EXTERNAL FOCUS OF ATTENTION TRAINING TO MITIGATE RISK FACTORS ASSOCIATED WITH NON-CONTACT ACL INJURIES

by

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A dissertation submitted to the faculty of
The University of North Carolina at Charlotte
in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in
Biology

Charlotte

2023

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ABSTRACT

SEAN KRYSAK. External Focus of Attention Training to Mitigate Risk Factors Associated with Non-contact ACL Injuries. (Under the direction of DR. ABBEY THOMAS FENWICK)

Anterior cruciate ligament (ACL) injury is one of the most common injuries in sport and brings with it life changing consequences. A considerable financial burden ($17,000) may be accompanied by strength deficiencies, mood disturbances and chronic pain. While long term outcomes may include secondary injury, osteoarthritis and a decreased quality of life. Although these debilitating injuries are frequently associated with contact sports, the majority (70-80%) occur in a non-contact manner and, thus, may be preventable. ACL injury risk reduction programs have been shown to be effective in the short term; however, they lack retention. Hence, it is essential to continue to enhance existing risk reduction strategies. It is highly recommended to include ACL injury risk reduction programs as part of an individual's training prior to engaging in sport. These programs typically target specific biomechanics that have been identified as high risk factors for ACL injuries. While they have shown short-term effectiveness in improving these risk factors, the challenge lies in sustaining these changes throughout the athletic season, which can compromise their injury reduction effectiveness. Traditionally injury risk reduction programs have relied on feedback directed towards the body’s movement (internal focus of attention), while research has shown that feedback directed towards the outcome of the movement (external focus of attention) is more effective for learning and performance of movement as well as retention of learned movements. However, the most effective mode of external focus of attention feedback has yet to be established. Therefore, our aims were to: 1. Evaluate the effectiveness of internal focus of attention feedback vs. external focus of attention feedback at improving high risk biomechanics associated with a non-contact ACL injury and retaining those improvements; 2. Compare the effectiveness of two novel modes of external focus of attention feedback (visual and auditory) at improving high risk biomechanics associated with a non-contact ACL injury. We did not find any significant differences in biomechanics between groups following the internal focus of attention and external focus of attention feedback or between the two modes of external focus of attention (visual and auditory). Thus, our findings do not support prior studies that demonstrate the effectiveness of different modes of feedback in modifying injury risk biomechanics. We did, however, identify statistically significant limb asymmetries regardless of feedback or time point. We also observed post intervention changes in Landing Error Scoring System scores and patient reported outcomes regardless of feedback. It is possible that applying different modes of feedback during different exercises or in individuals with pre-existing "at risk" biomechanics at baseline may return different results. The study also highlights the potential need to screen for limb asymmetries and individualizing the program to address any discrepancies.

ACKNOWLEDGMENTS

This project wouldn't have been possible without guidance of Dr. Abbey Thomas. She played a pivotal role in making this project a reality, and I am deeply grateful for her mentorship and support. I would also like to thank Dr. Luke Donovan and Dr. Shelley Linens for their support and contribution to the project. Gratitude is also due to my fellow graduate students: Dr. Hyunjae Jeon, Dr. Danielle Torp and Jerrell Bushel for their help in and out of the lab.

DEDICATION

I dedicate this dissertation to my wife, Abbey, for her patience and compassion. I can never express enough gratitude for the sacrifices she made during this entire process. It was her constant encouragement and unwavering support that made this dissertation possible. I would also like to dedicate this to my parents, whose belief in my abilities motivated me to work hard and never give up on my dreams.

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CHAPTER 1: INTRODUCTION

Anterior cruciate ligament (ACL) injury is one of the most commonly seen injuries in sport and may have a devastating impact on patients' physical activity levels and quality of life.[1] ACL injuries are highly prevalent in the United States, with more than 250,000 occurring per year.[2] Of those injured approximately 175,000 elect to undergo anterior cruciate ligament reconstruction (ACLR) surgery.[3] Each procedure and its accompanying rehabilitation carry an average cost of $17,000, which results in approximately $3 billion spent annually on ACLRs.[4] Beyond the financial burden, other short term consequences of ACL injuries include time away from sport (approximately 6-12 months), loss of function,[5] strength deficits,[6] chronic pain,[6] and mood disturbances.[7] ACL injuries also bring long term consequences including: loss of scholarships and future financial opportunities,[8] risk of second injury,[9] posttraumatic osteoarthritis (PTOA)[10], reduced physical activity,[11] obesity,[12] decreased quality of life,[11] and depression.[7]

While many ACL injuries occur during participation in contact sports, the majority of them (>70%) are classified as non-contact injuries.[13] Non-contact injuries are defined as those occurring without direct contact from another player.[14] Non-contact injuries are believed to be preventable[13] by mitigating risk factors associated with injury. The risk factors for non-contact ACL injuries are multifactorial, including numerous non-modifiable and modifiable contributors. Examples of non-modifiable risk factors include anatomical, hormonal, and environmental conditions. Modifiable risk factors can be broadly categorized as the biomechanical and neuromuscular components of dynamic movement.[13] For example, landing from a jump in or near full knee extension with increased knee abduction moments, may increase peak landing forces which can increase the stress put on the ACL.[15] There is a direct association between landing forces and lower extremity injuries[16] such that increased landing force increases risk of non-contact ACL injury. As such, decreasing peak landing forces is an emphasis of injury risk reduction (IRR) programs.[1,17,18]

Leg dominance in sports can lead to loading asymmetry and may contribute to unilateral damage to the lower limbs.[17,70] According to previous studies, leg dominance is an important factor in non-contact ACL injuries.[9,17] However, there has been conflicting evidence as to which limb, dominant or non-dominant, is at a greater risk of sustaining a non-contact ACL injury. Faude et al. assessed injury risk among elite soccer players and learned that 69% of ACL injuries occurred in the dominant limb.[71] Whereas, Boden et al. observed athletes from multiple sports and determined that 68% of ACL injuries occurred in the non-dominant limb.[13] It is important to highlight that these studies were conducted retrospectively, meaning they do not establish a cause-and-effect relationship. Although leg dominance is non-modifiable, training that targets limb-to-limb strength and biomechanics discrepancies (i.e., training both limbs not just one) may reduce the risk of a non-contact ACL injury.

ACL IRR programs have been shown to decrease the incidence of non-contact ACL injury by 51%.[19-21] Programs that integrate lower extremity muscle strengthening with neuromuscular training have shown to be the most effective.[2] The goal of a neuromuscular training program is to improve sensorimotor control and attain functional joint stabilization by addressing the quality of movement in all 3 planes of motion.[22] It has been postulated that neuromuscular training enhances automatic motor responses by stimulating the afferent signaling pathways and central mechanisms in charge of dynamic joint control.[23] As such, neuromuscular training may affect biomechanics and physiology by improving strength, decreasing landing forces, or altering hormone levels.[24] Squat jumps (when a squat immediately precedes a maximal vertical jump), tuck jumps (vertical jump, during which knees are brought to chest), crossover hops (3 single-leg hops during which the individual crosses from one side of a mark on the floor to the other)[25] and single leg squats are examples of some of the exercises used in neuromuscular ACL IRR programs that have been shown to reduce injury risk.[26] It is believed by stimulating the central control mechanisms governing dynamic joint motion that these IRR programs may significantly increase hamstring muscle power and strength[15] and increase hamstring-to-quadriceps peak torque ratios,[15] both of which have been shown to be effective in increasing knee joint stability.[24] Increased joint stability may equate to reduced injury risk.

A recent prospective analysis of 1263 athletes of various sports found that a 6-week neuromuscular training program reduced the incidence of knee injuries.[24] It was observed that untrained athletes were 3x more likely to sustain an injury than trained athletes in the same sports. The authors postulated that the decreased rate of injury in the trained group may be a result of the training program increasing dynamic stability of the knee.[24] Specific to ACL injuries, another group looked at the effectiveness of prophylactic neuromuscular training on the incidence rate of these injuries in female soccer players. One thousand forty-one individuals participated in a training intervention while 1905 other players, from the same league, made up the control group. During the two years that the groups were followed there were 88% and 74% decreases, respectively, of ACL injuries in the trained group compared to the control group.[27] Yet, the effectiveness of these IRR programs is still not enough to mitigate the annual incidence of ACL injuries.[3]

Numerous reasons exist for why ACL injuries continue to occur despite these promising data, among which is the possibility that the motor performance changes that occurred during the

IRR programs are not permanent and do not transfer from training to activity. Evidence supports neuromuscular training's effectiveness in reducing the risk of injury by targeting biomechanical risk factors of injury including poor strength, balance, and plyometric function[4] yet the lack of consideration for cognitive and neurological components may limit outcome potential. Cues and varied foci of attention used during IRR programs may have a significant effect on IRR programs and further investigation of these techniques may be necessary to improve outcomes.

One's focus of attention can be either internal or external. Internal focus of attention (InFOCUS) is said to occur if the patient's attention is directed to his or her body movements. Examples of internally directed focus of attention may include cues for the patients to bend at the waist or to land with feet shoulder width apart while observing themselves in a mirror. It has been reported that clinicians provide cues inducing InFOCUS 95% of the time.[28] Though extremely common, recent research has shown that InFOCUS may be detrimental to certain physical movements. The use of InFOCUS forces the individual to be consciously aware of their own movements, which makes movement less automatic. This reduction in automaticity constrains the way an individual moves and limits their ability to adapt to a dynamic and unpredictable environment, such as one that may be experienced during athletic activity. The inability to adapt biomechanics to a changing environment may lead to injury.

External focus of attention (ExFOCUS) is an alternative to InFOCUS and is directed to the effect of the movement (i.e., the ball going into the goal or the hand touching the wall). ExFOCUS promotes the use of unconscious or automatic mechanisms, allowing the motor system to more naturally self-organize,[29] and may improve motor learning efficacy.[30] Using external cues and goals such as cones, targets, or markers may allow individuals to direct focus externally to increase quality of movement. ExFOCUS training has been shown to improve biomechanics during single-leg hopping in patients after ACLR.[31] Specifically, significantly larger knee flexion angles at initial contact, peak knee flexion, total range of motion and time to peak knee flexion were observed. Participants were randomly allocated to an InFOCUS or ExFOCUS group and performed single leg hops for distance. The InFOCUS groups was instructed to "think about extending your knee as rapidly as possible." While the ExFOCUS group were told "think about pushing yourself off as hard as possible from the floor." While this study produced some pertinent data, it was not without limitations. The feedback methods used were only auditory and the ExFOCUS feedback still had the participants focusing on themselves, therefore it does not truly qualify as ExFOCUS. This could have been corrected by changing the wording of the command or using other tools (cones, tape, videos) to deliver the feedback. Additionally, the intervention was delivered in a controlled environment (outpatient physical therapy facility) and therefore may not transfer to a dynamic environment.

Understanding how ExFOCUS feedback improves biomechanics during more sport-specific tasks and under alternative cueing conditions may be vital to further improving IRR programs. ExFOCUS can be delivered in multiple ways, among which visual and auditory forms of feedback are common. Recent studies demonstrated that both auditory and visual modes of ExFOCUS feedback can improve biomechanics in patients with chronic ankle instability (CAI),[32,33] but their role in primary ACL injury prevention is unknown. A previous study on the effects of auditory feedback on plantar pressure in patients with CAI used a novel device, placed underneath the insole of the shoe, that elicited a noise if a specific threshold of plantar pressure was exceeded. The participants were instructed to walk in a manner that would not trigger the noise. Compared to a previously recorded baseline test, it was observed that patients significantly reduced plantar pressure in the lateral and central forefoot during walking.[33] Reduction of lateral plantar pressure in CAI patients was also studied using a visual form of ExFOCUS feedback.[32] A custom made laser pointer was attached to the foot of interest, movement of the laser corresponded with movement of the foot and ankle during walking. The laser produced a cross-line diode that the participants were instructed to walk in a manner in which the vertical laser line aligns with a piece of tape on the wall; the laser should only move up and down the piece of tape so try to walk in a manner in which the laser cross does not rotate. Results showed that the feedback was able to significantly reduce plantar pressure on the midfoot and forefoot compared to baseline. In short, both auditory and visual forms of ExFOCUS feedback have proven to be successful in altering movement patterns associated with CAI. However, to our knowledge there have been no studies that have compared the efficacy of these novel feedback methods to reduce the risk of ACL injury.

Therefore, the purpose of this dissertation was to determine the efficacy of novel forms of ExFOCUS feedback (visual and auditory) compared to InFOCUS feedback at improving biomechanical risk factors of non-contact ACL injury. Participants completed a four-week intervention that progressively moved them from simple to more complex tasks (single leg step down, single leg squat, drop landing and single leg landing) while receiving one of the two types of novel ExFOCUS feedback (visual or auditory). It was also our goal to further previous research that has shown ExFOCUS to be a superior feedback method by determining the most effective form of ExFOCUS feedback.

Specific Aim 1: Determine ExFOCUS's ability to reduce the risk of noncontact ACL injury by retaining improved biomechanics (increase knee flexion angle, decrease knee abduction moment, and decrease landing forces) compared to InFOCUS.

Hypothesis 1.1: The combined auditory and visual ExFOCUS groups would demonstrate greater improvements in biomechanics compared to InFOCUS. Specifically, participants in the ExFOCUS groups would demonstrate a greater reduction in knee abduction angles and moments (primary outcome), increase in knee flexion angles and moments, and reduction in vertical ground reaction force upon landing compared to InFOCUS at the 1-week post-intervention timepoint (primary endpoint).

Hypothesis 1.2: Participants in the ExFOCUS groups would retain the above hypothesized improvements 4 weeks after cessation of the intervention while InFOCUS would demonstrate minimal retention.

Specific Aim 2: Determine differences in the ability of the two modes (visual and auditory) of ExFOCUS to change biomechanics.

Hypothesis 2.1: There is insufficient evidence on which to base a hypothesis, though we believe the fast pace of the exercises involved in the prevention program would allow for better integration of auditory over visual feedback; thus, we hypothesize that the auditory ExFOCUS feedback will elicit superior results compared to visual ExFOCUS feedback immediately following the intervention. Specifically, participants in the auditory ExFOCUS groups would demonstrate a greater reduction in knee abduction angles and moments (primary outcome), increase in knee flexion angles and moments, and reduction in vertical ground reaction force upon landing compared to visual ExFOCUS at the 1-week post-intervention timepoint (primary endpoint).

Hypothesis 2.2: Participants in both the auditory and visual ExFOCUS groups would retain their respective above hypothesized improvements 4 weeks after cessation of the intervention.

Delimitations: Participants were recruited from the University of North Carolina at Charlotte and surrounding community. However, participants were not excluded if they presented with no injury risks. Therefore, not all participants may respond to the feedback.

CHAPTER 2: REVIEW OF RELATED LITERATURE

The purpose of this literature review is to detail: 1) knee joint anatomy and biomechanics, 2) mechanisms of anterior cruciate ligament injuries 3) anterior cruciate ligament injury prevention programs 4) motor control theories to enhance injury prevention.

2.1 Anatomy and Biomechanics of the Knee

The knee is one of the largest joints of the human body. It is a complex structure that allows flexion and rotation yet provides stability and support while under the stress of dynamic activity. The knee is made up of bones, ligaments, tendons, and muscles, all contributing to its function. The bony architecture of the knee joint complex consists of four bones, the femur, tibia, fibula, and patella. The knee can be subdivided into two distinct articulations, the tibiofemoral and the patellofemoral joints. The patellofemoral is central to knee function through its role in the extensor mechanism. The patella increases the moment arm of the knee extensors, thereby increasing mechanical advantage of the quadriceps to extend the lower leg. The tibiofemoral joint is composed of two condyloid articulations.[34] The medial and lateral menisci enhance the conformity of the tibiofemoral joint, as well as to assist with rotation of the knee.

The muscles that directly contribute to the functions of the knee include the quadriceps, hamstrings, and muscles of the calf. The quadriceps (rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius) extend the leg at the knee. Rectus femoris originates from the anterior inferior iliac spine and aligns with the base of patella to form the more central portion of the quadriceps femoris tendon. Vastus intermedius emanates from the upper two-thirds of the anterior and lateral surfaces of the femur. It descends and unites with the deep surface of rectus femoris, vastus lateralis and vastus medialis forming the deep part of the quadriceps tendon.

Vastus medialis originates along the length of the linea aspera of the femur and inserts along the medial base and border of patella. Vastus lateralis originates in the anterior and inferior borders of greater trochanter and lateral portion of gluteal tuberosity of femur. Its insertion in the lateral base of patella forms the lateral patellar retinaculum and lateral side of quadriceps femoris tendon. Due to their role in extending the knee, the quadriceps are considered antagonistic to the ACL. Contraction of the hamstring (semimembranosus, semitendinosus, and biceps femoris), muscles will cause flexion of the leg at the knee. The biceps femoris originates on the ischial tuberosity and linea aspera of the femur and inserts on the head of the fibula and the lateral condyle of the tibia. Semimembranosus and semitendinosus both originate on the ischial tuberosity. Semitendinosus inserts at the proximal, medial surface of the tibia while semimembranosus inserts at the posterior surface of the medial condyle of the tibia. The hamstrings help protect the ACL by flexing the knee and counteracting the quadriceps.

Four main ligaments connect the femur to the tibia and provide passive stabilization to the knee joint. The posterior cruciate ligament (PCL) extends anteromedially from the tibia posterior to the medial femoral condyle. This ligament prevents excessive posterior movement of the tibia on the femur. Lateral collateral ligament (LCL) extends from the lateral femoral epicondyle to the head of the fibula and prevents excessive adduction of the knee. Medial collateral ligament (MCL) extends from the medial femoral epicondyle to the tibia, it prevents excessive abduction of the knee. The anterior cruciate ligament (ACL) runs posterolaterally from the tibia and inserts on the lateral femoral condyle. The ACL prevents excessive anterior movement of the tibia under the femur and assists in providing rotational stability to the knee. It has been observed that cruciate ligaments are not the primary varus-valgus load bearing structures when collateral ligaments are intact.[35] Rather, the intact MCL is the major structure stopping valgus collapse and ACL strain was minimal in response to valgus loading. However, ACL strain significantly increased after a rupture to the MCL occurred.

The ACL consists of two major fiber bundles, namely the anteromedial and posterolateral bundle,[36] that work in unison with one another. When the knee is extended, the posterolateral bundle (PLB) is taught and the anteromedial bundle (AMB) is reasonably lax.[37] Thus, the PLB provides more resistance to anterior tibial translation when the knee is extended. As the knee is flexed, the femoral attachment of the ACL becomes more horizontal, causing the AMB to tighten and the PLB to relax, allowing for a greater contribution from the AMB to joint stability in these more flexed knee positions.[37-39] In addition to limiting anterior translation of the tibia, the ACL aids in the limitation of medial rotation about the knee joint, with the majority of this coming from the PLB.[40]

2.2 Mechanisms of Anterior Cruciate Ligament Injuries

ACL injuries are amongst the most common injuries sustained in an athletic population, with over 250,000 occurring in the United States each year.[2] More than half of those who sustain an ACL injury are between the ages of 15-25.[2,41] Alarmingly, the rate of ACL injury in the younger population (< 20 years old) increased rapidly from 17.6% in 1990 to 50.9% by 2009.[33] Athletic ACL injuries occur most often during sports that require rapid deceleration or the instantaneous change of directional forces. Basketball, football and soccer are just a few of the sports that see high rates of ACL injuries amongst their athletes.[5] As more and more individuals participate in sports, the rate of ACL injuries will likely continue to rise. Knee injuries account for 60% of all serious high school sport related surgeries[42,43] and ACL injuries account for 50% or more of all knee injuries.[6] These injuries are particularly concerning because they can lead to a premature retirement from sports participation and early onset osteoarthritis, leading to long-term disability and physical inactivity and their associated comorbidities (i.e., obesity, heart disease, etc.).

ACL injuries are classified as contact or non-contact. Contact injuries can be further categorized as direct and indirect, those in which external forces are applied to the injured knee are direct, while those in which external forces are applied to the athlete but not directly to the injured knee are indirect. Finally, non-contact injuries are those in which forces applied to the injured knee are result of the athlete's movements, independent of contact with another athlete or object.[17] While many ACL injuries occur during participation in contact sports, the majority of them (>70%) are classified as non-contact injuries.[13]

The risk factors for non-contact ACL injuries are multifactorial, including non-modifiable and modifiable. Examples of non-modifiable risk factors include anatomical, hormonal, environmental conditions (Table 1), while examples of modifiable risk factors include biomechanical and neuromuscular components (Table 2).[13] In consideration of these risk factors, a group of physicians, biomechanists, physical therapists, and athletic trainers met in Hunt Valley, Maryland, in June 1999 with the goal of developing a strategy to prevent ACL injuries.[41] After a thorough review of the existing literature, it was determined that no single risk factor (environmental, anatomical, hormonal) directly correlates with an increase in ACL injuries. As a result, the focus has shifted to biomechanical risk factors and the use of neuromuscular training programs to address potential biomechanical deficits and potentially reduce ACL injury risk and associated long-term consequences.

Table 1. Non-modifiable risk factors of non-contact ACL injuries

Anatomical	Hormonal	Environmental
• Ligament laxity[44] • Size of intercondylar notch[45] • Q-angle[13,18] • Size of ACL[46] • BMI[47]	• Changes in levels of estrogen and progesterone[48]	• Playing surface[49] • Footwear[50] • Climate[51] • Interaction of footwear with playing surface[50]

BMI – Body Mass Index

Table 2. Modifiable risk factors of non-contact ACL injuries

Biomechanical	Neuromuscular
• Landing from a jump in near or full extension[17] • Change of direction with knee in nearly full extension[13] • Knee abduction[52] • Tibial rotation[18] • Lateral trunk motion[17] • Posterior ground reaction force[1]	• Dominant recruitment of knee extensors[53] • Weak hip abductors[54]

2.2.1 Biomechanical Risk Factors

It has been postulated that an anterior translation force is the most detrimental direct isolated force associated with non-contact ACL injuries;[55] however, sagittal plane biomechanics alone cannot tear the ACL.[56] Thus, due to the complexity of load sharing between knee ligaments, understanding the frontal and transverse plane contributors to non-contact ACL injury risk is imperative (Table 3).

Table 3. Biomechanics of non-contact ACL injury by plane of motion

Sagittal	Frontal	Transverse
• Decreased trunk, hip, and knee flexion[57] • Decreased ankle dorsiflexion ROM[58]	• Lateral trunk displacement[18] • Hip and knee abduction[59,60]	• Increased hip internal rotation[18,60] • Increased tibial external rotation[18] • Foot pronation[61]

Several studies have observed that ACL loading increases as knee flexion angle decreases. Greater flexion angles at landing or while pivoting allow more of the ground reaction force to be absorbed by the musculature, thus reducing the amount of strain on the ACL. Knee flexion angles of 20º or less at landing have been repeatedly observed to cause the knee to collapse into a valgus position while also rotating internally or externally.[18,62,63] It has been observed that quadriceps activity does not strain the ACL when the knee flexion angle is greater than 60º; however the quadriceps strain the ACL from 0º to 45º of flexion.[7] Conversely, other studies have observed that peak quadriceps loading occurs from 0º-20º and that the quadriceps continues to strain the ACL until the flexion angle reaches 80º.[64] Similarly, a study using an in vivo strain gauge technique observed that contraction of the quadriceps increased ACL strain between 15º and 30º of flexion, with the highest strain occurring at 15º of flexion.[9-11,13] Therefore, contraction of the quadriceps when the knee is in a less flexed position may produce significant strain on the ACL that, when coupled with other movements, may result in damage to the ligament. In order to counter the potentially injurious quadriceps loading on the ACL, the hamstrings must activate. The hamstrings are able to decrease ACL loading at knee flexion angles greater than 10º.[65-67] However, the line of pull that the hamstrings exert on the tibia from 0-10º of knee flexion is not always enough to overcome the anterior drawer effect created by quadriceps contraction, which compresses the tibia and femur and allows the tibia to translate anteriorly and strain the ACL.[65-67] This effect, when combined with ACL loading from the frontal or transverse planes, may lead to ligament rupture. Through the use of video analysis and patient questionnaires, researchers concluded that a sudden deceleration prior to a change of direction or landing with the knee near full extension is a common component of ACL injuries.[1] Deceleration and change of direction require an eccentric quadriceps contraction to resist further knee flexion. Too much knee flexion would make the individual unable to complete the change of direction task. However, this sudden, forceful eccentric quadriceps contraction near full extension of the knee strains the ACL and may be difficult for the hamstrings to resist, possibly leading to ACL rupture.[1]

The effect of combined knee loading on ACL strain has been previously observed using cadaver knees.[68] The strain of the AMB of the ACL was recorded at 0º and 30º of flexion under a combination of the following loading conditions: 1) anterior shear force only; 2) anterior/posterior force; 3) medial/lateral force; 4) varus/valgus torque and; 5) internal/external axial torque. Anterior shear force on the proximal end of the tibia was observed as the main cause of AMB strain. Neither internal-external rotation moment nor pure knee varus/valgus torque produced significant AMB strain. Importantly, however, anterior shear force at the proximal end of the tibia combined with valgus torque resulted in significantly greater strain in the AMB than either component on their own. Only when combined with proximal tibia anterior force did valgus loading apply enough force to injure the ACL. Additionally, an in vitro study measured ligament strain under different combinations of the following loading states: 1) 100 N of anterior tibial force; 2)10 Nm of varus and valgus force and; 3)10 Nm of internal and external tibial force. Researchers found that the application of internal tibial torque to a knee already loaded by anterior tibial force produced dramatic increases of strain on the ACL.[67] It was determined that this combination had the greatest potential to injure the ligament. This observation further contributes to the idea that no single movement can cause an ACL tear, but there are many different combinations of movements that have the potential to produce the necessary force.

Frontal plane biomechanics have long been associated with ACL injuries. This is not just true of the knee joint, as hip adduction and lateral trunk movements have been associated with ACL injury risk. When investigating the effects of trunk movement on ligament injury it was found that lateral trunk displacement after sudden force release (cessation of isometric trunk muscle contraction) was the strongest predictor of ligament injury compared to displacement in the anterior or posterior directions.[69] Biomechanically, if the trunk tracks laterally the vertical ground reaction force (vGRF) follows, as it always acts through the center of mass (COM). As the vGRF moves lateral to the center of the knee joint, it compresses the lateral aspect of the joint which abducts the tibia, resulting in a valgus load on the knee. Valgus load is considered the largest risk for ACL injury. Knee abduction moments predicted ACL injury risk with 73% sensitivity and 78% specificity.[60] Knee abduction angle in the ACL injured group was more than 8° greater than in the uninjured groups and knee abduction angle correlated to peak vertical ground reaction force in ACL-injured athletes. It was postulated that the increased valgus angles observed in the injured cohort significantly contributed to the ACL injuries. Additionally, both in-vivo biomechanical data and video analysis have shown that increased lower extremity valgus loads and movements in the frontal plane are probably associated with an increased risk of ACL injury.[13,18,60] Increased peak posterior ground reaction forces during athletic tasks was observed to increase ACL loading as a result of an increased quadriceps muscle contraction.[19] The flexion moment generated by the posterior ground reaction force must be balance by a knee extension moment from the quadriceps muscles.[20] Quadriceps muscle contraction, as previously illustrated, adds an anterior shear force on the proximal end of the tibia, combined with valgus torque significant strain is put on the ACL. The greater the posterior ground reaction force is, the greater the quadriceps muscle force is, and the greater the strain on the ACL.

2.2.2 Neuromuscular Risk Factors

Neuromuscular control is defined as the unconscious efferent response to an afferent signal regarding dynamic joint stability. The neuromuscular system is responsible for unconsciously generating many of the movements responsible for action in sport. Differences in neuromuscular control may, in part, explain the increased ACL injury risk exhibited by certain athletes.

As described above, the hamstrings and quadriceps coactivate to protect the knee joint against knee abduction and excessive anterior tibial translation. The ratio of the recruitment of these muscles is known as “flexor to extensor recruitment” or hamstrings: quadriceps (H:Q) ratio. If there is a deficit in activation of the hamstrings the quadriceps activation would need to be reduced as well in order to deliver the net flexor moment necessary to complete the movement without causing excess strain on the ACL.[15,60] A H:Q ratio between 50%-80% (averaged through full range of knee motion) is generally accepted as normal.[72,73] As the ratio increases the hamstrings functional capacity to stabilize the knee increases. Conversely, a decrease in the H:Q ratio may lead to an increased possibility of anterior tibial translation. Individuals with a low H:Q ratio are considered quadriceps dominant.[74] A low H:Q ratio may be partly explained by poor pelvic neuromuscular control. Specifically, anterior pelvic tilt places the hip into an internally rotated, anteverted and flexed position, which lengthens and weakens the hamstrings.[75]

This may lead to a decreased in H:Q ratio and an increase in the strain applied to the ACL. There is still some dispute as to whether the increased risk is a result of the altered pelvic position or the functional malalignment that is created, nonetheless pelvic stability may play a key role in the mechanism of ACL injury.[76]

It has been noted that female athletes, compared to female non-athletes and male athletes, tend to be quadriceps dominant.[77] That is to say the female athletes contract their quadriceps muscles in response to anterior tibial translation, while the non-athletes and males tend to contract their hamstrings. This quadriceps dominance may allow for excess anterior strain on the ACL. This idea has been demonstrated during jump landing when it was found that increasing hamstrings activation during landing can decrease the peak relative strain on the ACL by >70%.[78] Thus, the quadriceps dominance and low hamstrings activity in female athletes may be a contributing factor that explains the significantly greater rate of female ACL injuries, compared to males in the same sport.

2.2.3 Sex Differences

It has been observed that females exhibit greater valgus moments than males when landing from a stop-jump task.[79] Though these finding are not representative of all females it is important to address the differences in biomechanics that have been observed between females and males.

Regarding females, research has shown that ACL injuries occur with a 4- to 6-fold greater incidence in female athletes compared with male athletes playing the same landing and cutting sports.[80] While specific high-risk biomechanics during landing have been associated with greater risk of ACL injuries, they are not exclusive to females. Within the same sport females may be at a higher risk of ACL injuries than their male counterparts; however, women only account for 20% of those participating in team sports.[81] The rate of injury per athlete may be higher in females but the total number of ACL injuries is higher in males. ACL injuries are not gender biased; they are a plague on all athletes.

2.2.4 ACL Reconstruction and Beyond

Regardless of injury severity, all patients have the option to remain ACL deficient or have the ligament surgically reconstructed. A determining factor in an athlete's choice to undergo ACLR is his/her desire to return to sport (RTS). Though an athlete can elect to forgo surgery, chances of gaining full functionality without it are very limited. Recent studies report that conservative treatments lead to instability issues as patients RTS.[82] Thus, over half of patients opt for surgical reconstruction in hopes of recovering functional stability and returning to sport.

The cost of ACLR, including diagnosis, surgery and rehabilitation, is approximately $17,000, with a total annual cost of approximately $2.5 billion in the United States.[83] A second injury sees the cost rise by an average of more than $12,000. Despite the high cost associated with ACLR the outcomes may be less than optimal as the residual effects can be life changing. As previously mentioned, patients after ACLR also see an exceptional increase in the likelihood of a future ACL injury.

ACLR can be performed with use of either allograft or autograft tissue. Allografts involve harvesting the tissue of a donor, usually a cadaver, in order to reconstruct the ACL. Allograft use presents some concerning factors: slower incorporation, inadequate ligamentization, and possible immunogenicity.[84-86] Moreover, the odds of graft rupture with an allograft reconstruction are 4 times higher than those of autograft reconstructions.[87] Despite these concerns, allograft use has seen an increase in the last decade perhaps due to a decrease in post-operative pain, easier early rehabilitation and shorter operating times.[87-89] However, autograft ACLR, removing tissue from the person's own body to use for reconstruction, remains the gold standard. The most commonly harvested sites for ACLR are the bone–patellar tendon–bone (BPTB) and quadrupled hamstring tendon.[90,91]

Subsequent to ACLR, the chances of having a second ACL injury, defined as ACL injury to the ipsilateral or contralateral limbs, can rise as much as 15 times that of someone who has not previously been injured.[92] The data predicting an athlete's chance of a second ACL injury may actually be askew as not all return to sport. Though activity level is not a statistically significant factor for the risk of second ACL injuries, research has shown that competitive-level activity increases the risk by 36% compared to recreational activity.[93]

Increased risk of a second injury is not the only adverse result of an ACL injury. The development of post traumatic osteoarthritis (PTOA), functional limitations and a decreased quality of life have all been associated with ACL injuries.[94] Recent research has found the incidence rate of PTOA following ACL injuries to be as high as 87%.[95] More than half of those that experience an ACL injury will experience PTOA within the first three decades post injury.[96] As already established the age group that sees the highest rate of ACL injuries is 18-25, meaning at least half will develop PTOA prior to the age of 55. It has been said that an ACL tear ages the knee by 30 years.[11] Therefore, mitigating primary ACL injuries is paramount to a reduction of secondary injuries, PTOA and decreased quality of life.

There are multiple roadblocks to successful return to previous activity level following ACLR. Impaired muscle strength which leads to altered lower extremity biomechanics has been observed while comparing patients with ACL injuries to uninjured controls.[97] A recent study examined the dominant limb biomechanics in a group of persons both pre-ACL injury and post-ACLR. The findings indicated that injury and subsequent ACLR resulted in altered movement patterns in both the injured and uninjured limbs.[97] Asymmetries such as these can lead to gait impairments and potentially decreased mobility.

Noyes et al.[98] hypothesized that approximately one-third of athletes that undergo ACLR are able to resume pre-injury activity levels, one-third compensate for the deficiency by modifying some sports activities and one-third have to cease many sports activities due to reduced knee function. With two thirds of athletes unable to return to pre-injury levels of activity, it is apparent that current rehabilitation protocols are not adequately restoring stability, strength, and biomechanics to a level that prepares patients to return to full activity. While return to sport after an ACLR is possible and advances in post-ACLR rehabilitation have been made, preventing the primary injury is still the main objective.

2.3 Non-contact Injury Risk Reduction Programs

Injury Risk Reduction Programs for the knee have succeeded in reducing knee injuries by 27% and ACL injuries by 51%.[21] Yet, the number of non-contact ACL injuries continues to increase each year.[99] These programs can be classified as field based (those that are performed in the athlete's natural setting) or laboratory based (performed in a controlled laboratory environment).

2.3.1 Field-Based

The FIFA 11+ is a clinical program composed of 15 exercises in a specific order that focus on strength, balance and plyometrics. It was designed to mitigate the risk of injury in soccer players and when implemented regularly into a team's warm ups at least twice a week for a minimum of 10 weeks a 30% reduction in injury has been observed.[100] The PEP (Prevent injury and Enhance Performance) is composed of 5 stages (warm-up, stretching, strengthening, plyometrics and sport specific agilities) the PEP's goal is to amend deficits in strength and coordination of the stabilizing muscles of the knee joint. The primary focus of the program is to address the feedforward mechanism—by anticipating external forces or loads to stabilize the joint, thus protecting the inherent structures. A two year study of the PEP was completed in order to determine the efficacy of the program in reducing ACL injury rates in female soccer players.

During the first year an 88% decrease in anterior cruciate ligament injury in the enrolled subjects compared to the control group was observed. During the second year, there was a 74% reduction in anterior cruciate ligament tears in the intervention group compared to the age- and skill-matched controls.[27] The Stanford Knee Injury Prevention Program aims to reduce risk of knee injuries and improve overall athletic performance by using a comprehensive approach of neuromuscular and proprioceptive training. The program focusses on dynamic stretching, lower extremity strengthening, plyometric training, hip and core activation and movement re-education. One unique component of this IRR program is the activation of hip muscles, as other prevention programs have not specifically addressed this.

2.3.2 Lab-Based

Numerous laboratory-based IRR programs have been developed incorporating a combination of plyometric exercise, balance, strength, and core stabilization exercises. A recent systematic review and meta-analysis sought to address IRR program effectiveness at reducing some biomechanical risk factors related to the quadriceps dominance theory, especially IRR programs that consist of activities to increase hip and knee flexion angles, such as plyometrics and jump-landing tasks.[101] Results found that peak knee abduction moment, an important predictor of ACL injury, decreased after the IRR program while other variables related to the ligament dominance theory did not change.[101] After the IRR program, angles of hip flexion at initial contact, peak hip flexion, and peak knee flexion increased (all associated with decreased risk of ACL injury). No change was found for peak vGRF. It was concluded that a comprehensive neuromuscular training program designed for injury prevention could simultaneously improve biomechanics without compromising performance.

One important limitation of these previous studies is that they have only observed the immediate changes in movements patterns after completion of an IRR program.[102,103] However, the retention of these new movements may not occur after discontinuing the training program. It has been speculated that current non-contact ACL IRR programs result in only temporary improvements in movement patterns that are associated with reduced ACL injury risk.[28] Failure to sustain the protective effects after cessation of the intervention may allow rates of non-contact ACL injury to continue to rise.

Instructional feedback may be key to eliciting lasting changes in biomechanics during interventions and training programs. Several researchers have investigated this idea of feedbackaugmented injury prevention training and reported short-term retention of learned movement patterns. For example, a recent investigation randomized participants into three groups (self-feedback, combination feedback or control) and had them perform a box drop task at both a pre and posttest as well as a one month follow up.[104] The self-feedback group viewed the video recordings of 4 of their 5 pretest drop landings. The combination group viewed two videos of their pretest drop landings and two videos of an expert performing the same task. During the viewing of the videos the instructor provided visual (pointing out proper and improper techniques) and oral (discussing the techniques) feedback. The control group did not view any videos or receive any form of feedback. It was found that the use of oral and video feedback successfully improved lower extremity biomechanics during jump-landing activities. The authors concluded that feedback involving the combination of self- and expert video feedback combined with oral feedback improved lower extremity kinematics in box–drop-jump task. Another lab-based experiment compared the differences of traditional (provided after task completion) and real-time (provided while completing the task) feedback on jump landing biomechanics. It was found that both feedback types produced greater hip and knee flexion and a greater decrease in vGRF when compared to a control group. However, in a follow up one week after completion of the intervention, there were no significant differences observed between any of the groups.[105]

The enhancement in motor skills through various modes of feedback has shown great potential. Unfortunately, these feedback studies have not shown retention of learned biomechanics beyond 1-week after cessation of the intervention and they have all used feedback delivery mechanisms that rely on expensive laboratory-based equipment. Thus, there is a critical need to develop methods for delivering feedback that changes biomechanics long-term and can be readily implemented into clinical practice.

2.4 Motor Control Theories to Enhance Injury Risk Reduction

The acquisition of motor skills, or motor learning, has been defined as the process of an individual's ability to acquire motor skills with a relatively permanent change in performance as a function of practice or experience.[106] While the immediate performance of a learned skill is often thought to be a triumph, the true test of permanence is a retention test conducted after an adequate amount of time after training has ceased. Retention of biomechanical changes may suggest permanent alterations to motor patterns, which may lead to changes outside of the controlled environment and conceivably reduction in injury risk.[107] Variables including schedule, volume and setting are commonly thought of when designing a successful training program yet equally important may be the roll of feedback in motor skill acquisition. It has been said that the influence of a small variation in instructional feedback may play a significant role in inducing the desired acquisition and retention of skilled movement.[108] Specifically, the effectiveness of internal focus (InFOCUS) or external focus (ExFOCUS) of attention feedback has been a major topic of discussion.

Shifting feedback from relying on an internal to an ExFOCUS during functional movement may have large impacts on movement patterns and outcomes of IRR programs. InFOCUS is said to occur if the individual's attention is directed to his or her body movements. This is often accomplished by having the athlete perform exercises in front of a mirror and providing cues to land with flexed knees or to land with feet together, for example. When retraining athletes after an ACL reconstruction rehabilitation professionals provide cues inducing InFOCUS 95% of the time.[28] Though prevalent, recent research has shown that InFOCUS may be less suitable for acquisition and retention of control of complex motor skills.[28] This conundrum may be a consequence of the Constrained Action Hypothesis. The Constrained Action Hypothesis suggests that performers utilizing an InFOCUS may constrain or interfere with movements that would otherwise be controlled by the body's natural mechanics, whereas an ExFOCUS allows the motor system to more naturally self-organize.[29]

ExFOCUS is directed to the environment (i.e. the ball going into the goal or the hand touching the wall) which promotes the use of unconscious or automatic mechanisms and may improve motor learning efficacy.[30] Using external cues and goals such as cones, targets, or markers may allow people to direct focus externally to increase quality of movement. Improvements in movement mechanics were found during single leg hopping in patients after ACLR using ExFOCUS versus InFOCUS.[31] While this study produced some pertinent data it was only looking at a singular task and the cues were only verbal. Moving forward it will be important to find out if this phenomenon is transferable to multiple tasks and with multiple ways of receiving cues (verbal/visual). An IRR program that uses external focus of attention feedback may enhance skill acquisition more efficiently and increase the potential to transfer to competitive sport.[28]

ExFOCUS feedback has shown significant rehabilitative benefits in other musculoskeletal conditions. A 2019 study on individuals with chronic ankle instability (CAI) sought to determine the effects of a novel, crosshair laser device (ExFOCUS) to cause alterations in plantar pressure measures.[32] Laterally shifted plantar pressure is a common biomechanical alteration of persons with CAI. The laser device was placed on the dorsum of the individual's foot so that a plus sign shone on the wall in front of them. They were instructed to walk so that the plus sign did not rotate or deviate. A significant reduction in lateral column plantar pressures was observed when comparing treadmill walking with the laser (ExFOCUS) to previously recorded walking with no feedback. This study demonstrated the ability to positively modify gait parameters of persons with CAI through the use of a novel ExFOCUS device. Pilot data collected in our laboratory using this same laser device in patients after ACLR demonstrated a 45% reduction in the external knee abduction moment and a 40% reduction in the vGRF after 4-weeks of training, suggesting reduced re-injury potential. In fact, our observed magnitude of change in vGRF is nearly twice that observed following 6-9 weeks of plyometric exercise training.[15,109] Though a different patient population than healthy adults, these results are promising to suggest the ability to mitigate biomechanical risk factors associated with non-contact ACL injury.

Auditory devices have also been used as ExFOCUS feedback to modify the gait of individuals with CAI. A 2016 study sought to determine the effectiveness of an auditory feedback device on the gait modification of CAI individuals.[33] The results of the study revealed the auditory feedback device was able to significantly reduce plantar pressure in the lateral column of the foot during treadmill walking in individuals with CAI. A recent study sought to determine the real-time effects of visual and auditory biofeedback on functional task biomechanics in individuals with CAI.[110] Nineteen participants with CAI performed a series of movements (single-leg static balance, step-downs, lateral hops, and forward lunges) during a baseline and the two biofeedback conditions. It was determined that both biofeedback conditions induced real-time improvements in balance strategies. The authors concluded both auditory and visual biofeedback are effective in moderating functional task biomechanics.

The incorporation of feedback into rehabilitation and IRR programs has also been used in patients with patellofemoral pain (PFP). PFP is one of the most common lower extremity injuries in recreational athletes,[88] with more than one third of runners reportedly experiencing chronic pain around and behind the patella.[89,90] The majority of the literature incorporating feedback for patients with PFP used InFOCUS to improve gait kinematics during running. Those studies have demonstrated a great deal of success in improving biomechanics.[111-113] Recently, however, researchers have begun using ExFOCUS feedback in patients with PFP as well.[114] Specifically, a recent investigation compared the difference in effectiveness of InFOCUS and ExFOCUS feedback during a 6 week hip-knee strengthening program to observe its effects on pain, strength, function, and kinematics. Subjects were randomly allocated into one of three groups InFOCUS, ExFOCUS or control and outcomes were measured at baseline and after completion of the intervention. The results indicated the use of ExFOCUS during strengthening exercises led to the improvement in knee valgus and external rotator strength compared to InFOCUS. The findings are consistent with previous studies which demonstrated the effectiveness of feedback in correcting movement patterns and strengthening exercises in treating PFP. The results may take a step forward in the search for the most efficient means of rehabilitation by displaying not only the effectiveness of feedback but specifically the superior efficiency of ExFOCUS feedback.

2.5 Conclusion

ACL injuries occur at a high rate and carry with them a host of long-term consequences ranging from second ACL injury to osteoarthritis development. Current IRR programs do not adequately address high risk biomechanics and neuromuscular deficiencies associated with ACL injuries. Therefore, research is needed to optimize these programs and improve long-term outcomes. This dissertation project represents one important step in improving patient outcomes by examining if ExFOCUS of attention feedback can improve biomechanics and provide patients a more ideal movement strategy to mitigate the risk of ACL injuries.

CHAPTER 3: METHODS

3.1 Study Design

A randomized controlled trial design was employed to quantify differences in biomechanics following four weeks of training with varied foci of attention feedback. Independent variables included: feedback group (InFOCUS, visual ExFOCUS and auditory ExFOCUS), time (baseline, 1 week and 4 week) and limb (dominant and non-dominant). Dependent variables included: hip and knee flexion/extension angles and moments, hip and knee abduction/adduction angles and moments, peak vGRF, LESS scores and patient reported outcome surveys.

3.2 Participants

Forty-four individuals (n=15 InFOCUS; n=13 visual ExFOCUS; n=14 auditory ExFOCUS) from University of North Carolina at Charlotte and the surrounding area participated in this study. The sample size for this investigation was determined based on previous IRR program research.[105,115] Data were used from knee joint angles and moments as well as vGRF during landing. It was determined that 20 participants per group would be sufficient to achieve a minimal statistical power of 80 % ($\alpha = 0.05$) and moderate to large effect sizes while allowing for minimal participant attrition (10% per group). Sample size estimate was completed using G*Power, (v. 3.1.9.7).

All participants were recreationally active (exercise 30+ minutes 3+ days/week) and have a body mass index (BMI) ≤40kg/m^2. Potential participants were excluded if they presented with: 1) history of lower extremity fracture or surgery to either limb; 2) history of ACL tear, meniscus, or collateral ligament injury at the knee to either limb; 3) history of ankle sprains to either limb; 4) history of musculoskeletal injury sustained in the 6 months prior to enrollment; 5) history of concussion or neurological disorders; 6) visual or hearing impairments that would limit receiving the appropriate feedback; 7) inability to comprehend and repeat back directions in English; or are a 8) current smoker.

Each participant was randomly assigned to one of three feedback groups: InFOCUS, auditory ExFOCUS or visual ExFOCUS. Randomization occurred following baseline testing and occurred by means of concealed allocation. A member of the study team not involved in data collection/processing or intervention delivery generated the randomization table using an online random number generator, stratifying randomization by participant sex. Once completed, group assignment was written on a piece of paper and placed inside of an envelope. Envelopes were opened in chronological order. All experimental methods were approved by the University's Institutional Review Board.

3.3 Procedures

Participants reported to the Biodynamics Research Laboratory for testing on three occasions as well as for 12 intervention sessions (Figure 1). Baseline testing included patient-reported outcomes, strength, functional performance, and biomechanics assessments. Strength and functional performance were only being captured to describe our participants; thus, they were only measured at baseline. Follow-up testing was identical to baseline except for the strength assessment. All baseline and follow up testing was performed on both limbs. Importantly, separate investigators conducted the testing and intervention sessions so that the investigator performing testing sessions was blinded to group allocation.

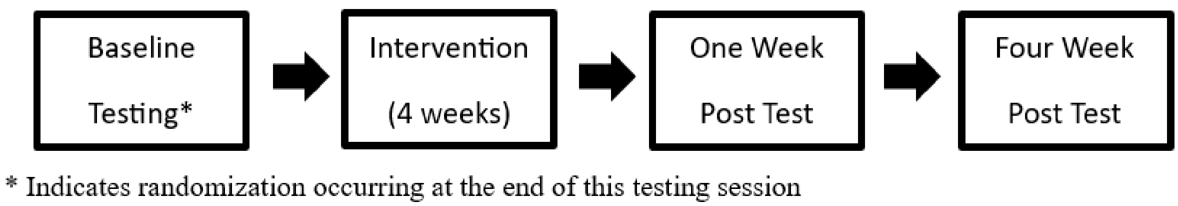

Figure 1. Study Timeline.

3.3.1 Strength Assessment

Quadriceps and hamstrings strength was assessed. Participants were seated on an isokinetic dynamometer (Biodex System 3, Biodex Inc., Shirley, NY) with the hip flexed to 85 degrees and the knee set to move between 0-100 degrees of flexion. Participants performed a series of continuous flexion and extension maximal voluntary concentric contractions in this position. They began with one set of warm-up contractions each at 25, 50, and 75% of their maximal ability. Next, they performed a set of 5 maximal voluntary concentric contractions in each direction, moving continuously through the flexion/extension range of motion. Participants were provided with verbal and visual feedback to encourage maximal effort. Data was normalized to body mass (Nm/kg) and averaged across trials.

3.3.2 Functional Performance Assessment

The functional performance assessment consisted of a battery of 4 hop tests and a vertical jump. These tests were chosen because they are easily implemented in the clinical setting and are associated with quadriceps strength (i.e., stronger quadriceps yield better performance).[116] For all functional tasks, participants were allowed to move their arms freely. Participants completed one practice trial followed by two recorded trials per limb. Participants maintained balance on the limb being tested following the final hop for each task. If balance was not maintained, the trial was repeated. All hop distance measures were normalized to participant leg length (supine measure of anterior superior iliac spine to medial malleolus).

The single leg forward hop begins with participants standing with their toe at the 0cm mark on the tape measure secured to the floor. The participant jumped forward, taking off of and landing on the same, single, limb on the tape measure. The location where the heel landed on the tape measure was recorded as the distance jumped.

To perform the crossover-hop participants stood with their toe at the 0cm mark on the tape measure secured to the floor. The participants jumped forward, taking off of and landing on the same, single limb but on the opposite side of the tape measure. The participants performed this task until 3 hops were completed, crossing over the tape measure with each hop. The location where the heel landed on the tape measure following the final jump was recorded as the total distance jumped.

The triple hop was performed with the participants standing with their toe at the 0cm mark on the tape measure secured to the floor. The participants jumped forward, taking off of and landing on the same, single limb on the same side of the tape measure. The participants performed this task until they completed 3 hops. The location where the heel landed on the tape measure following the final jump was recorded as the total distance jumped.

To perform the 6m timed hop participants stand with their toe at the 0cm mark on the tape measure secured to the floor. The participants jumped forward completing as many hops on a single limb as necessary to cover a distance of 6m. The time it took to complete this task was recorded.

The participants' vertical jump height was measured using a Vertec jump measuring device. The participants stood with their arm outstretched over their head to determine the starting position for the Vertec device. The participant jumped up in the air as high as possible, touching the uppermost vane of the Vertec that they were capable of reaching. The difference in position between the start position and the highest vane touched was used to quantify vertical jump height.

3.3.3 Biomechanics

All participants underwent a 3D biomechanical analysis during a jump landing and cutting task. Participants were outfitted with 36 retroreflective markers placed over specific anatomical landmarks on the trunk and lower extremities. A static standing trial was obtained to align the participant with the laboratory coordinate system and to serve as a reference point for kinematic data. Motion analysis was obtained using a 10-camera Vicon motion capture system (Vantage 5, Vicon Inc., Denver, CO). Kinetic data was collected from two identical force platforms (Bertec Corp., Columbus, OH) embedded into the floor and synchronized with the motion capture system. Kinematic data was sampled at 200 Hz and kinetic data at 2000 Hz. For the jump landing, participants stood atop a 30-cm box placed approximately 50% of the participant's leg length away from the force platforms. Participants dropped from the box, landing with one foot on each platform, then immediately performed a maximal vertical jump. A total of 15 trials of this task were performed. Prior to baseline testing, the participants performed practice trials until the investigator was satisfied that the participants were comfortable with the task.

Sagittal and frontal plane hip and knee angles and moments were analyzed because of their previous association with the risk of non-contact ACL injury:[60,117,118] These variables were extracted at the peak of vGRF during the first 25% of the stance phase (initial contact to toe off). The first 25% of the stance phase was selected for analysis as peak ACL loading has been estimated to occur within the first 60ms upon landing from a jump, which falls within the first 25% of the landing phase.[119] Initial contact and toe off were defined as the point at which the vGRF exceeded and fell below 10 N,[56] respectively, upon landing from a jump and rebounding for maximum height. Joint moments were calculated using inverse dynamic equations and were reported as internal moments. All joint moments were normalized to each participant's mass and height (Nm/kg·m).[120] The outcome measures of interest were averaged over 3 trials.

The first 5 jump landing trials were video recorded using GoPro cameras placed 3m in front of and 3m to the right side of the force plates.[121] A member of the research team, not involved in the data collection or intervention used these video recordings to determine the participant's landing error scoring system (LESS) score. Videos were reviewed using Kinovea software (www.kinovea.org). The LESS (Table 4) is a clinical assessment tool used to determine an individual's risk of sustaining a non-contact ACL injury. The LESS uses Likert-style scoring to identify movement errors, such as limited knee flexion or excessive medial knee displacement, that are associated with risk of non-contact ACL injury.[121] Higher LESS scores indicate a greater number of landing errors and thus a poorer jump-landing technique. A 1-point differential in the total LESS score can be associated with moderate to large differences in landing biomechanics.[122] Further, athletes with LESS scores of ≥5 are considered to be at higher risk of sustaining ACL injuries than athletes with LESS scores <5.[121]

Table 4. Landing Error Scoring System

Frontal- Plane Motion	Sagittal-Plane Motion
1. Stance width □ Normal (0) □ Wide (1) □ Narrow (1)	**6. initial landing of feet** □ Toe to heel (0) □ Heel to toe (1) □ Flat (1)
2. Maximum foot-rotation position □ Normal (0) □ Externally rotated (1) □ Internally rotated (1)	**7. Amount of knee-flexion displacement** □ Large (0) □ Average (1) □ Small (2)
3. Initial foot contact □ Symetric (0) □ Not symetric (1)	**8. Amount of trunk-flexion displacement** □ Large (0) □ Average (1) □ Small (2)
4. Maximum knee-valgus angle □ None (0) □ Small (1) □ Large (2)	9. **Total Joint displacement in sagittal plane** □ Soft (0) □ Average (1) □ Stiff (2)
5. Amount of lateral trunk flexion □ None (0) □ Small to moderate (1)	**10. Overall Impresion** □ Excellent (0) □ Average (1) □ Poor (2)

Landing from a jump and cutting or changing direction is one of the most common playing scenarios in which non-contact ACL injuries occur.[13] Therefore, a cutting task was included to determine the cross-over effect of our intervention to mitigate injury risk during other high-risk tasks. For the cutting task, participants started behind the force plates and took a 4-step approach prior to landing with one foot. Immediately upon landing they performed a 45 degree cut to the opposite side. For example, participants ran forward, landed with the left foot on the force plate, and immediately and aggressively cut to the right. The cutting task was performed 5 times per leg.

3.3.4 Patient Reported Outcomes

Patient-reported outcomes surveys to quantify knee function and physical activity were administered via Qualtrics after each testing session. The Marx Activity Scale[123] is used to assess physically active individuals with knee disorders. Scores represent the number of times a patient has participated in four different physical activities in the past month; higher scores are more favorable. The International Knee Documentation Committee (IKDC) subjective Knee Form[124] is used to detect improvement or deterioration in symptoms, function, and sports activities due to knee impairment. The IKDC is scored from 0 to 100, with higher scores indicating fewer symptoms or less dysfunction. The Lysholm Knee Scale[125] is an 8-item scale used to evaluate symptoms of knee instability The total possible scores range from 0-100. Higher scores indicate a better outcome with fewer symptoms or less disability.

The Patient-Reported Outcomes Measurement Information System (PROMIS)[126] is used to evaluate and monitor physical, mental, and social health in adults and children. The Tampa Scale for Kinesiophobia (TSK-11)[127] is used to assess pain-related fear of movement in patients with chronic musculoskeletal pain. The TSK-11 is made up of 11 items that are scored from 1- 4, and its score ranges from 11-44 (11 means no kinesiophobia, while 44 indicates severe kinesiophobia).

3.4 Intervention

All participants completed the same IRR program for 12 treatment sessions over 4 weeks (3x/week). Participants completed 10 of 12 treatment sessions or they were excluded from the follow up analysis. Exercises (Table 5.) were identical across groups with the only difference being the feedback provided. Feedback was provided for both the dominant and non-dominant limb. Prior to each intervention session, participants warmed-up for 5 minutes at a self-selected pace on a stationary bike. For each intervention task, 6 sets of 6 repetitions were completed which as has been previously used in ACL IRR programs.[105,115] A 2 minute rest was provided between sets.

During the first week (sessions 1-3), participants completed single-limb (SL) squats (Figure 2.) and single-limb step-down exercises (Figure 3.).

Figure 2. Single Leg Squat. The participants stood on the dominant limb with hands on hips 2m away from a wall/mirror and lifted the non-dominant limb off the floor by bending the knee. They lowered themselves toward the ground and then rose back to the starting position. Steps were then repeated while standing on the non-dominant limb.

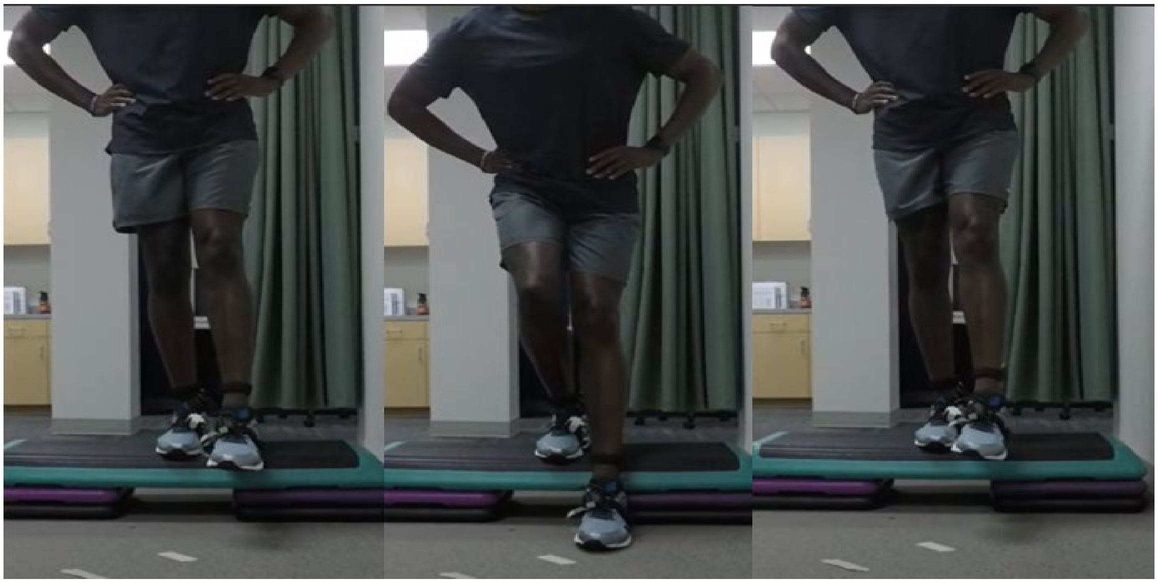

Figure 3. Single Leg Step-Down. The participants stood atop a box placed 2m from a wall/mirror. The participants stepped off the box with the non-dominant limb, landing on the floor, and returning to the start position. Step height was determined based on the participant's height to ensure the task was not excessively difficult for shorter vs. taller individuals. Steps were then repeated on the contralateral limb.

On session 3, a new exercise was added to the program, double-limb (DL) drop landing (Figure 4.). In the second week (sessions 4-6), participants completed single-limb squats, single-limb step-down, and DL drop-landing exercises.

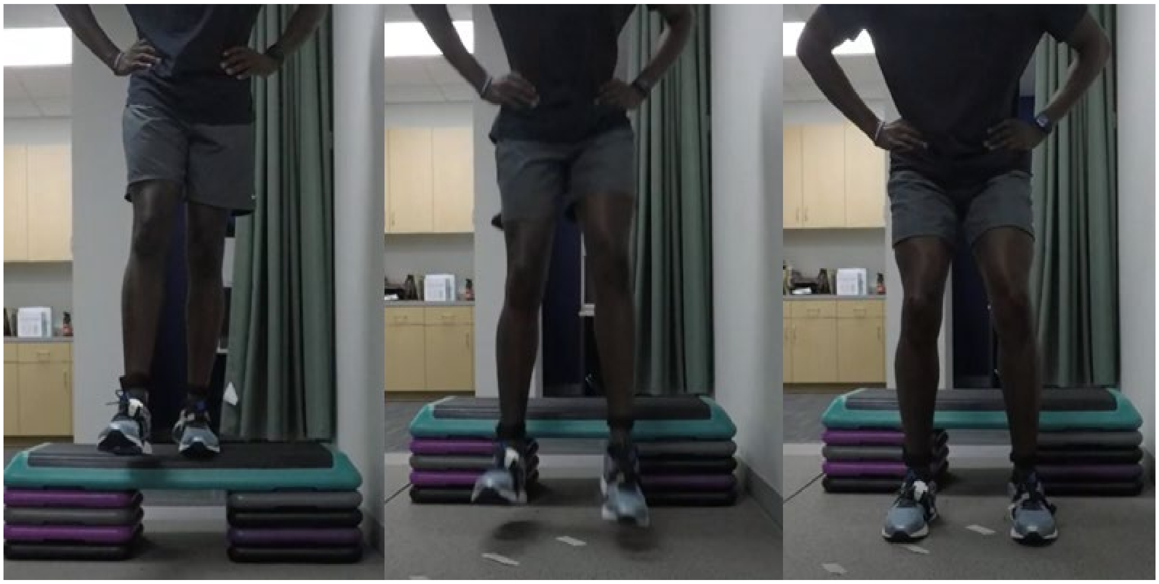

Figure 4. Double-Limb Drop Landing. Participants stood atop a 30cm box placed 2m from a wall/mirror. Participants dropped off the box so that they landed with both feet on the floor at the same time.

Similar to the previous week, on session 6, participants completed a new exercise (single-limb drop-landing [Figure 5.]) in addition to the previous exercises. During week 3 (sessions 7-9) and week 4 (sessions 10-12), participants completed all previous exercises (Table 6). Between intervention sessions, participants were asked to maintain activity level and not begin anything new or stop current activities.

Figure 5. Single-Limb Drop Landing. This task was identical to the double-leg drop landing, except the participant landed on only the dominant leg. Steps were then repeated on the contralateral limb.

Table 5. Summary of ExFOCUS and InFOCUS Group Exercise Progression

Week # Session #	Exercises	# of Sets and Repetitions	Week # Session #	Exercises	# of Sets and Repetitions
Week 1 Session 1	SL Squat Step-Down	6 x 6 6 x 6	Week 3 Session 7	SL Squat Step-Down DL Drop-Landing SL Drop-Landing	6 x 6 6 x 6 6 x 6 6 x 6
Week 1 Session 2	SL Squat Step-Down	6 x 6 6 x 6	Week 3 Session 8	SL Squat Step-Down DL Drop-Landing SL Drop-Landing	6 x 6 6 x 6 6 x 6 6 x 6
Week 1 Session 3	SL Squat Step-Down DL Drop-Landing	6 x 6 6 x 6 6 x 6	Week 3 Session 9	SL Squat Step-Down DL Drop-Landing SL Drop-Landing	6 x 6 6 x 6 6 x 6 6 x 6
Week 2 Session 4	SL Squat Step-Down DL Drop-Landing	6 x 6 6 x 6 6 x 6	Week 4 Session 10	SL Squat Step-Down DL Drop-Landing SL Drop-Landing	6 x 6 6 x 6 6 x 6 6 x 6
Week 2 Session 5	SL Squat Step-Down DL Drop-Landing	6 x 6 6 x 6 6 x 6	Week 4 Session 11	SL Squat Step-Down DL Drop-Landing SL Drop-Landing	6 x 6 6 x 6 6 x 6 6 x 6
Week 2 Session 6	SL Squat Step-Down DL Drop-Landing SL Drop-Landing	6 x 6 6 x 6 6 x 6 6 x 6	Week 4 Session 12	SL Squat Step-Down DL Drop-Landing SL Drop-Landing	6 x 6 6 x 6 6 x 6 6 x 6

Abbreviations: DL= double-limb; SL= single-limb

3.4.1 InFOCUS Feedback

The InFOCUS group completed the training as described; however, they received InFOCUS feedback via a mirror about the quality of their squatting/landing mechanics. The participants within the InFOCUS group were instructed to watch themselves in a mirror and keep their knee in line with their toe during each exercise. Specifically, they received the following feedback during the exercises:1) Single-limb squat: "lower yourself in a manner that allows you to go down as far as possible, but not move your knee left or right while you squat and then raise yourself in a similar manner"; or 2) Single-limb step-down: "step down and touch the ground, but do not move your stance-leg knee left or right while you are stepping". 3) Double- and Single-limb drop-landing: "Land in a manner so that you do not move your knee(s) left or right once you make contact with the ground."

3.4.2 Auditory ExFOCUS Feedback

The auditory ExFOCUS group completed the same progression as the InFOCUS group; however, auditory ExFOCUS feedback was delivered by force resistance sensors (FRS; FlexiForce, Tekscan Inc. South Boston, MA), a single voltage source circuit (Tekscan Inc.), sensor extension cables (Tekscan Inc.), and a buzzer (International Components Corp. Hauppauge, NY) powered by a 3V battery. To provide feedback, force resistance sensors connected to two buzzers each emitting a different tone (Tone A and Tone B) were placed in the shoe, one each under the ball of the foot and the heel. Participants were made familiar with the different tones prior to beginning the intervention. The participants within the auditory ExFOCUS group received the following feedback while they completed the exercises: 1) Single-limb squat: “lower yourself in a manner that allows you to go down as far as possible, but do not let the buzzers make a sound”; or 2) Single-limb step-down: “step down and touch the ground, but do not activate the buzzers in the stance leg while you are stepping”. 3) Double- and Single-limb drop-landing: “Land in a manner so that you do not activate the buzzers once you make contact with the ground.” All single leg exercises were performed using both the dominant and non-dominant limb as the stance limb. The conclusion of the 12th session was the last time that the patients received any instructions about the feedback. Patients were also asked to not discuss the mode of feedback during post-intervention data collection sessions to maintain blinding of the investigators who oversaw data collection and data processing.

3.4.3 Visual ExFOCUS Feedback

The visual ExFOCUS group completed the same progression as the InFOCUS and auditory ExFOCUS groups; however, during each exercise they had the custom-made laser pointer fixed to the lateral midline of the distal femur (5 cm superior to the proximal patella) of each limb with a strap. The laser was positioned in a manner that while the participants stood in a neutral position on the floor (for single-limb squat exercise) or on the box (for single-limb step-down, double-limb drop-landing, and single-limb drop-landing exercises) prior to squatting or dropping, the laser beam cross (horizontal beam and vertical beam) was projected onto the wall (2m away from the box) over a piece of white tape for a vertical point of reference. The participants within the visual ExFOCUS group received the following feedback while they completed the exercises:1) Single-limb squat: “Lower yourself in a manner that allows the laser to go up as far as possible, but not rotate or move left or right while you squat”; 2) Single-limb step-down: “Step off the box and land with your non-dominant limb in a manner in which the laser is able to go up as far as possible and does not rotate or move left or right”; 3) Double- and Single-limb drop-landing: “Land in a manner that allows the laser to go up as far as possible, but not rotate or move left or right while you land.” All single leg exercises were performed using both the dominant and non-dominant limb as the stance limb. The conclusion of the 12th session was the last time that the patients received any instructions about the feedback. Participants were also asked to not discuss the mode of feedback during post-intervention data collection sessions to maintain blinding of the investigators who oversaw data collection and data processing.

3.5 Statistical Analysis

All data was assessed for normality prior to analysis and appropriate non-parametric equivalents were used in the event of non-normally distributed data. All demographic and strength data was compared between groups at baseline using independent samples t-tests. Independent variables for analysis: limb (dominant and non-dominant), group (InFOCUS, visual ExFOCUS, and auditory ExFOCUS) and time (baseline, 1-week post-intervention, and 4-weeks post-intervention). Dependent variables for analysis: hip and knee flexion angles, hip adduction and knee abduction angles, external hip and knee extension moments, external hip adduction and knee abduction moments, peak vGRF during jump landing and cutting task. Additional dependent variables include LESS scores and patient reported outcome surveys. An intraclass correlation coefficient for absolute agreement was run to establish intra-rater reliability for LESS scores across trials.

For Aim 1, data were analyzed via 2x2x3 (limb [dominant, non-dominant] x feedback [InFOCUS, ExFOCUS] x time [baseline, 1- and 4-weeks post-intervention]) ANOVAs. It should be noted that for Aim 1, both ExFOCUS feedback groups were combined to establish the collective effect of ExFOCUS compared to InFOCUS on improving biomechanics. For Aim 2, the ExFOCUS groups were compared using 2x2x3 repeated measures ANOVAs to determine which group yielded the larger improvement in biomechanics. In the event participants did not return for follow up testing, the most recent testing session data were carried forward for statistical analysis. Alpha was set a priori at $P<0.05$ for all analyses. Post hoc testing was performed using one-way ANOVAs and t-tests in the event of significant interactions. Statistical analysis was conducted using IBM SPSS (v28, IBM Corporation, Armonk, NY, USA). Cohen's d effects sizes was calculated[128] in Microsoft Excel (2019, v.16.0, Microsoft Corporation, Seattle, WA, USA) (0.2 - 0.5 small, 0.5 - 0.8 medium and ≥ 0.8 large) to provide a measure of the clinical impact of our findings.

CHAPTER 4: RESULTS

4.1 Descriptive

There were no significant differences in age, height, body mass or BMI between groups (*P*>0.05, Table 7). Forty-four healthy adults participated in this study. Two participants withdrew following the baseline testing session. One participant withdrawal was due to injury; the other resulted from an inability to commit to the total length of the project. The data collected from these baseline sessions are included in the results.

Table 6: Participant Characteristics.

	InFOCUS (n=15)	ExFOCUS Visual (n=13)	ExFOCUS Auditory (n=14)	P-value
% Female	35.71%	46.15%	42.85%	
Age (years)	21.13±3.87	21.38±3.64	21.86±2.91	0.854
Height (m)	1.73±0.07	1.74±0.14	1.72±0.07	0.739
Mass (kg)	70.77±14.37	72.98±15.48	64.87±8.20	0.255
BMI (kg/m^2)	23.46±3.56	23.77±2.34	22.19±3.65	0.419

BMI = Body Mass Index
Data are mean±standard deviation unless otherwise noted.

4.2 Strength Assessment

There was no significant difference in quadriceps or hamstrings strength between groups (*P*>0.05, Table 8) or limbs (*P*>0.05, Table 8).

Table 7: Strength Assessment.

	InFOCUS		ExFOCUS Visual		ExFOCUS Auditory		P-value
	Dominant	Nondominant	Dominant	Nondominant	Dominant	Nondominant	
Quadriceps	2.49±0.34	2.61±0.46	2.52±0.88	2.381±0.76	2.47±0.65	2.45±0.55	0.785
Hamstrings	1.57±0.33	1.56±0.31	1.50±0.44	1.50±0.53	1.53±0.33	1.50±0.32	0.442

Data are mean±standard deviation unless otherwise noted.

4.3 Functional Performance Assessment

A significant limb main effect was detected during the single leg forward hop (*P*<0.001, Table 9) and the six-meter timed hop (*P*=0.049, Table 9). Specifically, participants hopped farther (*P*<0.001, d=0.29 [0.40,1.07) and faster (*P*<0.001, d = 0.23[-0.01,0.60]) using the non-dominant versus the dominant limb. There were no significant differences in crossover hop triple hop distance or vertical jump height (*P*>0.05, Table 9).

Table 8: Functional Performance Assessment.

	InFOCUS		ExFOCUS Visual		ExFOCUS Auditory		Group x Limb Interaction	Group Main Effect	Limb Main Effect	Effect Size (95% CI)
	Dom	Non-Dom	Dom	Non-Dom	Dom	Non-Dom				
Single Leg Hop (m)	1.2±0.3	1.4±0.3*	1.2±0.6	1.3±0.5*	1.1±0.3	1.3±0.3*	**<0.001**	**<0.001**	0.711	d=0.29 (0.40,1.07)
Triple Hop (m)	4.8±1.0	4.7±1.0	4.5±1.3	4.5±1.0	4.5±1.0	4.6±1.0	0.661	0.661	0.775	
Crossover Hop (m)	4.2±1.1	4.2±0.9	3.8±1.0	3.7±1.0	4.1±0.9	3.9±0.8	0.050	0.050	0.385	
Six Meter Timed Hop (s)	2.4±0.6	2.5±0.6*	2.5±0.6	2.6±0.7*	2.5±0.5	2.6±0.6*	**0.049**	**0.049**	0.831	d=0.23 (-0.01,0.60)
Vertical jump height (m)	18.9±5.5		20.3±4.4		20.1±4.9			0.724		

Dom: Dominant Limb
Non-Dom: Non-Dominant Limb
* Statistically significant difference from the Dominant Limb ($p<0.05$)
Data are mean±standard deviation unless otherwise noted.

4.4 Biomechanics

4.4.1 Jump Landing

When comparing data between the InFOCUS and combined ExFOCUS groups, there was a significant limb main effect for sagittal plane hip joint angles (*P*=0.049, Figure 6). Further testing revealed that there was significantly greater hip flexion in the non-dominant relative to the dominant limb (*P*<0.049, d=-0.89 [-1.36,-0.41]). No other significant differences in knee or hip joint angles were present between limbs (*P*>0.05, Figures 7-9). No significant differences in kinetic measurements or vGRF were detected during any of the testing sessions between or within any of the groups (*P*>0.05, Figures 10-14)

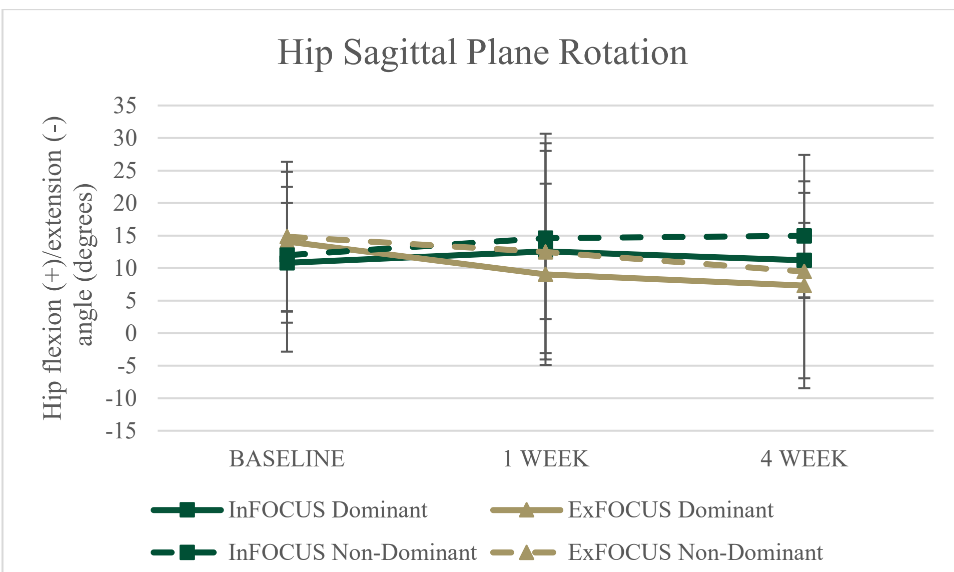

Figure 6: Hip Sagittal Plane Rotation During Jump Landing

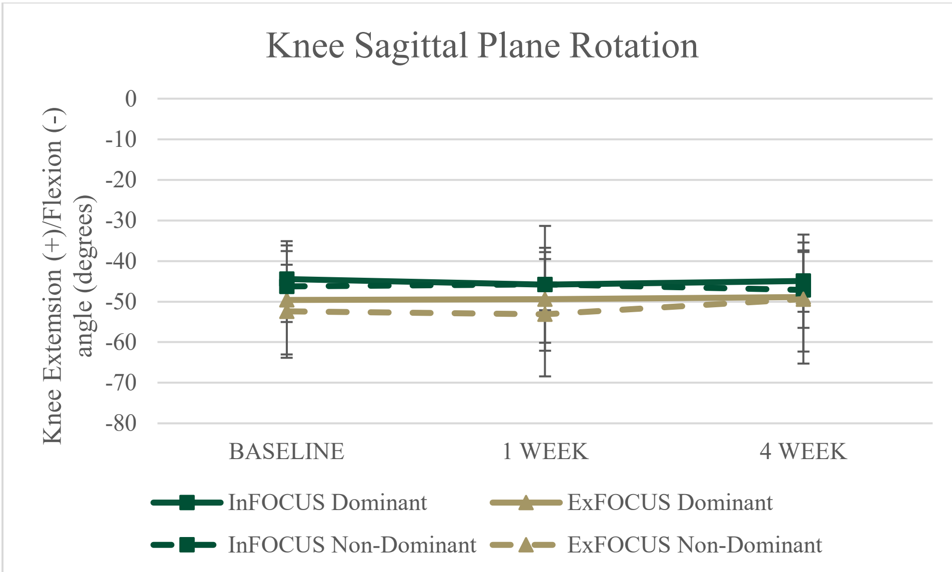

Figure 7: Knee Sagittal Plane Rotation During Jump Landing

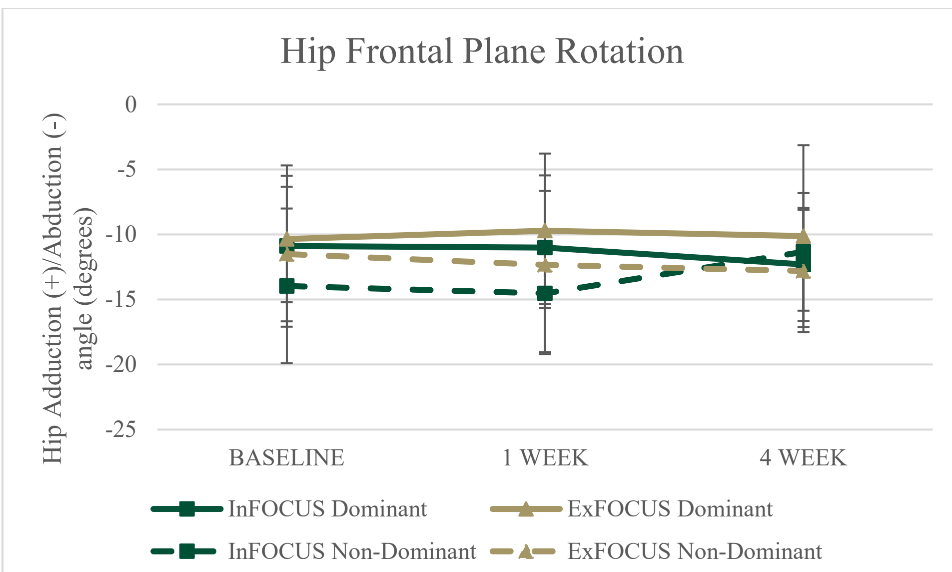

Figure 8: Hip Frontal Plane Rotation During Jump Landing

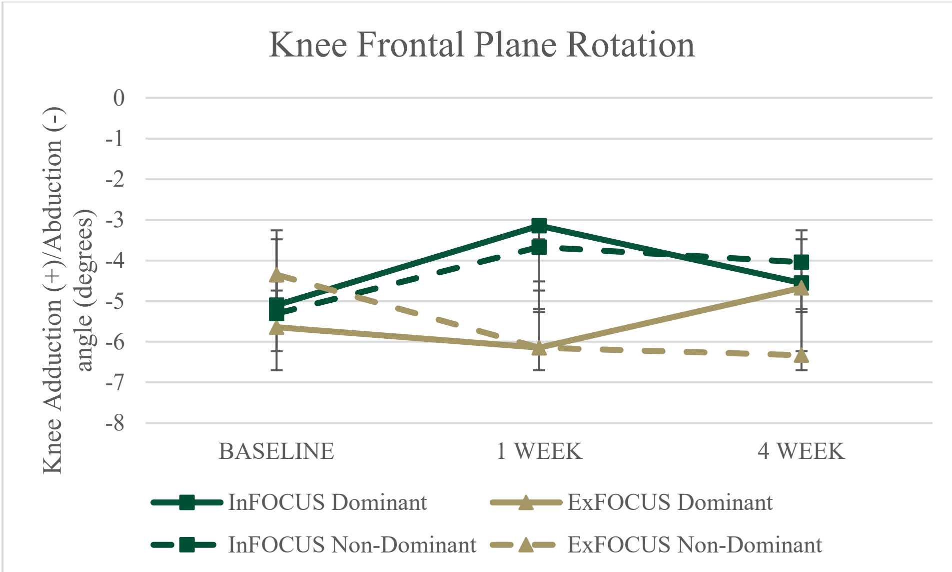

Figure 9: Knee Frontal Plane Rotation During Jump Landing

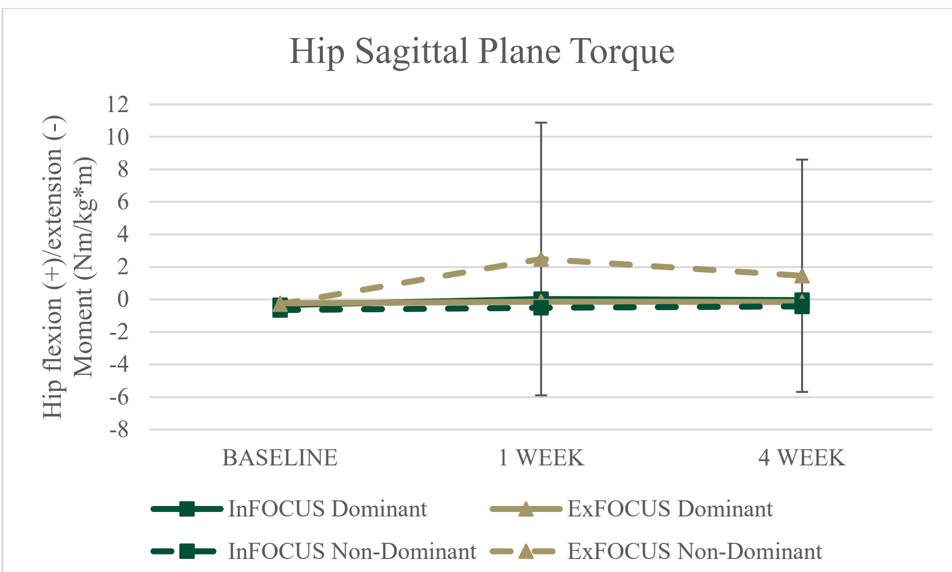

Figure 10: Hip Sagittal Plane Torque During Jump Landing

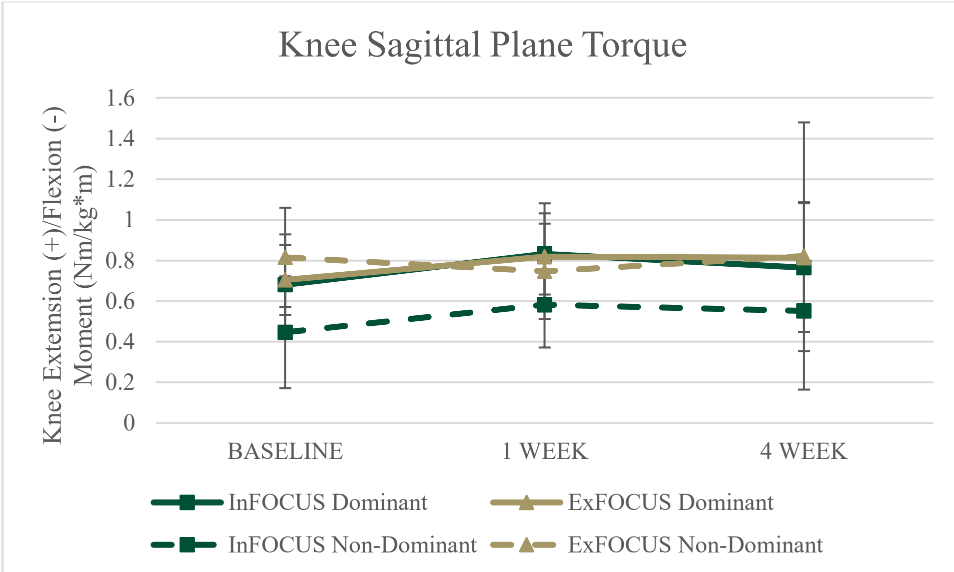

Figure 11: Knee Sagittal Plane Torque During Jump Landing

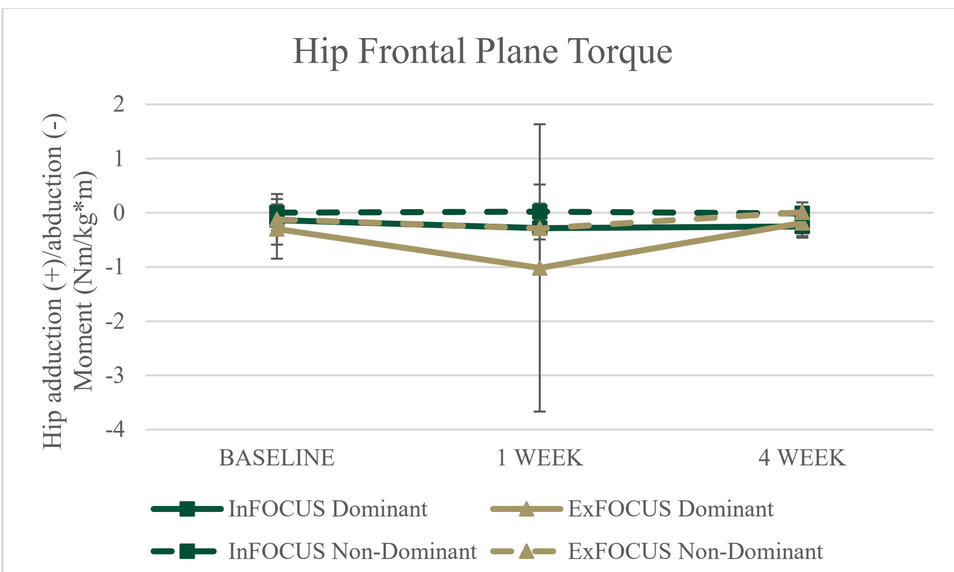

Figure 12: Hip Frontal Plane Torque During Jump Landing

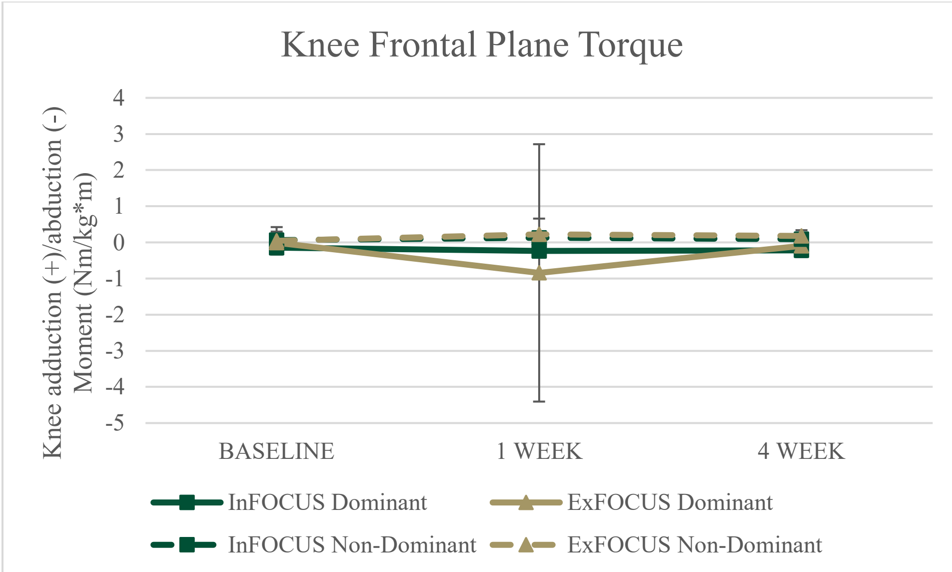

Figure 13: Knee Frontal Plane Torque During Jump Landing

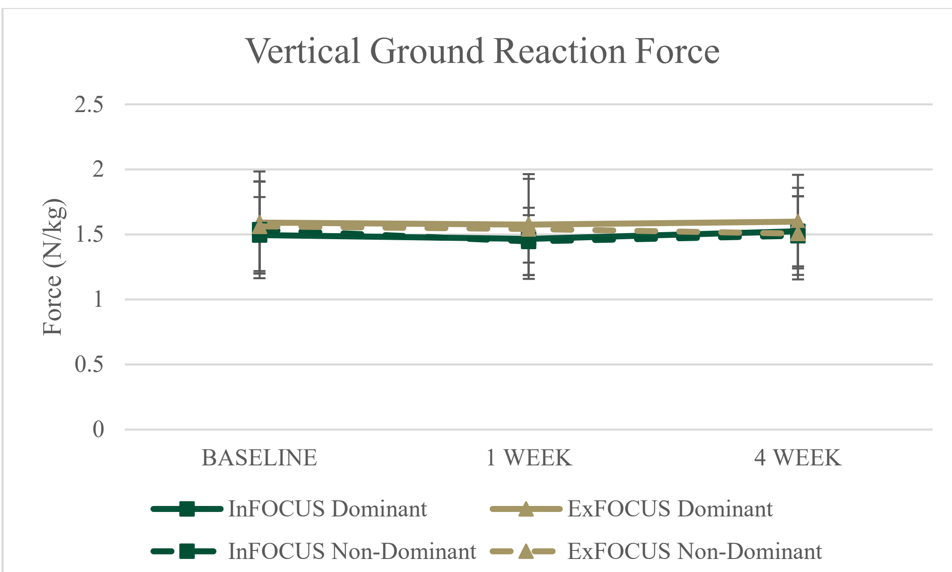

Figure 14: Vertical Ground Reaction Force During Jump Landing

When the visual and auditory ExFOCUS groups were compared, no significant differences in knee or hip joint angles (P>0.05, Figures 15-18), moments (P>0.05, Figures 19-

22), or vGRF (*P*>0.05, Figure 23) were present during any of the testing sessions between or within any of the groups.

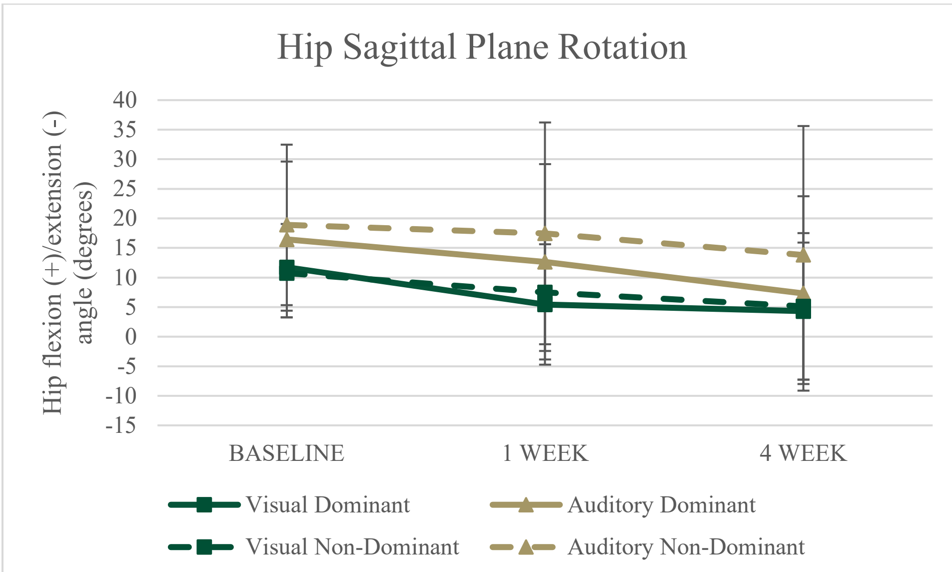

Figure 15: Hip Sagittal Plane Rotation During Jump Landing

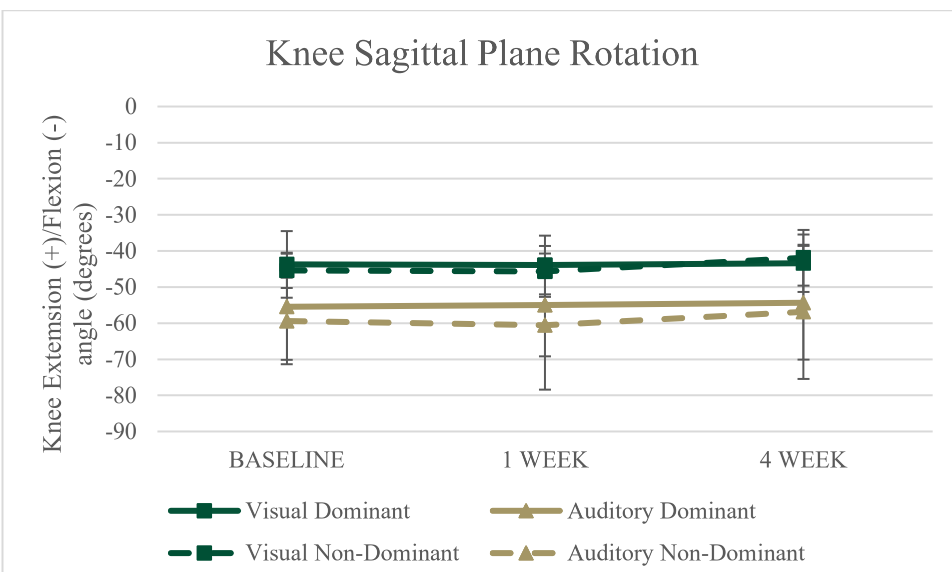

Figure 16: Knee Sagittal Plane Rotation During Jump Landing

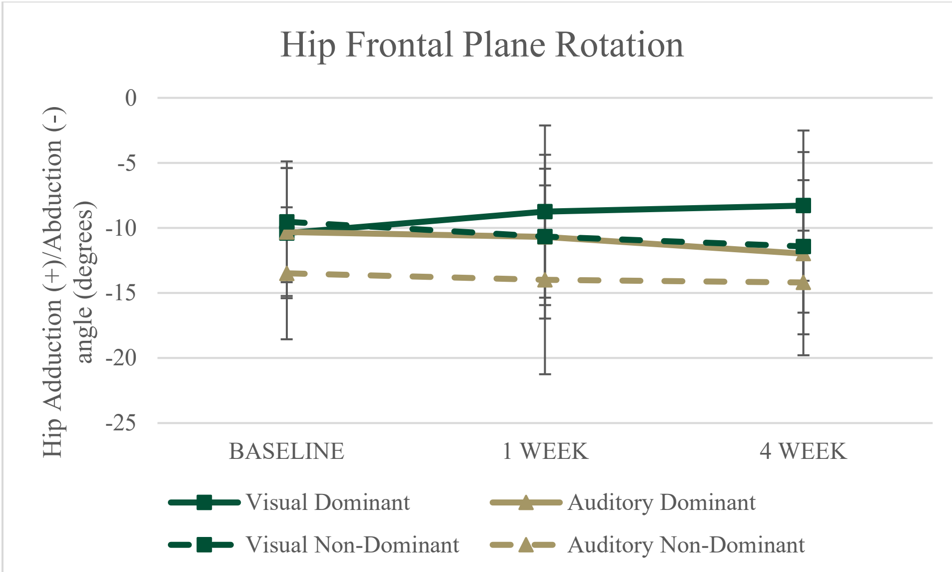

Figure 17: Hip Frontal Plane Rotation During Jump Landing

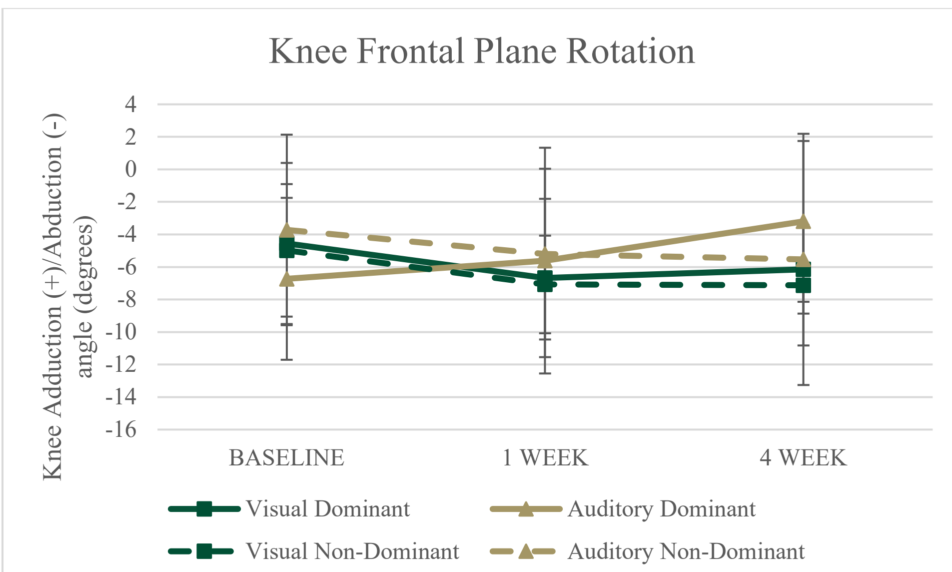

Figure 18: Knee Frontal Plane Rotation During Jump Landing

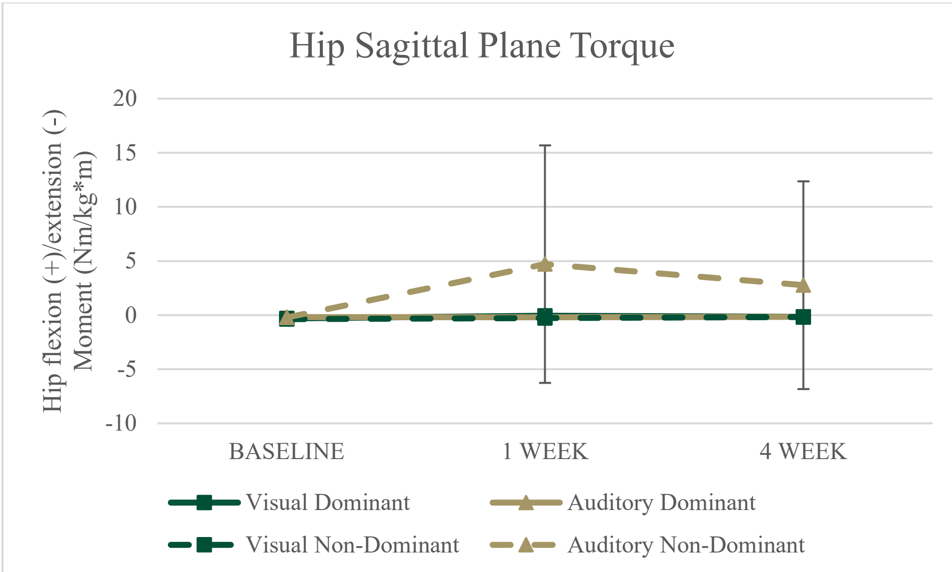

Figure 19: Hip Sagittal Plane Torque During Jump Landing

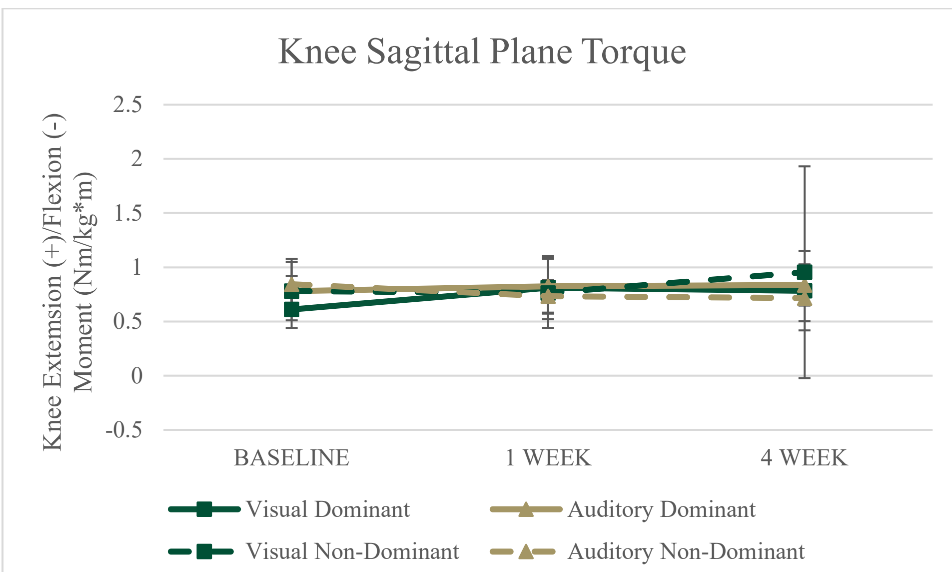

Figure 20: Knee Sagittal Plane Torque During Jump Landing

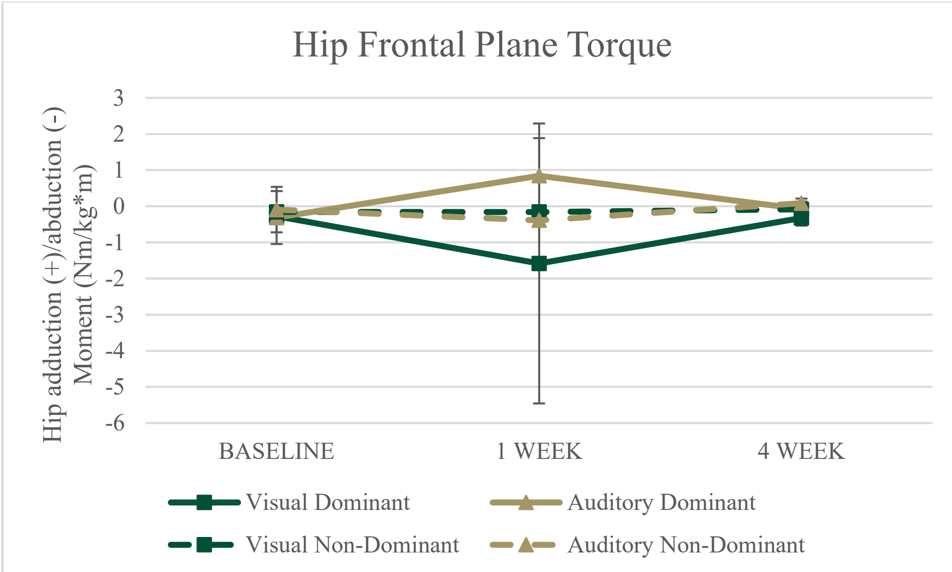

Figure 21: Hip Frontal Plane Torque During Jump Landing

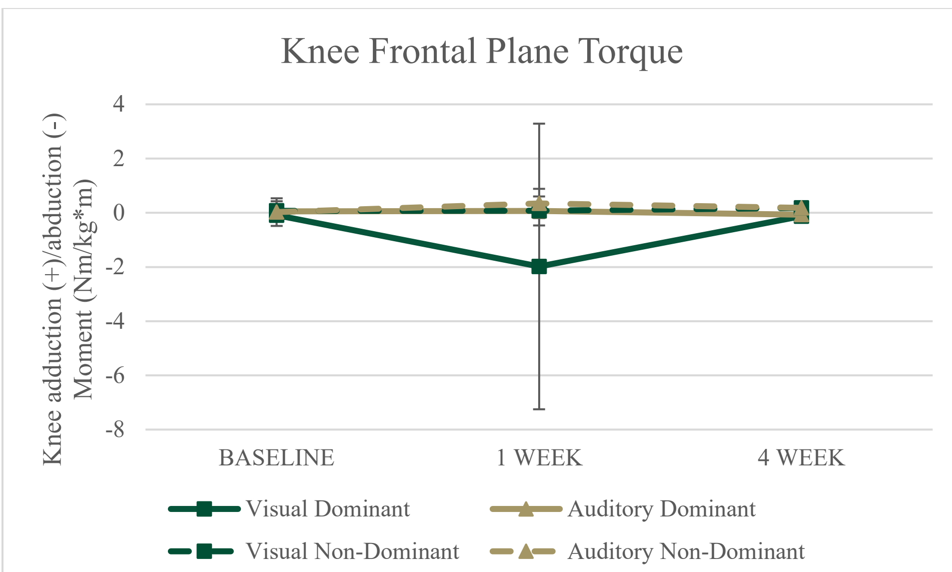

Figure 22: Knee Frontal Plane Torque During Jump Landing

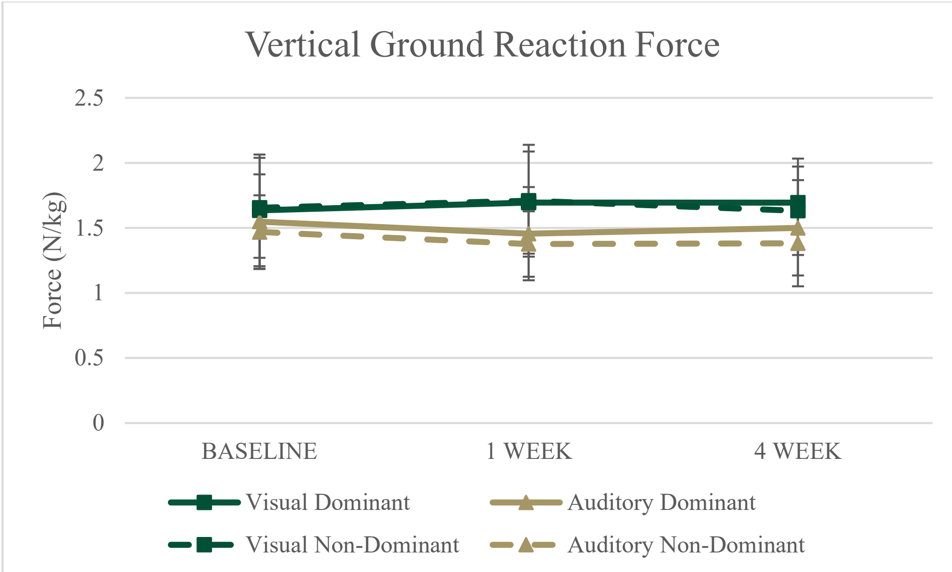

Figure 23: Vertical Ground Reaction Force During Jump Landing

4.4.2 Cutting Task

When comparing data between the InFOCUS and combined ExFOCUS groups, there was a significant limb by time interaction for sagittal plane hip joint angle (*P*=0.038, Figure 24). Further testing revealed that the dominant limb exhibited greater hip flexion than the non-dominant limb (*P*<0.001, d=-1.0 [-1.53,-0.52]), while hip joint angle did not differ significantly across study timepoints (*P*>0.05, Figure 24). There were also significant limb main effects in frontal plane hip (*P*<0.001, Figure 25) and knee (*P*=0.008, Figure 26) joint angles, as well as sagittal plane knee (*P<0.001*, Figure 27) joint angles. The non-dominant limb exhibited hip (*P*<0.001, d=-0.93 [-1.41,-0.42]) and knee (*P*=0.008, d=-0.25 [-0.72,0.23]) abduction while the dominant limb exhibited adduction. The dominant limb displayed significantly less knee flexion (*P*<0.001, d=3.38 [2.60,4.07]) when compared to the non-dominant limb. There was a time main effect for knee joint sagittal plane rotation (*P*<0.019, Figure 27). However, post hoc testing did not reveal any significant differences in knee flexion angle between testing sessions (*P*>0.05, Figure 27). No other significant differences in hip or knee joint angles were found during the cutting task (*P*>0.05).

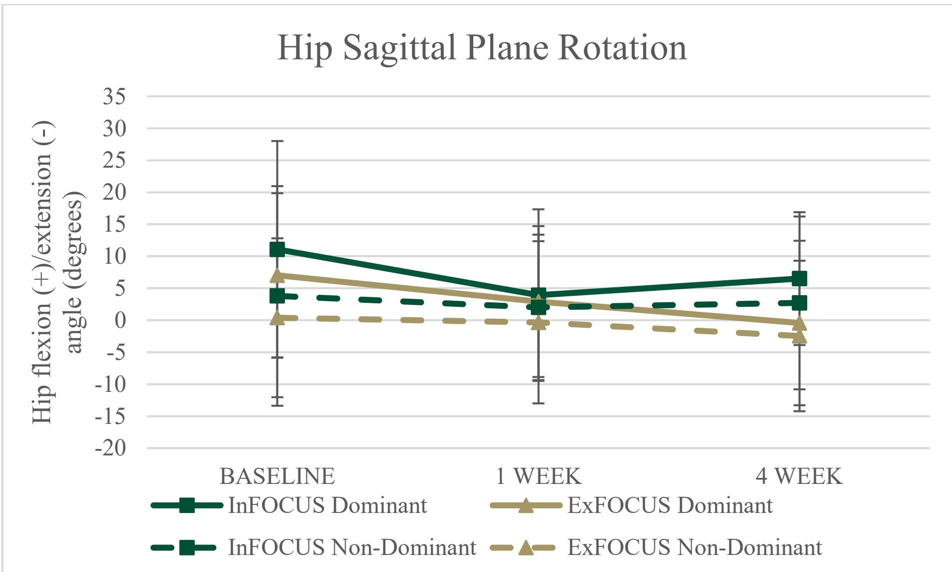

Figure 24: Hip Sagittal Plane Rotation During Cutting Task

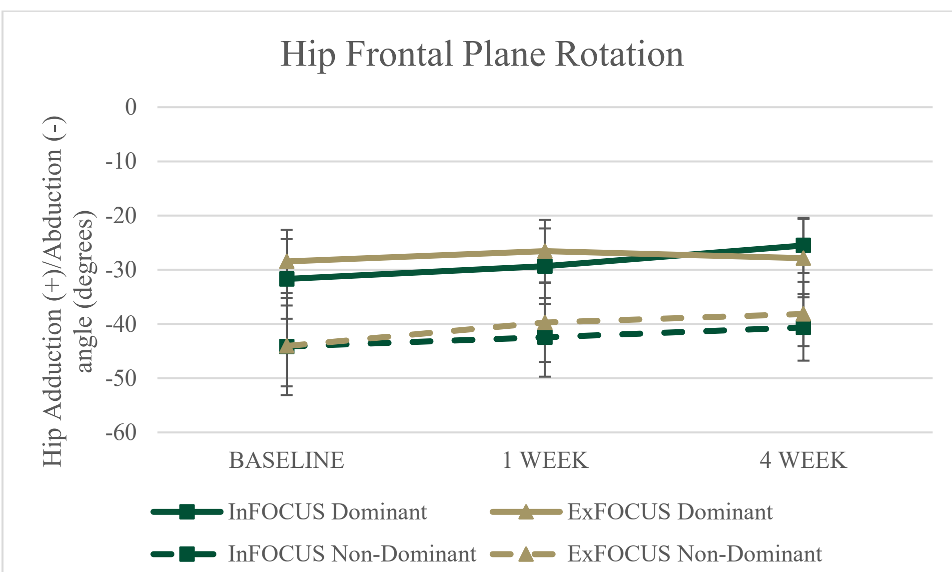

Figure 25: Hip Frontal Plane Rotation During Cutting Task

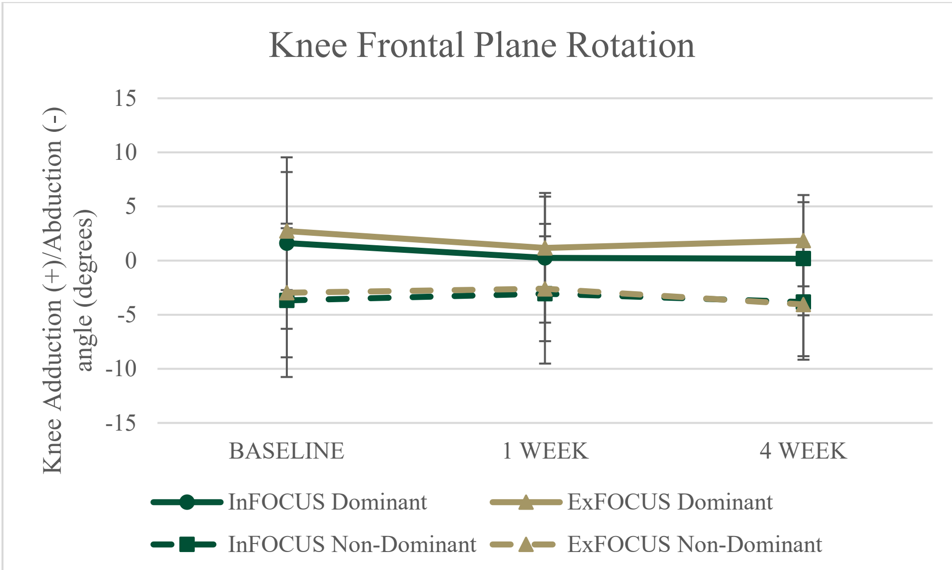

Figure 26: Knee Frontal Plane Rotation During Cutting Task

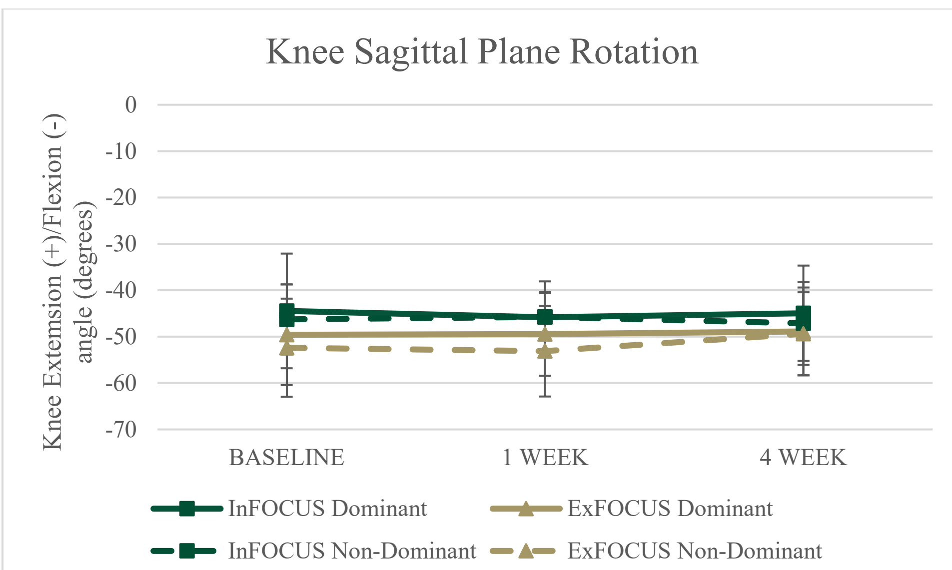

Figure 27: Knee Sagittal Plane Rotation During Cutting Task

Significant limb main effects in frontal plane hip (*P*<0.001, Figure 28) and knee (*P*=0.008, Figure 29) joint angles, as well as sagittal plane hip (*P*=0.002, Figure 30) and knee

(*P<0.001*, Figure 31) joint angles were observed between the visual and auditory ExFOCUS groups. The non-dominant limb hip (*P*<0.001, d=-0.89 [-1.49,-0.27]) and knee (*P*=0.008, d=-0.40 [-0.98,0.19]) were found to be abducted while the dominant limb was found to be adducted. The non-dominant hip (*P*=0.002, d=-0.30 [-0.87,-0.29]) was extended while the dominant hip was flexed and the dominant knee was less flexed(*P*<0.001, d=3.35 [2.11,4.18]) than the non-dominant. No other significant differences in hip or knee joint angles were found during the cutting task (*P*>0.05).

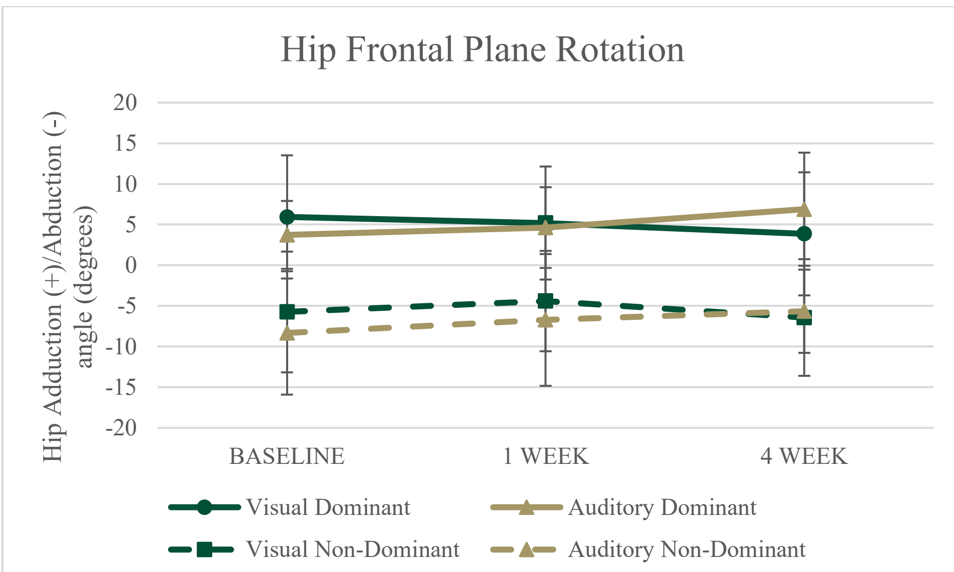

Figure 28: Hip Frontal Plane Rotation During Cutting Task

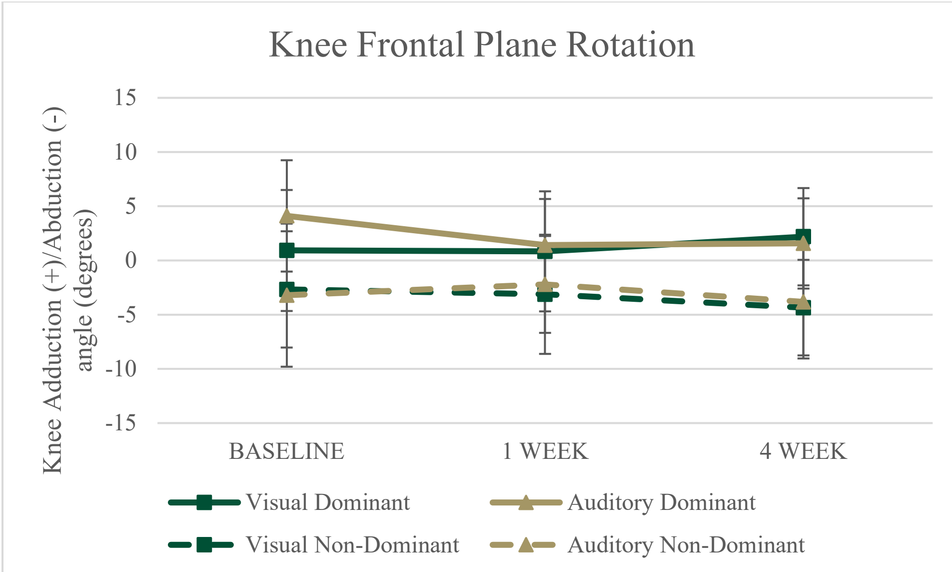

Figure 29: Knee Frontal Plane Rotation During Cutting Task

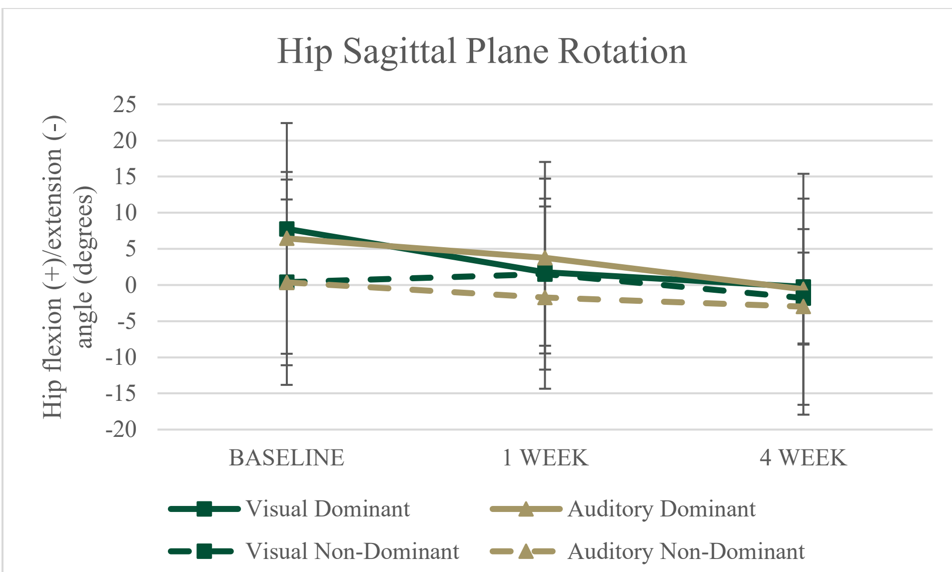

Figure 30: Hip Sagittal Plane Rotation During Cutting Task

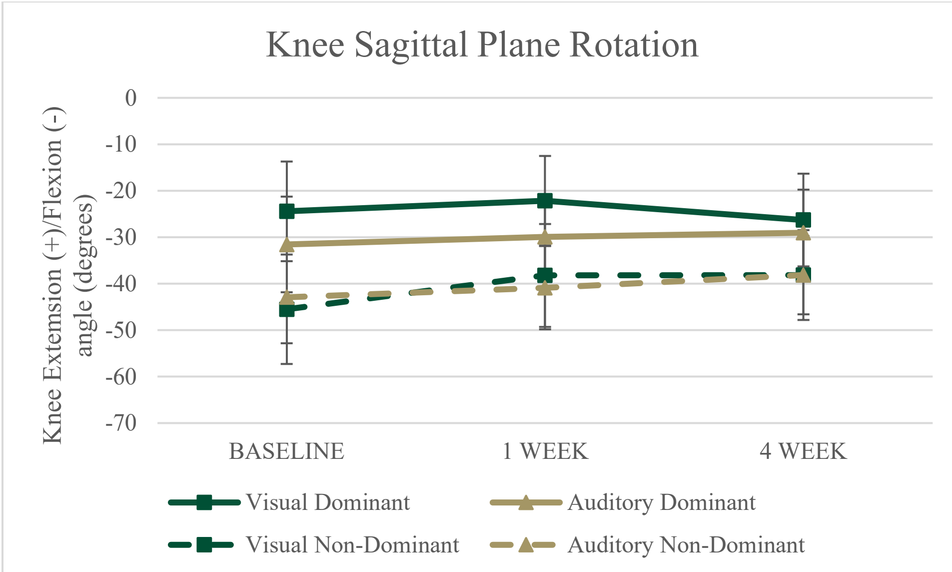

Figure 31: Knee Sagittal Plane Rotation During Cutting Task

When the InFOCUS and combined ExFOCUS groups were compared significant limb main effects were discovered for joint moments in the hip (*P*<0.001, Figure 32) and knee frontal (*P*=0.009, Figure 33) plane and knee sagittal (*P*<0.001, Figure 34) plane. The non-dominant limb experienced hip (*P*<0.001, d=-0.68 [-1.27,-0.06]) and knee (*P*<0.009, d=-0.30 [-0.89,0.30]) abduction torque while the dominant limb experienced hip and knee adduction torque. Further, the non-dominant limb experienced significantly greater knee extension torque (*P*<0.001, d=-2.07 [-2.76,-1.30]) compared to the dominant. No other significant differences in hip or knee torque were observed (*P*>0.05, Figure 35). No significant differences in vGRF were detected (*P*>0.05, Figure 36).

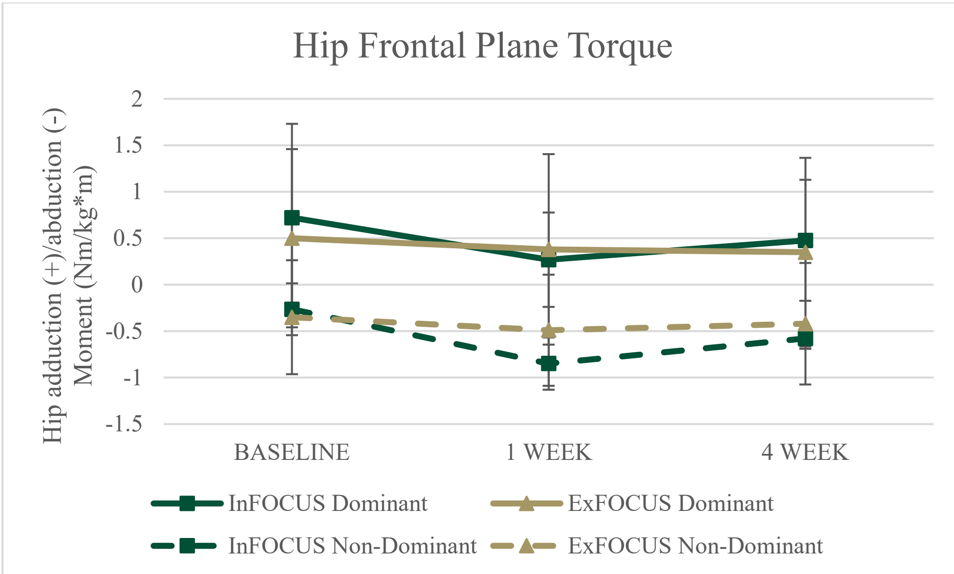

Figure 32: Hip Frontal Plane Torque During Cutting Task

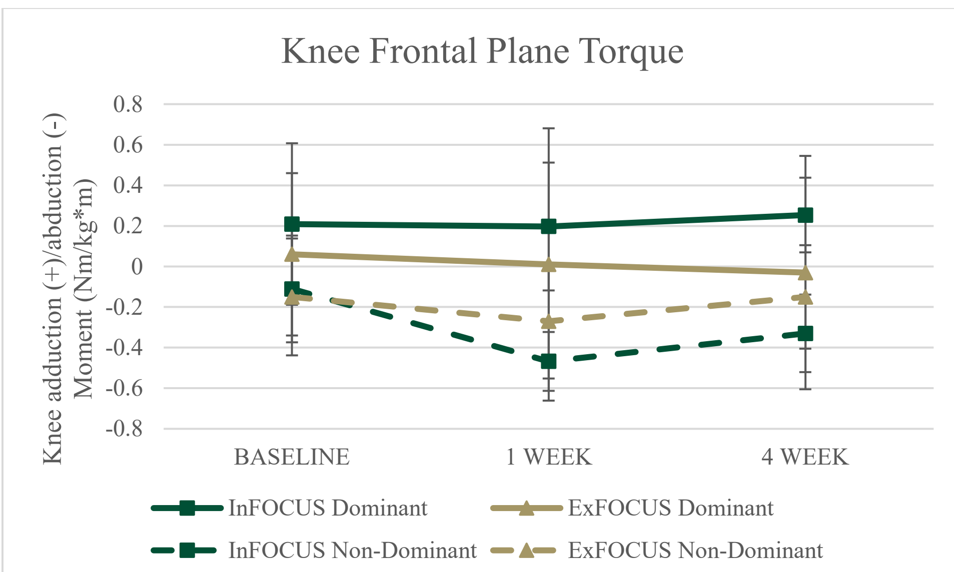

Figure 33: Knee Frontal Plane Torque During Cutting Task

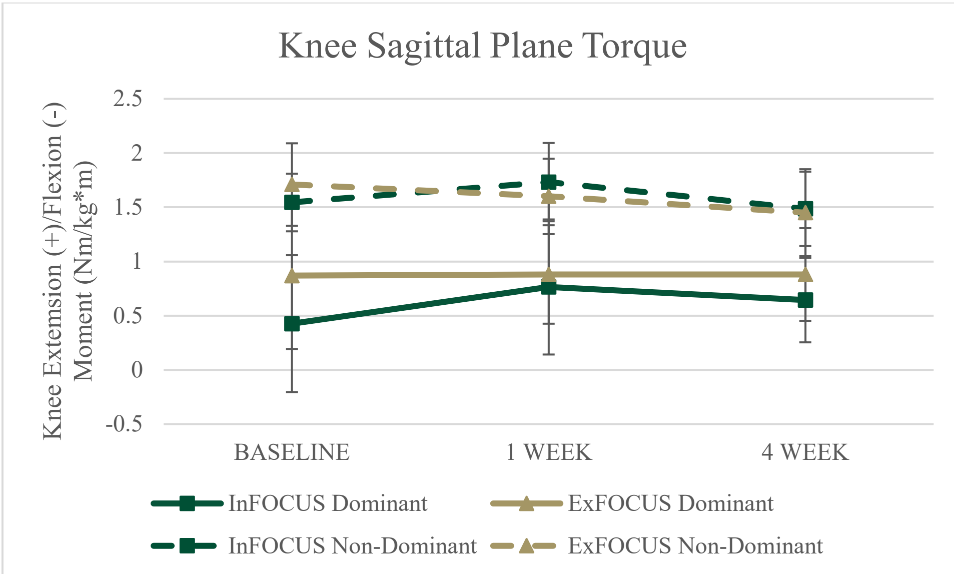

Figure 34: Knee Sagittal Plane Torque During Cutting Task

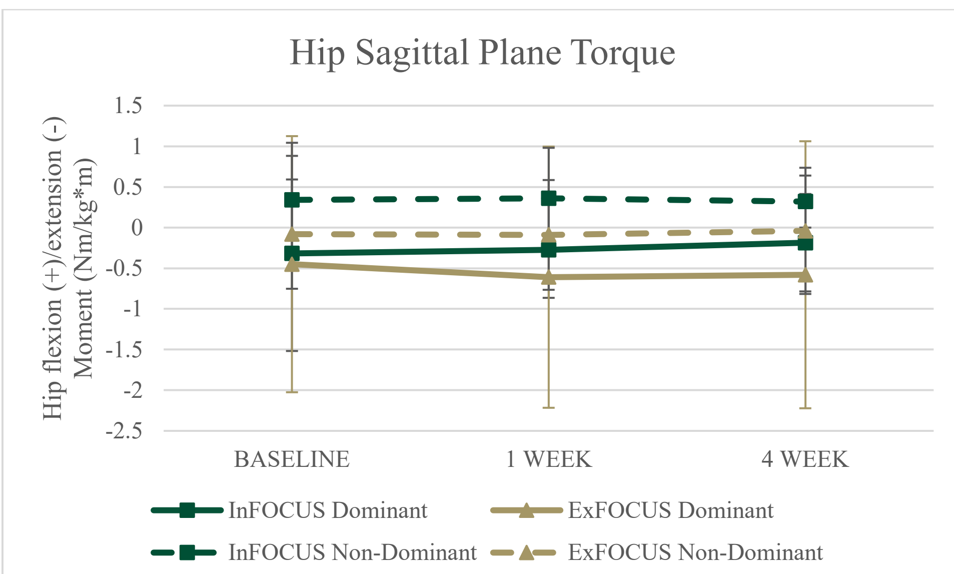

Figure 35: Hip Sagittal Plane Torque During Cutting Task

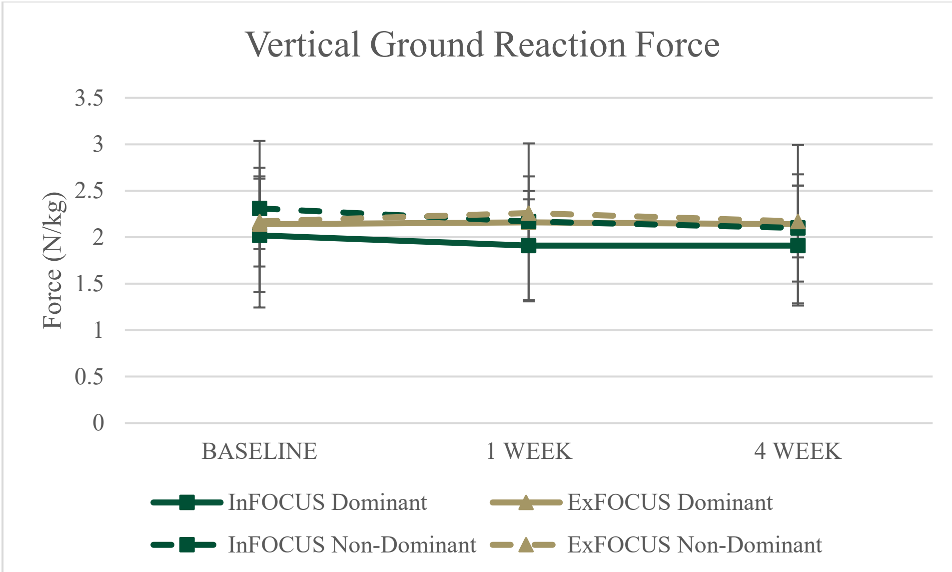

Figure 36: Vertical Ground Reaction Force During Cutting Task

There were significant limb main effects for joint moments in the hip frontal (*P*=0.003, Figure 37) and knee sagittal (*P*<0.001, Figure 38) planes in the visual and auditory ExFOCUS groups. The non-dominant limb experienced hip (*P*=0.003, d=-0.61 [-1.30,0.11]) abduction torque the dominant limb experienced hip adduction torque. It was also revealed that the non-dominant limb experienced significantly greater knee extension torque (*P*<0.001, d=-2.64 [-3.51,-1.63]) compared to the dominant. No other significant differences in hip or knee torque (*P*>0.05, Figures 39,40) or vGRF were detected (*P*>0.05, Figure 41).

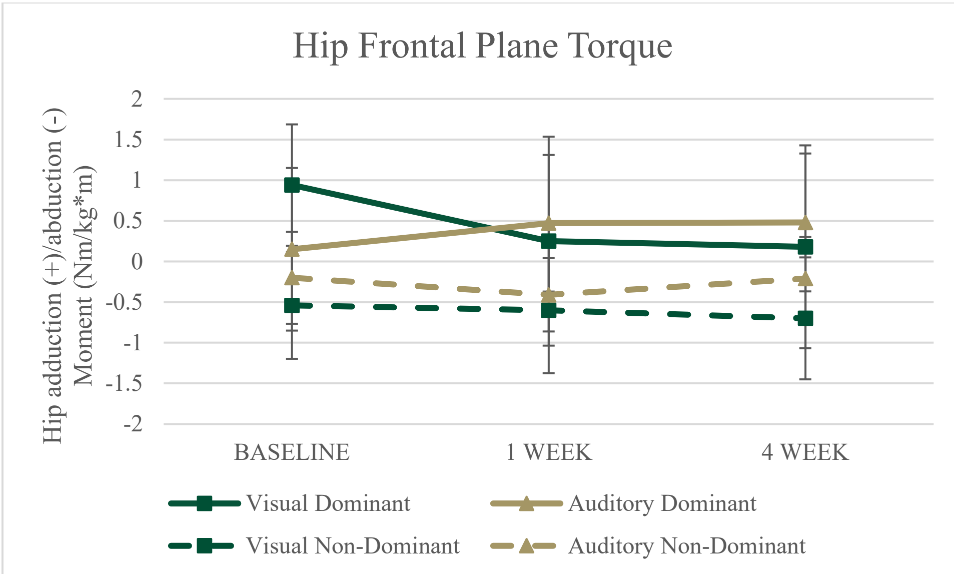

Figure 37: Hip Frontal Plane Torque During Cutting Task

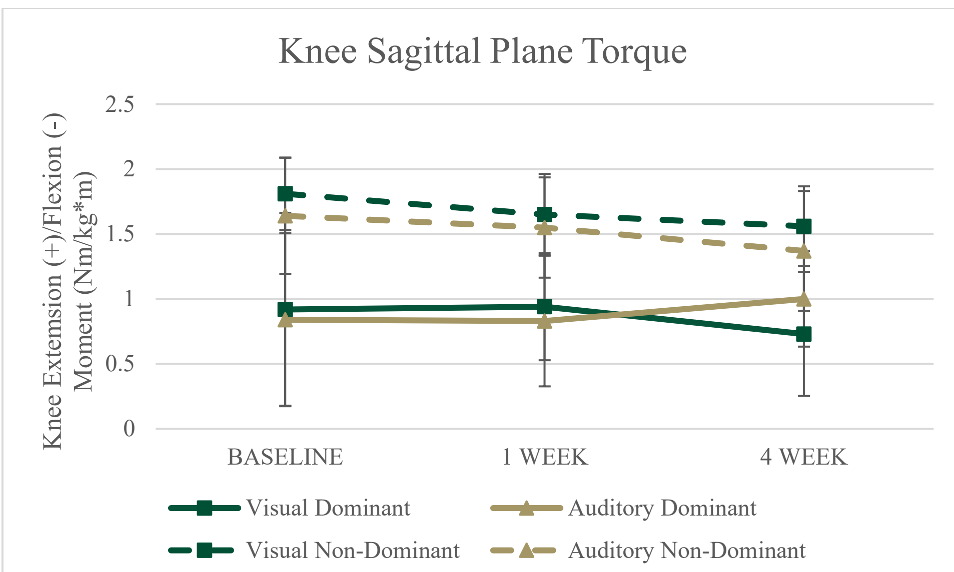

Figure 38: Knee Sagittal Plane Torque During Cutting Task

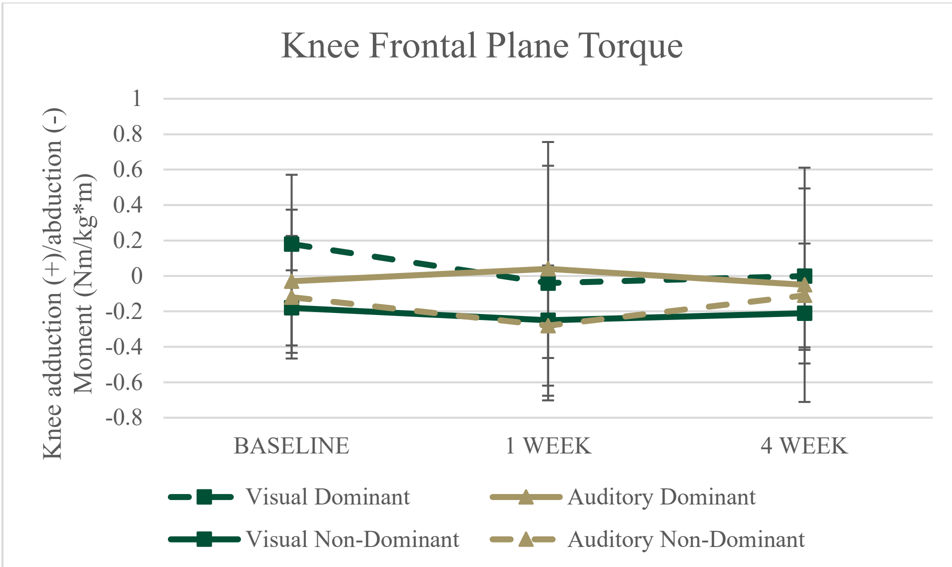

Figure 39: Knee Frontal Plane Torque During Cutting Task

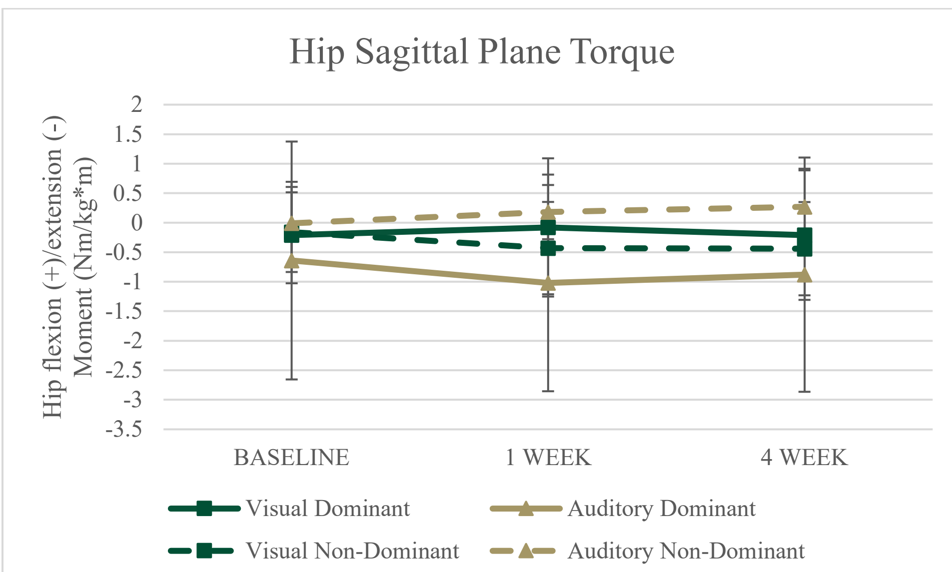

Figure 40: Hip Sagittal Plane Torque During Cutting Task

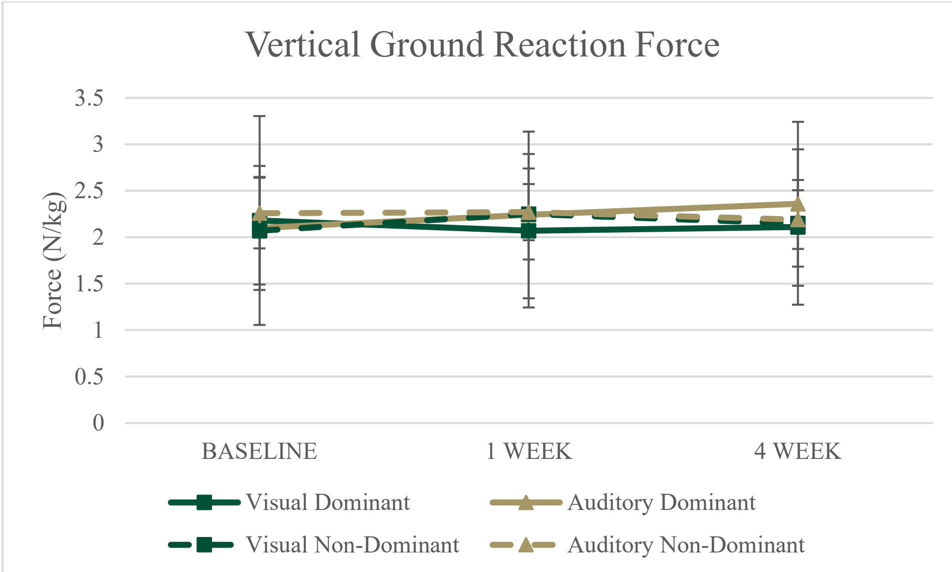

Figure 41: Vertical Ground Reaction Force During Cutting Task

4.3 Landing Error Scoring System

A significant time main effect for LESS scores (*P*<0.001, Figure 42) was detected when comparing data between the InFOCUS and combined ExFOCUS groups. Specifically, LESS scores declined significantly from the baseline to 4WK test (*P*<0.001, d=0.41 [-0.05,0.86]) and 1WK to 4 WK (*P*=0.007, d=-1.54 [-2.03,-1.01]) regardless of group. There were no significant LESS score differences between the BL and 1 WK tests (*P*>0.05, Figure 42).

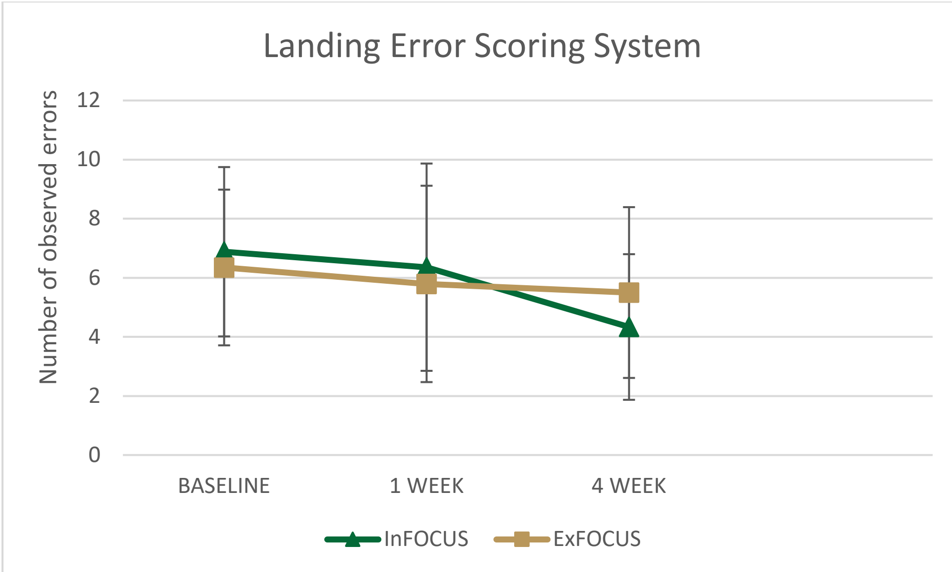

Figure 42: Landing Error Scoring System

No significant differences were found when comparing the LESS scores of the visual and auditory ExFOCUS groups (*P*>0.05, Figure 43). Finally, there was strong intra-rater reliability for LESS scores across trials ($ICC_{(3,1)}$ 0.889, *P*<0.001).

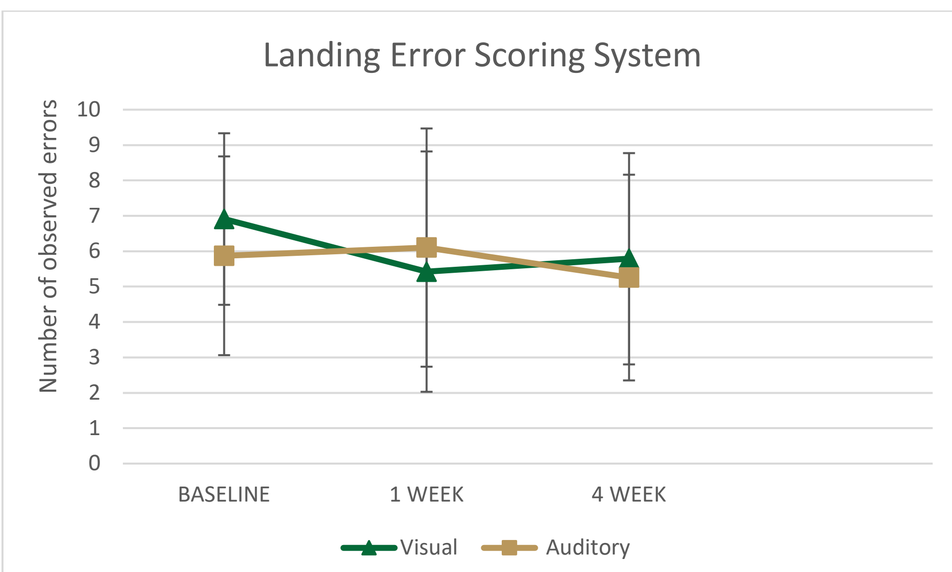

Figure 43: Landing Error Scoring System

4.4 Patient Reported Outcomes

When comparing data between the InFOCUS and combined ExFOCUS groups there were significant time main effects for the MARX ($P=0.009$, Table 10) and PROMIS ($P<0.001$, Table 10) questionnaires. MARX scores significantly increased from the BL to 4 WK ($P=0.006$, d= -0.26 [-0.78, 0.26])and 1WK to 4 WK ($P=0.019$, d= -2.31 [-2.94,-1.62]) timepoints regardless of group. In addition, there were significant increases from the BL to 4 WK ($P<0.001$, d=-0.32 [-0.83, 0.21]) and the 1WK to 4 WK ($P=0.007$, d=-7.98 [-9.40,-6.35]) sessions in PROMIS scores regardless of group. No other significant changes were discovered in patient reported outcome survey responses ($P>0.05$, Table 10).

Table 9: Patient Reported Outcomes - InFOCUS and ExFOCUS combined groups.

	InFOCUS			ExFOCUS			Group x Time Interaction	Group Main Effect	Time Main Effect	Effect Size d (95%CI)
	BL	1WK	4WK	BL	1WK	4WK				
MARX	12.41±9.42	11.41±8.51	13.91±9.51*†	8.27±4.91	9.38±4.64	9.61±4.24	0.092	0.495	0.009	-0.26 (-0.78, 0.26) -2.31 (-2.94,-1.62)†
PROMIS	44.91±17.98	45.58±17.73	48.00±17.00*†	39.83±6.11	40.33±5.19	41.33±5.80	0.230	0.696	<0.001	-0.32 (-0.83, 0.21) -7.98 (-9.40,-6.35)†
LYSHOLM	97.50±3.37	96.91±4.44	98.25±2.59	96.44±5.47	93.72±6.37	96.44±6.69	0.482	0.300	0.092	
IKDC	92.12±24.08	90.30±25.56	89.78±25.37	96.04±4.08	95.15±6.54	96.87±4.78	0.118	0.362	0.304	
TSK-11	15.58±5.70	16.98±5.66	15.13±4.05	17.06±3.35	17.72±4.22	17.66±3.71	0.488	0.218	0.847	

* Indicates significantly different from BL
† Indicates significantly different from 1WK
BL: baseline
IKDC: International Knee Documentation Committee
TSK-11: Tampa Scale of Kinesiophobia

When comparing the visual and auditory ExFOCUS groups significant time main effects for the MARX (*P*=0.012, Table 11) and Lysholm Knee Scale (*P*=0.044, Table 11) questionnaires were observed. MARX scores significantly increased from the BL to 4 WK (*P*=0.038, d= -0.22 [-0.87, 0.44]) and 1WK to 4 WK (*P*=0.023, d= -2.02 [-2.77,-1.180]) timepoints regardless of group. In addition, there were significant decreases for Lysholm Knee Scale scores from the baseline to 1WK (*P*=0.039, d=0.00 [-0.65, 0.65]) time point. However, they then increased from the 1WK to 4 WK (*P*=0.033, d=-0.43 [-1.08, 0.24]) time point with no differences observed between baseline and 4 WK (*P*>0.05, Table 11) regardless of group. No other significant changes were discovered in patient reported outcome survey responses (*P*>0.05, Table 11).

Table 10: Patient Reported Outcomes - Visual and Auditory ExFOCUS groups.

	InFOCUS			ExFOCUS			Group x Time	Group Main	Time Main	Effect Size d (95%CI)
	BL	1WK	4WK	BL	1WK	4WK	Interaction	Effect	Effect	
MARX	8.60±5.56	9.80±4.82	9.90±4.93*†	7.87±4.29	8.87±4.67	9.25±3.49	0.951	0.730	0.012	-0.22 (-0.87, 0.44) -2.02 (-2.77,-1.18)†
PROMIS	40.0±6.1	40.90±5.78	41.70±5.90	38.75±5.65	39.62±4.62	40.87±6.03	0.681	0.620	0.061	
LYSHOLM	96.60±6.41	93.20±7.59*	94.90±8.58†	96.25±4.43	94.37±4.83	98.37±2.50	0.295	0.594	0.044	0 (-0.65, 0.65) -0.43 (-1.08,0.24)†
IKDC	95.63±4.19	94.71±8.32	95.63±5.90	96.55±4.16	95.68±3.77	98.41±2.37	0.525	0.504	0.160	
TSK-11	16.90±4.14	16.50±4.45	18.20±4.15	17.25±2.25	19.25±3.61	15.13±4.05	0.279	0.577	0.802	

* Indicates significantly different from BL
† Indicates significantly different from 1WK
BL: baseline
IKDC: International Knee Documentation Committee
TSK-11: Tampa Scale of Kinesiophobia

CHAPTER 5: DISCUSSION

The purpose of this dissertation was to determine the efficacy of novel forms of ExFOCUS feedback (visual and auditory) compared to InFOCUS feedback at improving biomechanical risk factors of non-contact ACL injuries. Additionally, the project examined which mode of ExFOCUS feedback delivery, visual or auditory, was more effective at improving biomechanical risk factors of non-contact ACL injuries. It was hypothesized that the combined ExFOCUS groups would demonstrate greater improvements in biomechanics compared to the InFOCUS group and that these improvements would be retained after cessation of the intervention. Further, it was hypothesized that the auditory ExFOCUS group would elicit superior results compared to the visual ExFOCUS group.

5.1 Biomechanics

5.1.1 Jump Landings

A limb difference was observed during the jump landing task when comparing the InFOCUS group with the combined ExFOCUS group. The hip flexion angle in the non-dominant limb was significantly greater than that of the dominant limb. It is important to note that the mean difference in hip flexion angle between limbs was only 2.2 degrees. Though the effect size was large, the 95% confidence interval crossed zero, suggesting that some individuals may actually have the opposite effect (decreased hip flexion) in their non-dominant limb, and as such may not impact ACL injury risk. Further, previous research has suggested that there are approximately 3.8 degrees of error inherent to the motion capture process.[129] Since this value falls within that margin of error, we do not believe this finding supports our hypothesis.

Despite the absence of significant findings in jump landing biomechanics in our study, previous researchers have observed significant biomechanical changes when varied focus of attention feedback was used during an ACL injury risk reduction program. Specifically, Dalvandpour et al. investigated the effects of focus of attention feedback on jump landing kinematics in elite male soccer players.[130] The authors reported that ExFOCUS feedback significantly improved sagittal plane hip and knee joint kinematics during a jump landing, such that participants landed with greater hip and knee flexion post-feedback. This is important as decreased hip and knee flexion angles at landing may place the ACL at a greater risk of injury due to a greater peak landing force being conveyed to the knee.[15] Dalvandpour et al.'s study differs from ours in a few ways that may explain the different results. First, the previous investigators used a barefoot, single-leg (dominant limb) landing from a 30cm boxed placed 15cm away while we required participants to be shod, land on both limbs, and to jump off a 30cm box placed one half of their height away from the force plates. Also, participants in Dalvandpour's study completed an 8-week intervention following the Prevent injuries enhance performance (PEP) program, which is designed to be incorporated into a warm-up for soccer athletes, while our intervention was 4 weeks and used exercises developed from our own pilot work and clinical experience. The focus of attention instructions in their study were given by a coach during warm ups prior to practice. The ExFOCUS instructions mostly related to movement relative to cones or other stationary objects in the surrounding environment. The instructions in our study were delivered by a clinician in a controlled research laboratory while the actual feedback came from the laser or auditory devices. Despite the considerable methodological differences and inherent difficulties comparing the two studies, the inconsistent findings suggest future work is necessary to determine the optimal mode and duration of ExFOCUS intervention to reduce knee injury risk.

Previous investigators have also reported reductions in vGRF during landing after ExFOCUS cueing.[131] Specifically, the authors found that when instructing participants to use the sound of their landing to land more softly on subsequent landings, the vGRF was reduced compared to a control group receiving no feedback on their landing performance. It is possible, therefore, that changing the instruction from landing so the buzzers do not make a sound to more directly inform participants to use the feedback of the buzzers to change their next strategy on the next landing may have yielded different results.

5.1.2 Cuts

There was significantly more hip flexion observed in the dominant limb compared to the non-dominant while comparing the InFOCUS and ExFOCUS combined groups as well as when comparing the visual and auditory ExFOCUS groups. Landing with less hip flexion has been associated with increased knee loading in both the sagittal and frontal planes.[57] In fact a study from Pollard et al. found that participants who exhibited low hip and knee flexion angles during a landing displayed increased knee valgus angles and may be at an increased risk of ACL injury.[132] This may be a result of hamstring torque increasing with the increase in hip flexion angle. As was found by Guex et al., as hip flexion increases, hamstrings peak torque and hamstrings-to-quadriceps ratio increases.[133] The greater the ratio of hamstrings-to-quadriceps torque the greater their ability to provide stability to the knee and decrease ACL loading.[134]

A commonly observed component of non-contact ACL injuries is a shallow knee flexion angle (i.e., < 20° of knee flexion).[13] The non-dominant limb displayed greater knee flexion angles in both the comparison of the InFOCUS and combined ExFOCUS groups and when comparing the two ExFOCUS groups regardless of feedback or time. However, both limbs had greater than 20 degrees of knee flexion during the landing phase of the cutting task suggesting that neither limb was at an elevated risk of sustaining a non-contact ACL injury based on the knee flexion angle.

The non-dominant limb experienced greater knee extension moments relative to the dominant limb. Data were extracted at the instant of peak vGRF, which occurs during the first half of the stance phase of landing. During this early period of landing, the individuals were flexing their knees. When the knee is flexing during landing, the quadriceps fire eccentrically to protect against excessive flexion and ensure the individual can remain upright to complete the cutting task. Since the non-dominant limb demonstrated greater knee flexion angles, it makes sense that the quadriceps would be firing more (greater knee extension moment) to counter the knee flexing compared to if the knee was less flexed. Colby et al. investigated quadriceps muscles activation patterns during the eccentric motion of sidestep cutting in collegiate athletes and found that quadriceps muscle activation peaks in mid-eccentric motion.[135] So it is possible that the kinetic values recorded were post peak knee flexion and during the transition to knee extension.

Both the hip and knee of the non-dominant limb were abducted while the dominant limb's hip and knee were adducted. Correlations have been found between higher knee abduction moments and wider cutting angle, such that a decrease in cutting angle was associated with a decrease in knee abduction.[136] While cut width was not recorded in our study it is possible that when completing the cutting task with the non-dominant limb the participants used a wider cutting angle and a shallower angle when completing the task with the dominant limb. Hip abduction angles have been shown to increase with increases in knee abduction moments.[137] The abduction of the hip will work to counter the strain put on the ACL by the knee abduction by stopping the limb from going into a dynamic valgus position.

It has been postulated that the mechanism of ACL injury in regards to the knee joint is multiplanar,[138] this highlights the importance of reducing multiplanar knee joint loading during high risk activities such as sidestep cutting. When comparing the InFOCUS group with the combined ExFOCUS groups knee abduction torque was found to be greater in the non-dominant limb compared to the dominant limb. Knee abduction combined with other high risk factors is commonly a predictor of future non-contact ACL injury.[60] Though this difference was significant in regards to our study, the magnitude of abduction torque was not enough to be considered high risk.

While no cutting tasks were explicitly trained during the intervention there has been evidence of transference occurring between functional movements post intervention. A study by Benjaminse et al. found sidestep cutting biomechanics improved after participants were provided ExFOCUS feedback during an intervention made up exclusively of drop vertical jumps.[139] Contrary to these findings our study found kinetic and kinematic differences between limbs regardless of feedback or time point but no significant changes occurred as a result of the intervention. One possible explanation for these different findings is the number of exercises and feedback used during the intervention. The Benjaminse[139] study trained only jump landings during their intervention and the ExFOCUS feedback used instructed participants to “push yourself as hard as possible off the ground after landing on the force plate” whereas our study made use of novel devices to give the participants real time feedback during four different exercises. It is possible that the lack of results found in our study were a product of too many exercises coupled with novel feedback tools. Future studies may see more significant results by limiting the number of exercises when using novel feedback devices.

Another possible explanation is that participants self-selected the speed at which they performed the cutting task. While speed was consistent across trials (within 5% of baseline) for each participant, cutting speed was not standardized. This self-selected pace may have permitted additional time to safely prepare and execute the movement task. Elevated ACL injury risk body postures have been observed when the speed of a task increases.[137,140] Therefore, when participants self-selected the speed at which they performed the task it may have allowed them to execute the maneuver safely. Due to the participants not presenting with high risk biomechanics at baseline, there was minimal room for post-intervention improvement.

5.2 Landing Error Scoring System

LESS scores decreased from baseline to 4WK regardless of group allocation. However, when only the ExFOCUS groups were considered, there were no differences, suggesting that the decrease in LESS scores was driven by changes in the InFOCUS group. Further exploration of our data confirm that the InFOCUS group demonstrated a 2.5-point decrease in LESS scores from the beginning to end of the study, bringing the group average score below 5. This is important as LESS scores below 5 suggest the individual is not at risk of sustaining an ACL injury.[121] Goodman and Wood found that starting with a greater amount of feedback and decreasing the level over time does not lead to better transfer of training.[141] It is possible that our study may benefit from altering the volume of feedback as the participant progresses through the intervention.

Participants were not screened for risk prior to inclusion in the study and baseline LESS scores for all groups were very close to threshold. Thus, there was minimal room for improvement. Future studies may want to screen for risk prior to inclusion.

5.3 Patient Reported Outcomes

Both aims saw significant changes across timepoints regardless of group on the Marx Activity Scale. The Marx is used to subjectively evaluate physical activity level. While typically used for persons with knee disorders, the increase in self-reported physical activity level among our participants suggests that simply participating in our injury risk reduction program increased their perceived activity level. This increase in activity level may benefit the participants as regular physical activity has been linked to the prevention of several chronic diseases.[142] However, it should be noted that self-reports of activity levels have been shown to be overestimated compared to objective measures;[143] thus, it is possible that our participants were not any more active than they were at the beginning of the study despite the increased Marx Activity Scale scores.

The changes observed in PROMIS scores when comparing the InFOCUS group with the combined ExFOCUS groups from baseline to 4WK fall within the range (2-3 points) of what previous research has found to be clinically meaningful.[144] While the change from BL to 1 WK did not fall within this range it was still found to be significantly different. Even a minimal reduction in PROMIS scores may still be beneficial to the participants' overall quality of life.

The Lysholm Knee Scoring Scale is used to assess knee instability, impairments and limitations associated with knee disorders. Lysholm scores ranging from 91 to 100 points are considered excellent[145] and all groups fell within this range at all time points. Despite this, and in spite of the fact that all participants were healthy, there was still a significant decrease in Lysholm scores from baseline to 1WK when the auditory and visual ExFOCUS groups were being compared. While the difference was statistically significant it did not meet the established minimum detectable change of 8.9[146] and therefore should not be taken as a sign that the intervention caused knee instability. A variance in score of this magnitude may be the result of the objective nature of some of the questions in the survey.

5.4 Limitations

We acknowledge there were limitations in this research. To begin, frequency and timing of feedback may have played a role in the lack of significant changes observed in the ExFOCUS groups. Some studies have suggested the need for feedback withdrawal so that the learner can develop an internal movement representation and later (during retention testing) they can draw from said representation.[147,148] While other studies have found that continuous feedback may not benefit in the learning and transfer of desired movements.[149] Ultimately an ideal volume of feedback has yet to be established.

Next, all dependent variables were recorded at the instant of peak vGRF. Previous studies have found that this is the time point at which the ACL is under the greatest strain and the majority of non-contact ACL injuries occur.[150] However, analyzing biomechanical data at a discrete time point does not allow us to understand the biomechanics that presented from initial ground contact until the foot leaves the ground. Thus, it is possible that there were unobserved biomechanical changes throughout the rest of the stance phase. Therefore, future studies may benefit from reporting biomechanical variables during multiple time points throughout or during the entirety of the landing phase. Additionally, the speed of some of the exercises may be too quick for the participants to process the feedback. Specifically, the laser movements during the drop landings may have occurred too quickly. A study from Shelton et al. found that the average reaction time to a visual stimulus is 331 milliseconds,[151] while it takes just 247 milliseconds to contact the ground when dropping from a 30 cm box. However, since the time from movement initiation to ground contact was not recorded, we cannot be sure whether participants had sufficient time to process the feedback or not. Regardless, future studies may benefit from the use of other, slower-paced exercises that have been shown to reduce ACL injury risk that will still allow for the use of the cross-hair laser. Finally, there may be other limitations that we have yet to identify.

5.5 Conclusion

The lack of significant differences in biomechanics between groups receiving different modes of feedback (internal focus of attention and external focus of attention) or between visual and auditory external focus of attention do not support previous studies that demonstrate the efficacy of various modes of feedback in modifying injury risk biomechanics. Nonetheless, our findings revealed statistically significant limb asymmetries regardless of feedback or time point. Additionally, we observed changes in LESS scores and patient-reported outcomes after the intervention, regardless of the mode of feedback. These results suggest that applying different modes of feedback during different exercises or in individuals with pre-existing “at risk” biomechanics at baseline may potentially return different results. Furthermore, the study emphasizes the importance of screening for limb asymmetries and modifying interventions to address any identified discrepancies.

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APPENDIX A: IRB 21-0283

UNIVERSITY OF NORTH CAROLINA
CHARLOTTE

Department of Applied Physiology, Health, and Clinical Sciences
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Consent to Participate in a Research Study

Title of the Project: External Focus of Attention Feedback to Reduce Risk of Non-contact ACL Injury

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Study Sponsor: UNC Charlotte Faculty Research Grant

You are invited to participate in a research study. Participation in this research study is voluntary. The information provided is to help you decide whether or not to participate. If you have any questions, please ask.

Important Information You Need to Know

- The purpose of this study is to determine how different forms of feedback about your movement influence the way that you land from a jump. This information will help researchers determine the best way to reduce risk of knee injuries, such as ACL tears.

- We are asking 70 healthy adults with no history of knee injuries to participate in this study to determine how to reduce the risk of tearing an ACL. Participants will be both males and females ages 18-35 years. Participants will report to the lab for testing on 3 occasions, baseline and 1- and 4-weeks after an intervention. The intervention will last for 4 weeks. The experiment will include completion of an online survey, undergoing a biomechanical assessment while you jump from a 30cm box, and performing a series of hopping tasks. Interventions will consist of receiving feedback about the way you squat, step off a box, and land from a jump. Your total duration of participation will be 1.5 hours per testing session and 30 minutes per intervention session.

- During this experiment, you may be asked to wear:
  - Stickers placed on your skin and clothes to help us identify and track your body segments while you perform the biomechanical assessment.
  - A device in your shoe or attached to your knee to provide visual or auditory feedback about your movements. These devices will not do anything to you.

- Please read this form and ask any questions you may have before you decide whether to participate in this research study.

Why are we doing this study?

The purpose of this study is to determine how different forms of feedback about your movement influence the way that you land from a jump. We will also determine how your brain responds to the feedback you receive and if this has any influence on your movement. All of the information we collect will help researchers determine the best way to reduce risk of knee injuries, such as ACL tears.

Why are you being asked to be in this research study.

You are being asked to be in this study because you are between the ages of 18-35 years and you are a healthy adult without a history of knee injury. Additionally, you are eligible to participate if you have a body mass index $<40 kg/m^2$ and exercise 3 or more days per week for at least 30 minutes at a time.

No participant may have: 1) ever broken a bone in your leg/foot; 2) ever had surgery on your legs/feet; 3) ever torn their ACL, meniscus, or collateral ligament in either knee; 4) sprained an ankle in either limb; or 5) sustained any musculoskeletal injuries in the previous 6 months. No participant may have: a history of concussion or other neurological disorder that can influence data collection; impaired balance; or inability to consistently comprehend and repeat back directions regarding details of the study. Finally, you may not be a current smoker.

What will happen if I take part in this study?

If you choose to participate in this study, you will be asked to report to the Biodynamics Research Laboratory at UNC Charlotte on 3 occasions for testing and 12 occasions for interventions. Testing sessions will take place at baseline and 1-, and 4- weeks after the intervention. Interventions will last 3 days/week for 4 weeks. Testing sessions last approximately 1.5 hours, while intervention sessions last approximately 30 minutes. Below, you will find more information about each type of visit.

Testing Sessions:

Survey completion: You will be asked to complete an electronic survey at each testing session. The survey will ask questions about your knee function and physical activity levels. This will take approximately 5 minutes to complete.

Strength assessment: You will have your thigh muscle strength assessed by sitting in a chair with your hips and knees bent to 90 degrees. You will perform a series of continuous motions to straighten and bend your knee. You will begin with one set of warm-up contractions each at 25, 50, and 75% of your maximal ability. Next, you will perform a set of 5 maximal effort movements in each direction. The investigators will give you verbal encouragement to help you put forth your maximal effort.

Functional performance assessment: This will consist of a battery of 4 hop tests and a vertical jump.

- Single-leg forward hop: You will stand with your toe at the 0cm mark on a tape measure secured to the floor. You will jump forward, taking off of and landing on the same, single, limb on the tape measure. The distance you jumped will be recorded. You will perform this test 2 times per leg and it will take approximately 3 minutes to complete.
- Crossover hop: You will stand with your toe at the 0cm mark on a tape measure secured to the floor. You will jump forward, taking off of and landing on the same, single limb but on the opposite side of the tape measure. You will perform this task until you have completed 3 hops, crossing over the tape measure with each hop. The distance you jumped will be recorded. You will perform this test 2 times per leg and it will take approximately 3 minutes to complete.
- Triple hop: You will stand with your toe at the 0cm mark on a tape measure secured to the floor. You will jump forward, taking off of and landing on the same, single limb on the same side of the tape measure. You will perform this task until you have completed 3 hops. The distance you jumped will be recorded. You will perform this test 2 times per leg and it will take approximately 3 minutes to complete.
- 6m timed hop: You will stand with your toe at the 0cm mark on a tape measure secured to the floor. You will jump forward completing as many hops on a single limb as necessary to cover a distance of 6m. The time it takes you to complete this task will be recorded. You will perform this test 2 times per leg and it will take approximately 3 minutes to complete.
- Vertical jump: You will stand with your arm outstretched over your head to determine the starting position for the measurement. You will jump up in the air as high as possible, touching the uppermost vane of the measurement device that you are capable of reaching. You will perform this task 2 times. It takes approximately 2 minutes to complete this task.

<u>Biomechanics and EEG assessment</u>: To assess biomechanics, you will have a series of retroreflective markers (Styrofoam balls) taped to your legs in specific spots. These markers allow us to record your motion in 3 dimensions. You will then perform a series of different tasks.

- Jump-landing. For this task, you will stand on top of a 30cm tall box located ½ of your height away from a force plate. The force plate allows us to measure how hard or soft you land. You will jump forward from the box, land on the force plate, and jump up in the air as high as possible. You will perform this test 20 times and it will take approximately 15 minutes to complete. The first 5 jump landing trials will be video recorded using GoPro cameras placed to the front and side of the force plates. These video recordings will be used to determine your clinical risk of sustaining an ACL injury.
- Cutting. For the cutting task, you will start behind the force plates and take a 4-step approach prior to landing with one foot. Immediately upon landing you will perform a 45-degree cut to the opposite side. The cutting task will be performed 5 times per leg and take approximately 10 minutes to complete.
- Electroencephalography (EEG) assessment. During this jump landing, you will have your brain activity and leg biomechanics assessed. To determine brain activity, we will use EEG. You will wear a cap similar to a swim cap on your head. Attached to this cap are electrodes. We will lightly abrade and clean your scalp before applying these electrodes to improve our data. Please note that the EEG electrodes will not do anything to you except record the electrical activity occurring in your brain.

<u>Intervention Sessions:</u>
All participants will complete the same injury prevention program for 12 treatment sessions over 4 weeks (3x/week). Exercises will be identical across groups with the only difference being the feedback provided. Which feedback you receive will be randomly determined.

- Internal focus of attention feedback will be provided by a mirror placed in front of you. You will watch your knee in the mirror and be instructed to "keep the knee in line with the toes" during all exercises.
- Auditory external focus of attention feedback will be delivered by two sensors placed in the shoes. Each sensor will be connected to a buzzer. Each buzzer will make a different sound when a certain amount of force is applied to its sensor. You will be instructed to move such that the buzzers make noise in a particular order.
- Visual external focus of attention feedback will be delivered via a cross-hair laser pointer secured to a strap wrapped around your thigh. The laser pointer will be oriented so that the lines on the crosshair form a plus sign on a wall in front of you. You will focus on the laser beam, making the crosshair go as far up on the wall as possible without it deviating to the side or rotating.

Prior to each intervention session, you will warm-up for 5 minutes at a self-selected pace on a stationary bike. For each intervention task, 6 sets of 6 repetitions will be completed. During the first week (sessions 1-3), you will complete single-limb squats and single-limb step-down exercises. On session 3, a new exercise will be added to the program, double-limb drop landing. In the second week (sessions 4-6), participants will complete single-limb squats, single-limb step-down, and bilateral-limb drop-landing exercises. Similar to the previous week, on session 6, you will complete a new exercise (single-limb drop-landing) in addition to the previous exercises. During week 3 (sessions 7-9) and week 4 (sessions 10-12), you will complete all previous exercises. Between intervention sessions, you will be asked to maintain activity level and not begin anything new or stop current activities.

- Single-leg squat: You will stand with hands on hips 2m away from a wall/mirror and lift one limb off the floor by bending the knee. You will lower yourself toward the ground and then rise back to the starting position. A 2-minute rest will be provided between sets.
- Single-leg step down: You will stand atop a 30cm box placed 2m from a wall/mirror. You will step off the box with the dominant limb, landing on the floor, and taking 2 additional steps as if coming down off the stairs or a curb. A 2-minute rest will be provided between sets.
- Double-leg drop landing. You will stand atop a 30cm box placed 2m from a wall/mirror. You will step off the box so that they land with each foot on the floor at the same time. A 2-minute rest will be provided between sets.
- Single-leg drop landing. This task is identical to the double-leg drop landing, you will land only on the dominant leg. A 2-minute rest will be provided between sets.

<u>What benefits might I experience?</u>
You will receive feedback on the way you perform the squat, step down, and landing tasks. However, we cannot and do not guarantee or promise that you will receive any benefits from this research.

<u>What risks might I experience?</u>
Likely risks:

- Knee pain or muscle soreness

Unlikely risks:

- Knee injury
- Loss of confidentiality
- The project may involve risks that are not currently known

<u>How will my information be protected?</u>
Any identifiable information collected as part of this study will remain confidential to the extent possible and will only be disclosed with your permission or as required by law.

The consent forms with signatures will be kept separate from the other information we collect, which will not have your name on them. All paperwork associated with this study will be kept in a locked filing cabinet in the Biodynamics Research Laboratory at UNC Charlotte. Only the investigators will have access to study-related paperwork. Any electronic data obtained during the study will not show your name but will have a code that will allow researchers to link the information to you. Electronic data will be stored in a password-protected folder on a password-protected computer. Only members of the investigative team will have access to the computer and folder. When the results of the study are published, participants' names will not be linked to the data.

How will my information be used after the study is over?

After this study is complete, study data may be shared with other researchers for use in other studies or as may be needed as part of publishing our results. The data we share will NOT include information that could identify you.

Will I be paid for taking part in this study?

You will receive $100 total in Amazon gift cards for completing this study. You will receive the gift card at the end of the 4-week follow-up session.

Incentive payments are considered taxable income. Therefore, we are required to give the University's Financial Services division a log/tracking sheet with the names of all individuals who received a gift card. This sheet is for tax purposes only and is separate from the research data, which means the names will not be linked to (survey or interview) responses.

What other choices do I have if I don't take part in this study?

This study is designed to learn ways to better prevent ACL injury. The alternative to participating in this study is not to participate.

What are my rights if I take part in this study?

It is up to you to decide to be in this research study. Participating in this study is voluntary. Even if you decide to be part of the study now, you may change your mind and stop at any time. You do not have to answer any questions you do not want to answer.

Who can answer my questions about this study and my rights as a participant?

For questions about this research, you may contact Dr. Abbey Thomas Fenwick (afenwick@uncc.edu), principal investigator.

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Office of Research Protections and Integrity at 704-687-1871 or uncc-irb@uncc.edu.

<u>Consent to Participate</u>

By signing this document, you are agreeing to be in this study. Make sure you understand what the study is about before you sign. You will receive a copy of this document for your records. If you have any questions about the study after you sign this document, you can contact the study team using the information provided above.

I understand what the study is about and my questions so far have been answered. I agree to take part in this study.

____
Name (PRINT)

____
Signature   Date

____
Name & Signature of person obtaining consent   Date

APPENDIX B: PATIENT REPORTED OUTCOME SURVEYS

ACL Risk Reduction PROs

Q1 The following pages contain a series of patient-reported outcomes surveys about your current physical activity level, quality of life, and knee function. Your ID number and testing session were provided to you in the email containing the link to this survey. Please copy those into the appropriate spaces below before continuing. You may save this survey and come back to it at a later time, but please try to complete all questions in the survey within 24 hours. If you have any questions, please let us know.

Q2 What is your study ID number? (NOTE: This is not your UNCC ID number)

Q3 For which testing session are you completing this survey?

○ baseline

○ 1-week post

○ 4-weeks post

MARX Scale

Q4 Please indicate how often you performed each activity in your healthiest and most active state, in the past year.

	Less than 1 time in a month	1 time in a month	1 time in a week	2 or 3 times in a week	4 or more times in a week
Running: running while playing a sport or jogging	○	○	○	○	○
Cutting: changing directions while running	○	○	○	○	○
Deceleration: coming to a quick stop while running	○	○	○	○	○
Pivoting: turning your body with your foot planted while playing sport; For example: skiing, skating, kicking, throwing, hitting a ball (golf, tennis, squash), etc.	○	○	○	○	○

PROMIS

Q27 Please respond to each of the following questions or statement by marking one selection per row.

	Excellent	Very good	Good	Fair	Poor
In general, would you say your health is	○	○	○	○	○
In general, would you say your quality of life is	○	○	○	○	○
In general, how would you rate your physical health?	○	○	○	○	○
In general, how would you rate your mental health, including your mood and ability to think?	○	○	○	○	○
In general, how would you rate your satisfaction with your social activities and relationships?	○	○	○	○	○
In general, please rate how well you carry out your usual social activities and roles. (This includes activities at home, at work and in your community, and responsibilities as a parent, child, spouse, employee, friend, etc.)	○	○	○	○	○

Q28 Please respond to each of the following questions or statement by marking one selection per row.

	Completely	Mostly	Moderately	A little	Not at all
To what extent are you able to carry out your everyday physical activities such as walking, climbing stairs, carrying groceries, or moving a chair?	○	○	○	○	○

Q29 In the past 7 days...

	Never	Rarely	Sometimes	Often	Always
How often have you been bothered by emotional problems such as feeling anxious, depressed or irritable?	○	○	○	○	○
How would you rate your fatigue on average?	○	○	○	○	○

Q30 In the past 7 days, how would you rate your pain on average?

- ◯ 0 (no pain)
- ◯ 1
- ◯ 2
- ◯ 3
- ◯ 4
- ◯ 5
- ◯ 6
- ◯ 7
- ◯ 8
- ◯ 9
- ◯ 10 (worst pain imaginable)

Lysholm Knee Questionnaire

Q18 Below are common complaints which people frequently have with their knees. Please answer every section and mark the ONE box which best describes you.

Q19 Limp

- ◯ I have no limp when I walk
- ◯ I have a slight or periodical limp when I walk
- ◯ I have a sever and constant limp when I walk

Q20 Support

- ◯ I do not use a cane or crutches
- ◯ I use a cane or crutches with some weight-bearing
- ◯ Putting weight on my hurt leg is impossible

Q21 Locking

- ◯ I have no locking and no catching sensation in my knee
- ◯ I have a catching sensation but no locking sensation in my knee
- ◯ My knee locks occasionally
- ◯ My knee locks frequently
- ◯ My knee feels locked at this moment

Q22 Instability

- ◯ My knee never gives way
- ◯ My knee rarely gives way, only during athletics or vigorous activities
- ◯ My knee frequently gives way during athletics or other vigorous activities; in turn, I am unable to participate in these activities
- ◯ My knee occasionally gives way in daily activities
- ◯ My knee often gives way in daily activities
- ◯ My knee gives way every step I take

Q23 Pain

- ◯ I have no pain in my knee
- ◯ I have intermittent or slight pain in my knee during vigorous activities
- ◯ I have marked pain in my knee during vigorous activities
- ◯ I have marked pain in my knee during or after walking more than 1 mile
- ◯ I have marked pain in my knee during or after walking less than 1 mile
- ◯ I have constant pain in my knee

Q24 Swelling

- ◯ I have no swelling in my knee
- ◯ I have swelling in my knee only after vigorous activities
- ◯ I have swelling in my knee after ordinary activities
- ◯ I have swelling constantly in my knee

Q25 Stair Climbing

- ◯ I have no problems climbing stairs
- ◯ I have slight problems climbing stairs
- ◯ I can climb stairs only one at a time
- ◯ Climbing stairs is impossible for me

Q26 Squatting

- ◯ I have no problems squatting
- ◯ I have slight problems squatting
- ◯ I cannot squat beyond a 90 degree bend in my knee
- ◯ Squatting is impossible because of my knee

International Knee Documentation Committee (IKDC) Subjective Knee Questionnaire

Q5 For all questions on this page, grade symptoms at the highest activity level at which you think you could function without significant symptoms, even if you are not actually performing activities at this level.

Q6 What is the highest level of activity that you can perform without significant knee pain?

- ○ Very strenuous activities like jumping or pivoting as in basketball or soccer
- ○ Strenuous activities like heavy physical work, skiing, or tennis
- ○ Moderate activities like moderate physical work, running, or jogging
- ○ Light activities like walking, housework, or yard work
- ○ Unable to perform any of the above activities due to knee pain

Q7 During the past 4 weeks, or since your injury, how often have you had pain?

- ○ 0 (never)
- ○ 1
- ○ 2
- ○ 3
- ○ 4
- ○ 5
- ○ 6
- ○ 7
- ○ 8
- ○ 9
- ○ 10 (constant)

Q8 If you have pain, how severe is it?

- ◯ 0 (no pain)
- ◯ 1
- ◯ 2
- ◯ 3
- ◯ 4
- ◯ 5
- ◯ 6
- ◯ 7
- ◯ 8
- ◯ 9
- ◯ 10 (worst pain imaginable)

Q9 During the past 4 weeks, or since your injury, how stiff or swollen was your knee?

- ◯ Not at all
- ◯ Mildly
- ◯ Moderately
- ◯ Very
- ◯ Extremely

Q10 What is the highest level of activity you can perform without significant swelling in your knee?

- ◯ Very strenuous activities like jumping or pivoting as in basketball or soccer
- ◯ Strenuous activities like heavy physical work, skiing, or tennis
- ◯ Moderate activities like moderate physical work, running, or jogging
- ◯ Light activities like walking, housework, or yard work
- ◯ Unable to perform any of the above activities due to knee pain

Q11 During the past 4 weeks, or since your injury, did your knee lock or catch?

- ◯ Yes
- ◯ No

Q12 What is the highest level of activity you can perform without significant giving way in your knee?

- ◯ Very strenuous activities like jumping or pivoting as in basketball or soccer
- ◯ Strenuous activities like heavy physical work, skiing, or tennis
- ◯ Moderate activities like moderate physical work, running, or jogging
- ◯ Light activities like walking, housework, or yard work
- ◯ Unable to perform any of the above activities due to knee pain

Q13 What is the highest level of activity you can participate in on a regular basis?

- ◯ Very strenuous activities like jumping or pivoting as in basketball or soccer
- ◯ Strenuous activities like heavy physical work, skiing, or tennis
- ◯ Moderate activities like moderate physical work, running, or jogging
- ◯ Light activities like walking, housework, or yard work
- ◯ Unable to perform any of the above activities due to knee pain

Q14 How does your knee affect your ability to:

	Not difficult at all	Minimally difficult	Moderately difficult	Extremely difficult	Unable to do
Go up stairs	○	○	○	○	○
Go down stairs	○	○	○	○	○
Knee on the front of your knee	○	○	○	○	○
Squat	○	○	○	○	○
Sit with your knee bent	○	○	○	○	○
Rise from a chair	○	○	○	○	○
Run straight ahead	○	○	○	○	○
Jump and land on your involved leg	○	○	○	○	○
Stop and start quickly	○	○	○	○	○

Q15 How would you rate the function of your knee on a scale of 0 to 10 with 10 being normal, excellent function and 0 being the inability to perform any of your usual daily activities which may include sports?

- ○ 0 (cannot perform daily activities)
- ○ 1
- ○ 2
- ○ 3
- ○ 4
- ○ 5
- ○ 6
- ○ 7
- ○ 8
- ○ 9
- ○ 10 (no limitation in daily activities)

Tampa Scale of Kinesiophopbia-11

Q17 This is a list of phrases which other patients have used to express how the view their condition. Please select the number that best describes how you feel about each statement.

	Strongly disagree	Somewhat disagree	Somewhat agree	Strongly agree
I'm afraid I might injure myself if I exercise	○	○	○	○
If I were to try to overcome it, my pain would increase	○	○	○	○
My body is telling me I have something dangerously wrong	○	○	○	○
People aren't taking my medical condition serious enough	○	○	○	○
My accident/problem has put my body at risk for the rest of my life	○	○	○	○
Pain always means I have injured my body	○	○	○	○
Simply being careful that I do not make any unnecessary movements is the safest thing I can do to prevent my pain from worsening	○	○	○	○
I wouldn't have this much pain if there wasn't something potentially dangerous going on in my body	○	○	○	○
Pain lets me know when to stop exercising so that I don't injure myself	○	○	○	○
I can't do all the things normal people do because it's too easy for me to get injured	○	○	○	○
No one should have to exercise when he/she is in pain	○	○	○	○