THE ASSOCIATION BETWEEN AUDITORY EXTERNAL FOCUS OF ATTENTIONAL FEEDBACK AND DROP LANDING BIOMECHANICAL RISK FACTORS OF ACL INJURY

by

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ABSTRACT

JERREL BUSHEL. The association between auditory external focus of attentional feedback and drop landing biomechanical risk factors of ACL injury. (Under the direction of ABBEY THOMAS FENWICK)

Introduction: Poor lower limb biomechanics during drop landing can increase the risk of anterior cruciate ligament (ACL) injury. Landing with decreased hip and knee joint flexion and increased vertical ground reaction force (vGRF) may place greater strain on the ACL and result in serious injury. External focus of attention has proven to yield better functional performance in the lower extremities during drop landing compared to internal focus of attention. Moreover, the use of auditory biofeedback (AudFB) during an external attentional focus-based exercise intervention may be beneficial in producing biomechanical changes during drop landing tasks.

Objective: To determine the association between AudFB and changes in biomechanical risk factors associated with ACL injury.

Methods: Participants performed fifteen jump landing trials at baseline. Participants then completed 12 AudFB sessions over 4 weeks. During each session, participants completed 6 sets of 6 reps of each exercise on both limbs. New exercises were added throughout the progression of the program. Participants' jump landing biomechanics were retested 1week after the intervention. Biomechanical data were processed using a standard inverse dynamics approach and submitted to statistical analysis. Errors committed during the exercises were tracked throughout the 4 weeks and totaled across each limb for every exercise. The association between number of errors committed and changes in jump landing biomechanics were determined via Pearson Product Moment correlation analysis.

Results: There were significant associations between changes in left hip sagittal torque and total errors, total errors on the left leg, errors on DL landing, and total and left leg errors on the SL squat and SL step down. There was a significant association between change in right hip sagittal torque with the right leg errors on the SL step down. Change in left knee sagittal torque was associated with errors on right leg SL squat, while changes in right knee sagittal torque were associated with total errors, total errors on the right, errors on the right leg SL and DL drop landing, errors on the right leg SL step down, and the total and right leg errors on the SL squat. A change in right knee frontal torque was significantly associated with total errors on SL step down, and errors on DL drop landing. There was a change in left hip frontal rotation associated with errors on DL drop landing. A change in right knee sagittal rotation was significantly associated with errors on DL drop landing, and total and left leg errors on SL drop landing. Finally, there was a significant association between changes in left knee frontal rotation with total and right errors on SL drop landing. There were no significant associations between changes in vGRF with errors committed.

Conclusions: While AudFB yielded changes in lower extremity biomechanics, the changes presented were primarily to sagittal plane biomechanics and, as such, may not be sufficient to reduce ACL injury risk. The practical use of an AudFB device with the aim of improving drop landing biomechanics and reducing the risk of ACL injury may be valuable but warrants refinement.

DEDICATION

I would first like to dedicate this thesis to my parents, Geri, and Pierre Bushel, for their constant support and encouragement. They have bestowed confidence and determination upon me that has allowed me to reach this accomplishment. I would also like to dedicate this thesis to my sister who has been a tremendous role model and motivator for my hard work.

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LIST OF ABBREVIATIONS

ACL	Anterior cruciate ligament
ACLR	Anterior cruciate ligament reconstruction
AM	Anteromedial
ATT	Anterior tibial translation
AudFB	Auditory feedback
DL	Double leg
EF	External focus
H:Q	Hamstrings to quadriceps ratio
IF	Internal focus
L	Left
LCL	Lateral collateral ligament
LESS	Landing error scoring system
MCL	Medial collateral ligament
PCL	Posterior cruciate ligament
PL	Posterolateral
R	Right
ROM	Range of motion
SL	Single leg
T	Total
vGRF	Vertical ground reaction force

CHAPTER 1: INTRODUCTION

ACL injury has plagued sports with one of the highest incidence rates of all sports-related injuries. An estimate of 1 in 3500 athletes experience an ACL injury in their career, jeopardizing the integrity of their knee, athletic career and, ultimately, quality of life.[1, 2] ACL injuries are frequently observed in sports requiring cutting, jumping, and/or pivoting (basketball, soccer, and alpine skiing) and occur at a higher rate in females compared to males.[1, 2] ACL injuries may be attributable to poor neuromechanical control over the lower extremity leading to excessive dynamic knee valgus during landing or cutting. Dynamic knee valgus is a position of excessive hip adduction and internal rotation and knee abduction. When coupled with reduced knee flexion angle and increased ground reaction force, strain on the ACL is increased.[1, 3, 4] Over 70% of ACL injuries are noncontact, suggesting they may be prevented.

Preventing, or at least reducing the risk of, ACL injury is critical for several reasons. First, ACL reconstruction (ACLR) is the go-to method for most athletes that experience an ACL injury. In a single year in the US, there are about 200,000 ACLR surgeries, totaling more than $3 billion.[5] That is a substantial financial burden on the healthcare system. Second, patients who have sustained an ACL injury are at elevated risk of second ACL injury to the ipsilateral or contralateral limb, potentially leading to further surgery and healthcare costs.[6, 7] In a study on athletes who returned to high-risk sport after undergoing ACLR, the incidence rate of a second ACL injury was 15 times greater than that of a healthy individual.[8] Third, patients are at elevated risk of posttraumatic osteoarthritis development after ACL injury and subsequent reconstruction.

Specifically, 50% of patients will have radiographic evidence of knee osteoarthritis by the third decade after ACL injury regardless of treatment approach.[9]

Numerous injury risk reduction programs exist, yet the rate of ACL injury continues to rise. Common ACL injury risk reduction programs include components such as a dynamic warm-up, lower limb and trunk strengthening, and plyometric exercises.[10] Also common to many of these programs is feedback on movement errors. Providing participants feedback about what unwanted movements has been shown to be critical to improving biomechanics and reducing injury risk.[11] These programs, however, are mostly focused on internal attentional feedback. This flaw in current ACL injury risk reduction programs fails to optimize biomechanical and motor learning improvements.

Internal focus of attention occurs when an individual is given cues directing them to focus attention on their body movement to complete task.[12] For example, when instructed to perform a squat, the individual would be told to focus on full flexion and extension of their knee. While internal focus of attention-based training is capable of changing movement patterns such as reducing dynamic knee valgus angles and moments and vertical ground reaction force, once that feedback is removed movement patterns revert back to their pre-training form.[11, 13] In other words, changes in movement patterns are not retained. Unfortunately, time and resources are major barriers to administering these programs regularly enough to see improvements; thus, hindering ACL injury risk reduction.

Feedback can also be provided using an external focus of attention, defined as attentional focus beyond the body and on the surroundings or environment. For example, when performing a vertical jump, a participant may focus on pushing the floor away to move as close to the ceiling (or target) as possible. In contrast to internal attentional focus, external focus of attention has yielded benefits regarding retention of learned movements – hip and knee flexion angles, notably.[14, 15] As a result, external focus of attention is a powerful motor learning tool to incorporate into biomechanical retraining to reduce ACL injury risk.

As previously noted, learned movements such as, but not limited to, decreased hip and knee flexion angles, increased dynamic knee valgus, and increased vGRF are significant risk factors for increasing ACL loading during a drop landing.[16] Previous evidence suggests that AudFB may be a successful means of discouraging improper biomechanics throughout intervention training.[17, 18] Specifically, patients with chronic ankle instability demonstrated a medial shift in plantar pressure during functional movement after a two-week training session with an AudFB device placed on the plantar surface of the foot. In contrast, a recent study[19] conducted to determine both immediate and retained changes in biomechanics following similar AudFB compared to that of a visual biofeedback (VisFB) group found no significant differences in knee or hip joint kinematics, kinetics, or vGRF observed at the 4-week post-intervention session.[19] There was, however, a high variance observed in the AudFB group data, possibly due to the variable amount of feedback provided to participants individually. In other words, participants that performed the exercises more correctly (produced less errors) received less feedback from the device than those who performed the task less correctly and produced more errors. One consideration of this design is the tapered feedback as participants learn to produce less errors. Previous research suggests that as external focus of attentional feedback is given less frequently, individuals may begin to relapse into movements induced by an internal attentional focus.[20] Given the novelty of this specific AudFB strategy and the paucity of data using AudFB to reduce knee injury risk, we believe secondary analysis is needed to determine any association between number of errors produced and biomechanical changes and retention post intervention.

To address this gap in the literature, the purpose of this study was to determine the association between the number of errors committed during an AudFB-based intervention and the change in biomechanical measures associated with non-contact ACL injury risk. Primary outcomes of interest included changes from baseline to 1-week following the 4-week intervention in hip and knee frontal and sagittal plane joint angles and moments as well as vGRF during drop landing.

Hypothesis: A lesser number of errors (less times the AudFB device makes a sound) during the intervention sessions will be associated with greater changes in landing biomechanics.

CHAPTER 2: REVIEW OF RELATED LITERATURE

The purpose of this literature review is to detail the: 1) relevant anatomy and biomechanics of the knee joint; 2) mechanisms of non-contact ACL injuries; 3) current strategies of ACL injury risk reduction programs; and 4) basics of the focus of attention theories of motor control and motor learning.

2.1 Anatomy and Biomechanics of the Knee

The knee, or the tibiofemoral joint, is a complex joint composed of ligaments and supporting structures that assist with its movement and stability. The knee joint moves upon three different axes in the tibial shaft axis, the epicondylar axis, and the anteroposterior axis. The various movements around these axes include flexion and extension in the sagittal plane, internal and external rotation in the transverse plane, and abduction and adduction in the frontal plane.[21]

The ligaments in the knee provide support and stability by preventing excessive movement outside of the normal range of motion (ROM). First, the lateral collateral ligament (LCL) is located on the outside of the knee, originating from the epicondyle of the femur, and inserting at the head of the fibula. The LCL provides stability to the lateral side of the knee, preventing excess adduction movement of the knee. Second, the medial collateral ligament (MCL) is located on the inside of the knee, originating from the medial epicondyle of the femur, and inserting at the head of the tibia. The MCL provides stability to the medial aspect of the knee, preventing excess abduction movement of the knee. Additionally, the posterior cruciate ligament (PCL), originating from the posterior intercondylar portion of the tibia, extends anteromedially and inserts at the medial femoral condyle. The PCL prevents excess posterior movement of the tibia relative to the femur. Finally, the anterior cruciate ligament (ACL) originates from the lateral femoral condyle and attaches to the anterior intercondylar portion of the tibia. The ACL prevents excess anterior translation of the tibia and acts as secondary protection to internal rotation and abduction of the tibia.

With the purpose of this study being reducing the risk of noncontact ACL injury, the ACL will be focused on in its regards to the overall function of the knee. The ACL is composed of two functional bundles, determined by their insertion sites on the tibia — the anteromedial (AM) and posterolateral (PL) bundles.[22, 23] The AM bundle, sitting more vertically, becomes more engaged with the knee at 90° flexion, whereas the PL bundle, oriented more horizontally to the knee baseline, contributes more to joint stability as the knee is extended.[24] A vast understanding of the origin, insertion, and functions of the two ACL bundles is especially important regarding ACL reconstruction; it is also essential in determining best practice to prevent ACL injury.

Apart from the ligaments, the hamstring and quadricep muscle groups also provide support and stability to the knee during high-risk sports-related tasks. A significant imbalance in the ratio of hamstring strength to quadricep strength (H:Q) is considered to translate to higher risk of ACL injury.[25] The quadriceps muscle group is composed of the vastus intermedius, medialis, and lateralis, and rectus femoris. Inserting at the anterior portion of the tibia, dominance of the quadriceps muscle compared to the hamstring results in anterior translation of the tibia during high-risk tasks. Conversely, the hamstrings, composed of the semitendinosus, semimembranosus, and biceps femoris, provide counteracting force against anterior tibial displacement when dominantly active.[25]

2.2 Mechanism of Non-contact ACL Injury

The cohesiveness of the ACL bundles and surrounding muscles allow for stability in cutting, jumping, and pivoting tasks.[26] The ACL, however, is placed under stress during these tasks and when an individual applies greater force on the ligament than it can withstand, a partial or full tearing of the ligament fibers occurs. A few sports with the highest rates of ACL injury include basketball, football, and alpine skiing.[1] Individuals participating in competitive or recreational sports in the 15 – 25 year old age range are most at risk of sustaining an ACL injury, with an overwhelming majority characterized as a non-contact injury.[26] Non-contact injuries are defined as those occurring without contact from an opponent or surface causing the injury.[27] This young age range is particularly concerning due to the early onset of osteoarthritis and retirement from sport after ACL injury,[28] meaning these individuals are developing osteoarthritis and becoming less physically active at a younger age than their uninjured peers.

Studies testing the mechanism of non-contact injury have increased over the past decade, in efforts to better understand the inner workings of the ACL and risk factors during active movement. Anterior tibial translation (ATT) prevention is the primary function of the ACL. Studies conducted by Shoemaker and DeMorat[29, 30] found that quadricep muscle force has a significant impact on ATT and ACL strain/injury during flexion angles ranging from 0° - 45°.[31] Additionally, Herzog and Read[32] determined that with a decrease in knee flexion angle is an increase in ACL elevation angle, defined as the angle of the longitudinal axis of the ACL and posterior portion of the tibia.[31, 32]

Subsequently, an increase in ACL elevation angle results in greater ACL loading with an anterior force on the ligament.[31] These findings are directly translated to non-contact ACL injuries as athletes who tend to have small knee flexion angle during athletic tasks are at higher risk of sustaining an injury than those with a greater flexion angle. Female athletes have been shown to be at greater risk than their male counterparts starting at an earlier age.[26, 31] Generally, in a higher level of play, females were about five times more likely to sustain an ACL injury than males in the equivalent sport.[26] Additionally, females have shown a sharp increase in injury after age 13, as physical changes associated with puberty alter biomechanics and lead to less knee flexion during an ACL loading task (e.g., landing, cutting, etc.).[31]

Common in high level sports, landing and cutting maneuvers happen concurrently with rapid acceleration and deceleration. Rapid deceleration requires an athlete to suddenly stop their forward momentum, often resulting in decreased knee flexion angles and increased quadricep muscle activation.[33] During the landing portion of the deceleration, peak ground reaction force — the force exerted by the ground on a body in contact with it — occurs placing greater strain on the ligament.[31] This action alone, however, is not the sole cause of ACL injury, rather, when high-risk motions in multiple planes happen collectively.

Dynamic knee valgus, originally questioned on its effect on ACL loading and injury, has recently been reconsidered as a risk factor for non-contact ACL injuries. Knee valgus is a compound movement of the lower limbs, and a combination of hip adduction and internal rotation, knee abduction, and ankle eversion. A study conducted by Kristianslund *et al*[34] linked an increase in knee valgus to greater knee abduction moments during side-step cutting tasks. Larger moments place more stress on the ligament and increase the risk for ACL injury. Additionally, high school athletes' knee valgus and abduction angles were measured during a drop vertical landing-jump task. Results showed a greater peak knee valgus angle in ACL-injured athletes than their healthy counterparts, reinforcing a connection between knee valgus and ACL injury.[31, 35] Despite the clear understanding of the mechanism of ACL injury, more research is needed to affirm that greater knee valgus angle is a direct cause of ACL load and injury. It is understood, however, that various risk factors, including lower limb misalignment and decreased knee flexion angle during ACL loading tasks, are primary mechanisms of injury. Knowing this, appropriate interventions can be applied to athletes to correct these aberrant biomechanics and reduce the risk of ACL injury.

2.3 Non-contact ACL Injury Risk Reduction

The reliability and effectiveness of various ACL injury risk reduction interventions including plyometric exercises, static stretching, and the LESS test in injury prevention programs have been circulating in the literature. First, plyometric exercise training has proven to increase athletic performance as it relates to ACL injury risk during jumping, cutting, and deceleration. A review conducted by Al Attar *et al*[36] reviewed nine studies in a variety of countries measuring ACL injuries after delivery of exercise interventions with built-in plyometric exercises. The pooled data for non-contact ACL injuries reported a 66% per 1000 hours of exposure injury reduction compared to their respective control intervention (no plyometric exercises). In addition, static stretching and balance training may reduce and increase the risk of injury, respectively. Taylor *et al*[37] suggests a potential risk reduction with longer and increased focus of static stretching in injury prevention programs. However, it should be noted that the benefits of balance training and stretching are inconclusive when other studies are considered.[38-40] Overall, the key component of ACL injury risk reduction programs is their ability to reduce dynamic knee valgus during specific high-risk tasks that athletes commonly experience in sports.[41]

Over time three-dimensional (3D) motion systems have allowed researchers to study the biomechanical mechanisms of ACL injury; more precisely than two-dimensional (2D) motion analysis.[42] Traditionally, researchers assess 3D biomechanics before delivering an injury prevention program to determine risk, and after to determine program success. These 3D capture systems, however, are a huge limitation from a clinical perspective as they are costly and require time consuming data tracking/analysis. A reliable alternative is the Landing Error Scoring System (LESS) test. The LESS test assesses irregularities or "errors" during a drop vertical jump landing task to identify individuals at high risk of non-contact ACL injuries. Individuals that score higher on the LESS test are associated with greater ACL loads due to decreased knee and hip flexion angles and increased dynamic knee valgus.[43] The LESS test as a non-contact ACL injury risk screening tool has great potential in combination with prevention programs to assess the biodynamics of athletes' in-game movements.

2.4 Internal and External Focus of Attention

Despite the reported success of existing ACL injury risk reduction programs, injuries continue to occur. In fact, ACL injury rates reportedly rose, particularly among the most vulnerable population of adolescent females.[44] As researchers and clinicians search for ways to reverse this trend, emphasis has turned toward providing feedback on movement errors made during training to change biomechanics more optimally at the end of an injury risk reduction program. Internal focus (IF) and external focus (EF) of attention, notably, have been shown to have a positive influence on body mechanics, performance, and motor learning.[12, 45, 46] More importantly, the two foci of attention have been compared to determine which has a greater effect on performance.

IF of attention can be described as the focus of one's attention on their own body and movements during a given task. IF of attention is most used by rehabilitation professionals, determined about 95% of the time during instructional cues.[47] IF of attention, however, has shown to be a less effective strategic learning method, specifically for motor skills in sports reintegration.[47] The limitation of an IF of attention is thought to be attributable to the constrained action hypothesis. This hypothesis suggests that the greater the space between one's body and the effect of the action, the greater learning advantages they will experience.[48] A study conducted by McNevin *et al* [48] found lesser enhanced learning results the closer the focus of attention was to the participant's body, reinforcing the constrained action hypothesis.

EF can be described as the focus of one's attention beyond the body, onto their surroundings or environment during a given task. With the use of external cues such as targets and markers, individuals may see an increase in functional performance and mechanics at the knee. A study testing EF and IF of attention on a single leg jumping for distance task resulted in a greater knee flexion angle on landing in the EF group compared to that of the IF group.[45] This indicates that the IF group demonstrated a stiffer landing, increasing the ACL load, and ultimately, posing a greater risk of ACL injury.

AudFB is a feedback strategy given with an EF-focused task. This mode of feedback produces an audible sound signifying unwanted movements. Previous studies of gait patterns have shown significant evidence in changes of knee flexion, external rotation, abduction, and adduction moments after the delivery of AudFB-based interventions.[18, 49, 50] Common methods of these studies utilize a sensor placed under the insole of the participants shoes. The sensor, measuring plantar pressure, was connected to a buzzer that was calibrated to produce a loud noise when excessive pressure was applied.[17, 18, 51] Such studies demonstrate promising evidence to change the lower extremity movements associated with ACL injury.

EF of attention is a considerable method to conduct jump-landing tasks as it may yield positive results in knee mechanics and motor learning. By utilizing this method of instruction, clinical professionals can teach effective practices in order to prevent a primary ACL injury.

CHAPTER 3: METHODS

3.1 Participants

Fifteen healthy adults between the ages 18 and 35 with no history of knee injury were recruited to participate in this study. Individuals from the University of North Carolina at Charlotte (UNC Charlotte) and surrounding communities were recruited. Participants were eligible if they have a body mass index (BMI) of <40 kg/m^2 and exercise for at least 30 minutes 3 days a week. An individual was ineligible to participate if they had one of the following: 1.) History of a broken bone in their leg or foot 2.) History of surgery in either leg or foot 3.) History of torn an anterior cruciate ligament (ACL), meniscus or a collateral ligament in either knee 4.) History of sprained an ankle in either extremity 5.) History of sustained a musculoskeletal injury in the past 6 months 6.) History of concussion or neurological disorder that will hinder data collection, impaired balance, or inability to comprehend and repeat back instructions regarding the study 7.) Current smoker. One participant did not complete the intervention sessions and was not included in the analysis. All participants read and provided informed consent, and the study was approved by UNC Charlotte's Institutional Review Board.

3.2 Procedures

When recruited, participants reported to the Biodynamics Lab at UNC Charlotte for several sessions including a baseline, 4-week long intervention, and 1-week follow up. Baseline and 1-week follow-up sessions were identical with lower extremity biomechanics being recorded at each session.

3.2.1 Biomechanical Assessments

Participants began with a jump landing task where they were outfitted with 36 retroreflective markers (Styrofoam balls), placed on significant joints and landmarks of the body as follows: bilaterally over the acromioclavicular joints, anterior and posterior superior iliac spines, iliac crests, greater trochanters, distal femur, medial and lateral femoral epicondyles, tibial tuberosity, lateral shank, distal shank, medial and lateral malleoli, head of the 2nd metatarsal, base of the 5th metatarsal, dorsal navicular, and posterior calcaneus. Additional markers were placed on the sternum and spinous process of C7. Ten Vantage 5 (Vicon, Inc, Denver, CO) motion capture cameras were placed around the room to capture the participant’s movement and connected and synchronized with two adjacent 1000Hz Bertec force plates to measure vertical ground reaction force (Bertec Corp., Columbus, OH).

To perform the jump landing task the participant stood atop a 30cm tall box placed half of their height away from two force plates. The participant jumped down from the box landing with either foot on its respective force plate. Upon landing, the participant jumped straight up and landed onto the force plates in the same position. This task was repeated 15 successful times – a successful trial being one in which no markers fell off and the participant landed cleanly on the force plates.

The jump landing task was specifically chosen for this study in its relationship to non-contact ACL injury. There is significantly greater ACL loading and strain with improper technique during a jump landing as seen in many high-risk sports.[52] The jump landing task, coupled with 3D motion capture, has been established as the gold standard for assessing ACL injury risk and potential risk reduction.[53]

3.2.2 Intervention Sessions

After the baseline session, participants went through a series of 12 exercise intervention sessions over the span of 4 weeks (3x/week). Intervention exercises were consistent across each participant.

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 of the exercise were completed on each limb. During the first week (sessions 1-3), the participants completed single-limb squats and single-limb step-down exercises (Table 1). On session 3, a double-leg drop-landing exercise was added to the program. In the second week (sessions 4-6), the participants completed single-limb squats, single-limb step-down, and bilateral-limb drop-landing exercises. Similar to the previous week, during session 6, participants added a single-limb drop-landing exercise in addition to the previous exercises. During week 3 (sessions 7-9) and week 4 (sessions 10-12), the participant completed all previous exercises. Between intervention sessions, the participant was asked to maintain activity level and not begin anything new or stop current activities.

Table 1. Exercise Description.

Exercise	Start Position	Task	Cue Provided
Single-leg squat	Hands on the hips; 2m away from the wall	Lower hips toward ground and rise back to starting position	Keep your hands on your hips and squat down so the buzzers do not make a sound
Single-leg step down	Hands on hips; stand atop a box* placed 2m away from the wall	Step down, perform a light toe tap with one foot, and return to the start position	Keep your hands on your hips, step down, lightly tap your toe, do not let the buzzers on your stance leg foot make a sound

Table 1. Exercise Description (continued).

Double-leg drop landing	Hands on hips; stand atop a 30cm box placed 2m away from the wall	Drop down to the floor, landing on both feet at the same time	Keep your hands on your hips, drop down, land on both feet, do not let the buzzers make a sound
Single-leg drop landing	Hands on hips; stand atop a 30cm box placed 2m away from the wall	Drop down to the floor, landing on one foot	Keep your hands on your hips, drop down, land on one foot, do not let the buzzers make a sound

*box height was adjusted depending on participant height to equalize the complexity of the task

Auditory external focus of attention feedback was delivered during each exercise by a sensor placed under the great toe and calcaneus in each of the participant’s shoes. The placement of the sensors were chosen based on pilot data obtained on 5 participants that demonstrated these are the areas of peak pressure during landing. Landing on the great toe may correspond to increased dynamic knee valgus and landing on the heel may correspond to a heavy, stiff-legged landing; both of which are associated with increased ACL injury risk. The two toe sensors were connected to identical buzzers and the two calcaneus sensors connected to a different pair of identical buzzers. The threshold of each buzzer was adjusted each session to not go off if weight is distributed evenly, but to elicit a sound if weight is not evenly distributed. The participant was instructed to move such that the buzzers do not make a sound.

Every time the buzzers made a sound, the investigator delivering the intervention made a tally mark on the participant’s intervention log. The total number of errors made by each participant was quantified by counting all of the tally marks across all intervention sessions for each participant.

3.3 Data Processing

Biomechanical data was processed using a standard inverse dynamics approach. Briefly, a static recording was captured of the participant standing in a T-pose, from which a 3D biomechanical model was generated in Visual3D (C-Motion, Inc., Germantown, MD, USA). Joint rotations will be calculated in Visual3D using a Cardan rotation sequence and expressed relative to each participant's static trial. Kinetic data was smoothed using a 4th order, zero lag, low-pass Butterworth filter with a 12Hz cutoff frequency. Following initial processing, peak sagittal and frontal plane hip and knee angles and moments as well as vertical ground reaction force (vGRF) was determined because of their previous association with the risk of non-contact ACL injury. These variables were extracted as the peak value 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.[54] Initial contact and toe off was defined as the point at which the vertical ground reaction force exceeds and falls below 10 N upon landing from a jump and rebounding for maximum height.[55] Joint moments were reported as external moments. All joint moments were normalized to each participant's mass and height (Nm/kg·m). The outcome measures of interest were averaged over 3 trials.

3.4 Statistical Analysis

Dependent variables for analysis were changes in biomechanical outcomes of interest (sagittal and frontal plane hip and knee angles and moments as well as vGRF during landing) from baseline to 1-week follow-up. Independent variables for analysis were the number of errors per limb made during the single leg squat, step down, and single leg landing; the number of errors made during the double leg landing; total errors made on each limb (sum of all errors made by a single limb across all single leg tasks for that limb); and the total number of errors (sum of all errors made for each limb during single leg tasks plus all errors made during double leg tasks). The association between errors made and change in biomechanics (post – baseline) was determined using a Pearson Product Moment Correlation. Statistical analysis was conducted using SPSS. Alpha level was set at <0.05 for all analyses.

CHAPTER 4: RESULTS

Participant demographic data are located in Table 2. The change in left hip sagittal torque was associated with total errors (P=0.018), total errors on the left leg (P=0.014), errors on DL landing (P=0.046), and total and left leg errors on the SL squat (total: P=0.022; left leg: P=0.007) and SL step down (total: P=0.049; left leg: P=0.008; Table 3). No other significant changes in left hip sagittal torque associated with errors were present. A significant change in right hip sagittal torque was associated with the right leg errors on the SL step down (P=0.026; Table 3). No changes in right hip sagittal or left and right hip frontal torque associated with errors on any tasks were present.

Table 2. Participant Demographics

Age (yrs.)	Height (m)	Body Mass (kg)	Sex	Dominant Limb
21.80±2.80	1.71±0.07	64.72±7.93	n=9 male, n=6 female	n=2 left, n=13 right

A change in left knee sagittal torque was associated with errors on right leg SL squat (P=0.044; Table 3). No other significant change in left knee sagittal torque associated with errors on any other tasks was present. However, a change in right knee sagittal torque was associated with total errors (P=0.013), total errors on the right leg (P=0.004), errors on the right leg SL and DL drop landing (right SL: P=0.030; DL: P=0.009; Table 3), errors on the right leg SL step down (P=0.033), and the total and right leg errors on the SL squat (total: P=0.030; right: P=0.006; Table 3). No other significant change in right knee sagittal or in left knee frontal torque associated with errors was present. A change in right knee frontal torque was associated with total errors on SL step down (P=0.047), and errors on DL drop landing (P=0.045; Table 3). No additional change in right knee frontal torque associated with errors on any other tasks was present.

Table 3. Results of correlation analysis for joint kinetics during landing.

		Torque							
		Hip Sagittal		Hip Frontal		Knee Sagittal		Knee Frontal	
		L	R	L	R	L	R	L	R
SL Squat L	r	0.661	0.022	0.313	0.297	-0.059	-0.225	0.023	-0.334
	P	**0.007***	0.938	0.256	0.283	0.835	0.421	0.934	0.224
SL Squat R	r	0.311	-0.452	0.274	0.324	-0.525	-0.678	-0.305	-0.305
	P	0.259	0.091	0.323	0.239	**0.044***	**0.006***	0.270	0.269
SL Squat T	r	0.584	-0.273	0.356	0.378	-0.366	-.560*	-0.179	-0.388
	P	**0.022***	0.325	0.192	0.164	0.180	**0.030***	0.524	0.153
SL Step L	r	.652	0.083	0.364	0.357	-0.136	-0.277	0.175	-0.478
	P	**0.008***	0.769	0.182	0.192	0.629	0.318	0.534	0.071
SL Step R	r	0.214	-0.571	0.238	0.295	-0.421	-.553	0.002	-0.401
	P	0.444	**0.026***	0.393	0.286	0.118	**0.033***	0.996	0.139
SL Step T	r	0.517	-0.281	0.358	0.386	-0.326	-0.487	0.106	-0.521
	P	**0.049***	0.310	0.191	0.155	0.236	0.065	0.707	**0.047***
DL Landing	r	0.522	-0.364	0.359	0.383	-0.192	-.648	0.032	-0.524
	P	**0.046***	0.182	0.188	0.159	0.493	**0.009***	0.909	0.045*
SL Land L	r	0.389	-0.172	0.112	0.115	-0.029	-0.305	0.080	-0.134
	P	0.152	0.539	0.690	0.682	0.919	0.268	0.777	0.634
SL Land R	r	0.470	-0.043	0.358	0.382	-0.324	-.560	-0.297	-0.336
	P	0.077	0.879	0.190	0.160	0.239	**0.030***	0.282	0.221
SL Land T	r	0.480	-0.119	0.265	0.280	-0.200	-0.486	-0.125	-0.264
	P	0.070	0.673	0.339	0.312	0.474	0.067	0.656	0.341
Total L	r	0.618	-0.058	0.272	0.266	-0.077	-0.319	0.105	-0.327
	P	**0.014***	0.838	0.326	0.337	0.785	0.246	0.708	0.235
Total R	r	0.421	-0.344	0.356	0.402	-0.475	-0.692	-0.260	-0.403
	P	0.118	0.209	0.193	0.137	0.074	**0.004***	0.350	0.136
Total	r	0.600	-0.278	0.375	0.400	-0.297	-0.624	-0.060	-0.465
	P	**0.018***	0.316	0.168	0.140	0.282	**0.013***	0.831	0.080

L= left leg; R= right leg; T=total when errors on left and right limbs were added; SL= single leg; DL= double leg; r= Pearson r value; *=statistically significant at $P<0.05$

No changes in left or right hip sagittal rotation associated with errors was present. However, a change in left hip frontal rotation was associated with errors on DL drop landing (P=0.016, Table 4). No change in left hip frontal, right hip frontal, or left knee frontal rotation associated with errors was present. A change in right knee sagittal rotation was associated with errors on DL drop landing (P=0.022), and total and left leg errors on SL drop landing (total: P=0.028; left: P=0.033; Table 4). No change in right knee sagittal rotation associated with errors in any other tasks was present. A change in left knee frontal rotation was associated with total and right errors on SL drop landing (total: P=0.028; right: P=0.023; Table 4). No other change in left knee frontal or right knee frontal rotation associated with errors was present.

Table 4. Results of correlation analysis for joint rotation during landing.

		Rotation							
		Hip Sagittal		Hip Frontal		Knee Sagittal		Knee Frontal	
		L	R	L	R	L	R	L	R
SL Squat L	r	-0.289	-0.310	-0.240	0.021	0.199	0.207	-0.142	0.232
	P	0.296	0.261	0.389	0.941	0.478	0.458	0.613	0.406
SL Squat R	r	0.163	0.330	-0.109	-0.106	0.316	0.142	0.255	0.317
	P	0.562	0.230	0.698	0.707	0.251	0.614	0.359	0.250
SL Squat T	r	-0.066	0.027	-0.209	-0.055	0.316	0.211	0.078	0.336
	P	0.814	0.924	0.454	0.846	0.251	0.450	0.783	0.221
SL Step L	r	-0.220	-0.276	-0.375	0.045	0.195	0.227	-0.221	0.259
	P	0.432	0.319	0.168	0.872	0.486	0.416	0.428	0.352
SL Step R	r	0.437	0.417	-0.166	-0.072	0.191	0.168	0.098	0.428
	P	0.104	0.122	0.555	0.799	0.495	0.548	0.730	0.112
SL Step T	r	0.121	0.075	-0.322	-0.014	0.228	0.234	-0.077	0.404
	P	0.668	0.789	0.241	0.960	0.413	0.400	0.786	0.135
DL Landing	r	0.232	-0.120	-.611	0.314	0.077	.586	0.428	0.453
	P	0.405	0.670	**0.016***	0.254	0.785	**0.022***	0.111	0.090
SL Land L	r	0.108	-0.322	-0.322	0.357	-0.039	0.553	0.428	0.479
	P	0.702	0.242	0.241	0.191	0.890	**0.033***	0.111	0.071
SL Land R	r	0.027	-0.053	-0.442	0.147	0.182	0.461	0.582	0.293
	P	0.923	0.850	0.099	0.600	0.517	0.084	**0.023***	0.289
SL Land T	r	0.075	-0.207	-0.428	0.279	0.082	0.565	0.565	0.429
	P	0.791	0.460	0.112	0.313	0.771	**0.028***	**0.028***	0.111
Total L	r	-0.102	-0.354	-0.364	0.210	0.103	0.429	0.112	0.407
	P	0.718	0.196	0.182	0.453	0.715	0.111	0.691	0.132
Total R	r	0.201	0.205	-0.325	0.023	0.260	0.347	0.428	0.392
	P	0.473	0.463	0.237	0.934	0.350	0.205	0.112	0.148
Total	r	0.108	-0.096	-0.471	0.188	0.181	0.502	0.356	0.476
	P	0.702	0.732	0.076	0.502	0.518	0.056	0.193	0.073

L= left leg; R= right leg; T=total when errors on left and right limbs were added; SL= single leg; DL= double leg; r= Pearson r value; *=statistically significant at $P<0.05$

No change in left or right vGRF associated with errors was present.

Table 5. Results of correlation analysis for vertical ground reaction force during landing.

		vGRF	
		L	R
SL Squat L	r	-0.131	0.399
	P	0.642	0.141
SL Squat R	r	-0.180	0.040
	P	0.521	0.887
SL Squat T	r	-0.190	0.259
	P	0.497	0.351
SL Step L	r	-0.060	0.178
	P	0.831	0.525
SL Step R	r	-0.197	-0.156
	P	0.482	0.579
SL Step T	r	-0.150	0.017
	P	0.593	0.952
DL Landing	r	-0.110	-0.061
	P	0.695	0.830
SL Land L	r	-0.111	0.349
	P	0.695	0.203
SL Land R	r	0.091	0.330
	P	0.748	0.229
SL Land T	r	-0.009	0.379
	P	0.975	0.164
Total L	r	-0.118	0.364
	P	0.676	0.183
Total R	r	-0.069	0.145
	P	0.806	0.607
Total	r	-0.113	0.207
	P	0.689	0.459

L= left leg; R= right leg; T=total when errors on left and right limbs were added; SL= single leg; DL= double leg; r= Pearson r value

CHAPTER 5: DISCUSSION

The aim of this study was to determine the association between a reduction in errors committed during an AudFB-based intervention and changes in biomechanical measures associated with non-contact ACL injury risk during a drop landing task. It was hypothesized that fewer errors (less times the feedback device made a sound) during the AudFB intervention sessions would yield greater improvements in biomechanical risk factors associated with non-contact ACL injury at the 1-week post-intervention follow-up session.

Contrary to our hypothesis, greater changes in hip sagittal plane torques were associated with more errors committed during exercises. The opposite effect was observed for changes in knee sagittal and frontal plane torque, however, with more errors committed being associated with greater changes in knee joint torque. To the best of our knowledge, only one other study has used auditory feedback to alter landing biomechanics.[56] In that study, participants were asked to listen to the sound of their own landing and use that information to land more softly. Participants in the auditory feedback group demonstrated a reduction in vGRF during landing following training. No other kinetic or kinematic data were reported. While the methods between our study and the previous are different, making it challenging to compare the results, it appears that AudFB may be beneficial in altering joint kinetics and its utility should continue to be explored.

Regarding joint kinematics, smaller hip frontal plane rotation changes were associated with more errors committed during exercise (DL landing, specifically), while changes in knee sagittal and frontal plane rotations were greater when more errors were committed during exercise. In terms of EF of attentional feedback on knee and hip kinematics, it is understood that utilizing external-focused feedback during exercise interventions is effective in providing changes and eliciting retention. Heinert et al. provided verbal and visual post-trial feedback to participants performing drop landing tasks in an attempt to reduce vGRF and knee to ankle ratio (a surrogate measure for knee valgus in drop landing).[57] Over the 4-week period, participants showed improvements in landing techniques, thus, less feedback was given and became more self-controlled. By the last week of the intervention, none of the participants was provided with verbal feedback. The authors reported significant changes in knee to ankle ratio at 17.2% from week 1 to week 4.[57] Additionally, Ericksen et al. demonstrated changes in peak hip flexion angles and peak knee flexion angles during drop landing when provided with traditional feedback + real-time feedback compared to traditional feedback alone.[58] Similarly, this study implemented a 4-week feedback-based exercise intervention where verbal (traditional) feedback and visual (real-time) feedback were provided. The real-time feedback + traditional feedback group demonstrated significantly greater changes in peak knee and peak hip flexion angles than the control group. No changes in frontal plane movements were reported. Despite the considerable differences in modes of feedback given of these studies and ours, it is apparent that EF is a capable means of producing kinematic changes during drop landing.

The AudFB device used in our study was intended to provide real-time feedback that would naturally taper throughout the intervention as the participants continued to improve and retain the learned movements. However, based on the presence of errors committed throughout all 12 sessions, it appears that all participants did not naturally taper their feedback. In fact, review of our data indicates that only approximately half of all participants naturally tapered their feedback as intended; though tapering or lack of tapering was consistent across exercises within individuals. Application of the same auditory feedback device in our laboratory during walking in patients with chronic ankle instability demonstrated that after 4 sessions of walking, patients were able to retain their learned gait pattern (i.e., they committed fewer errors and received less feedback during walking).[59] It seems the ability to taper feedback may be task specific (walking vs. squatting, stepping, or landing) as well as individual specific. The variable nature of the amount of feedback received may help explain why errors were inconsistently associated with biomechanical changes. An important consideration is the processing ability of the auditory cue relative to the speed of the intervention exercise task. We speculate that during the faster and more dynamic tasks (double and single leg drop landing) participants had minimal time to process and react to the sound of the buzzer; thus, they were unable to correct their movements in real-time. During these tasks, participants did not receive a feedback cue until the very end of the task (upon landing), essentially nullifying the real-time feedback aspect of the cue. It takes approximately 160ms to react to an auditory stimulus.[60] Even at that rate, if the individual is already making ground contact when the stimulus is triggered, then the individual cannot react in sufficient time to change their movement strategy for that repetition. As a result, the cue might have been used to internalize the unwanted movement and produce a different response on subsequent reps. Instead, auditory cues utilized in slower, methodical movements (walking) may be more beneficial in producing biomechanical changes.

Additionally, instructions targeted on an external environmental cue, such as a cone, where attention is directed further away from the body, may improve motor learning and task performance.[61] According to the "constrained action hypothesis", the closer an individual's focus on an effect is in proximity to their body, the higher degree of interference with natural control mechanisms of the body.[48] This suggests that providing an additional external visual cue further away from the body during intervention tasks may enhance learning and control of the task, and ultimately improve performance.

The AudFB device used in our study is a viable preliminary method in an effort to influence neuromuscular learning and reduce non-contact ACL injury risk. However, there are several comparative differences in similar studies assessing AudFB and EF of attentional feedback on changes in lower limb kinematics, thus further research is needed to determine optimal methods in order to maximize biomechanical changes.

5.1 Limitations

We acknowledge that there were limitations in this study. First, this study used a relatively small sample size of 15. A larger sample size may yield different results. Second, we did not assess neuromuscular changes after the intervention compared to before. Future research should study neuromuscular changes after an external focused intervention and the association with drop landing biomechanical changes. We also did not screen participants for risk of ACL injury prior to enrollment in the study. Thus, it is possible some participants experienced less biomechanical changes as they had less room for improvement. Another potential limitation was the sensor placements in participants' shoes. Although the sensor placements in our study were determined based on pilot testing, alternative strategies for sensor placement or instructing the participant to try to make the buzzer sound could be considered in future studies. Finally, all testing was conducted in a controlled lab environment. Extraneous factors an athlete may experience in his/her athletic environment may change the effectiveness of AudFB.

5.2 Conclusion

The AudFB device elicited changes in drop landing biomechanical measures in the sagittal plane, primarily, when utilized during a 4-week ACL injury risk reduction program. Our findings suggest that the practical use of an EF AudFB device may not be sufficient to reduce ACL injury risk. However, future research should investigate more effective uses for the device.

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APPENDIX A: IRB 21-0283

UNIVERSITY OF NORTH CAROLINA
CHARLOTTE

Department of Applied Physiology, Health, and Clinical Sciences

9201 University City Boulevard, Charlotte, NC 28223-0001

Consent to Participate in a Research Study

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

Principal Investigator:

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Avinash Narasimhan Jayakumar, Undergraduate Student, Department of Applied Physiology, Health, and Clinical Sciences, UNC Charlotte
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 <40kg/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 it. 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.

<u>How will my information be used after the study is over?</u>

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.

<u>Will I be paid for taking part in this study?</u>

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.

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

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

<u>What are my rights if I take part in this study?</u>

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.

Consent to Participate

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