IMMEDIATE EFFECTS OF EXTERNAL VS. INTERNAL FOCUS OF ATTENTION FEEDBACK ON LANDING BIOMECHANICS AND FUNCTIONAL PERFORMANCE IN INDIVIDUALS AFTER ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

by

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A thesis submitted to the faculty of
The University of North Carolina at Charlotte
in partial fulfillment of the requirements
for the degree of Master of Science in
Kinesiology

Charlotte

2019

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ABSTRACT

SEAN KRYSAK. Immediate Effects of vs. Internal focus of attention feedback on landing biomechanics and Functional performance in individuals after anterior cruciate ligament reconstruction. (Under the direction of ABBEY THOMAS FENWICK)

Introduction: More than 150,000 people each year undergo anterior cruciate ligament (ACL) reconstruction (ACLR) and associated rehabilitation in hopes of restoring knee joint stability and returning to sport. However, 25% of these individuals will go on to sustain a second ACL injury. The incidence rate of a second ACL injury is as high as 15 times that of someone who has never had an ACL tear. Postoperative rehabilitation is instrumental in the return to pre-injury strength, gait and functional performance. However, rehabilitation does not improve biomechanics, likely due to its reliance on an internal focus of attention. Both internal and external feedback methods are currently used to help patients return to sport, however implementation of the most effective feedback technique may be successful in lowering the rate of secondary injuries.

Objective: To quantify differences in biomechanics and functional performance following a single session of external focus of attention (ExFOCUS) versus internal focus of attention (InFOCUS) feedback in individuals after ACL-R compared to controls.

Methods: Ten adults were recruited to participate in this study (healthy n=3; ACL-R n=7). All participants completed two testing sessions separated by a minimum of 1 week. InFOCUS feedback cues were given during the first session while and ExFOCUS cues were given during the second. This order was chosen due to the potential of ExFOCUS to change biomechanics long-term. Biomechanics were quantified during a both a single-leg step down and jump-landing tasks using 3D motion capture Participants

were outfitted with 36 retroreflective markers that were tracked via a 10 camera (200Hz) motion-capture system (MX-T40S; Vicon, Oxford, UK). A static recording was captured to generate a kinematic model in Visual3D (C-Motion, Inc. Germantown, MD, USA). Joint rotations were calculated in Visual3D using a Cardan rotation sequence and expressed relative to each participant's static trial. Three-dimensional ground reaction force data were collected synchronously with the kinematic data from two Bertec (Bertec, Columbus, OH, USA) non-conductive force platforms (1000Hz). Kinetic data were smoothed using a 4th order zero lag low pass Butterworth filter with a cutoff frequency of 12 Hz and processed using a standard inverse dynamics approach. Joint moments were normalized to participant body mass and height (Nm/kg*m) and presented as external moments. All biomechanical data were time normalized to 100% of the stance phase (initial contact to toe-off), with initial contact and toe-off representing the instants when the vertical ground reaction force (vGRF) first exceeded or fell below 10N, respectively. Independent variables for analysis were group (ACL-R, control), limb (involved, uninvolved or matched in contralateral in the control group), and condition (ExFOCUS, InFOCUS). All data were assessed for normality prior to analysis. For all aims, change scores (pre – post) were calculated for all biomechanical and functional performance variables. Next, a series of 2x2x2 repeated measures ANOVAs were conducted to identify group x condition x limb differences in knee biomechanics and functional performance. 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 (v26, IBM Corporation, Armonk, NY, USA).

Results: During single-leg step downs there was a significant limb by condition interaction for sagittal plane hip rotation (*P*=0.023). However, neither the limb (*P*=0.855) nor the condition (*P*=0.647) main effects were statistically significant for either variable. Changes in hip frontal, knee sagittal or frontal plane rotations, and hip and knee sagittal and frontal plane moments were not statistically different between groups, limbs, or conditions during the single-leg step downs.

Drop vertical jump did not show significant changes in hip nor knee sagittal and frontal plane angles between groups, limbs, or conditions. However, there was a significant limb by group interaction for frontal plane knee moment (P=0.027) and peak vGRF (P=0.044) during drop vertical jumps. Though, neither the limb (P=0.142) nor the group (P=0.792) was statistically significant for either variable. There was a significant main effect of condition for hip frontal plane torque (P=0.025). Specifically, participants demonstrated a greater increase in external hip abduction moment from pre- to post-testing in the InFOCUS compared to the ExFOCUS session. There was a significant main effect of condition for vGRF (P=0.041), with the differences from baseline being greater during the ExFOCUS than the InFOCUS session.

Finally, the triple hop for distance test demonstrated a significant group main effect (P=0.016) such that the control group demonstrated greater changes in triple hop distance from baseline compared to the ACL-R group regardless of limb or condition.

Conclusions: This preliminary investigation suggests that a single session of InFOCUS or ExFOCUS training is not sufficient to alter lower extremity biomechanics or functional performance in patients after ACL-R or healthy adults. To effectively reduce the risk of ACL injury, this intervention may need to last longer than a single session. Strategies to reduce injury risk among patients after ACL-R are necessary; therefore, future studies should have participants preform multiple sessions of each condition so that it can be observed whether or not changes occur.

DEDICATION

To my wife Abbey, without whom none of this would be possible. Thank you for your support, inspiration and patience throughout this process. To my parents, for always believing in me, encouraging me and loving me. You taught me to work hard and believe in myself and that I could accomplish anything.

ACKNOWLEDGMENTS

First, I would like to thank Dr. Abbey Thomas for her encouragement and seemingly inexhaustible patience throughout this journey. I truly appreciate all of the support and advise you gave me throughout this process. This project would not have been possible without your guidance. I would also like to thank Dr. Tricia Turner and Dr. Luke Donovan for all of their help and support as my thesis committee. Lastly, I would like to thank all members of the Biodynamics Laboratory for supporting me throughout this process, you are great colleagues and friends and were always willing to lend a hand when I needed it.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

Anterior cruciate ligament (ACL) injuries are highly prevalent in the United States, with more than 250,000 occurring per year.[1] Of those injured approximately 150,000 elect to undergo anterior cruciate ligament reconstruction (ACLR) surgery. Each procedure and its accompanying rehabilitation carry an average cost of $17,000, which results in approximately $2.55 billion spent annually on ACLRs.[2] Despite the high cost associated with ACL injury and subsequent reconstruction, the outcomes may be less than optimal as the residual effects can be life changing. Regardless of treatment approach, by the 3rd decade after surgery, approximately 50% of individuals have osteoarthritis. This suggests that current techniques are not efficient for decreasing long-term posttraumatic osteoarthritis development.[3]

Subsequent to ACLR, the chances of having a second ACL injury can rise as much as 15 times compared to that of someone who has not previously been injured.[4] These second ACL injuries can occur to the ipsilateral or contralateral knee and it has been suggested that the same poor biomechanics (i.e., dynamic knee valgus, decreased hip flexion, and peak external knee flexion moment)[5] that cause primary ACL injury also cause second ACL injury. The high rate of subsequent injury and similar injury mechanisms add further evidence that current interventions do not adequately improve biomechanics and that current treatment strategies need to be optimized to improve long-term outcomes in these patients.

Post-operative rehabilitation is typically a lengthy process, targeting muscular strength, gait mechanics and functional performance. Interventions are focused on both short- and long-term outcomes and look to use the most efficient and effective techniques to return patients to pre-injury functionality and limit re-injury or adverse long-term effects. Cues and varied foci of attention used during the rehabilitation of patients after ACLR may have a significant effect on outcome and re-injury risk and further investigation of these techniques may be necessary to improve outcomes following ACLR.[6]

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.[7] Though extremely common, recent research has shown that InFOCUS may be detrimental to certain physical movements. By breaking down the movement instructions into individual components the patient may see a reduction in movement automaticity.[8]

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) which promotes the use of unconscious or automatic mechanisms, allowing the motor system to more naturally self-organize,[9] and may improve motor learning efficacy.[6] 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.[10] Specifically, significantly larger knee flexion angles at initial contact, peak knee flexion, total range of motion and time to peak knee flexion were observed. While this study produced some pertinent data, it was only looking at a singular task and the cues were only verbal. Understanding how ExFOCUS feedback improves biomechanics during more sport-specific tasks and under alternative cueing conditions is vital to further improving post-operative rehabilitation.

Despite advances in ACLR rehabilitation practices the re-injury rate is still distressingly high and residual complications persist after completion of rehabilitation in a large percentage of patients. The purpose of this study is to determine efficacy of a novel form of ExFOCUS feedback compared to standard of care InFOCUS feedback at improving biomechanics of patients post-ACLR as well as in healthy individuals. It is our goal to further previous research that has shown ExFOCUS to be a superior feedback method when working with patients rehabilitating post-ACLR.

Specific Aim 1: To determine if a single ExFOCUS intervention can improve biomechanics compared to InFOCUS in patients after ACLR and healthy controls.

Hypothesis 1.1: Patients will demonstrate greater increases in knee flexion and decreases in knee abduction angle during step down and jump-landing following external versus internal focus of attention feedback.

Hypothesis 1.2: Patients will demonstrate greater increases in external knee flexion moment with concurrent decreases in knee abduction moment and peak vertical ground reaction force during stepping down and landing following external compared to internal focus of attention feedback.

Hypothesis 1.3: While all participants will improve biomechanics after ExFOCUS training, patients after ACLR will demonstrate greater improvements in biomechanics than healthy controls.

Specific Aim 2: To determine if a single ExFOCUS intervention can improve functional performance compared to InFOCUS in patients after ACLR.

Hypothesis 2.1: Following ExFOCUS training, patients will increase their single-leg (SL) hop, triple hop, and crossover hop distance and decrease their 6m timed hop time compared to InFOCUS training. Additionally, patients will increase their jump height on a vertical jump test following external versus internal focus of attention feedback training.

Hypothesis 2.2: While all participants will improve their functional performance following ExFOCUS training, patients in the ACLR group will demonstrate greater improvements than healthy controls.

Exploratory Aim 3: To determine if there is a limb-to-limb difference in biomechanical and functional performance improvements following unilateral training in patients post-ACLR after both types of feedback interventions.

Hypothesis 3.1: Patients will demonstrate greater contralateral limb improvements in biomechanics and functional performance following unilateral training utilizing external versus internal focus of attention feedback.

Delimitations: Patients were recruited from the University of North Carolina at Charlotte and surrounding community. Therefore, patients were treated by a variety of different surgeons using different graft types and following multiple rehabilitation protocols. While this variety increases generalizability of our findings, it may also influence our outcomes. Therefore, graft type was collected, as were concomitant surgical procedures, for use in data analysis as necessary. Additionally, this is a single intervention session and it is not possible to discern whether the effects of the different focus of attention are long term or repeatable. However, determining the single-session benefits of the intervention is an important step in designing a long-term training study.

CHAPTER 2: REVIEW OF RELATED LITERATURE

The purpose of this literature review is to detail: 1) knee joint anatomy and biomechanics, 2) anterior cruciate ligament injury and reconstruction, 3) the rehabilitative process, including: testing for return to sport and leg symmetry and 4) Internal and External Focus of Attention.

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 great stress. 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.[11] 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. The ACL consists of two major fiber bundles, namely the anteromedial and posterolateral bundle,[12] 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.[13] 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.[13] [14] [15] 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.[16]

2.2 Anterior Cruciate Ligament Injuries and Reconstruction

ACL injuries are amongst the most common injuries sustained in an athletic population, with over 250,000 occurring in the United States each year.[1] 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.[17] As more and more individuals participate in these activities, the rate of ACL injuries is likely to rise. 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.[18] 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.).

Like all ligament sprains, ACL injuries can be divided into three levels of severity: Grades I, II or III. An injury is diagnosed as Grade I if the ligament is mildly damaged, a few fibers may be torn. The ligament has been slightly stretched and may be loosened but is still able to help keep the knee joint stable. More severe is the Grade II sprain, wherein a large number of fibers are torn. This may also be referred to as a partial tear. The ligament stretches to the point that it becomes loose and a partial thickness tear is observed. The most severe is a Grade III sprain or a complete tear of the ligament. This results in an unstable knee joint.

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.[19] Thus, over half of patients opt for surgical reconstruction.

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.[20-22] Moreover the odds of graft rupture with an allograft reconstruction are 4 times higher than those of autograft reconstructions.[23] 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.[23-25] 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.[26,27]

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.[4] 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.[28]

The cost of initial ACLRs, including diagnosis, surgery and rehabilitation, is approximately $17,000, with a total annual cost of approximately $2.5 billion in the United States.[29] A second injury sees the cost rise by an average of more than $1,200.[2] 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. Electing to have the surgery is, however, only the first step in RTS; the next step is the rehabilitation of the injury.

2.3 Rehabilitation

Rehabilitation typically lasts six months post-operatively, with patients expected to be cleared to resume full activity by 12 months following surgery.[30] Early emphasis is placed on gait training and mobilization of the knee joint as extended immobilization has negative effects on the structures surrounding the knee and may increase pain.[31] Next, patients progress to full weight bearing and closed kinetic chain exercise by the third week post operation. Beyond this time point, emphasis continues to be placed on restoring muscle strength, neuromuscular control, and cardiovascular endurance (approximate time frame: 4-10 weeks post-operatively). Once the graft has adequately strengthened (around 11-12 weeks post-operatively), advanced strength training, plyometric, and agility exercises begin. Finally, by the fifth post-operative month, patients perform sport-specific exercise in final preparation for return to full activity.

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.[32] In a recent study, Goerger et al.[32] examined dominant limb biomechanics in a group of persons both pre-ACL injury and post-ACLR. Their findings indicated that injury and subsequent ACLR resulted in altered movement patterns in both the injured and uninjured limbs. This suggests the need to reevaluate current rehabilitation protocols in order to more optimally restore lower extremity biomechanics.[6]

Noyes et al.[33] 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.

2.4 Internal and External Focus of Attention

Shifting rehabilitation from relying on an internal to an ExFOCUS during functional movement may have large impacts on movement patterns and post-operative outcomes. 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 patient perform exercises in front of a mirror and providing cues to land with flexed knees or to land with feet together, for example. Rehabilitation professionals provide cues inducing InFOCUS 95% of the time.[7] Though prevalent, recent research has shown that InFOCUS may be less suitable for acquisition and retention of control of complex motor skills required for sport reintegration.[7] 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.[9]

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.[6] 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 ACLR subjects using ExFOCUS versus InFOCUS.[10] 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 externally focused rehabilitation strategy may enhance skill acquisition more efficiently and increase the potential to transfer to competitive sport.[7]

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 post-operative rehabilitation techniques do not adequately protect against these future sequelae. Therefore, research is needed to optimize rehabilitation and improve long-term outcomes. This thesis project represents one important step in improving patient outcomes by examining if ExFOCUS of attention feedback can improve biomechanics and provide patients are more ideal movement strategy for RTS following ACLR.

CHAPTER 3: METHODS

3.1 Study Design

This was a preliminary cross-sectional study designed to quantify differences in biomechanics and functional performance following a single session of ExFOCUS versus InFOCUS feedback in individuals after ACLR compared to controls.

3.2 Participants

Ten adults ranging (n=7 ACLR; n=3 healthy) were recruited from the University of North Carolina at Charlotte and the surrounding community. Healthy participants were sex, age, body mass index (BMI), and activity level matched to the ACLR group. All participants were 18-35 years of age, had a BMI $\leq 35 kg/m^2$ and were free from: 1) history of lower extremity fracture or ankle sprains; 2) lower extremity injury within the past three months from which they are still experiencing symptoms; and 3) any injury or illness that precludes safe participation in exercise. Participants in the ACLR group had to have: 1) undergone a primary, unilateral ACLR within the previous 6-24 months as deficits normalize after 2 years;[34] and 2) received clearance from a physician for return to full activity. All experimental methods were approved by the University’s Institutional Review Board. All participants read and provided informed consent.

3.3 Procedures

All participants completed two testing sessions separated by a minimum of 1 week. InFOCUS was completed prior to ExFOCUS due to the potential of ExFOCUS to change biomechanics long-term. Biomechanics and functional performance were assessed bilaterally prior to and following each feedback session. The uninvolved limb was tested prior to the involved limb.

3.4 Biomechanics

Biomechanics were quantified during both a single-leg (SL) step down and jump-landing tasks using 3D motion capture. Participants were outfitted with 36 retroreflective markers placed over the spinous process of C7, the sternum, and bilaterally over the following anatomical landmarks: acromioclavicluar joint, anterior superior iliac spine, iliac crest, posterior superior iliac spine, greater trochanter, distal thigh, lateral and medial femoral epicondyles, tibial tuberosity, lateral shank, distal shank, lateral and medial malleoli, head of the 2nd metatarsal, base of the 5th metatarsal, dorsal navicular, and calcaneus. Markers were tracked via a 10 camera (200Hz) motion-capture system (MX-T40S; Vicon, Oxford, UK). A static recording was captured to generate a kinematic model in Visual3D (C-Motion, Inc. Germantown, MD, USA). Joint rotations were calculated in Visual3D using a Cardan rotation sequence and expressed relative to each participant's static trial. Three-dimensional ground reaction force data were collected synchronously with the kinematic data from two Bertec (Bertec, Columbus, OH, USA) non-conductive force platforms (1000Hz). Kinetic data were smoothed using a 4th order zero lag low pass Butterworth filter with a cutoff frequency of 12 Hz and processed using a standard inverse dynamics approach. Joint moments were normalized to participant body mass and height (Nm/kg*m) and presented as external moments. All biomechanical data were time normalized to 100% of the stance phase (initial contact to toe-off), with initial contact and toe-off representing the instants when the vertical ground reaction force (vGRF) first exceeded or fell below 10N, respectively. [35] Data were extracted at the instant of peak vGRF as this is a time when injury may occur prior to statistical analysis.[36]

For the SL step down, participants stood atop a 20cm box located adjacent to the force platforms, crossed their arms over their chests, and stepped down lowering the foot to the floor and returning to the start position. The stair height was chosen to mimic standard stair riser height. For the jump-landing task, participants stood atop a 30cm box located 50% of the participant's height away from the force platforms.[37] Participants jumped forward toward the force platforms, landing with one foot centered on each platform, and immediately upon landing performed a maximal vertical jump landing, once again, with on foot on each of the force platforms. Five good trials were performed. Good trials necessitated each foot landing squarely within the borders of the force platform. Data were averaged across trials and submitted to statistical analysis. No feedback was provided during jump-landing assessment.

3.5 Functional Performance

A series of four hopping tasks and maximal vertical jump (VJ) were utilized to assess functional performance. 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).[38] 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 were required to maintain balance on the limb being tested following the final hop for each task, if not the trial was repeated. All hop distance measures were normalized to participant leg length (supine measure of anterior superior iliac spine to medial malleolus). VJ testing required one practice trial and two recorded trials. For each functional performance task, the best of the two trials (i.e., farthest hop or highest jump) was submitted to statistical analysis.

The SL hop for distance measures the distance between the starting (toe) and landing (heel) positions along a standard tape measure.[39] The SL crossover hop for distance required the participant to hop forward as far as possible while crossing over a tape measure on the floor for three consecutive hops.[39] The distance between the starting (toe) and final landing (heel) positions along a standard tape measure was recorded. The SL triple hop for distance measures the distance between the starting (toe) and landing (heel) positions as the participant completes three consecutive forward hops along a standard tape measure.[39] The 6m timed hop requires the participant hop as quickly as possible for 6m on a single-limb. The time it takes to hop 6m was recorded.[39] VJ was completed using a Vertec vertical jump measuring device. Participants stood with one arm outstretched above their heads to determine starting position. Participants jumped as high as possible, touching the highest vane possible. The difference between standing and jumping heights indicated jump height (cm).

3.6 Feedback

Feedback was provided during a SL step down task. During this step down, participants crossed their arms over their chests and stood on the injured/matched limb, lowering the contralateral limb to the floor before returning to the start position. This task was completed 120 times with feedback. Repetitions were split into sets of 10; thus, participants completed 12 sets of 10 step downs with a minimum 1-minute rest between sets and a 5-minute break between the 6th and 7th sets to minimize any fatigue effects that may have occurred. During InFOCUS, participants watched their knee in a mirror placed in front of them and were instructed to “watch the mirror and keep your knee in line with your toes” during the step down (Figure 1).

FIGURE1. Feedback via InFOCUS.

For ExFOCUS, participants perform the step down with external feedback via a crosshair laser pointer strapped to the midline of the distal thigh of the involved/matched limb. Participants focused on the laser beam and were instructed to keep the crosshairs in a plus sign shape and allow the beam to travel up and down the wall without deviating to the side or rotating (Figure 2). Instructions for both tasks were provided prior to each set of step downs.

FIGURE 2. Feedback via ExFOCUS.

3.7 Statistical Analysis

Independent variables for analysis were group (ACL-R, control), limb (involved, uninvolved or matched in contralateral in the control group), and condition (ExFOCUS, InFOCUS). Dependent variables were hip and knee sagittal and frontal plane angles and moments at peak knee flexion (SL stepdown) or peak vGRF (DVJ), peak vGRF, SL hop distance, crossover hop distance, triple hop distance, 6m timed hop time (s), and VJ height (cm). All data were assessed for normality prior to analysis. For all aims, change scores (pre – post) were calculated for all biomechanical and functional performance variables. Next, a series of 2x2x2 repeated measures ANOVAs were conducted to identify group x condition x limb differences in knee biomechanics and functional performance. 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. To assess magnitude of change over time, Cohen's d effect sizes and associated 95% confidence intervals (CIs) were calculated. Effect sizes were interpreted as: ≥0.80 as large; 0.79-0.50 as moderate; 0.49-0.20 as small; ≤0.19 as trivial.[40] Only differences that had a p-value ≤0.05 and a large or moderate effect size with associated 95% CIs that did not cross 0 as statistically significant and clinically meaningful were interpreted.[41] Statistical analysis was conducted using IBM SPSS (v26, IBM Corporation, Armonk, NY, USA).

CHAPTER 4: RESULTS

A total of 10 individuals (n=7 ACL-R, n=3 control) participated in this study. There were no differences in demographic data between groups with the exception of IKDC. All demographic data are located in Table 1.

TABLE 1. Participant demographic data presented as mean ± standard deviation unless otherwise noted.

	ACLR	Control	P-value
Age (years)	20.86±1.86	20.00±2.00	0.531
Height (m)	1.71±0.7	1.68±0.03	0.400
Mass (kg)	75.81±14.36	65.00±6.55	0.258
BMI (kg/m^2)	25.81±4.44	23.10±1.79	0.349
Tegner Score (median[min, max])	8 (6,10)	8.5 (7,10)	1.000
IKDC	73.23±3.56	77.00±0.00	0.113
Time Since Surgery (mos.)			

ACL-R: anterior cruciate ligament reconstruction
BMI: body mass index
IKDC: International Knee Documentation Committee

4.1 Single-Leg Step Down Kinematic Data

There was a significant limb by condition interaction for sagittal plane hip rotation (*P*=0.023). However, neither the limb (*P*=0.855) nor the condition (*P*=0.647) main effects were statistically significant for either variable (Table 2; Figures 3-6).

TABLE 2. Pre- and post-intervention kinematic data for single limb step down are presented as mean ± standard deviation.

	ACL-R				Control				Group Effect	Limb Effect	Cond. Effect
	Involved		Uninvolved		Involved		Uninvolved				
	Pre	Post	Pre	Post	Pre	Post	Pre	Post			
Hip Sagittal Plane Rotation									0.288	0.855	0.647
InFocus	33.5±11.5	32.2±11.5	28.3±11.8	34.7±17.4	33.3±2.6	32.5±7.8	23.9±2.2	28.8±8.6			
ExFocus	27.1±8.8	27.4±8.7	27.6±11.6	23.3±11.4	35.6±20.9	32.4±20.0	34.3±21.3	27.6±25.0			
Hip Frontal Plane Rotation									0.275	0.797	0.560
InFocus	-5.0±17.3	-2.7±15.4	-1.4±15.6	4.3±17.7	2.7±17.9	2.9±19.4	-8.7±19.5	-9.7±22.5			
ExFocus	-9.0±16.7	-11.8±17.1	10.5±12.5	11.3±14.8	15.9±0.3	14.8±1.0	-24.0±1.3	-22.6±1.3			
Knee Sagittal Plane Rotation									0.756	0.373	0.838
InFocus	-85.1±9.2	-73.0±30.2	-71.5±33.3	-64.6±43.8	-83.7±7.2	-81.9±2.7	-78.5±5.3	-77.5±9.3			
ExFocus	-68.0±28.6	-79.1±6.6	-81.6±3.8	-79.5±5.9	-82.0±2.5	-68.7±11.8	-76.9±3.9	-74.2±7.2			
Knee Frontal Plane Rotation									0.311	0.806	0.520
InFocus	7.3±10.8	5.9±8.4	0.6±9.1	2.q±11.3	0.6±6.8	1.7±8.9	1.6±9.8	7.3±5.0			
ExFocus	2.6±10.6	0.2±11.9	0.6±8.1	-1.0±8.5	-1.8±2.5	3.2±6.4	4.6±0.6	0.4±7.1			

ACL-R: anterior cruciate ligament reconstruction; Cond.: condition; InFocus: internal focus of attention feedback; ExFocus: external focus of attention feedback; Hip flexion (+)/extension (-); Hip adduction (+)/abduction (-); Knee flexion (+)/extension (-);
Knee adduction (+)/abduction (-)

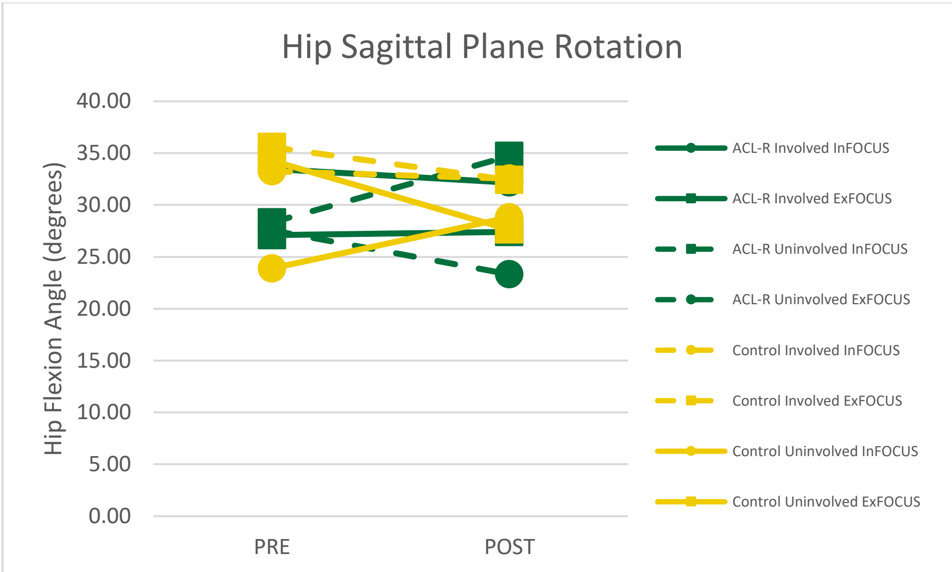

FIGURE 3. Average hip sagittal plane rotation during SL step down for each group. Involved limbs are represented by solid lines, uninvolved by dashed lines. InFOCUS is represented by circles, ExFOCUS by squares. The ACL-R group is in green and the control in gold.

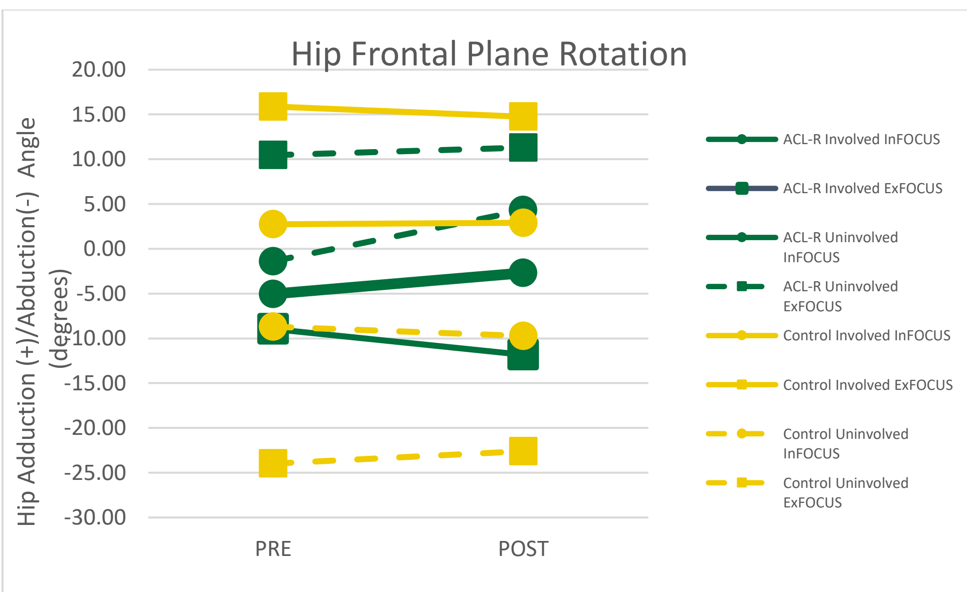

FIGURE 4. Average hip frontal plane rotation during SL step down for each group.

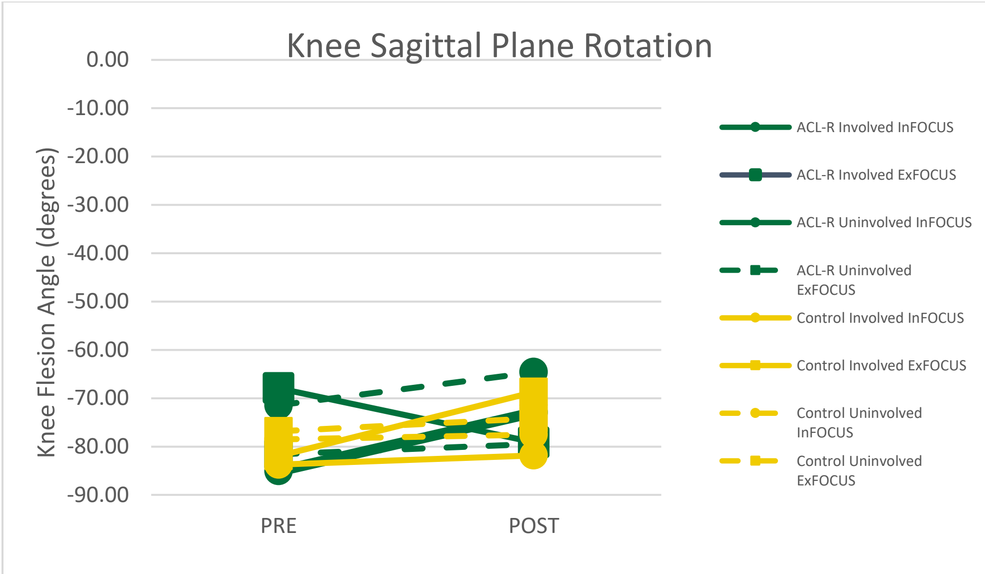

FIGURE 5. Average knee sagittal plane rotation during SL step down for each group.

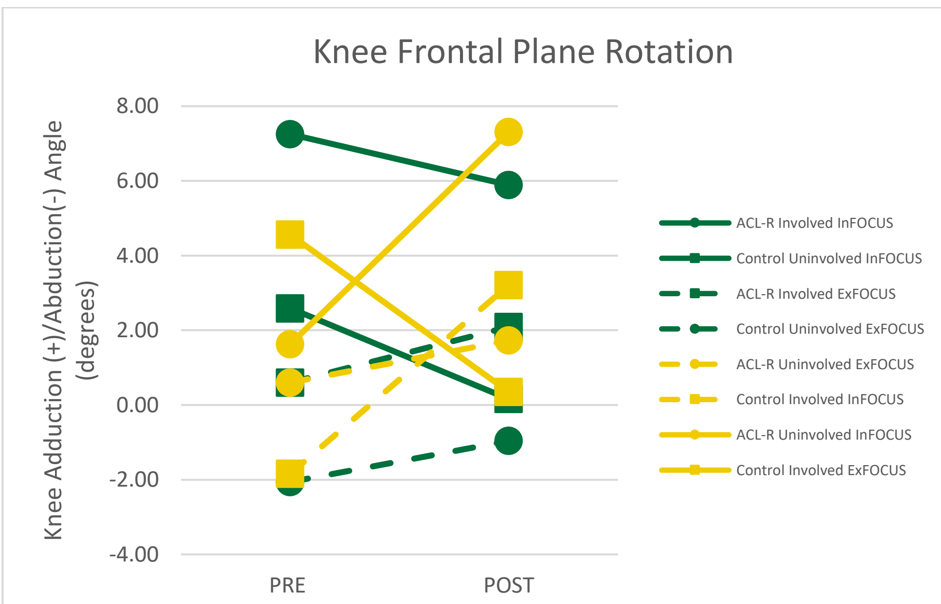

FIGURE 6. Average knee frontal plane rotation during SL step down for each group.

4.2 Single-Leg Step Down Kinetics

Changes in neither hip nor knee sagittal and frontal plane moments differed between groups, limbs, or conditions (Table 3; Figures 7-10).

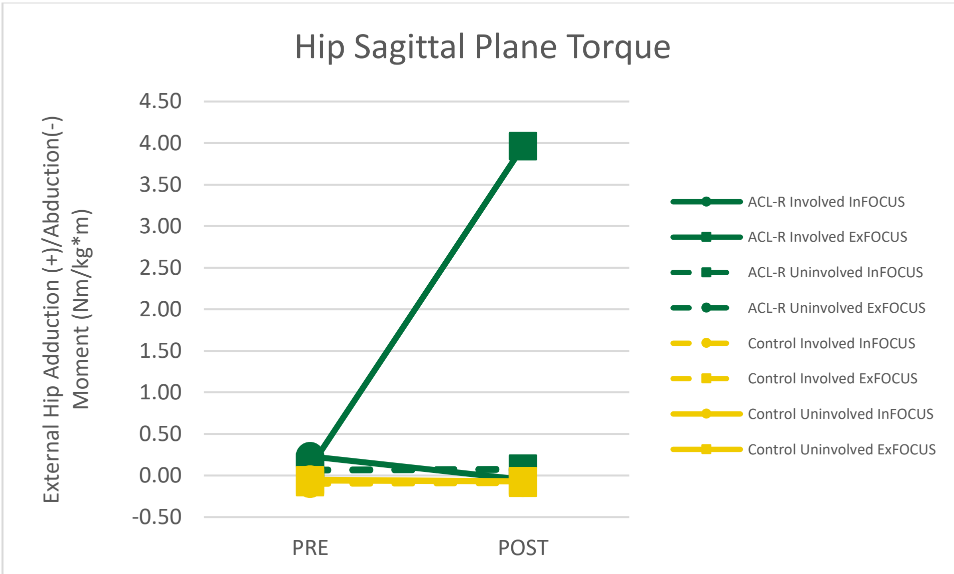

FIGURE 7. Average hip sagittal plane moment during SL step down for each group. Involved limbs are represented by solid lines, uninvolved by dashed lines. InFOCUS is represented by circles, ExFOCUS by squares. The ACL-R group is in green and the control in gold.

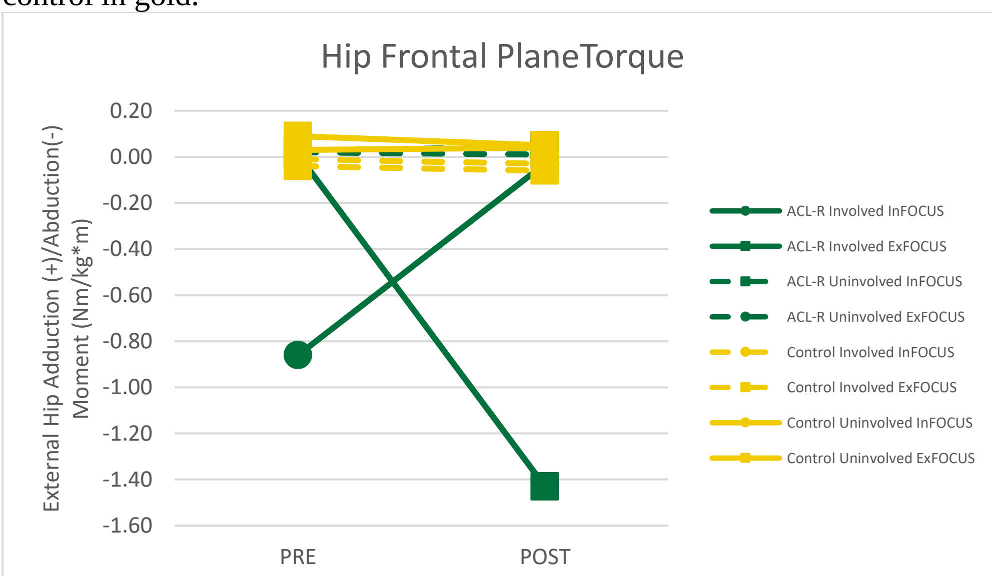

FIGURE 8. Average hip frontal plane moment during SL step down for each group.

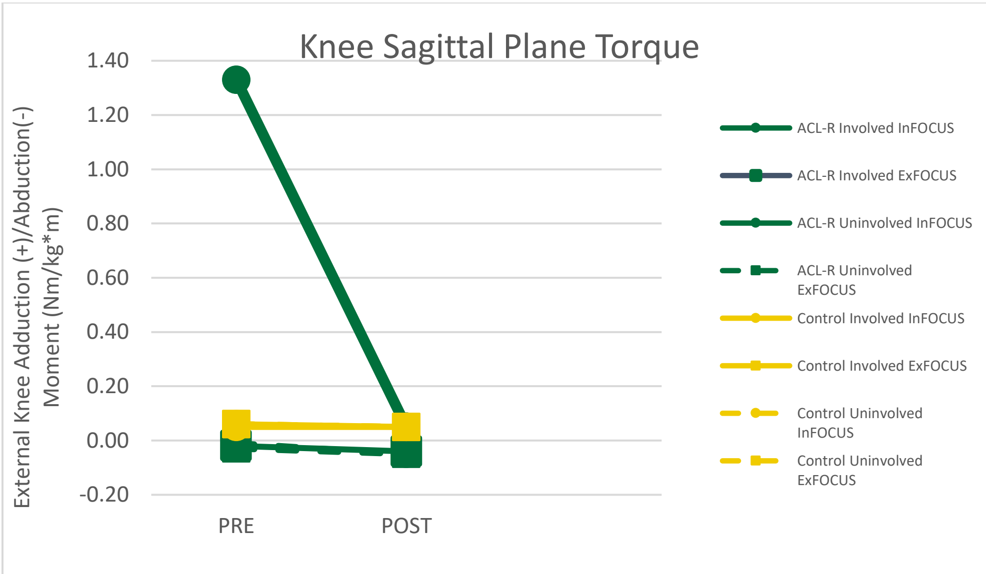

FIGURE 9. Average knee sagittal plane moment during SL step down for each group.

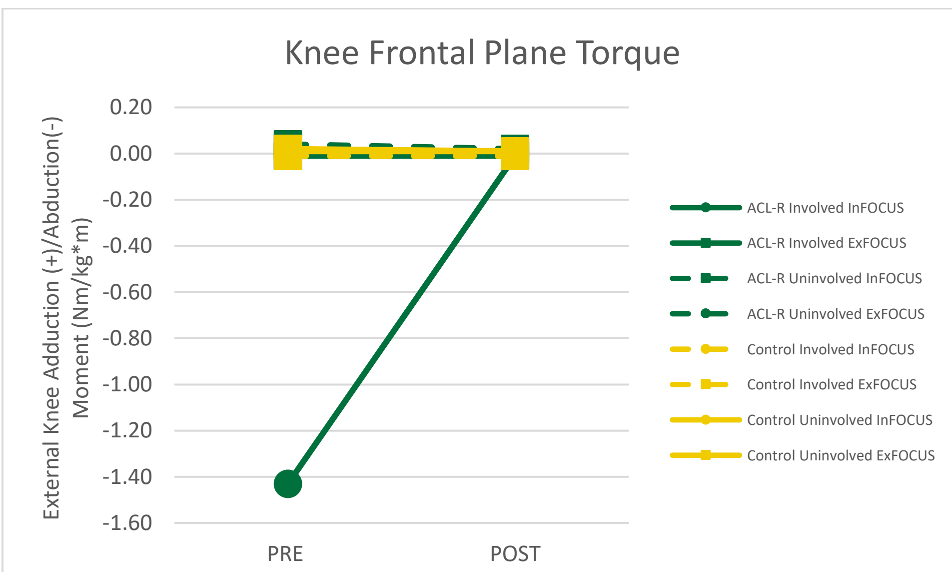

FIGURE 10. Average knee frontal plane moment during SL step down for each group.

TABLE 2. Pre- and post-intervention kinetic data for single limb step down are presented as mean ± standard deviation.

	ACL-R				Control				Group Effect	Limb Effect	Cond. Effect
	Involved		Uninvolved		Involved		Uninvolved				
	Pre	Post	Pre	Post	Pre	Post	Pre	Post			
Hip Sagittal Plane Torque									0.988	0.425	0.122
InFocus	0.23±0.85	-0.05±0.13	-0.07±.0.07	-0.08±0.07	-0.10±0.02	-0.09±0.02	-0.05±0.02	-0.07±0.03			
ExFocus	-0.10±0.06	-3.96±9.45	-0.06±0.09	-0.07±0.09	-0.08±0.01	-0.09±.04	-0.06±0.01	-0.07±0.03			
Hip Frontal Plane Torque									0.842	0.909	0.624
InFocus	-0.86±2.26	-0.04±0.08	-0.02±0.04	-0.05±0.06	-0.01±0.04	-0.03±0.06	0.03±0.06	0.04±0.06			
ExFocus	-0.01±0.06	1.43±3.45	-0.02±0.03	-0.01±0.04	-0.04±0.02	-0.06±0.07	0.09±0.02	0.05±0.02			
0Knee Sagittal Plane Torque									0.130	0.324	0.565
InFocus	1.33±3.42	0.05±0.02	0.01±0.08	0.05±0.01	0.05±0.01	0.05±0.01	0.06±0.01	0.52±0.01			
ExFocus	0.02±0.04	0.04±0.01	0.03±0.06	0.05±0.01	0.06±-0.01	0.05±0.02	0.06±0.01	0.05±0.01			
Knee Frontal Plane Torque									0.747	0.342	0.968
InFocus	-1.43±3.80	-0.01±0.04	-0.04±0.08	-0.02±0.01	-0.01±0.01	-0.01±0.02	0.01±0.02	0.01±0.02			
ExFocus	0.01±0.01	0.01±0.01	-0.01±0.01	-0.01±0.01	-0.01±0.03	-0.01±0.01	0.02±0.01	0.01±0.01			

ACL-R: anterior cruciate ligament reconstruction; Cond.: condition; InFocus: internal focus of attention feedback; ExFocus: external focus of attention feedback; Hip flexion (+)/extension (-); Hip adduction (+)/abduction (-); Knee flexion (+)/extension (-);
Knee adduction (+)/abduction (-)

4.3 Drop Vertical Jump Kinematic Data

Changes in neither hip nor knee sagittal and frontal plane angles differed between groups, limbs, or conditions (Table 4; Figures 11-14).

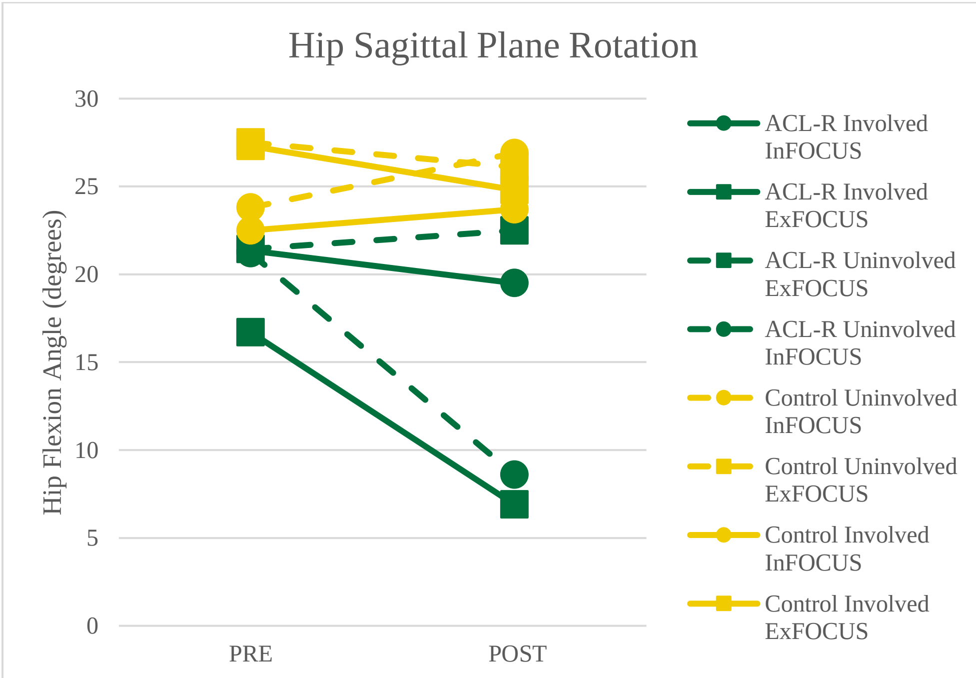

FIGURE 11. Average hip sagittal plane rotation during DVJ for each group. Involved limbs are represented by solid lines, uninvolved by dashed lines. InFOCUS is represented by circles, ExFOCUS by squares. The ACL-R group is in green and the control in gold.

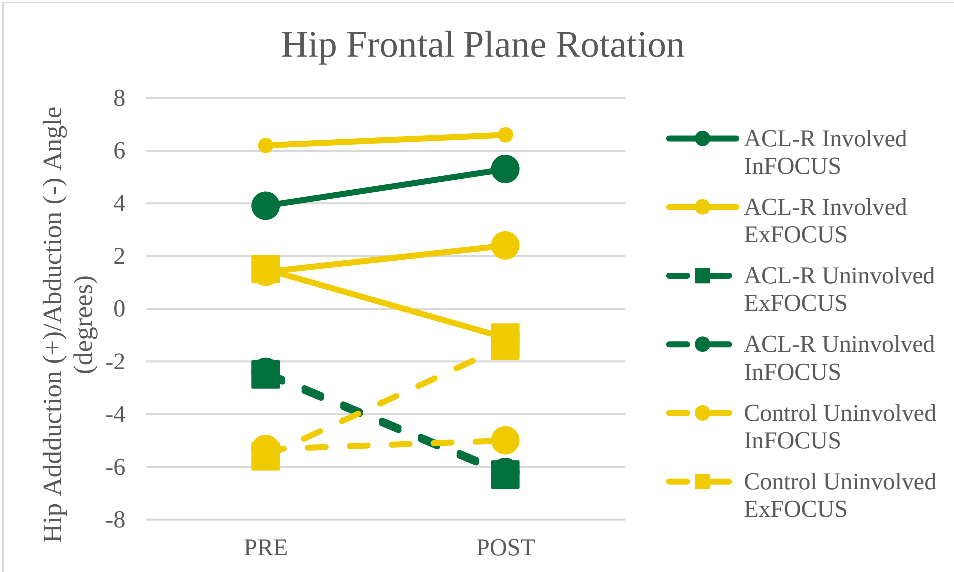

FIGURE 12. Average hip frontal plane rotation during DVJ for each group.

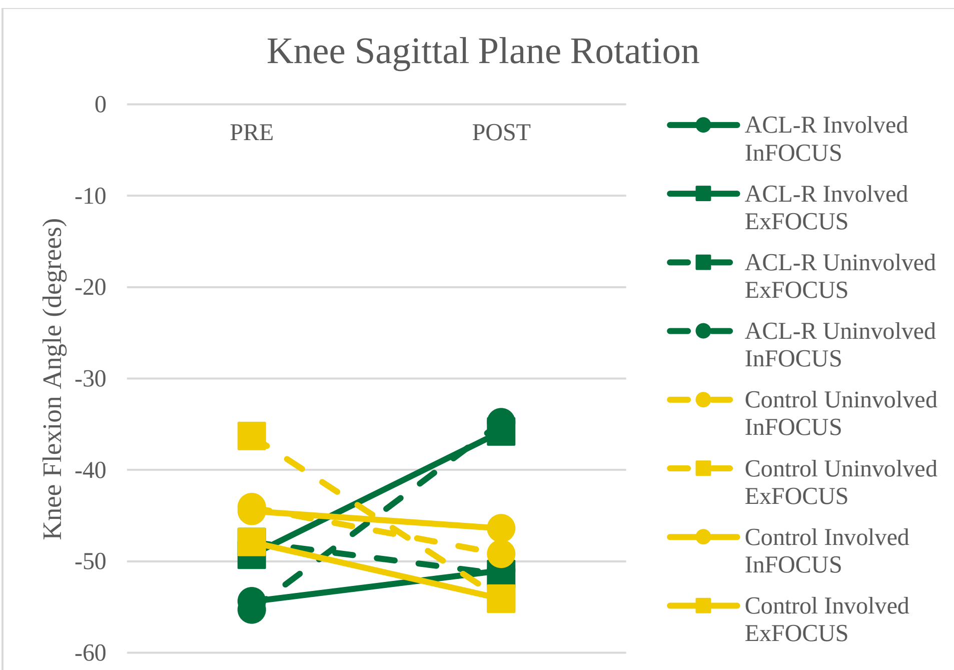

FIGURE 13. Average knee sagittal plane rotation during DVJ for each group.

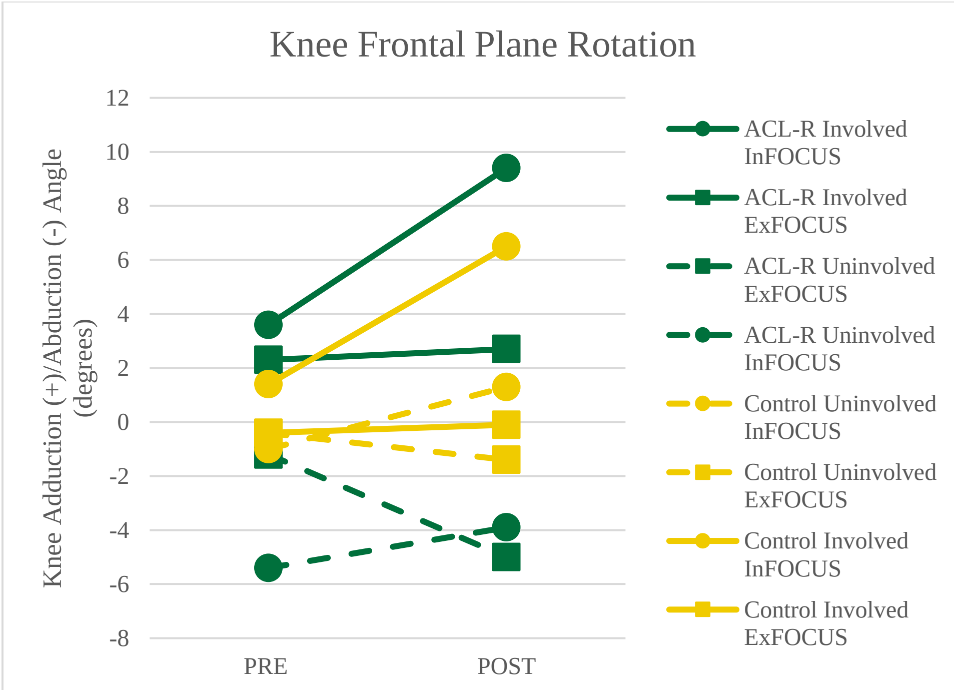

FIGURE 14. Average knee frontal plane rotation during DVJ for each group.

TABLE 4. Pre- and post-intervention data for kinematic data for drop vertical jump are presented as mean ± standard deviation.

	ACL-R				Control				Group Effect	Limb Effect	Cond. Effect
	Involved		Uninvolved		Involved		Uninvolved				
	Pre	Post	Pre	Post	Pre	Post	Pre	Post			
Hip Sagittal Plane Rotation									0.396	0.880	0.718
InFocus	21.35±11.1	19.5±10.8	21.44±11.8	22.5±14.3	23.8±9.0	26.9±6.9	22.5±9.9	23.7±2.7			
ExFocus	16.7±10.4	6.9±18.9	21.2±8.2	8.6±22.5	27.5±15.4	26.1±25.4	27.3±18.6	24.8±24.7			
Hip Frontal Plane Rotation									0.068	0.240	0.876
InFocus	3.912.8	5.3±9.5	-2.5±8.6	-6.3±8.6	-5.3±15.2	-5.0±17.8	1.4±12.8	2.4±10.0			
ExFocus	6.2±9.2	6.6±6.9	-9.5±7.2	-12.1±3.6	-5.6±17.2	-1.4±4.4	1.5±13.4	-1.1±12.8			
Knee Sagittal Plane Rotation									0.277	0.460	0.351
InFocus	-54.4±7.5	-51±12.8	-47.9±11.2	-51.4±8.3	-44.1±6.12	-49.2±3.4	-44.5±4.2	-46.4±7.7			
ExFocus	-49.3±11.9	-35.8±44.1	-55.3±6.2	-34.8±56.2	-36.3±17.6	-54.1±2.7	-47.9±4.6	-54.1±8.1			
Knee Frontal Plane Rotation									0.544	0.763	0.142
InFocus	3.6±8.5	9.4±8.7	-1.2±9.8	-5.0±5.0	-1.00±3.8	1.3±7.8	1.4±6.2	6.5±8.1			
ExFocus	2.3±0.2	2.7±10.2	-5.4±3.9	-3.9±7.16	-0.4.1±3.5	-1.4±4.4	-0.4.2±2.9	-0.1±2.9			

ACL-R: anterior cruciate ligament reconstruction; Cond.: condition; InFocus: internal focus of attention feedback; ExFocus: external focus of attention feedback; Hip flexion (+)/extension (-); Hip adduction (+)/abduction (-); Knee flexion (+)/extension (-); Knee adduction (+)/abduction (-)

There was a significant limb by group interaction for frontal plane knee moment (*P*=0.027) and peak vGRF (*P*=0.044). However, neither the limb (*P*=0.142) nor the group (*P*=0.792) main effects were statistically significant for either variable.

There was a significant main effect of condition for hip frontal plane torque (*P*=0.025). Specifically, participants demonstrated a greater increase in external hip abduction moment from pre- to post-testing in the InFOCUS compared to the ExFOCUS session. Finally, there was a significant main effect of condition for vGRF (*P*=0.041), with the differences from baseline being greater during the ExFOCUS than the InFOCUS session (Table 5; Figures 15-19).

TABLE 5. Pre- and post-intervention data for kinetic data for drop vertical jump are presented as mean ± standard deviation.

	ACL-R				Control				Group Effect	Limb Effect	Cond. Effect
	Involved		Uninvolved		Involved		Uninvolved				
	Pre	Post	Pre	Post	Pre	Post	Pre	Post			
Hip Sagittal Plane Torque									0.557	0.691	0.063
InFocus	1.54±4.9	-0.1±0.4	1.8±5.5	-0.4±0.3	-0.7±0.2	-0.7±0.3	1.7±0.3	-.8±0.2			
ExFocus	-0.9±0.5	-0.2±0.1	-0.7±0.3	-0.5±0.5	-0.2±0.3	-0.4±0.4	-0.5±0.4	-0.4±0.4			
Hip Frontal Plane Torque									0.638	0.768	0.960
InFocus	2.3±5.4	0.2±0.3	-0.8±1.9	-0.1±0.2	0.2±0.2	0.1±0.1	4.3±0.9	0.2±0.2			
ExFocus	0.2±0.3	0.1±0.2	-0.1±0.2	0.1±0.7	0.2±0.1	0.1±0.1	0.1±0.1	0.1±0.2			
Knee Sagittal Plane Torque									0.351	0.215	0.269
InFocus	-6.6±21.1	0.9±.5	-7.1±20.9	0.9±0.2	0.7±0.2	0.8±0.1	5.4±1.5	1.1±0.1			
ExFocus	0.9±04	0.8±0.5	0.9±0.2	0.8±00.4	0.9±0.2	0.9±0.3	0.9±0.2	1.1±0.			
Knee Frontal Plane Torque									0.792	0.142	0.396
InFocus	2.5±6.4	0.01±0.11	-1.2±3.4	0.1±0.1	0.2±0.1	0.1±0.1	2.3±0.2	0.1±0.2			
ExFocus	0.15±0.18	0.1±0.17	0.1±0.1	0.1±0.1	0.2±01	0.1±0.1	0.2±0.1	0.1±0.1			
vGRF											
InFocus	1.7±0.5	1.7±0.61	1.3±0.20	1.3±0.2	1.8±0.2	1.7±0.3	1.9±0.1	2.1±0.2	0.738	0.187	**0.044**
ExFocus	1.4±0.33	1.3±0.2	1.7±0.4	1.5±0.4	1.7±0.3	1.8±0.1	1.4±0.4	1.6±0.4			

ACL-R: anterior cruciate ligament reconstruction; Cond.: condition; InFocus: internal focus of attention feedback; ExFocus: external focus of attention feedback; Hip flexion (+)/extension (-); Hip adduction (+)/abduction (-); Knee flexion (+)/extension (-);
Knee adduction (+)/abduction (-)

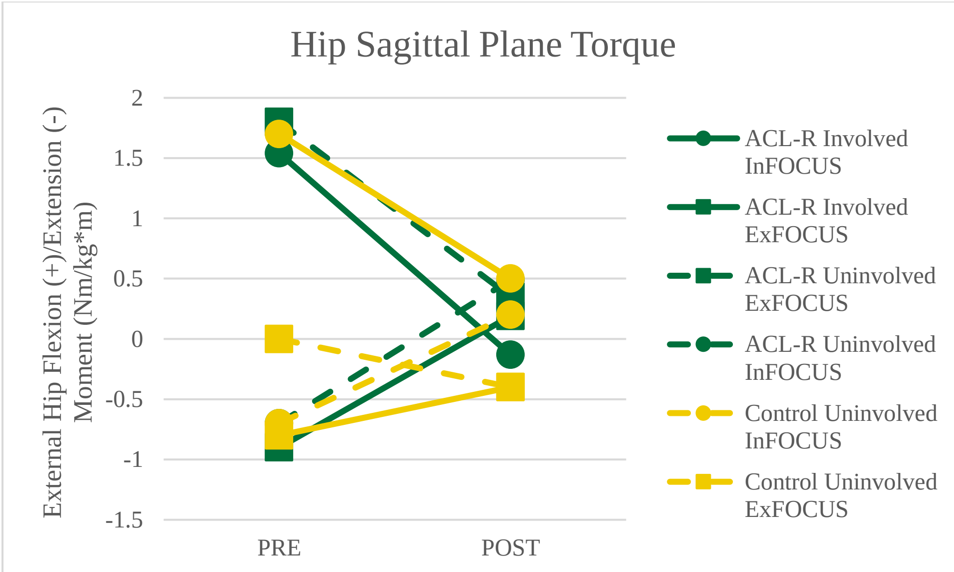

FIGURE 15. Average hip sagittal plane moment during DVJ for each group. Involved limbs are represented by solid lines, uninvolved by dashed lines. InFOCUS is represented by circles, ExFOCUS by squares. The ACL-R group is in green and the control in gold.

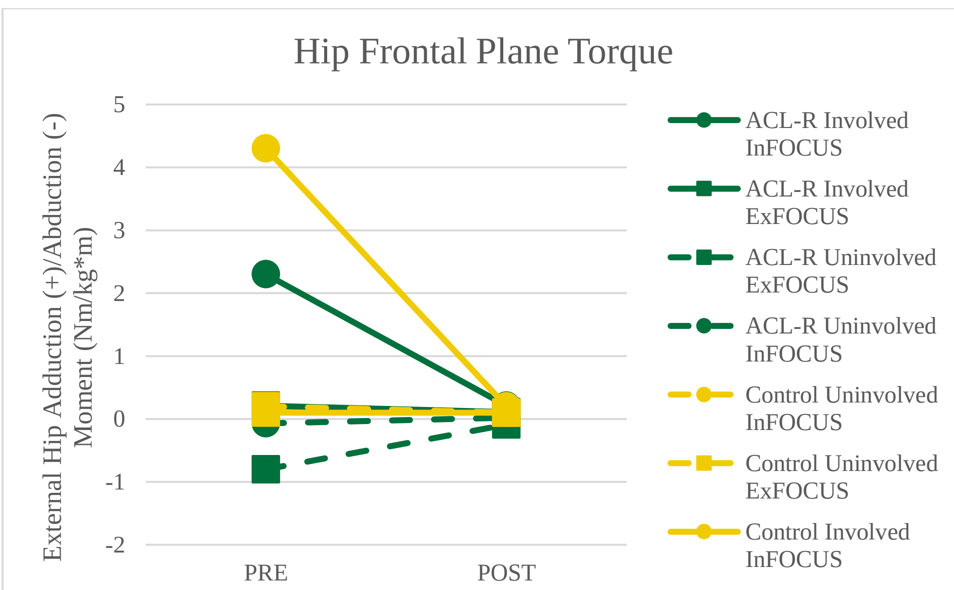

FIGURE 16. Average hip frontal plane moment during DVJ for each group.

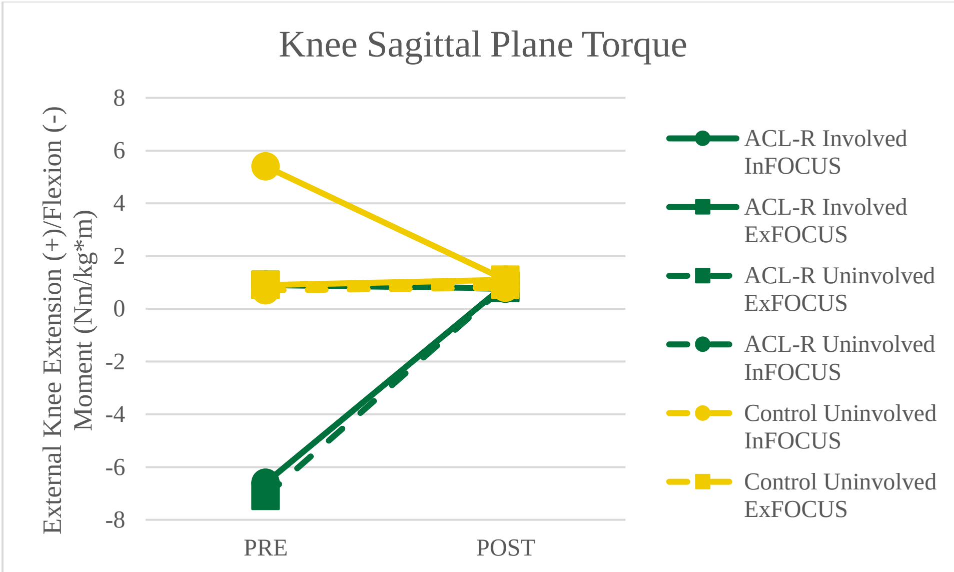

FIGURE 17. Average knee sagittal plane moment during DVJ for each group.

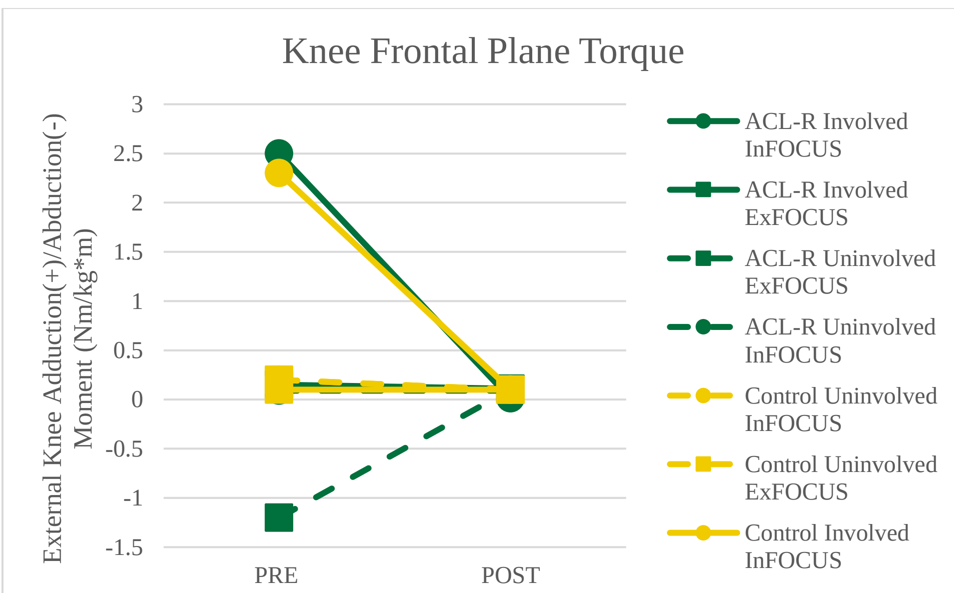

FIGURE 18. Average knee frontal plane moment during DVJ for each group.

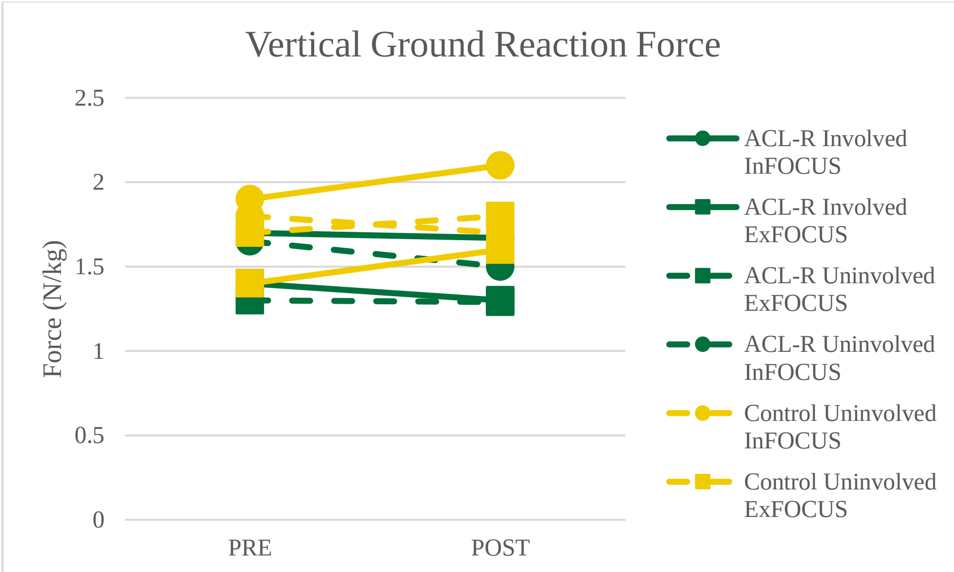

FIGURE 19. Average vertical ground reaction force during DVJ for each group.

4.3 Functional Performance Data

With the exception of the triple hop for distance test, there were no differences between groups, limbs, or conditions for any of the functional performance measures (Table 4; Figure 10-14). The triple hop for distance test demonstrated a significant group main effect (P=0.016) such that the control group demonstrated greater changes in triple hop distance from baseline compared to the ACL-R group regardless of limb or condition (Table 6; Figures 20-24).

TABLE 6. Pre- and post-intervention data for functional hop tests. Data are presented as mean ± standard deviation.

	ACL-R				Control				Group Effect	Limb Effect	Condition Effect
	Involved		Uninvolved		Involved		Uninvolved				
	Pre	Post	Pre	Post	Pre	Post	Pre	Post			
Single Leg Hop									0.658	0.303	0.125
InFocus	1.9±0.2	2.0±0.3	1.8±0.3	2.0±0.3	1.7±0.2	1.9±0.2	1.7±0.3	1.9±0.3			
ExFocus	1.9±0.3	2.0±0.3	2.0±0.3	2.1±0.3	2.1±0.3	2.1±0.4	2.1±0.2	2.2±0.3			
Crossover Hop									0.376	0.751	0.381
InFocus	4.6±0.8	4.9±0.7	4.6±0.9	5.0±0.8	4.4±1.0	4.5±1.5	4.3±0.9	4.4±1.4			
ExFocus	4.9±0.7	5.0±0.7	5.2±0.7	5.3±0.7	5.6±1.6	5.6±1.5	5.7±1.5	5.7±1.4			
Triple Hop									**0.016**	0.279	0.851
InFocus	5.2±0.8	5.3±0.7	5.3±0.9	5.4±0.7	5.4±1.4	4.9±1.2	5.4±1.5	5.3±1.8			
ExFocus	5.4±0.8	5.3±0.7	5.5±0.8	5.5±0.7	6.3±1.6	6.0±1.5	6.4±1.4	6.2±1.3			
Six meter timed hop (s)									0.773	0.318	0.110
InFocus	2.2±0.1	2.5±0.2	2.3±0.2	2.3±0.2	2.3±0.2	2.5±0.4	2.3±0.2	2.3±0.3			
ExFocus	2.3±0.2	2.4±0.1	2.3±0.3	2.3±0.1	2.1±0.2	2.2±0.3	2.2±0.2	2.2±0.2			
Vertical Jump (cm)									0.211		0.859
InFocus	8.3±1.7	8.7±1.6			7.3±0.6	7.1±1.0					
ExFocus	8.0±0.9	8.2±1.0			7.7±0.6	7.6±0.8					

ACL-R: anterior cruciate ligament reconstruction; InFocus: internal focus of attention feedback; ExFocus: external focus of attention feedback; Hip flexion (+)/extension (-); Hip adduction (+)/abduction (-); Knee flexion (+)/extension (-); Knee adduction (+)/abduction (-)

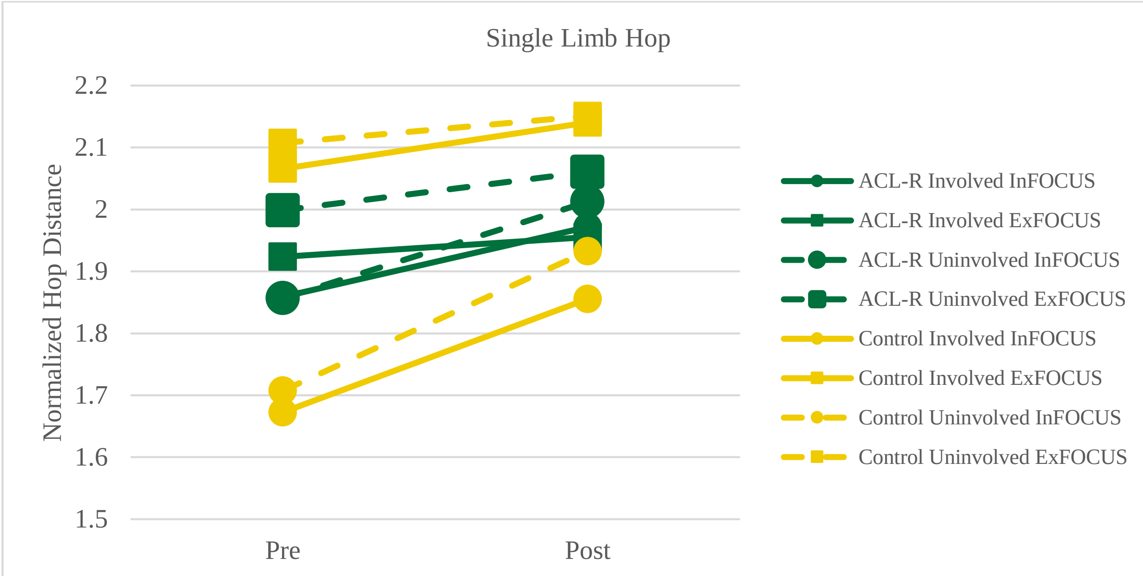

FIGURE 20. Average normalized single limb hop distance for each group. Involved limbs are represented by solid lines, uninvolved by dashed lines. InFOCUS is represented by circles, ExFOCUS by squares. The ACL-R group is in green and the control in gold.

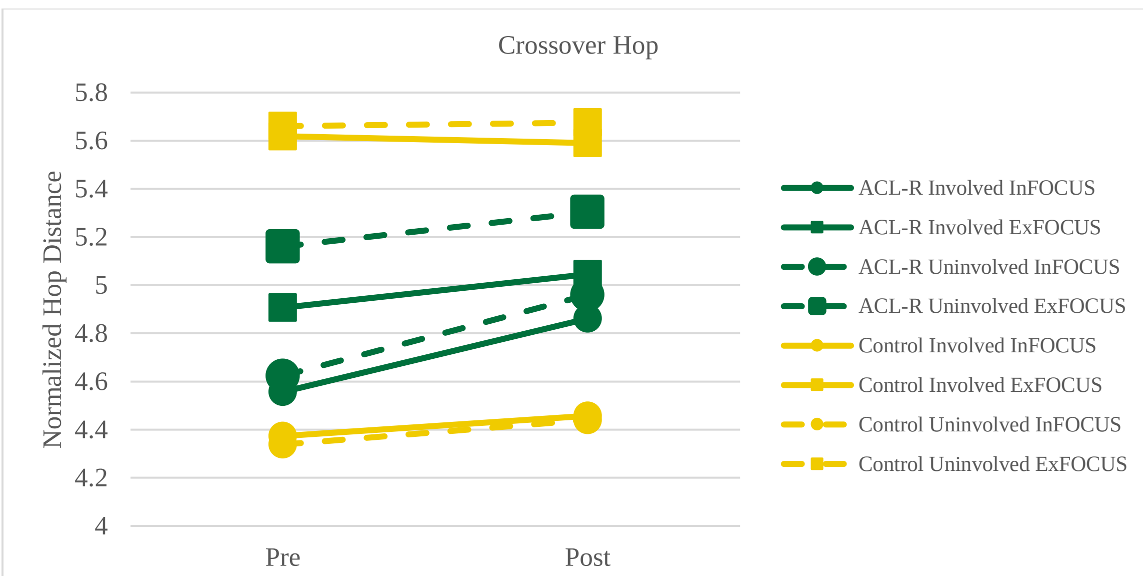

FIGURE 21. Average normalized crossover hop distance for each group.

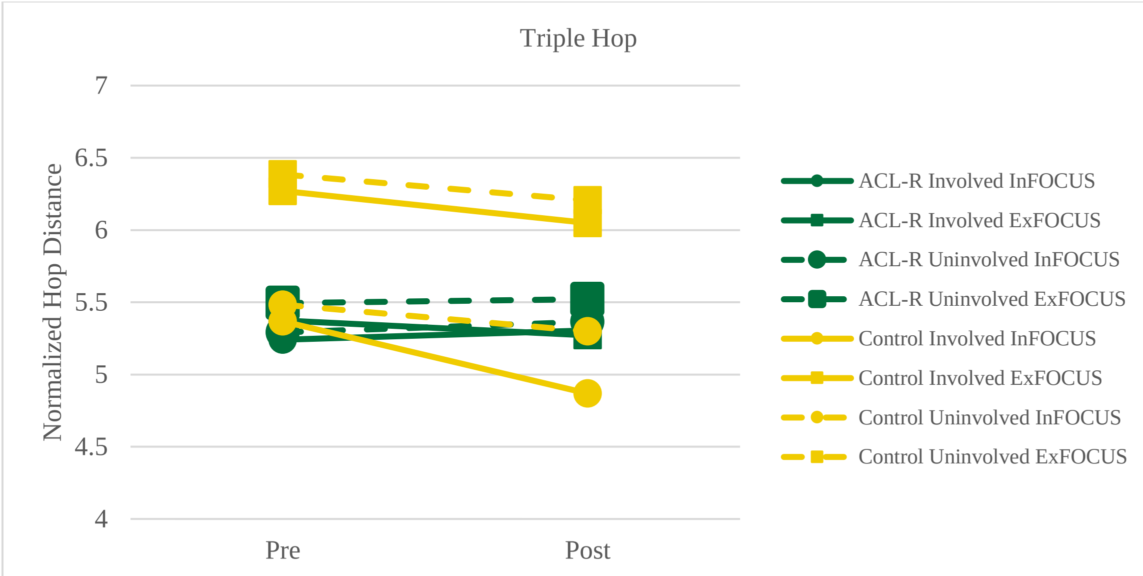

FIGURE 22. Average normalized triple hop distance for each group

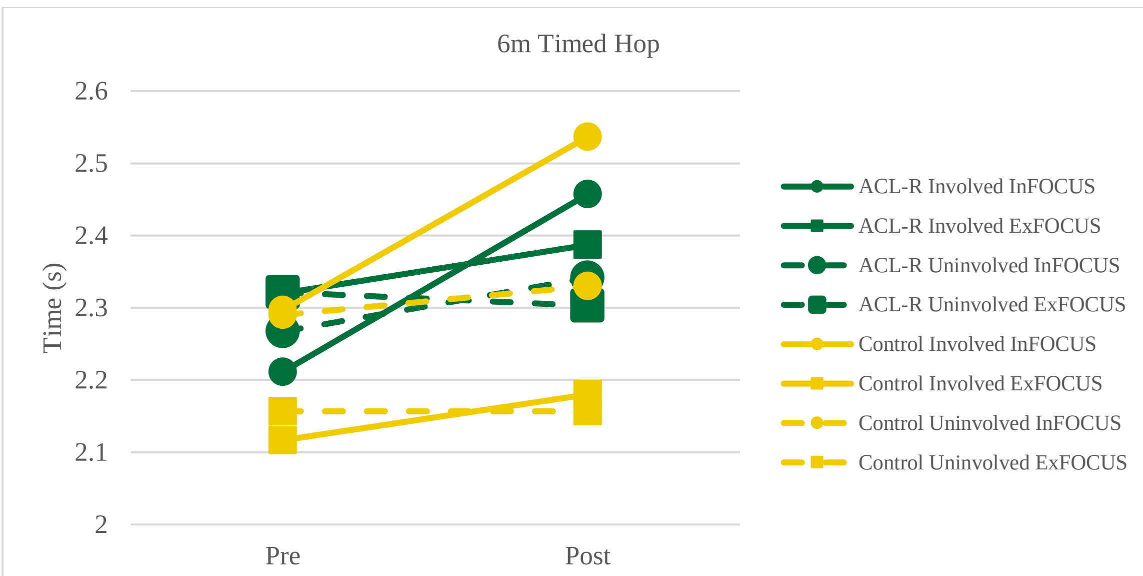

FIGURE 23. Average 6m hop time for each group.

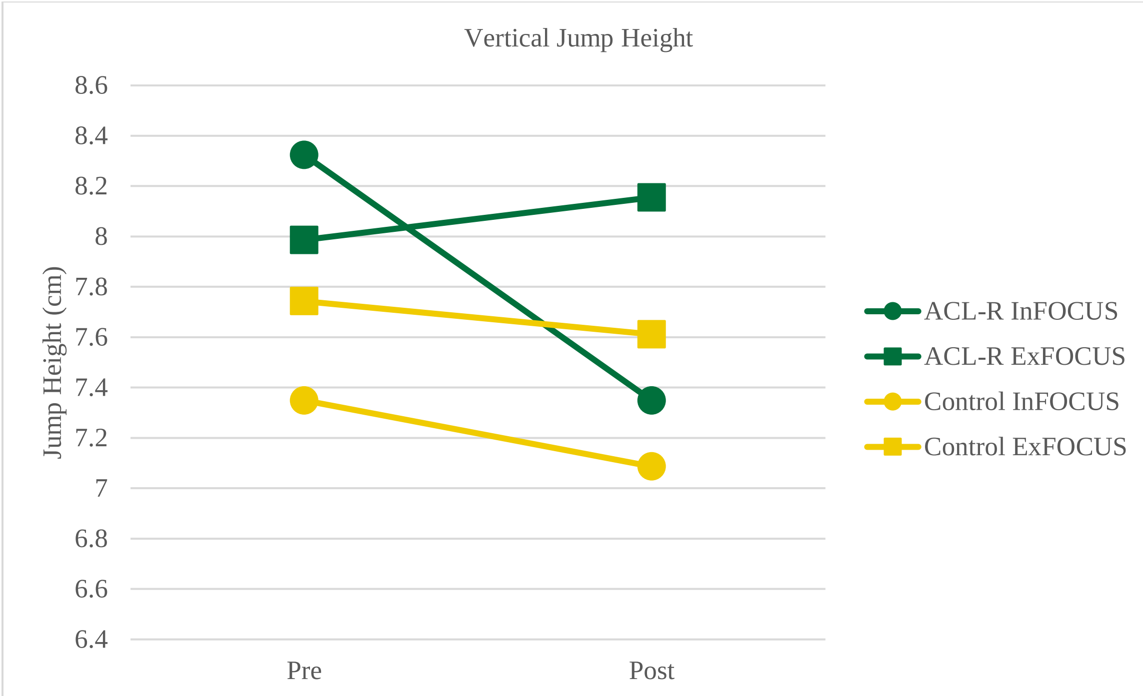

FIGURE 24. Average vertical jump height for each group.

CHAPTER 5: DISCUSSION

This preliminary study investigated the effects of a single bout of InFOCUS or ExFOCUS training on functional performance and biomechanics of patients post ACL-R and healthy adults Overall, neither training effectively changed biomechanics or functional performance.

5.1 Single Leg Step Down Kinematic Data

Minimal kinematic changes were observed during single-leg step down following InFOCUS or ExFOCUS training. We did observe a significant group x condition interaction for sagittal plane hip rotation. However, neither main effect was significant. After graphically viewing the data, it appears that this interaction is driven by increase in hip flexion angle in the ACL-R group. However, these changes were less than 10º and associated effect sizes were small (-0.04 to -0.46). Thus, this change, while positive, would not be clinically impactful in terms of reducing the risk of ACL injury. There were no other changes observed in hip joint angles, nor were there any changes observed in knee joint angles.

5.2 Single Leg Step Down Kinetic Data

No changes were observed in hip or knee joint kinetics during the step down task. While differences were not statistically significant, there was a large effect (d=-1.46) with a confidence interval that does not cross zero for the ACL-R group following the InFOCUS intervention. Notably, ACL-R participants demonstrated a greater abduction moment at the hip following InFOCUS. On the contrary, ExFOCUS training brought ACL-R participants toward more neutral hip joint moments. Despite the absence of statistical significance, the implications of a hip abduction moment in non-contact ACL injury risk warrant further investigation of these findings upon completion of this study.

5.3 Drop Vertical Jump Kinematic Data

Contrary to our hypothesis, no changes were observed in hip or knee joint angles following training. Previous research has demonstrated the capability of individuals to increase hip and knee flexion immediately after a training session.[42] However, there are notable differences between our study and that of Ericksen et al. First, the previous study provided participants with error-based feedback or error based-feedback plus real-time visualization of vGRF. Our participants did not receive feedback on any errors they may have performed during training. Feedback of errors made is known to improve performance.[43-45] Second, the previous study trained individuals during the jump-landing task while we provided feedback during SL step down. The reason for not providing feedback during jump-landing was that it is too quick of a movement for participants to adequately view the laser during ExFOCUS feedback training. Third, the previous study utilized healthy adults as it was examining primary ACL injury prevention strategies. Examining our data, the healthy group change scores approached comparable magnitudes of differences in joint angle when compared to those in the study by Ericksen et al. However, with only 3 healthy adults in our study we cannot conclude that our training protocol would be beneficial to changing biomechanics to prevent primary injury.

5.4 Drop Vertical Jump Kinetic Data

Minimal changes were observed during drop vertical jump joint kinetics following InFOCUS or ExFOCUS training. We did observe a significant group x limb interaction for knee frontal plane moment. However, neither main effect was significant.

After graphically viewing the data, it appears that this interaction is driven by changes in landing strategy among the patients in the ACL-R group as these participants went from an adducted to a neutral knee moment in the involved limb while the uninvolved went from an abducted to a neutral knee moment following ExFOCUS training. The control group experienced a more neutral knee moment throughout. It is well-established that a greater external knee abduction moment may contribute to non-contact ACL injury and re-injury. [46,47] Thus, landing with a more neutral frontal plane moment at the knee may be beneficial. It is possible that any changes we did observe in knee frontal plane kinetics were not statistically significant as we did not screen individuals for an increased external knee abduction moment prior to enrollment. If participants did not land with a large knee abduction load initially, it would have been difficult to improve upon their landing strategy. Future investigations may consider screening for biomechanics prior to enrollment.

The hip frontal plane moment and vGRF demonstrated significant condition main effects, with the change hip frontal plane moment being greater following InFOCUS training and the change in vGRF being greater following ExFOCUS training. Landing with a more neutral hip frontal plane moment is beneficial to reducing ACL injury risk. It is possible that the difference in the directions provided during InFOCUS to “keep the knee in line with the toe” compared to ExFOCUS to “move the laser up the wall without letting it rotate or deviate to the side” help explain this finding. Keeping the knee in line with the toe while watching oneself step down in a mirror requires activation of the hip joint musculature and may lend itself to a strategy whereby participants alter frontal plane hip joint loading to ensure a more neutral (knee over toe) posture. Conversely, the

ExFOCUS instructions may have lent to more of a transverse plane control over the hip rather than a frontal plane strategy. Examining muscle activation or transverse plane biomechanics would provide more insight into this hypothesis.

Regarding changes in vGRF, while the condition main effect was statistically significant, and the magnitude of change is similar to that previously reported, both groups and limbs increased and decreased vGRF following training making it difficult to meaningfully interpret these outcomes. Greater vGRF is associated with greater ACL injury risk. Therefore, the greater change (increase) in vGRF following ExFOCUS is not the ideal response to the training. Modifying the training task or directions appears necessary to reduce, not increase, injury risk.

5.5 Functional Performance

The change in triple hop distance was greater in the control compared to the ACL-R group. That the healthy group decreased triple hop distance without decreasing performance on any of the other functional tasks suggests that this was not related to either of the training interventions. Recent evidence [48]suggests that even if our InFOCUS or ExFOCUS training had improved biomechanics that this may not have transferred to the functional performance tasks as there are numerous discrepancies between 3D biomechanics and functional performance abilities, meaning that just because someone demonstrates optimal biomechanics when assessed using 3D motion capture that these biomechanics do not lend to greater hop distances. Further, as our tasks were not designed to improve muscle strength or power, which have been associated with performance on these functional tasks, it is not surprising that hop distance and jump height did not improve consistently across tasks in either of our groups.

5.6 Limitations

This study was not without limitations. First, we were not able to control for time since surgery. Participants were, on average, 32 months post-ACL-R. While it seems possible to change biomechanics at any time point following surgery, there may be an ideal window in which to intervene where changes may be greatest. Alternatively, a single bout of training may not be able to change biomechanics further out from surgery whereas participants in their initial post-operative rehabilitation period may see greater within-session changes as they have more room to improve their biomechanics at this early time point. Additionally, we were unable to control for graft type. However, there is little evidence to suggest that graft type influences jump-landing biomechanics. Another limitation is the small sample size of the present dataset. Additional participants are needed before our findings can be generalized to the population as a whole.

5.7 Conclusion

This preliminary investigation suggests that a single session of InFOCUS or ExFOCUS training is not sufficient to alter lower extremity biomechanics or functional performance in patients after ACL-R or healthy adults. To effectively reduce the risk of ACL injury, this intervention may need to last longer than a single session. Strategies to reduce injury risk among patients after ACL-R are necessary; therefore, future studies should have participants preform multiple sessions of each condition so that it can be observed whether or not changes occur.

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APPENDIX A: PATIENT REPORTED OUTCOMES

TEGNER ACTIVITY LEVEL SCALE

Please indicate in the spaces below the HIGHEST level of activity that you participated in
<u>BEFORE YOUR INJURY</u> and the highest level you are able to participate in <u>CURRENTLY</u>.

BEFORE INJURY: Level__________ CURRENT: Level___________

Level 10	**Competitive sports- soccer, football, rugby (national elite)**
Level 9	**Competitive sports- soccer, football, rugby (lower divisions), ice hockey, wrestling, gymnastics, basketball**
Level 8	**Competitive sports- racquetball or bandy, squash or badminton, track and field athletics (jumping, etc.), down-hill skiing**
Level 7	**Competitive sports- tennis, running, motorcars speedway, handball** **Recreational sports- soccer, football, rugby, bandy, ice hockey, basketball, squash, racquetball, running**
Level 6	**Recreational sports- tennis and badminton, handball, racquetball, down-hill skiing, jogging at least 5 times per week**
Level 5	**Work- heavy labor (construction, etc.) Competitive sports- cycling, cross-country skiing,** **Recreational sports- jogging on uneven ground at least twice weekly**
Level 4	**Work- moderately heavy labor (e.g. truck driving, etc.)**
Level 3	**Work- light labor (nursing, etc.)**
Level 2	**Work- light labor** **Walking on uneven ground possible, but impossible to backpack or hike**
Level 1	**Work- sedentary (secretarial, etc.)**
Level 0	**Sick leave or disability pension because of knee problems**

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2000 IKDC SUBJECTIVE KNEE EVALUATION FORM

Your Full Name____

Today's Date: ______/______/______ (Day / Month / Year)

Date of Injury: ______/______/______ (Day / Month / Year)

SYMPTOMS*:

*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.

1. 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

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

	0	1	2	3	4	5	6	7	8	9	10	
Never	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	Constant

3. If you have pain, how severe is it?

	0	1	2	3	4	5	6	7	8	9	10	
No pain	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	Worst pain imaginable

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

   ❑Not at all
   ❑Mildly
   ❑Moderately
   ❑Very
   ❑Extremely

5. 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 swelling

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

   ❑Yes ❑No

7. 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 giving way of the knee

Page 2 – 2000 IKDC SUBJECTIVE KNEE EVALUATION FORM

SPORTS ACTIVITIES:

8. 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

9. How does your knee affect your ability to:

		Not difficult at all	Minimally difficult	Moderately Difficult	Extremely difficult	Unable to do
a.	Go up stairs	❑	❑	❑	❑	❑
b.	Go down stairs	❑	❑	❑	❑	❑
c.	Kneel on the front of your knee	❑	❑	❑	❑	❑
d.	Squat	❑	❑	❑	❑	❑
e.	Sit with your knee bent	❑	❑	❑	❑	❑
f.	Rise from a chair	❑	❑	❑	❑	❑
g.	Run straight ahead	❑	❑	❑	❑	❑
h.	Jump and land on your involved leg	❑	❑	❑	❑	❑
i.	Stop and start quickly	❑	❑	❑	❑	❑

FUNCTION:

10. 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?

FUNCTION PRIOR TO YOUR KNEE INJURY:

Cannot perform daily activities	0	1	2	3	4	5	6	7	8	9	10	No limitation in daily activities
	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	

CURRENT FUNCTION OF YOUR KNEE:

Cannot perform daily activities	0	1	2	3	4	5	6	7	8	9	10	No limitation in daily activities
	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	❑	

APPENDIX B: EFFECT SIZE DATA

TABLE B1. Effect sizes for kinematic step-down data in the ACL-R group between InFOCUS and ExFOCUS conditions ([ExFOCUS-InFOCUS]/pooled standard deviation)

	d	**Lower Bound**	**Upper Bound**
Involved Limb			
Hip sagittal plane rotation	-0.46	-1.53	0.67
Hip frontal plane rotation	-0.56	-1.63	0.58
Knee sagittal plane rotation	-0.27	-1.35	0.84
Knee frontal plane rotation	-0.57	-1.64	0.58
Uninvolved Limb			
Hip sagittal plane rotation	-0.76	-1.83	0.42
Hip frontal plane rotation	0.43	-0.70	1.50
Knee sagittal plane rotation	-0.46	-1.53	0.68
Knee frontal plane rotation	-0.30	-1.38	0.81

TABLE B2. Effect sizes for kinematic step-down data in the ACL-R group ([post-pre]/pooled standard deviation)

	InFOCUS			**ExFOCUS**		
	d	Lower Bound	Upper Bound	d	Lower Bound	Upper Bound
Involved Limb						
Hip sagittal plane rotation	-0.11	-1.16	0.94	0.04	-1.06	1.12
Hip frontal plane rotation	0.14	-0.92	1.18	-0.17	-1.25	0.93
Knee sagittal plane rotation	0.54	-0.56	1.57	-0.52	-1.59	0.63
Knee frontal plane rotation	-0.14	-1.18	0.92	-0.22	-1.29	0.89
Uninvolved Limb						
Hip sagittal plane rotation	0.42	-0.71	1.49	-0.37	-1.44	0.76
Hip frontal plane rotation	0.34	-0.78	1.41	0.06	-1.03	1.15
Knee sagittal plane rotation	0.17	-0.93	1.25	0.44	-0.69	1.51
Knee frontal plane rotation	0.14	-0.96	1.23	0.13	-0.97	1.21

TABLE B3. Effect sizes for kinetic step-down data in the ACL-R group between InFOCUS and ExFOCUS conditions ([ExFOCUS-InFOCUS]/pooled standard deviation)

	d	**Lower Bound**	**Upper Bound**
Involved Limb			
Hip sagittal plane moment	-0.58	-1.69	0.61
Hip frontal plane moment	0.60	-0.60	1.71
Knee sagittal plane moment	-0.10	-1.18	1.00
Knee frontal plane moment	**0.81**	**-0.38**	**1.88**
Uninvolved Limb			
Hip sagittal plane moment	0.06	-1.03	1.15
Hip frontal plane moment	0.78	-0.40	1.85
Knee sagittal plane moment	-0.14	-1.22	0.96
Knee frontal plane moment	0.77	-0.41	1.84

Bolded value represents large treatment effect where knee frontal plane moment changed as a result of the ExFOCUS intervention; however, the confidence interval crosses zero.

TABLE B4. Effect sizes for kinetic step-down data in the ACL-R group ([post-pre]/pooled standard deviation)

	InFOCUS			ExFOCUS		
	d	Lower Bound	Upper Bound	d	Lower Bound	Upper Bound
Involved Limb						
Hip sagittal plane moment	0.27	-0.84	1.35	-0.64	-1.71	0.52
Hip frontal plane moment	-0.54	-1.61	0.61	0.61	-0.54	1.68
Knee sagittal plane moment	0.57	-0.54	1.59	2.09	0.63	3.27
Knee frontal plane moment	-0.54	-1.56	0.56	1.46	0.15	2.57
Uninvolved Limb						
Hip sagittal plane moment	**-2.00***	**-3.17**	**-0.56**	**-1.43***	**-2.53**	**-0.12**
Hip frontal plane moment	**-1.46***	**-2.57**	**-0.15**	**-0.93**	**-2.00**	**0.28**
Knee sagittal plane moment	**0.97**	**-0.24**	**2.05**	**1.80**	**0.40**	**2.94**
Knee frontal plane moment	**-0.94**	**-2.02**	**0.27**	**-1.85***	**-3.00**	**-0.45**

Bolded value represents large treatment effects suggesting that moments decreased in response to the intervention. *represent confidence intervals that do not cross zero.

TABLE B5. Effect sizes for kinematc step-down data in the ACL-R vs. Control group ([control-ACL-R]/pooled standard deviation)

	InFOCUS			ExFOCUS		
	d	Lower Bound	Upper Bound	d	Lower Bound	Upper Bound
Involved Limb						
Hip sagittal plane rotation	-0.04	-1.38	1.32	-0.44	-1.99	1.23
Hip frontal plane rotation	-0.34	-1.67	1.05	**-1.70**	**-3.23**	**0.28**
Knee sagittal plane rotation	0.34	-1.05	1.67	**-1.35**	**-2.87**	**0.53**
Knee frontal plane rotation	0.49	-0.93	1.81	-0.27	-1.84	1.37
Uninvolved Limb						
Hip sagittal plane rotation	0.38	-1.02	1.70	-0.30	-1.86	1.35
Hip frontal plane rotation	0.74	-0.72	2.05	**2.51***	**0.26**	**4.11**
Knee sagittal plane rotation	0.34	-1.05	1.66	-0.87	-2.40	0.88
Knee frontal plane rotation	-0.52	-1.84	0.90	-0.16	-1.74	1.46

Bolded value represents large treatment effects. Negative values suggest greater rotations in the ACL-R group compared to the control group. *represent confidence intervals that do not cross zero.

TABLE B6. Effect sizes for kinetic step-down data in the ACL-R vs Control group ([control-ACL-R]/pooled standard deviation)

	InFOCUS			ExFOCUS		
	d	Lower Bound	Upper Bound	d	Lower Bound	Upper Bound
Involved Limb						
Hip sagittal plane moment	0.30	-1.12	1.66	-0.45	-2.00	1.22
Hip frontal plane moment	-0.15	-1.52	1.26	0.47	-1.20	2.02
Knee sagittal plane moment	-0.66	-1.97	0.78	-0.65	-2.19	1.06
Knee frontal plane moment	-0.16	-1.50	1.21	**3.02**	**0.57**	**4.68**
Uninvolved Limb						
Hip sagittal plane moment	-0.14	-1.48	1.23	-0.05	-1.64	1.56
Hip frontal plane moment	**-1.58**	**-2.92**	**0.06**	**-1.69**	**-3.22**	**0.28**
Knee sagittal plane moment	-0.14	-1.48	1.23	-0.49	-2.04	1.19
Knee frontal plane moment	**-1.91**	**-3.27**	**-0.17**	**-3.49**	**-5.21**	**-0.85**

Bolded value represents large treatment effects. Negative values suggest larger moments in the ACL-R group compared to the control group. *represent confidence intervals that do not cross zero.

TABLE B7. Effect sizes for kinematic data in the ACL-R group between InFOCUS and ExFOCUS conditions ([ExFOCUS-InFOCUS]/pooled standard deviation)

	d	**Lower Bound**	**Upper Bound**
Involved Limb			
Hip sagittal plane rotation	**-0.83**	**-30.98**	**5.88**
Hip frontal plane rotation	0.16	-9.02	11.68
Knee sagittal plane rotation	0.48	-23.18	53.32
Knee frontal plane rotation	-0.71	-18.21	4.87
Uninvolved Limb			
Hip sagittal plane rotation	-0.75	-36.48	8.68
Hip frontal plane rotation	**-0.86**	**-14.19**	**2.47**
Knee sagittal plane rotation	0.43	-30.37	63.61
Knee frontal plane rotation	0.18	-6.39	8.61

Bolded value represents large treatment effect suggesting InFOCUS yielded large clinical effect on hip sagittal and frontal plane rotation in the involved and uninvolved limbs, respectively. However, confidence intervals cross zero.

TABLE B8. Effect sizes for kinematic data in the ACL-R group ([post-pre]/pooled standard deviation)

	InFOCUS			**ExFOCUS**		
	d	Lower Bound	Upper Bound	d	Lower Bound	Upper Bound
Involved Limb						
Hip sagittal plane rotation	-0.17	-14.65	10.85	-0.66	-28.02	8.42
Hip frontal plane rotation	0.12	-11.78	14.52	0.05	-9.70	10.56
Knee sagittal plane rotation	0.33	-8.78	15.66	0.43	-24.52	51.48
Knee frontal plane rotation	0.57	-5.52	16.06	-0.10	-12.37	10.55
Uninvolved Limb						
Hip sagittal plane rotation	0.08	-14.18	16.30	-0.77	-32.51	7.39
Hip frontal plane rotation	-0.44	-13.85	6.23	-0.45	-9.85	4.53
Knee sagittal plane rotation	-0.35	-14.90	8.06	0.54	-26.18	67.26
Knee frontal plane rotation	-0.49	-12.91	5.31	0.26	-5.41	8.33

TABLE B9. Effect sizes for kinetic data in the ACL-R group between InFOCUS and ExFOCUS conditions ([ExFOCUS-InFOCUS]/pooled standard deviation)

	d	**Lower Bound**	**Upper Bound**
Involved Limb			
Hip sagittal plane moment	0.22	-0.31	0.43
Hip frontal plane moment	0.39	-0.22	0.40
Knee sagittal plane moment	0.26	-0.60	0.88
Knee frontal plane moment	-0.69	-0.30	0.10
Vertical ground reaction force	-0.77	-0.97	0.27
Uninvolved Limb			
Hip sagittal plane moment	0.39	-0.36	0.64
Hip frontal plane moment	-0.73	-0.32	0.10
Knee sagittal plane moment	0.36	-0.34	0.58
Knee frontal plane moment	0.17	-0.14	0.18
Vertical ground reaction force	**0.82**	**-0.15**	**0.69**

Bolded value represents large treatment effect where vertical ground reaction force changed as a result of the ExFOCUS intervention; however, the confidence interval crosses zero.

TABLE B10. Effect sizes for kinetic data in the ACL-R group ([post-pre]/pooled standard deviation)

	InFOCUS			**ExFOCUS**		
	d	Lower Bound	Upper Bound	d	Lower Bound	Upper Bound
Involved Limb						
Hip sagittal plane moment	0.46	-2.73	6.07	-1.32	-0.47	0.07
Hip frontal plane moment	0.52	-2.80	6.92	-0.41	-0.38	0.24
Knee sagittal plane moment	-0.50	-25.70	10.74	0.45	-0.65	1.09
Knee frontal plane moment	0.53	-3.28	8.30	0.13	-0.26	0.30
Vertical ground reaction force	0.02	-0.76	0.78	-0.36	-0.62	0.40
Uninvolved Limb						
Hip sagittal plane moment	-0.36	-6.49	3.57	0.09	-0.73	0.81
Hip frontal plane moment	-0.47	-2.50	1.12	0.51	-0.18	0.32
Knee sagittal plane moment	-0.52	-26.95	10.93	**0.82**	**-0.39**	**1.05**
Knee frontal plane moment	-0.51	-4.37	1.79	0.41	-0.17	0.27
Vertical ground reaction force	-0.29	-0.32	0.20	-0.13	-0.71	0.61

Bolded value represents large treatment effect where knee sagittal plane moment changed as a result of the ExFOCUS intervention; however, the confidence interval crosses zero.

TABLE B11. Effect sizes for functional performance data in the ACL-R group between InFOCUS and ExFOCUS conditions ([ExFOCUS-InFOCUS]/pooled standard deviation)

	d	**Lower Bound**	**Upper Bound**
Involved Limb			
Single leg hop	-0.03	-0.35	0.33
Crossover hop	0.27	-0.63	1.01
Triple hop	-0.06	-0.84	0.76
Six-meter timed hop	-0.39	-0.28	0.14
Uninvolved Limb			
Single leg hop	0.19	-0.26	0.36
Crossover hop	0.45	-0.55	1.25
Triple hop	0.23	-0.66	0.98
Six-meter timed hop	-0.27	-0.21	0.13
Vertical Jump	-0.41	-2.14	1.02

TABLE B12. Effect sizes for functional performance data in the ACL-R group ([post-pre]/pooled standard deviation)

	InFOCUS			**ExFOCUS**		
	d	Lower Bound	Upper Bound	d	Lower Bound	Upper Bound
Involved Limb						
Single leg hop	0.47	-0.16	0.38	0.12	-0.33	0.41
Crossover hop	0.40	-0.56	1.16	0.20	-0.66	0.94
Triple hop	0.10	-0.78	0.92	-0.14	-1.00	0.80
Six-meter timed hop	**1.40**	**0.04**	**0.46**	0.39	-0.14	0.28
Uninvolved Limb						
Single leg hop	0.54	-0.18	0.48	0.22	-0.26	0.38
Crossover hop	0.42	-0.62	1.32	0.19	-0.71	0.99
Triple hop	0.07	-0.90	1.02	0.04	-0.85	0.91
Six-meter timed hop	0.36	-0.16	0.30	-0.08	-0.33	0.29
Vertical Jump	0.24	-1.56	2.36	0.18	-0.94	1.28

Bolded value represents large treatment effect where six-meter hop time improved as a result of the InFOCUS intervention.

TABLE B13. Effect sizes for functional performance data in the ACL-R vs. Control group ([ACL-R-Control]/pooled standard deviation)

	InFOCUS			**ExFOCUS**		
	d	Lower Bound	Upper Bound	d	Lower Bound	Upper Bound
Involved Limb						
Single leg hop	0.46	-0.27	0.49	-0.57	-0.72	0.34
Crossover hop	0.42	-1.11	1.91	-0.68	-2.08	0.84
Triple hop	0.57	-1.02	1.90	**-1.05**	**-2.33**	**0.47**
Six-meter timed hop	-0.32	-0.55	0.39	**1.35**	**-0.04**	**0.50**
Uninvolved Limb						
Single leg hop	-0.44	-0.60	0.34	-0.32	-0.54	0.36
Crossover hop	-0.63	-2.26	0.98	-0.39	-1.87	1.13
Triple hop	-0.68	-2.30	0.92	**-0.80**	**-2.04**	**0.68**
Six-meter timed hop	**0.84**	**-0.14**	**0.46**	0.79	-0.14	0.42
Vertical Jump	**1.08**	**-0.76**	**4.02**	0.57	-0.99	2.09

Bolded values represent large treatment effect; however, the confidence interval crosses zero.