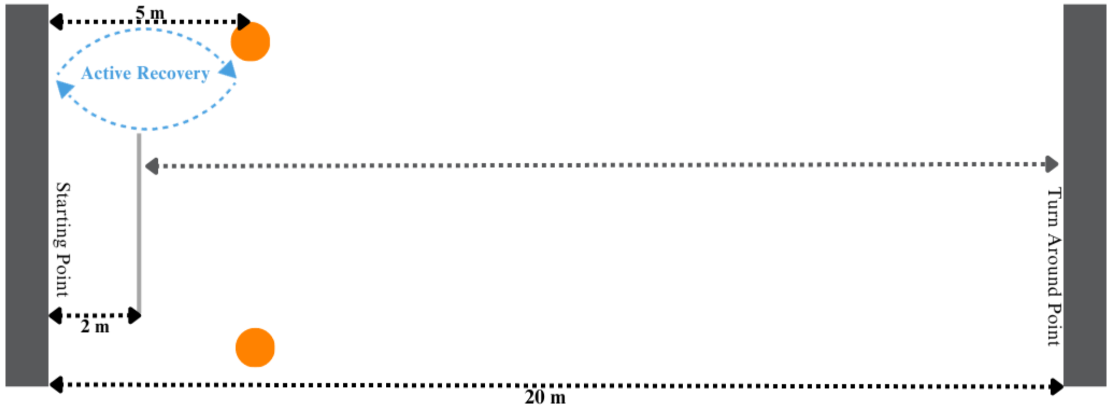

Figure 4: A visual aid of the modified Yo-Yo Test set up for the fatigue protocol.

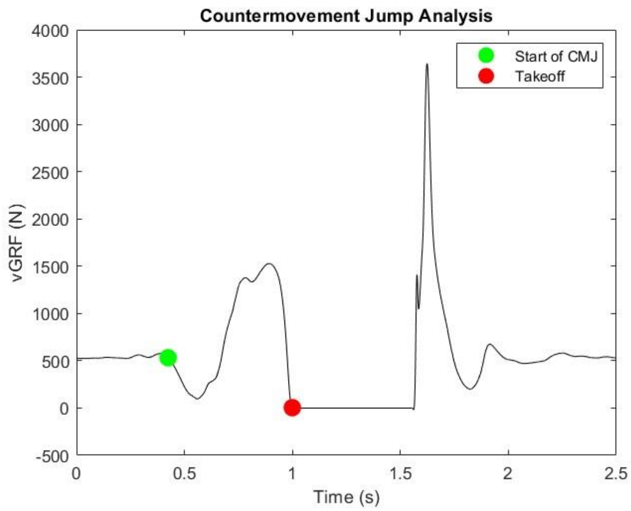

Figure 5: Vertical ground reaction force (vGRF) curve of the countermovement jump (CMJ) with the defined start and takeoff points.

Appendix D. Chapter 4 Tables

Table 3: Anterior knee laxity across the time points of the study protocol and the p-value.

Table 3: Anterior Knee Laxity Displacement: Mean ± SD

	Pre Warm-Up	Post Warm-Up	Yo-Yo Round 1	Yo-Yo Round 2	Yo-Yo Round 3	30 Min Post Fatigue	*p* -value
AKL Average of 3 Trials (mm)	4.32 ± 1.09	4.47 ± 0.96	4.90 ± 1.31	4.77 ± 1.31	4.75 ± 1.22	4.63 ± 0.88	0.138
AKL Average of Last 2 Trials (mm)	4.34 ± 0.97	4.54 ± 1.00	4.90 ± 1.23	4.77 ± 1.26	4.75 ± 1.14	4.66 ± 0.79	0.175

Table 4: Peak impact loading and average loading rate for drop cut task. Normalized to body weight.

Table 4: Drop Cut Peak Loading and Average Loading Rate: Mean ± SD

	Baseline	Yo-Yo Round 1	Yo-Yo Round 2	Yo-Yo Round 3	*p*-value
Peak Loading (BW)	2.86 ± 0.66	2.90 ± 0.58	2.97 ± 0.56	2.89 ± 0.58	0.278
Average Loading Rate (BW/s)	73.38 ± 59.16	75.03 ± 53.46	78.74 ± 57.64	76.07 ± 58.80	0.521

Table 5: Peak impact loading and average loading rate for drop cut task. Normalized to body weight.
[a] Indicates statistical significance Baseline to Yo-Yo Round 1
[b] Indicates statistical significance Baseline to Yo-Yo Round 2
[c] Indicates statistical significance Baseline to Yo-Yo Round 3
[d] Indicates statistical significance Yo-Yo Round 1 to Yo-Yo Round 2
[e] Indicates statistical significance Yo-Yo Round 1 to Yo-Yo Round 3
[f] Indicates statistical significance Yo-Yo Round 2 to Yo-Yo Round 3

Table 5: Drop Jump Peak Loading and Average Loading Rate: Mean ± SD

	Baseline	Yo-Yo Round 1	Yo-Yo Round 2	Yo-Yo Round 3	*p* -value
Peak Loading (BW)[a,b,c,f]	1.81 ± 0.41	2.07 ± 0.49	2.00 ± 0.48	2.11 ± 0.55	0.002
Average Loading Rate (BW/s)[a,b]	52.61 ± 49.41	63.94 ± 53.71	61.09 ± 53.94	61.95 ± 49.71	0.019

Table 6: Jump height calculated from the vGRF data from the countermovement jump, which is used to assess fatigue.
[a] Indicates statistical significance Baseline to Yo-Yo Round 1
[b] Indicates statistical significance Baseline to Yo-Yo Round 2
[c] Indicates statistical significance Baseline to Yo-Yo Round 3
[d] Indicates statistical significance Yo-Yo Round 1 to Yo-Yo Round 2
[e] Indicates statistical significance Yo-Yo Round 1 to Yo-Yo Round 3
[f] Indicates statistical significance Yo-Yo Round 2 to Yo-Yo Round 3

Table 6: Jump Height from Countermovement Jump : Mean ± SD

	Baseline	**Yo-Yo Round 1**	**Yo-Yo Round 2**	**Yo-Yo Round 3**	***p*-value**
Jump Height (m)[b,c,e]	0.25 ± 0.06	0.24 ± 0.06	0.23 ± 0.06	0.21 ± 0.06	0.009

Table 7: Median frequency and co-contraction ratio from EMG data for the pre-activation and landing phases of the drop cut task.
[a] Indicates statistical significance Baseline to Yo-Yo Round 1
[b] Indicates statistical significance Baseline to Yo-Yo Round 2
[c] Indicates statistical significance Baseline to Yo-Yo Round 3
[d] Indicates statistical significance Yo-Yo Round 1 to Yo-Yo Round 2
[e] Indicates statistical significance Yo-Yo Round 1 to Yo-Yo Round 3
[f] Indicates statistical significance Yo-Yo Round 2 to Yo-Yo Round 3

Table 7: Drop Cut Median Frequency and Co-Contraction Ratio for Pre-Activation and Landing Phases: Mean ± SD

	Baseline	Yo-Yo Round 1	Yo-Yo Round 2	Yo-Yo Round 3	*p*-value
Pre-Activation Phase					
Median Frequency VM (Hz)[b,c,d,e]	69.66 ± 7.20	71.58 ± 8.75	79.46 ± 12.79	78.74 ± 12.54	0.003
Median Frequency MH (Hz)	63.73 ± 6.15	66.82 ± 13.45	67.85 ± 11.39	68.80 ± 10.13	0.216
Co-Contraction Ratio (VM/MH)	1.03 ± 0.98	1.39 ± 1.57	1.52 ± 1.95	1.13 ± 1.06	0.113
Landing Phase					
Median Frequency VM (Hz)	71.58 ± 15.83	71.20 ± 13.67	71.80 ± 15.11	72.10 ± 15.50	0.944
Median Frequency MH (Hz)	72.96 ± 15.16	76.31 ± 14.71	74.60 ± 13.44	73.27 ± 15.62	0.643
Co-Contraction Ratio (VM/MH)	3.80 ± 1.56	4.42 ± 2.20	4.16 ± 2.36	4.15 ± 2.11	0.199

Table 8: Median frequency and co-contraction ratio from EMG data for the pre-activation and landing phases of the drop jump task.
[a] Indicates statistical significance Baseline to Yo-Yo Round 1
[b] Indicates statistical significance Baseline to Yo-Yo Round 2
[c] Indicates statistical significance Baseline to Yo-Yo Round 3
[d] Indicates statistical significance Yo-Yo Round 1 to Yo-Yo Round 2
[e] Indicates statistical significance Yo-Yo Round 1 to Yo-Yo Round 3
[f] Indicates statistical significance Yo-Yo Round 2 to Yo-Yo Round 3

Table 8: Drop Jump Median Frequency and Co-Contraction Ratio for Pre-Activation and Landing Phases: Mean ± SD

	Baseline	**Yo-Yo Round 1**	**Yo-Yo Round 2**	**Yo-Yo Round 3**	***p*-value**
Pre-Activation Phase					
Median Frequency VM (Hz)	77.24 ± 11.04	79.99 ± 14.67	80.33 ± 12.79	82.70 ± 13.02	0.173
Median Frequency MH (Hz)	83.04 ± 17.01	76.95 ± 14.74	80.14 ± 15.28	79.53 ± 16.51	0.371
Co-Contraction Ratio (VM/MH)	1.78 ± 1.25	1.92 ± 1.23	1.89 ± 1.71	2.07 ± 1.66	0.641
Landing Phase					
Median Frequency VM (Hz)	79.49 ± 12.18	77.23 ± 15.62	78.95 ± 18.85	81.67 ± 19.17	0.227
Median Frequency MH (Hz)	70.63 ± 17.31	72.62 ± 16.10	68.86 ± 16.07	71.01 ± 12.96	0.518
Co-Contraction Ratio (VM/MH)	6.71 ± 3.09	6.64 ± 3.39	6.28 ± 2.79	6.45 ± 3.12	0.692

Appendix E. Chapter 4 Figures

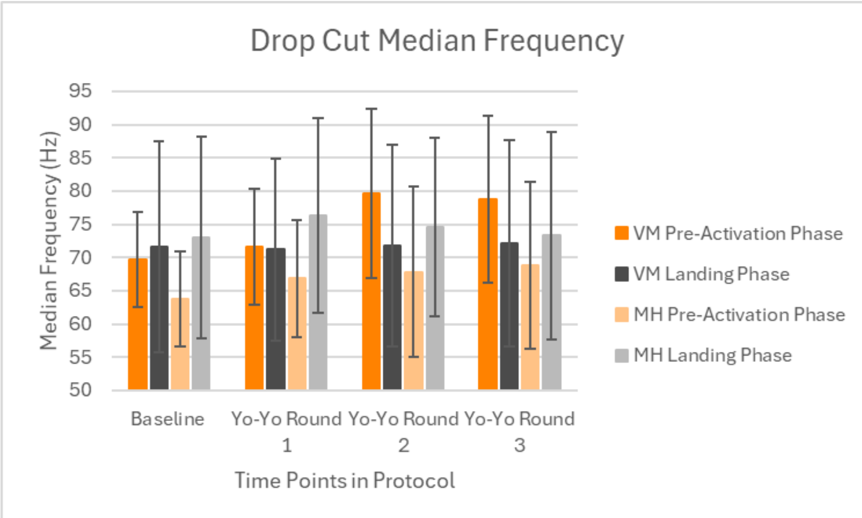

Figure 6: Median frequency of the vastus medialis and medial hamstrings muscles in the drop cut task.

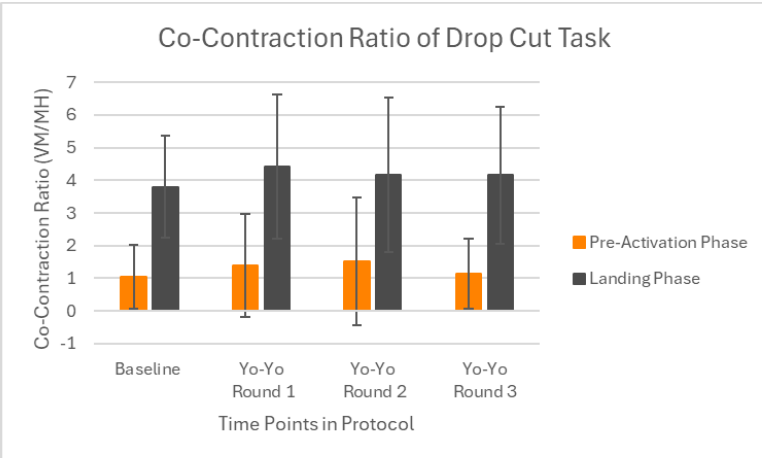

Figure 7: Co-Contraction Ratio of quadriceps (VM) to hamstrings (MH) muscle force for the pre-activation and landing phases of the drop cut task.

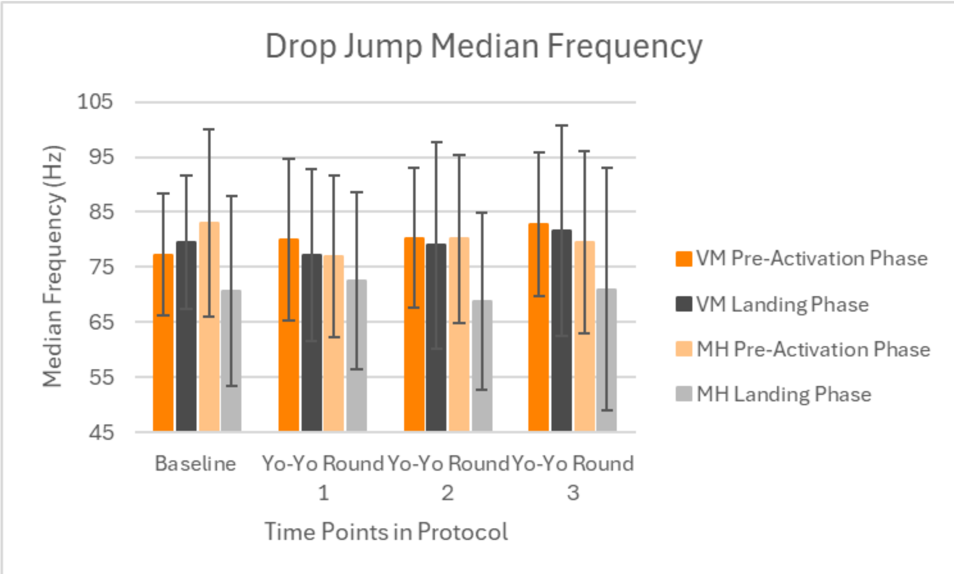

Figure 8: Median frequency of the vastus medialis and medial hamstrings muscles in the drop jump task.

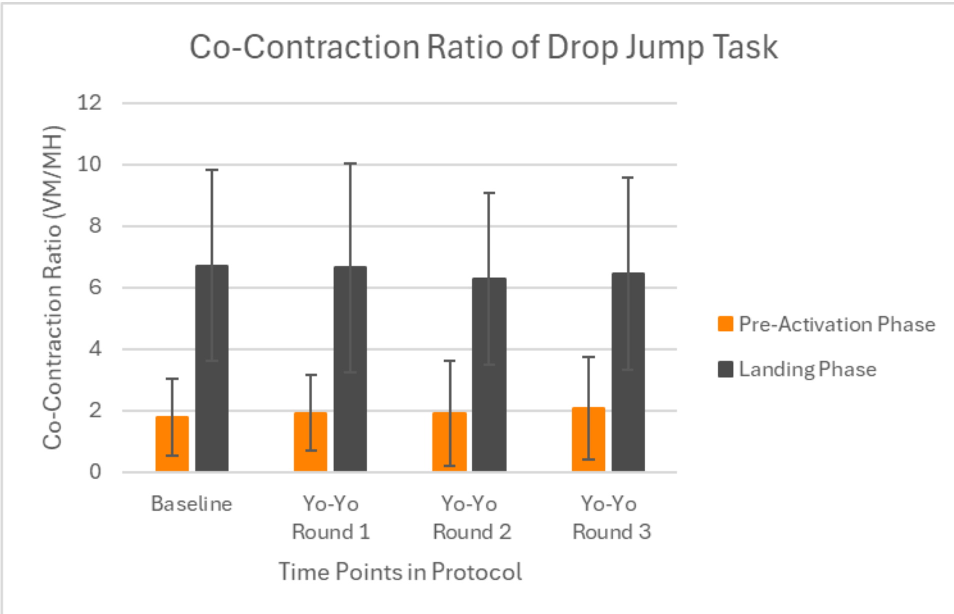

Figure 9: Co-Contraction Ratio of quadriceps (VM) to hamstrings (MH) muscle force for the pre-activation and landing phases of the drop jump task.

Appendix F. Chapter 5 Tables

Table 9: Anterior knee laxity displacement with the criteria of 10% difference between the baseline (Pre Warm-Up) measurements and the Yo-Yo Round 3.
[a] *Indicates statistical significance Pre Warm-Up to Post Warm-Up*
[b] *Indicates statistical significance Pre Warm-Up to Yo-Yo Round 1*
[c] *Indicates statistical significance Pre Warm-Up to Yo-Yo Round 2*
[d] *Indicates statistical significance Pre Warm-Up to Yo-Yo Round 3*
[e] *Indicates statistical significance Pre Warm-Up to 30 Min Post Fatigue*
[f] *Indicates statistical significance Post Warm-Up to Yo-Yo Round 1*
[g] *Indicates statistical significance Post Warm-Up to Yo-Yo Round 2*
[h] *Indicates statistical significance Post Warm-Up to Yo-Yo Round 3*
[i] *Indicates statistical significance Post Warm-Up to 30 Min Post Fatigue*
[j] *Indicates statistical significance Yo-Yo Round 1 to Yo-Yo Round 2*
[k] *Indicates statistical significance Yo-Yo Round 1 to Yo-Yo Round 3*
[l] *Indicates statistical significance Yo-Yo Round 1 to 30 Min Post Fatigue*
[m] *Indicates statistical significance Yo-Yo Round 2 to Yo-Yo Round 3*
[n] *Indicates statistical significance Yo-Yo Round 2 to 30 Min Post Fatigue*
[o] *Indicates statistical significance Yo-Yo Round 3 to 30 Min Post Fatigue*

Table 9: Anterior Knee Laxity Displacement with 10% Difference Between Baseline and Yo-Yo Round 3 Criteria: Mean ± SD

	Pre Warm-Up	**Post Warm-Up**	**Yo-Yo Round 1**	**Yo-Yo Round 2**	**Yo-Yo Round 3**	**30 Min Post Fatigue**
AKL Positive Responders (mm)[b,c,d,e,g,h]	3.97 ± 0.95	4.45 ± 1.01	4.91 ± 1.04	5.27 ± 1.41	5.38 ± 1.26	4.76 ± 0.67
AKL Negative Responders (mm)[d,h,k]	5.20 ± 1.43	4.93 ± 0.06	5.11 ± 1.15	4.30 ± 0.44	3.77 ± 0.12	4.90 ± 1.27
AKL None Responders (mm)	4.43 ± 1.06	4.32 ± 1.11	4.80 ± 1.76	4.33 ± 1.26	4.33 ± 1.01	4.35 ± 1.02

Table 10: Two-tailed t-tests comparing the positive and negative AKL responders.

Table 10: Two-tailed T-Tests Comparing Anterior Knee Laxity
Positive and Negative Responders

Variable	Positive Responders Mean (N=10)	Negative Responders Mean (N=3)	*p*-value	Cohen's d
Height (m)	1.65	1.65	0.90	0.08
Mass (kg)	61.45	63.91	0.78	0.19
Yo-Yo Test Round 1 Distance (m)	390	280	0.24	0.82
Yo-Yo Test Round 2 Distance (m)	336	273.33	0.35	0.64
Yo-Yo Test Round 3 Distance (m)	282	186.67	0.25	0.81
Yo-Yo Test Total Distance (m)	1008	740	0.20	0.91
RPE Yo-Yo Test Round 1 (6-20 scale)	14.70	14	0.61	0.34
RPE Yo-Yo Test Round 2 (6-20 scale)	15.60	15	0.66	0.30
RPE Yo-Yo Test Round 3 (6-20 scale)	16.20	15	0.38	0.60
Current Aerobic Exercise Frequency (days)	4.90	4.33	0.56	0.39
Current Aerobic Exercise Duration (minutes)	44.50	37.50	0.38	0.60
Current Aerobic Exercise Intensity (1-4)	2	1.67	0.33	0.68
Length of Participation in Aerobic Activity (years)	8.10	3.50	0.17	0.98
Current Anaerobic Exercise Frequency (days)	2.80	2.33	0.86	0.12
Current Anaerobic Exercise Duration (minutes)	45.50	45	0.97	0.03
Current Anaerobic Exercise Intensity (1-4)	2.30	2.33	0.94	0.05
Length of Participation in Anaerobic Activity (years)	3.95	1.83	0.24	0.83
Baseline CMJ Jump Height (m)	0.27	0.21	0.19	0.93
Yo-Yo Test Round 1 CMJ Jump Height (m)	0.26	0.19	0.07	1.33
Yo-Yo Test Round 2 CMJ Jump Height (m)	0.25	0.19	0.11	1.15
Yo-Yo Test Round 3 CMJ Jump Height (m)	0.22	0.18	0.34	0.66

Appendix G. Chapter 5 Figures

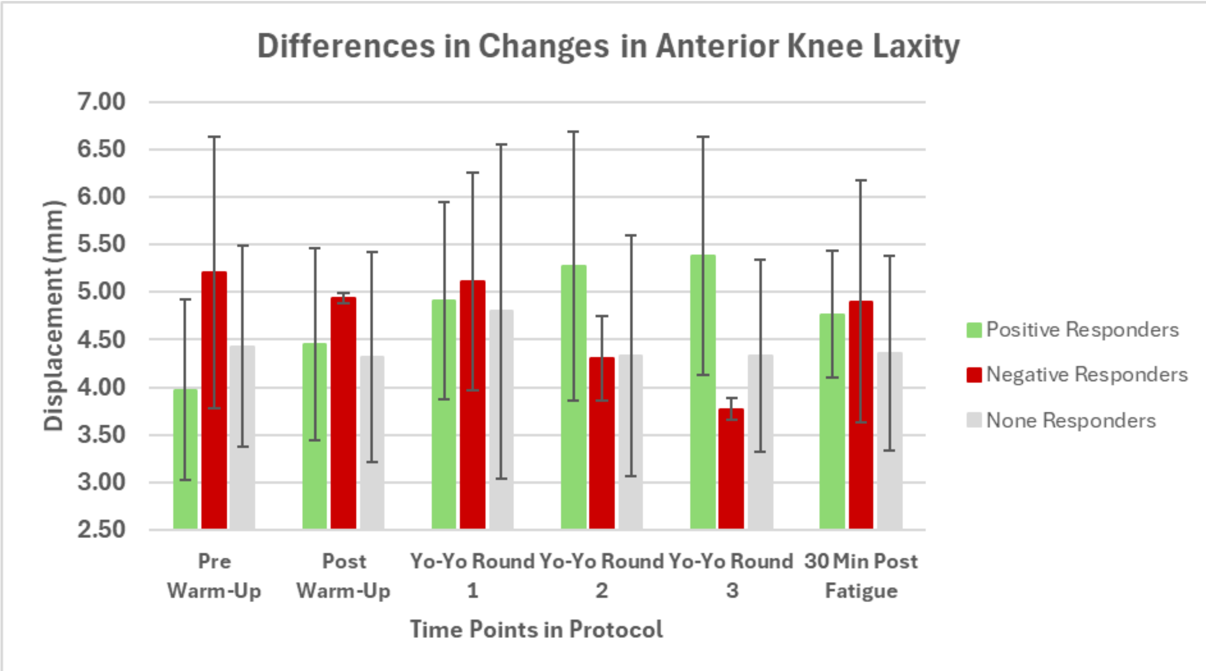

Figure 10: Comparison of AKL positive, negative, and none responders to the fatigue protocol.

Appendix H. Informed Consent

Consent for Research Participation

Research Study Title: Determining the Effects of Fatigue on Anterior Knee Laxity

Researcher(s): Joshua T. Weinhandl, PhD, University of Tennessee, Knoxville
Taliah J. Carlson, BS, University of Tennessee, Knoxville

Why am I being asked to be in this research study?

We are asking you to be in this research study because you are healthy and between the ages of 18 to 35 years old and are recreationally active. Being recreationally active means, you are engaging in physical activity at least 3 times a week for a minimum of 30 minutes per session. Examples of this are running, weight training, elliptical, pick-up basketball, etc. If you are not between the ages of 18 to 35, not recreationally active 3 days a week for a minimum of 30 minutes each, have injured your legs in the past 6 months, or have ever had a leg surgery you will not be asked to be in this research study.

How long will I be in the research study?

If you agree to be in the study, your participation will involve 1 study visit lasting approximately 3 hours.

What will happen if I say "Yes, I want to be in this research study"?

If you agree to be in this study, we will ask you to come to the Biomechanics Lab for one testing session.

Preparation:

1. You will complete injury history and fitness activity questionnaires to determine if you can participate in the study.
2. You will then change into compression shorts and a generic T-shirt, which will be provided if you do not have them.
3. Your height and weight will be measured.
4. Next, sensors to measure your muscle activity will be placed on your preferred kicking leg. This includes shaving, lightly scraping the skin, and cleaning it with alcohol where the sensors go.
5. Points on your knee and shin will be marked to measure knee movement accurately.

Testing Procedures:

1. Knee laxity will be tested when you are relaxed and sitting.

2. Then you will complete a warm-up.
3. You will jump on force plates to measure jump height.
4. Your knee strength will be measured.
5. Knee laxity will be tested again.
6. You will complete drop jump and drop cut tasks.
   - Drop Jump Task: You will drop from a box and immediately jump as high as possible.
   - Drop Cut Task: You will drop from a box on to your testing limb, and immediately cut to the opposite side.
7. You will complete 3 rounds of the Yo-Yo Test, in which you will run for as long as you can maintain the pace.
   - Following each round of running, your jump heigh and knee laxity will be measured, and you will complete the drop jump and drop cut tasks.
8. You will sit for 30 minutes
9. Your knee laxity will be measured one last time.

What happens if I say "No, I do not want to be in this research study"?

Being in this study is up to you. You can say no now or leave the study later. Either way, your decision won't affect your grades, your relationship with your instructors, or standing with the University of Tennessee, Knoxville.

What happens if I say "Yes" but change my mind later?

Even if you decide to be in the study now, you can change your mind and stop at any time. If you decide to stop before the study is completed, you can tell the PI and/or co-PI that you want to withdraw from the study at any time. If you decide to withdraw from the study, your information will be kept de-identified and kept in a locked drawer in the Biomechanics lab. Only study personnel will have access to any forms and data that have already been collected.

Are there any possible risks to me?

It is possible that someone could find out you were in this study or see your study information, but we believe this risk is small because of the procedures we use to protect your information. These procedures are described later in this form.

Possible risks include lower extremity injury during the landings and cardiovascular exertion during the Yo-Yo Test. These risks will be minimized. At the beginning of the data collection, you will complete a required warm-up to get your muscles ready and provide an opportunity to become familiar with the movements. The movements included are movements you should be familiar with, due to your being recreationally active. In the *very* unlikely case that you hurt yourself during the study visit, emergency services will be contacted immediately for assistance. If you realize afterwards that you have become injured, you should seek medical assistance.

Are there any benefits to being in this research study?

We do not expect you to benefit from being in this study. By participating, you can help us learn more about the relationship between fatigue and how "loose" the knee joint is as well as improve our understanding of how this relates to ACL injuries. We hope the knowledge gained from this study will benefit others in the future.

Who can see or use the information collected for this research study?

We will protect the confidentiality of your information by keeping all forms in a locked drawer or on a password-encrypted computer drive in the Biomechanics lab, which is locked every day. Only the investigators conducting this study will have access to your personal information. If information from this study is published or presented at scientific meetings, your name and other personal information will not be used. We will make every effort to prevent anyone who is not on the research team from knowing that you gave us information or what information came from you. Although it is unlikely, there are times when others may need to see the information, we collect about you. These include people at the University of Tennessee, Knoxville who oversee research to make sure it is conducted properly. Government agencies (such as the Office for Human Research Protections in the U.S. Department of Health and Human Services), and others responsible for watching over the safety, effectiveness, and conduct of the research. If a law or court requires us to share the information, we would have to follow that law or final court ruling.

What will happen to my information after this study is over?

We will keep your information to use for future research. Your name and other information that can directly identify you will be kept secure and stored separately from your research data collected as part of the study. We will not share your research data with other researchers.

Will I be paid for being in this research study?

You will not be paid for being in this study.

Will it cost me anything to be in this research study?

It will not cost you anything to be in this study.

What else do I need to know?

We may need to stop your participation in the study without your consent if you do not follow the study instructions, no longer meet the study's eligibility requirements, if your safety comes into question, or if the study is stopped for any reason.

The University of Tennessee does not automatically pay for medical claims or give other compensation for injuries or other problems should you realize you are injured outside of the study visit.

Who can answer my questions about this research study?

If you have questions or concerns about this study, or have experienced a research related problem or injury, contact the researchers, Dr. Joshua Weinhandl (**jweinhan@utk.edu**, 865-974- 9556) or Taliah Carlson (**tcarlso3@vols.utk.edu**, 865-974-2091)

For questions or concerns about your rights or to speak with someone other than the research team about the study, please contact:

Institutional Review Board

The University of Tennessee, Knoxville

Phone: 865-974-7697

Email: **utkirb@utk.edu**

STATEMENT OF CONSENT

I have read this form, and the research study has been explained to me. I have been given the chance to ask questions and my questions have been answered. If I have more questions, I have been told who to contact. By signing this document, I am agreeing to be in this study. I will receive a copy of this document after I sign it.

______________________	______________________	__________
Name of Adult Participant	Signature of Adult Participant	Date

Researcher Signature (to be completed at time of informed consent)

I have explained the study to the participant and answered all his/her questions. I believe that he/she understands the information described in this consent form and freely consents to be in the study.

Name of Research Team Member	Signature of Research Team Member	Date

Appendix I. Lower Extremity Functional Scale

SUBJECT: _____________ DATE: _________________

Lower Extremity Functional Scale

We are interested in knowing whether or not you are having any difficulty at all with the activities listed below. Please provide an honest answer for each activity.

KEY

0 - Extreme difficulty or unable to perform activity
1 - Quite a bit of difficulty
2 - Moderate difficulty
3 - A little bit of difficulty
4 - No difficulty

Today, ***do you*** or ***would you*** have any difficulty at all with:	Extreme 0	Quite a bit 1	Moderate 2	Minimal 3	None 4
1. Any of your usual work, housework or school activities	☐	☐	☐	☐	☐
2. Your usual hobbies, recreational or sporting activities	☐	☐	☐	☐	☐
3. Getting into or out of the bath	☐	☐	☐	☐	☐
4. Walking between rooms	☐	☐	☐	☐	☐
5. Putting on your shoes or socks	☐	☐	☐	☐	☐
6. Squatting	☐	☐	☐	☐	☐
7. Lifting an object, like a bag of groceries from the floor	☐	☐	☐	☐	☐
8. Performing light activities around your home	☐	☐	☐	☐	☐
9. Performing heavy activities around your home	☐	☐	☐	☐	☐
10. Getting into or out of a car	☐	☐	☐	☐	☐
11. Walking 2 blocks	☐	☐	☐	☐	☐
12. Walking a mile	☐	☐	☐	☐	☐
13. Going up or down 10 stairs (about 1 flight)	☐	☐	☐	☐	☐
14. Standing for 1 hour	☐	☐	☐	☐	☐
15. Sitting for 1 hour	☐	☐	☐	☐	☐
16. Running on even ground	☐	☐	☐	☐	☐

17. Running on uneven ground	☐	☐	☐	☐	☐
18. Making sharp turns while running fast	☐	☐	☐	☐	☐
19. Hopping	☐	☐	☐	☐	☐
20. Rolling over in bed	☐	☐	☐	☐	☐

Total Score: _________/80

SUBJECT: ______________ DATE: __________________

MUSCULOSKELETAL QUESTIONNAIRE

Hip/Groin

Have You Ever Suffered An Injury To Your Hip / Groin *(including hernias and/or sports hernias)?*

☐ YES ☐ NO

- List Time Missed ____
- Please Describe ____

  ____

Were Any Diagnostic Tests Performed? (check all that apply)

☐ X-Rays ☐ MRI ☐ CT-Scan ☐ Bone Scan

Have You Ever Been Hospitalized For A Hip / Groin Injury?

☐ YES ☐ NO

- When? ____

  ____

- Please Describe ____

  ____

Have You Ever Had Surgery For A Hip / Groin Injury?

☐ YES ☐ NO

- When? ____

- ♦ Please Describe ____

  ____

Have You Ever Been Advised Not To Participate In Athletic Activities Due To A Hip and/or Groin Injury?

☐ YES ☐ NO

- ♦ Please Describe ____

  ____

Thigh / Hamstring / Quadriceps:

Have You Ever Suffered An Injury To Your Thigh, Hamstring, and/or Quadriceps?

☐ YES ☐ NO

- ♦ List Time Missed ____
- ♦ Please Describe ____

  ____

Were Any Diagnostic Tests Performed? (check all that apply)

☐ X-Rays ☐ MRI ☐ CT-Scan ☐ Bone Scan

Have You Ever Been Hospitalized For A Thigh, Hamstring, and/or Quadriceps Injury?

☐ YES ☐ NO

- ♦ When? ____
- ♦ Please Describe ____

  ____

Have You Ever Had Surgery For A Thigh, Hamstring, and/or Quadriceps Injury?

☐ YES ☐ NO

- When? ______________________________
- Please Describe ______________________________

____

Have You Ever Been Advised Not To Participate In Athletic Activities Due To A Thigh, Hamstring, or Quadriceps Injury?

☐ YES ☐ NO

- When? ______________________________
- Please Describe ______________________________

____

Knee / Patella:

Have You Ever Suffered An Injury To Your Knee and/or Patella (kneecap)?

☐ YES ☐ NO

- List Time Missed ______________________________
- Please Describe ______________________________

____

Were Any Diagnostic Tests Performed? (check all that apply)

☐ X-Rays ☐ MRI ☐ CT-Scan ☐ Bone Scan

Have You Ever Been Hospitalized For A Knee and/or Patella Injury?

☐ YES ☐ NO

- When? ______________________________
- Please Describe ______________________________

____

Have You Ever Had Surgery For A Knee and/or Patella Injury?

☐ YES ☐ NO

- When? ____

- Please Describe ____

  ____

Have You Ever Been Advised Not To Participate In Athletic Activities Due To A Knee / Patella Injury?

☐ YES ☐ NO

- Please Describe ____

  ____

Have You Ever / Do You Presently Wear A Knee Brace?

☐ YES ☐ NO

- Which Knee? ____________________ Brand / Model of Brace? ________________

- Reason for Wearing? ____________________________________

  ____

Ankle / Lower Leg:

Have You Ever Suffered An Injury To Your Ankle / Lower Leg?

☐ YES ☐ NO

- List Time Missed _______________________________________

- Please Describe ____

  ____

Were Any Diagnostic Tests Performed? (check all that apply)

☐ X-Rays ☐ MRI ☐ CT-Scan ☐ Bone Scan

Have You Ever Been Hospitalized For An Ankle / Lower Leg Injury?

☐ YES ☐ NO

- When? ______________________________
- Please Describe ______________________________

____

Have You Ever Had Surgery For An Ankle / Lower Leg Injury?

☐ YES ☐ NO

- When? ______________________________
- Please Describe ______________________________

____

Have You Ever Been Advised Not To Participate In Athletic Activities Due To An Ankle / Lower Leg Injury?

☐ YES ☐ NO

- Please Describe ______________________________

____

Do You Presently: ☐ Tape Your Ankle(s) ☐ Use Ankle Brace(s) ☐ Other

- Please Describe ______________________________

____

<u>Foot / Toes:</u>

Have You Ever Suffered An Injury To Your Foot / Toe(s)?

☐ YES ☐ NO

- ♦ List Time Missed ____

- ♦ Please Describe ____

  ____

Were Any Diagnostic Tests Performed? (check all that apply)

☐ X-Rays ☐ MRI ☐ CT-Scan ☐ Bone Scan

Have You Ever Been Hospitalized For A Foot / Toe Injury?

☐ YES ☐ NO

- ♦ When? ____

- ♦ Please Describe ____

  ____

Have You Ever Had Surgery For A Foot / Toe Injury?

☐ YES ☐ NO

- ♦ When? ____

- ♦ Please Describe ____

  ____

Have You Ever Been Advised Not To Participate In Athletic Activities Due To An Foot and/or Toe Injury?

☐ YES ☐ NO

- ♦ Please Describe ____

  ____

Anterior Cruciate Ligament (ACL):

Have You Ever Experienced An Anterior Cruciate Ligament (ACL) Injury?

☐ YES ☐ NO

- ♦ List Time Missed ______________________________
- ♦ Please Describe ______________________________

____

What Knee? (check all that apply)

☐ Left Knee ☐ Right Knee ☐ Both

Were Any Diagnostic Tests Performed? (check all that apply)

☐ X-Rays ☐ MRI ☐ CT-Scan ☐ Bone Scan

- ♦ Please Describe ______________________________

____

What Activity Were You Doing At The Time of Injury?

- ♦ Please Describe ______________________________

____

Have You Ever Had an ACL Reconstruction?

☐ YES ☐ NO

- ♦ List Time Missed ______________________________
- ♦ Please Describe ______________________________

____

What Knee? (check all that apply)

☐ Left Knee ☐ Right Knee ☐ Both

What Type of Graft Did You Receive During ACL Reconstruction?

☐ Semitendinosus-Gracilis Graft ☐ Patellar Tendon Graft ☐ Donor Graft ☐ Other

- Please Describe ____

  ____

Did You Participate in Any Prehabilitation (i.e. Physical Therapy) Before Surgery?

☐ YES ☐ NO

- Please Describe ____

  ____

- How Long? ____

Did You Participate in Any Rehabilitation (i.e. Physical Therapy) Before Surgery?

☐ YES ☐ NO

- Please Describe ____

  ____

- How Long? ____

How Long Was It Until You Returned Back To Play (i.e. Time Between Surgery To Clearance Back To Sport)?

- Please Describe ____

  ____

Have You Ever Had Multiple ACL Reconstructions?

☐ YES ☐ NO

- Please Describe ____

  ____

<u>Menstrual Cycle:</u>

Are You Currently On Your Menstrual Cycle?

☐ YES ☐ NO

- How Long? ____________________

How Long Does Your Typical Menstrual Cycle Last?

- Please Describe ____________________

  ____

When Was Your Last Menstrual Cycle?

- Please Describe ____________________

  ____

- How Long? ____________________

When Was Your First Menstrual Cycle?

- Please Describe ____________________

  ____

Have You Ever Been Pregnant?

☐ YES ☐ NO

SUBJECT: _____________ DATE: _________________

FITNESS ACTIVITY QUESTIONNAIRE

Please describe your current participation in the following types of exercise:

1. Aerobic (aerobic classes, walking, jogging, stair climbing, hiking, cycling, etc.)

Frequency (# of days per week): __________________

Duration (time spent per session): __________________minutes

Intensity (difficulty level): light somewhat hard hard very hard

How long have you been participating in aerobic activity as described above?

__________________Years

2. Anaerobic (weight training, sprinting, etc.)

Frequency (# of days per week): __________________

Duration (time spent per session): __________________minutes

Intensity (difficulty level): light somewhat hard hard very hard

How long have you been participating in anaerobic activity as described above?

__________________Years

3. Organized or Recreational sports

Type of sport(s):____

Frequency (# of days per week): __________________

Duration (time spent per session): __________________minutes

Intensity (difficulty level): light somewhat hard hard very hard

How long have you been participating in sports activity as described above?

__________________Years

Appendix L. Recruitment Flyer

THE UNIVERSITY OF TENNESSEE KNOXVILLE

BIOMECHANICS

Females Needed for a Biomechanical Study

The University of Tennessee Biomechanics/Sports Medicine Lab is conducting a research study to examine the relationship between anterior knee laxity, how "loose" the knee joint is, and muscular fatigue

You May Qualify If You

- Are between 18 and 35 years old
- Recreationally active
  - Such as running, weight training, elliptical, pick-up basketball
- No previous lower extremity surgery ever or a lower extremity injury in the past 6 months

Participation Involves

- Engaging in three rounds of a fatigue protocol that simulates a game or practice situation
- Engaging in three jumping and cutting tasks
- Approximately 3 hours

FOR MORE INFORMATION:

Contact: Dr. Weinhandl
jweinhan@utk.edu

Contact: Taliah Carlson
tcarlso3@vols.utk.edu

IRB NUMBER: UTK IRB-24-07958-XP
IRB APPROVAL DATE: 02/12/2024

or scan the QR Code to be contacted via email

Appendix M. IRB Approval Letter

THE UNIVERSITY OF
TENNESSEE
KNOXVILLE

January 25, 2024

Joshua Trueblood Weinhandl,
UTK - Coll of Education, Hlth, & Human - Kinesiology, Recreation & Sports Studies

Re: UTK IRB-24-07956-XP
Study Title: Determining the Effects of Fatigue on Anterior Knee Laxity

Dear Joshua Trueblood Weinhandl:

The UTK Institutional Review Board (IRB) reviewed your application for the above referenced project. It determined that your application is eligible for expedited review under 45 CFR 46.110(b)(1), categories (4) and (7). The IRB has reviewed these materials and determined that they do comply with proper consideration for the rights and welfare of human subjects and the regulatory requirements for the protection of human subjects.

Therefore, this letter constitutes full approval by the IRB of your application (Version 1.2) as submitted, including:

Documents Stamped:

- Consent for Research Participation (English) - (Version 1.1)
- FatigueAKL_Recruitment_Script - (Version 1.1)
- FatigueAKL_Instructions - (Version 1.0)
- FatigueAKL_Musculoskeletal_Questionnaire - (Version 1.0)
- FatigueAKL_Lower_Extremity_Functional_Scale_Form - (Version 1.0)
- FatigueAKL_Fitness_Activity_Questionnaire - (Version 1.0)

That have been dated and stamped IRB approved. You are approved to enroll a maximum of 60 participants. Approval of this study will be valid from 01/25/2024 to 01/24/2025.

Any revisions in the approved application, consent forms, instruments, recruitment materials, etc., must also be submitted to and approved by the IRB prior to implementation. In addition, you are responsible for reporting any unanticipated serious adverse events or other problems involving risks to subjects or others in the manner required by the local IRB policy.

Finally, re-approval of your project is required by the IRB in accord with the conditions specified above. You may not continue the research study beyond the time or other limits specified unless you obtain prior written approval of the IRB.

Sincerely,

Lora Beebe, Ph.D., PMHNP-BC, FAAN
Chair

Appendix N. Individual Participant Demographics and Results

Table 11: Demographic information for the individual participants.

Table 11: Individual Participant Demographics

Participant	Height (m)	Weight (kg)	Age (years)	LEFS
1	1.61	65.65	26	80
2	1.76	81.51	20	80
3	1.64	74.66	24	77
4	1.80	71.37	25	80
5	1.62	55.32	19	77
6	1.66	49.30	19	80
7	1.63	50.21	22	80
8	1.58	54.05	22	80
9	1.58	55.19	19	80
10	1.57	58.79	19	80
11	1.63	67.84	21	80
12	1.80	65.50	22	80
13	1.73	76.05	21	80
14	1.58	55.80	21	80
15	1.60	76.71	24	80
16	1.81	74.62	22	79
17	1.63	55.96	20	80
18	1.58	65.47	22	80
19	1.79	94.81	26	80
20	1.66	60.66	21	75
21	1.65	58.23	20	79

Table 12: Individual participant AKL average displacements (mm) of the three trials at each time point.

Table 12: Individual Participant Anterior Knee Laxity (134N) Displacements (mm): Mean

Participant	Pre Warm-Up	Post Warm-Up	Yo-Yo Round 1	Yo-Yo Round 2	Yo-Yo Round 3	30 Min Post Fatigue
1	3.85	5.73	4.87	7.37	4.80	4.33
2	3.47	3.63	3.23	3.90	3.40	3.77
3	2.93	2.50	2.23	2.27	2.83	3.07
4	3.87	4.93	3.20	3.30	3.53	4.07
5	4.77	4.83	5.73	5.30	6.50	4.93
6	4.10	4.50	3.70	3.27	4.87	5.03
7	4.57	4.90	4.73	4.13	3.90	4.20
8	3.70	4.03	6.17	5.50	6.50	5.30
9	3.03	3.60	4.07	4.33	4.80	4.53
10	4.10	3.97	4.43	4.00	4.30	3.77
11	4.53	5.73	6.23	4.27	4.47	4.53
12	5.30	6.00	5.80	6.13	7.17	4.43
13	4.20	4.90	4.20	3.97	3.70	4.13
14	2.70	3.30	3.43	3.40	3.57	3.93
15	5.57	4.13	6.87	5.87	5.23	6.53
16	4.87	3.87	5.80	5.10	5.27	4.40
17	6.10	5.77	6.40	5.93	5.63	4.70
18	6.83	5.00	6.40	4.80	3.70	6.37
19	2.97	3.27	4.23	5.57	4.37	5.70
20	3.90	3.83	4.87	4.60	4.37	3.80
21	5.40	5.43	6.27	7.23	6.87	5.63

*Table 13: Individual participant co-contraction ratios for the pre-activation and landing phases of the drop cut task. *Subjects 1 and 21 were not utilized because they had incomplete datasets.*

Table 13: Individual Participant Drop Cut Pre-Activation and Landing Phase Co-Contraction Ratio (VM/MH): Mean

	Baseline		**Yo-Yo Round 1**		**Yo-Yo Round 2**		**Yo-Yo Round 3**	
Participant	Pre-Activation	Landing	Pre-Activation	Landing	Pre-Activation	Landing	Pre-Activation	Landing
1	2.2	3.20	0.73	3.50	*	*	*	*
2	0.41	4.70	0.62	4.51	1.56	3.32	0.93	3.22
3	1.34	5.33	0.86	4.33	0.48	4.08	0.35	4.18
4	0.29	2.72	0.35	2.41	0.34	2.12	0.45	3.74
5	0.37	4.04	0.44	4.45	0.43	3.91	0.42	4.12
6	0.54	1.52	0.47	1.05	0.38	1.13	0.30	0.99
7	0.94	2.62	1.10	2.57	1.18	2.55	0.91	2.04
8	0.36	3.10	0.24	2.34	0.25	2.00	0.18	2.40
9	1.04	3.02	1.24	3.40	1.19	3.34	1.17	3.90
10	0.64	5.01	1.30	6.70	1.48	6.06	0.85	4.84
11	2.94	4.07	6.49	6.48	8.66	7.63	4.71	7.41
12	4.12	6.15	4.39	8.75	4.16	8.06	2.72	7.18
13	0.75	3.02	0.84	3.25	1.11	2.07	0.90	2.21
14	0.94	3.65	2.26	5.59	1.19	2.78	1.13	3.34
15	1.13	5.70	1.77	6.84	1.85	6.83	1.55	6.01
16	1.52	2.12	1.50	3.33	1.82	3.82	1.72	4.17
17	0.25	1.24	0.23	1.31	0.22	1.87	0.13	1.65
18	1.17	6.85	1.16	7.15	1.30	5.78	1.25	6.47
19	0.47	2.77	0.73	2.85	0.71	2.65	0.79	2.53
20	0.43	4.58	0.38	6.68	0.65	9.06	1.05	8.51
21	2.84	4.44	3.51	3.11	*	*	*	*

*Table 14: Individual participant pre-activation phase median frequencies for the drop cut task. *Subjects 1 and 21 were not utilized because they had incomplete datasets.*

Table 14: Individual Participant Drop Cut Median Frequency for Vastus Medialis and Medial Hamstrings Pre-Activation Phase : Mean

	Baseline		Yo-Yo Round 1		Yo-Yo Round 2		Yo-Yo Round 3	
Participant	Vastus Medialis	Medial Hamstrings	Vastus Medialis	Medial Hamstrings	Vastus Medialis	Medial Hamstrings	Vastus Medialis	Medial Hamstrings
1	56.88	60.00	56.64	65.20	*	*	*	*
2	80.06	58.08	70.96	48.48	93.19	52.34	78.36	56.46
3	69.20	62.37	75.71	69.42	90.52	69.58	83.00	65.77
4	73.16	78.01	57.80	78.33	78.27	54.97	63.86	59.74
5	66.19	55.62	70.83	48.49	80.77	62.54	76.65	69.71
6	67.71	61.55	84.42	64.83	89.34	68.93	72.38	73.84
7	66.81	54.07	65.55	61.83	69.79	57.57	76.97	58.92
8	81.72	61.87	75.56	53.02	70.67	57.83	99.83	59.29
9	79.81	71.96	80.85	94.87	70.33	73.17	94.04	89.18
10	76.78	67.35	64.46	76.40	89.06	75.15	76.98	77.44
11	57.88	69.63	89.90	82.54	104.84	88.89	82.04	74.91
12	75.47	61.13	74.30	52.33	97.01	95.09	87.04	85.63
13	61.73	59.31	73.16	56.76	56.58	60.35	66.89	59.06
14	68.47	56.62	65.33	64.77	64.80	58.22	71.05	59.76
15	67.48	67.21	70.44	55.71	75.46	56.98	108.86	60.12
16	71.16	62.00	71.59	64.72	73.92	69.83	83.59	68.04
17	55.35	66.47	53.50	81.57	70.08	73.72	66.41	79.54
18	73.04	71.33	74.34	68.57	70.77	65.57	62.98	74.19
19	65.87	64.19	63.82	86.66	93.76	78.15	81.95	77.28
20	65.68	62.14	77.59	60.26	70.49	70.34	63.22	58.27
21	72.76	77.30	64.43	91.20	*	*	*	*

*Table 15: Individual participant landing phase median frequencies for the drop cut task. *Subjects 1 and 21 were not utilized because they had incomplete datasets.*

Table 15: Individual Participant Drop Cut Median Frequency for Vastus Medialis and Medial Hamstrings Landing Phase : Mean

	Baseline		Yo-Yo Round 1		Yo-Yo Round 2		Yo-Yo Round 3	
Participant	Vastus Medialis	Medial Hamstrings	Vastus Medialis	Medial Hamstrings	Vastus Medialis	Medial Hamstrings	Vastus Medialis	Medial Hamstrings
1	51.92	67.35	51.06	81.05	*	*	*	*
2	107.94	77.14	90.70	86.54	93.68	60.26	96.39	70.01
3	57.85	69.03	55.25	83.33	55.16	93.96	61.58	84.16
4	67.50	123.78	65.28	102.42	70.99	86.01	45.08	100.08
5	105.11	78.93	87.77	103.42	95.52	82.75	68.76	89.37
6	62.11	75.68	82.86	80.58	75.89	79.95	87.51	80.08
7	76.64	83.55	72.16	84.71	69.76	75.95	75.03	80.86
8	66.51	60.43	67.88	67.83	72.03	68.24	57.19	65.30
9	81.78	65.39	74.30	66.92	82.78	76.07	79.51	74.00
10	82.66	53.77	91.26	53.50	98.91	72.61	96.03	65.68
11	66.95	80.21	81.86	98.48	83.42	104.65	86.51	92.95
12	68.07	64.98	66.02	73.40	72.07	72.40	72.35	55.71
13	49.21	68.50	43.73	56.49	45.31	49.75	49.89	42.32
14	89.73	77.49	92.22	65.87	75.56	51.97	93.54	57.79
15	65.20	58.37	63.54	59.47	63.48	62.12	70.22	48.56
16	70.38	59.18	72.79	66.57	71.07	72.26	82.46	68.41
17	55.15	80.36	54.54	72.65	47.40	88.22	54.63	78.20
18	60.28	79.19	62.18	82.70	63.20	75.56	61.50	77.22
19	68.77	67.41	66.09	65.77	74.13	72.77	69.01	66.85
20	58.13	62.83	62.40	79.19	53.93	71.92	62.77	94.52
21	60.92	67.02	65.76	43.90	*	*	*	*

Table 16: Individual participant means for peak loading and average loading rate for the drop cut task.

Table 16: Individual Participant Drop Cut Peak Loading and Average Loading Rate: Mean

	Baseline		**Yo-Yo Round 1**		**Yo-Yo Round 2**		**Yo-Yo Round 3**	
Participant	Peak Load	Avg Loading Rate	Peak Load	Avg Loading Rate	Peak Load	Avg Loading Rate	Peak Load	Avg Loading Rate
1	2.60	42.39	2.79	47.53	2.83	44.63	2.71	47.72
2	3.24	108.60	3.04	118.82	3.21	138.15	3.34	122.11
3	2.39	28.45	2.72	32.97	2.50	26.50	1.93	38.56
4	2.11	29.97	2.16	43.02	2.30	54.21	2.38	50.65
5	2.47	24.26	2.48	41.50	2.56	37.43	2.53	29.25
6	3.28	47.84	2.83	48.18	2.94	41.88	2.76	36.14
7	3.85	96.85	4.06	108.43	4.13	107.40	4.02	119.77
8	2.64	23.00	2.62	26.14	2.64	27.35	2.63	28.15
9	3.59	94.43	3.23	74.10	3.11	71.17	2.98	59.57
10	2.99	79.80	3.30	84.85	3.30	94.42	3.15	69.77
11	2.86	94.35	2.91	146.03	3.51	199.62	3.38	199.35
12	3.19	222.52	3.25	200.44	3.36	201.62	3.21	202.65
13	2.86	57.41	2.79	55.18	2.91	56.19	2.75	49.50
14	3.06	71.70	2.75	57.66	3.06	62.17	2.96	63.61
15	2.14	36.91	2.59	49.92	2.44	38.54	2.43	51.06
16	3.30	61.47	3.55	68.09	3.52	57.46	3.47	55.20
17	2.23	31.81	2.35	22.56	2.50	31.62	2.54	18.63
18	2.57	86.62	2.41	81.04	2.54	90.81	2.46	73.93
19	1.94	32.62	2.07	36.16	2.22	41.14	2.18	38.52
20	2.19	30.95	2.55	26.12	2.54	36.38	2.64	38.47
21	4.66	238.95	4.40	206.97	4.17	194.79	4.25	204.91

*Table 17: Individual participant co-contraction ratios for the pre-activation and landing phases of the drop jump task. *Subjects 1 and 21 were not utilized because they had incomplete datasets.*

Table 17: Individual Participant Drop Jump Pre-Activation and Landing Phase Co-Contraction Ratio (VM/MH): Mean

	Baseline		**Yo-Yo Round 1**		**Yo-Yo Round 2**		**Yo-Yo Round 3**	
Participant	Pre-Activation	Landing	Pre-Activation	Landing	Pre-Activation	Landing	Pre-Activation	Landing
1	1.07	5.24	1.38	4.76	*	*	*	*
2	3.27	12.96	2.73	11.36	1.77	6.71	1.54	7.12
3	1.63	5.51	1.56	6.16	1.45	6.97	1.28	7.55
4	0.43	4.26	0.75	3.57	0.63	4.39	0.82	4.47
5	1.45	8.95	2.39	8.04	0.93	7.85	1.21	8.72
6	1.35	2.88	1.88	2.32	0.89	2.67	0.81	2.22
7	0.47	5.36	0.34	3.99	0.40	3.58	0.39	3.16
8	1.28	9.06	0.96	7.31	1.30	7.52	0.91	7.25
9	0.94	10.23	1.01	9.46	1.42	9.97	2.88	11.37
10	1.44	8.62	1.34	7.51	1.08	7.24	0.83	5.78
11	1.15	5.02	5.06	7.66	5.34	7.61	6.48	7.90
12	1.92	6.54	2.03	6.26	1.80	6.95	3.05	8.47
13	1.89	3.76	1.38	4.71	0.82	2.18	0.84	2.25
14	1.25	11.05	2.72	16.67	1.59	10.58	2.12	9.70
15	5.07	5.13	4.47	6.08	6.46	4.73	5.42	6.10
16	1.15	4.54	1.29	5.54	0.97	6.45	1.42	6.02
17	0.45	1.81	0.66	2.38	0.62	2.21	0.87	1.61
18	2.72	9.46	2.08	6.65	4.34	7.23	3.81	6.81
19	4.29	3.67	2.61	3.17	3.23	2.86	2.27	3.13
20	1.64	8.72	1.17	7.29	0.92	11.57	2.36	12.90
21	4.02	4.19	3.08	3.03	*	*	*	*

*Table 18: Individual participant pre-activation phase median frequencies for the drop jump task. *Subjects 1 and 21 were not utilized because they had incomplete datasets.*

Table 18: Individual Participant Drop Jump Median Frequency for Vastus Medialis and Medial Hamstrings Pre-Activation Phase: Mean

	Baseline		**Yo-Yo Round 1**		**Yo-Yo Round 2**		**Yo-Yo Round 3**	
Participant	Vastus Medialis	Medial Hamstrings	Vastus Medialis	Medial Hamstrings	Vastus Medialis	Medial Hamstrings	Vastus Medialis	Medial Hamstrings
1	61.89	77.89	52.14	95.86	*	*	*	*
2	109.89	58.24	113.52	74.04	109.60	59.56	117.31	64.75
3	69.40	74.31	75.46	71.05	81.25	79.92	87.55	82.44
4	62.78	104.54	60.53	76.21	67.92	92.86	67.00	88.27
5	78.03	57.22	107.22	62.97	74.74	68.28	86.25	81.24
6	79.56	69.12	84.59	67.17	75.85	74.24	85.26	79.85
7	74.60	97.43	82.92	96.62	75.17	97.96	88.95	90.28
8	91.62	110.16	68.08	92.29	75.44	106.10	77.40	81.14
9	83.75	67.21	91.02	72.63	94.45	79.79	96.18	113.52
10	79.49	80.03	79.93	84.01	92.08	80.58	80.26	81.97
11	73.40	108.72	101.28	89.56	100.54	98.95	89.77	97.18
12	70.86	93.09	77.72	106.26	69.93	89.97	73.83	52.78
13	65.24	86.52	69.49	72.59	62.78	80.02	63.89	53.61
14	84.89	86.41	81.56	74.29	65.60	69.92	83.02	69.69
15	69.66	68.50	71.56	50.25	76.59	48.83	84.57	58.08
16	78.70	56.13	78.82	52.93	79.51	62.69	78.48	66.11
17	69.35	94.97	63.72	74.32	75.05	69.78	76.29	75.25
18	77.42	93.37	79.35	98.46	93.71	91.71	75.15	98.77
19	84.30	87.40	71.01	78.39	88.48	98.09	98.65	101.34
20	64.63	84.36	61.94	68.07	67.50	73.41	61.46	74.88
21	69.58	100.76	80.91	81.02	*	*	*	*

*Table 19: Individual participant landing phase median frequencies for the drop jump task. *Subjects 1 and 21 were not utilized because they had incomplete datasets.*

Table 19: Individual Participant Drop Jump Median Frequency for Vastus Medialis and Medial Hamstrings Landing Phase: Mean

	Baseline		Yo-Yo Round 1		Yo-Yo Round 2		Yo-Yo Round 3	
Participant	Vastus Medialis	Medial Hamstrings	Vastus Medialis	Medial Hamstrings	Vastus Medialis	Medial Hamstrings	Vastus Medialis	Medial Hamstrings
1	61.41	65.49	62.55	57.07	*	*	*	*
2	90.36	81.77	87.91	83.13	96.58	60.75	99.56	74.76
3	63.93	63.48	57.85	66.65	52.44	70.28	59.43	70.94
4	90.91	98.30	81.38	89.19	78.43	69.99	84.90	75.39
5	88.39	103.37	89.64	115.08	96.03	109.05	92.56	104.23
6	99.16	85.17	114.59	67.36	120.67	67.41	131.81	68.43
7	76.77	63.75	85.50	67.85	70.88	77.10	63.96	80.04
8	73.19	84.00	72.19	75.85	76.24	80.16	79.22	76.90
9	66.84	51.57	72.35	53.86	74.22	57.20	71.55	72.60
10	87.60	44.67	82.72	55.42	76.42	57.85	80.85	62.47
11	81.55	85.20	82.42	81.65	91.38	95.13	93.75	90.68
12	90.27	91.30	94.85	103.51	96.63	69.20	87.09	63.62
13	61.23	48.07	46.04	58.50	50.24	38.71	55.49	43.13
14	64.49	58.39	67.17	61.24	70.31	54.58	73.93	62.35
15	97.40	79.21	81.58	75.09	93.11	80.95	96.07	70.94
16	78.24	57.60	81.04	58.79	87.20	50.55	86.47	73.69
17	77.26	63.18	59.86	70.33	54.01	77.23	59.94	71.01
18	67.27	63.60	66.22	68.02	68.69	70.81	68.88	70.89
19	89.47	63.14	83.62	65.75	93.53	57.57	104.83	52.44
20	65.91	56.28	60.51	62.60	53.01	63.79	61.37	64.69
21	85.77	61.61	75.38	53.74	*	*	*	*

Table 20: Individual participant means for peak loading and average loading rate for the drop jump task.

Table 20: Individual Participant Drop Jump Peak Loading (BW) and Average Loading Rate (BW/s): Mean

	Baseline		**Yo-Yo Round 1**		**Yo-Yo Round 2**		**Yo-Yo Round 3**	
Participant	Peak Load	Avg Loading Rate	Peak Load	Avg Loading Rate	Peak Load	Avg Loading Rate	Peak Load	Avg Loading Rate
1	1.42	32.88	1.38	32.69	1.40	31.56	1.46	36.92
2	2.40	72.85	2.31	96.27	2.09	59.06	2.18	73.97
3	1.56	30.55	1.63	31.42	1.64	30.80	1.93	38.56
4	1.28	18.11	1.57	21.81	1.57	20.85	1.57	23.38
5	1.53	33.46	2.02	48.75	1.49	40.25	2.05	57.93
6	1.67	30.02	1.96	41.52	1.73	34.53	1.73	36.97
7	1.77	28.24	2.36	55.69	2.56	63.64	2.54	64.54
8	1.47	24.24	1.76	38.17	2.18	47.40	1.98	34.70
9	2.02	51.87	1.87	47.28	1.71	36.34	1.68	33.87
10	2.63	77.05	2.78	86.39	2.83	78.63	3.06	72.42
11	2.46	206.37	2.64	210.51	2.65	212.08	2.47	193.56
12	2.36	161.94	2.36	176.02	2.16	168.86	2.38	143.48
13	1.73	35.14	2.16	44.80	1.98	57.47	2.15	42.45
14	1.45	50.48	1.59	46.73	1.45	35.15	1.60	57.05
15	2.08	32.46	1.90	32.54	1.94	31.59	2.10	36.31
16	1.69	15.28	2.13	35.26	1.84	24.14	2.05	31.45
17	1.82	24.62	2.81	35.25	2.90	38.80	3.36	49.52
18	1.84	35.13	1.93	40.29	1.80	37.00	1.87	36.96
19	1.01	16.10	1.19	18.69	1.57	28.27	1.14	18.30
20	1.74	24.62	2.04	38.63	1.77	34.40	1.90	34.50
21	2.06	103.34	3.11	163.92	2.82	172.05	3.01	184.14

Table 21:Individual participant jump height calculated from the countermovement jump.

Table 21: Individual Participant Countermovement Jump Height (m): Mean				
Participant	**Baseline**	**Yo-Yo Round 1**	**Yo-Yo Round 2**	**Yo-Yo Round 3**
1	0.33	0.31	0.32	0.10
2	0.21	0.19	0.19	0.18
3	0.19	0.20	0.20	0.19
4	0.35	0.31	0.32	0.31
5	0.21	0.20	0.20	0.19
6	0.18	0.27	0.28	0.27
7	0.18	0.21	0.20	0.19
8	0.37	0.36	0.33	0.33
9	0.25	0.26	0.26	0.26
10	0.22	0.21	0.19	0.17
11	0.30	0.28	0.28	0.27
12	0.33	0.35	0.31	0.31
13	0.26	0.19	0.21	0.20
14	0.26	0.25	0.25	0.23
15	0.26	0.16	0.16	0.16
16	0.23	0.22	0.23	0.22
17	0.20	0.20	0.18	0.18
18	0.19	0.16	0.16	0.15
19	0.17	0.18	0.18	0.16
20	0.31	0.23	0.21	0.22
21	0.26	0.21	0.19	0.18

Appendix O. Within-Subjects ANOVA Tables

Table 22: Within-Subjects 1x4 ANOVA Tables for the vGRF and EMG variables during the drop cut task.

Table 22: Within-Subjects 1x4 ANOVA Tables for Drop Cut

Source	Mean Square	df	F	*p*-value	η^2
Peak Load	0.056	2.072	1.323	0.278	0.062
Average Loading Rate	239.829	1.328	0.532	0.521	0.026
Pre-Activation Phase					
Median Frequency VM	468.275	3	5.248	0.003	0.226
Median Frequency MH	91.91	3	1.534	0.216	0.079
Co-Contraction Ratio (VM:MH)	2.049	1.42	2.538	0.113	0.124
Landing Phase					
Median Frequency VM	4.246	1.941	0.054	0.944	0.003
Median Frequency MH	44.238	3	0.561	0.643	0.03
Co-Contraction Ratio (VM:MH)	2.102	1.758	1.71	0.199	0.087

Table 23: Within-Subjects 1x4 ANOVA Tables for the vGRF and EMG variables during the drop jump task.

Table 23: Within-Subjects 1x4 ANOVA Tables for Drop Jump

Source	Mean Square	df	F	*p*-value	η^2
Peak Load	0.617	1.784	7.841	0.002	0.282
Average Loading Rate	825.275	1.911	4.476	0.019	0.183
Pre-Activation Phase					
Median Frequency VM	94.917	3	1.724	0.173	0.087
Median Frequency MH	193.673	1.837	1.005	0.371	0.053
Co-Contraction Ratio (VM:MH)	0.431	1.888	0.428	0.641	0.023
Landing Phase					
Median Frequency VM	96.916	1.965	1.549	0.227	0.079
Median Frequency MH	70.933	1.921	0.658	0.518	0.035
Co-Contraction Ratio (VM:MH)	1.192	1.831	0.345	0.692	0.019

Table 24: Within-Subjects 1x4 ANOVA Tables for the jump height calculated from the countermovement jump.

Table 24: Within-Subjects 1x4 ANOVA Table for Countermovement Jump

Source	Mean Square	df	F	*p* -value	η^2
Jump Height	0.008	1.967	5.324	0.009	0.21

Table 25: Within-Subjects 1x6 ANOVA Tables for the anterior knee laxity.

Table 25: Within-Subjects 1x6 ANOVA Tables for Anterior Knee Laxity

Source	Mean Square	df	F	*p*-value	η^2
AKL Average of 3 Trials	0.955	5	1.714	0.138	0.079
AKL Average of Last 2 Trials	0.801	5	1.573	0.175	0.073

Table 26: Within-Subjects 1x6 ANOVA Tables for the anterior knee laxity for the comparison of positive and negative responders.

Table 26: Within-Subjects 1x6 ANOVA Tables for Anterior Knee Laxity
Positive and Negative Responders

Source	Mean Square	df	F	*p*-value	η^2
AKL Responders	2.446	5	5.031	<0.001	0.314

Vita

Taliah Carlson was born in West Allis, WI in 2000 and is the daughter of Kendra and Kenneth Carlson. Taliah graduated from Hamilton High School in Sussex, Wisconsin in 2018. After high school, Taliah attended the University of Kentucky where she graduated with a Bachelors of Science in Kinesiology and Health Promotion with minors in psychology and coaching in 2022. She then chose to attend the University of Tennessee, Knoxville to pursue a Masters of Science in Kinesiology and Sport Studies with a concentration in Biomechanics and graduated in 2024. She is incredibly grateful for all the support from her friends and family throughout her education.