EFFECTS OF A FOCUSED PLYOMETRIC INTERVENTION ON BIOMECHANICS AFTER ACL RECONSTRUCTION

by

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ABSTRACT

STEVEN JAMES PFEIFFER. Effects of a focused plyometric intervention on biomechanics after ACL reconstruction. (Under the direction of DR. ABBEY THOMAS)

PURPOSE: After an ACL reconstruction, patients demonstrate aberrant biomechanics when they return to sport. These aberrant biomechanics lead to joint degeneration, secondary injuries to the involved or uninvolved limb, and knee osteoarthritis. The purpose of this study was to determine whether or not a focused plyometric intervention had any effect on biomechanics in patients after an ACL reconstruction. METHODS: 4 subjects, 2 in the control group and 2 in the intervention group, completed our study. All four subjects completed a baseline and follow-up session. During these sessions, vertical ground reaction force and isokinetic strength were measured and the subjects completed multiple subjective self-reported surveys. The 2 subjects in the intervention group completed 12 plyometric sessions over 4 weeks, 3 times a week. RESULTS: The 2 intervention subjects showed changes in vertical ground reaction force and isokinetic strength in their hamstrings when compared to the intervention group. CONCLUSION: We concluded that our intervention shows trends towards improvements in biomechanics for patients post-ACL reconstruction. A major limitation of this study was the small sample size. With a larger sample size, our results may prove to have more significance.

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CHAPTER 1: INTRODUCTION

In the United States, up to 250,000 anterior cruciate ligament (ACL) tears occur annually.[1] The most common treatment for these injuries is surgical reconstruction and post-operative rehabilitation to help restore strength and function to the injured knee. The estimated total cost of ACL reconstruction and post-operative rehabilitation exceeds $10 billion annually. It must be noted that this value only accounts for the short-term costs associated with ACL injury and reconstruction; it does not account for long term effects, such as post-traumatic osteoarthritis, which occurs in up to 50% of all individuals who sustain an ACL injury.[2] With the large financial burden that has been put on the health care system, a great deal of emphasis has been placed on preventing ACL injuries. However, not only is the occurrence of ACL tears high, but the re-injury rate is also high. According to Paterno et al., a person who has undergone ACL reconstruction is 15 times more likely to sustain a second ACL injury (defined as injury to the same or opposite knee) than someone who has not sustained an ACL injury.[1]

ACL injuries typically occur by non-contact mechanisms such as twisting, pivoting, cutting, or landing from a jump.[3] In fact, an estimated 70% of ACL injuries are due to non-contact mechanisms are may be preventable by modifying lower extremity biomechanics. Risk factors for second ACL injury are likely similar to those for initial injury and may include poor biomechanics, neuromuscular imbalances, altered loading patterns, and compensatory movement patterns.[1] It is imperative that these modifiable risk factors be addressed so that the risk of subsequent ACL injuries is reduced and health care costs decrease.

One significant factor that influences ACL re-injury risk is poor biomechanics. Factors that are often implicated in the initial injury are reduced knee flexion angle and an increase in dynamic knee valgus. Dynamic knee valgus has been defined by Hewett[4] as combined motion at all lower extremity joints and potentially includes hip adduction and internal rotation, knee abduction and tibial external rotation, and ankle eversion. Patients after ACL reconstruction have similarly been shown to land with reduced knee flexion angles.[5] These aberrant biomechanics also lead to an increase in vertical ground reaction force (vGRF).[5] The vGRF occurs during jumping, walking, standing, or any activity in which something or someone is in contact with the ground. Further complicating the problem of poor biomechanics is lingering quadriceps weakness. When the quadriceps are weak, patients avoid flexing the knee to limit the eccentric demands on the muscle. Additionally, the function of the quadriceps is to absorb the energy of impact during landing. The quadriceps are unable to do this in the presence of muscle weakness and, therefore, the energy caused by the vGRF has to be absorbed by the static structures of the knee (i.e., the ACL and articular cartilage). This can lead to joint degeneration, pain, discomfort, and ACL injury.[5] Reducing vGRF to decrease the potentially injurious loads through the knee following ACL reconstruction seems imperative to optimize long-term joint health and reduce risk of second ACL injury.

Many studies have added and experimented with the rehabilitation process of the ACL injury with the intent of maximizing quadriceps strength and improving biomechanics. Some, such as Risberg et al.,[6] have designed neuromuscular training protocols that encompass exercises to improve balance, dynamic joint stability, and agility, demonstrating that pre-operative function may be restored as a result of these training protocols. None, however, have studied the effects of a focused plyometric intervention on vGRF. Plyometrics are quick and powerful movements to produce a stronger concentric contraction than that achieved through normal resistance training.[6] Due to the fact that most plyometric movements involve some kind of jump-landing motion, lowered vGRF is a logical outcome for patients who go through a plyometric intervention. In fact, researchers have shown that a focused plyometric intervention helps to improve jump performance and lower vGRF in healthy populations.[7,8] A supplemental, focused, plyometric intervention may be a valuable addition to post-operative rehabilitation following ACL injury and may aid in improving long-term outcomes for these patients. This study represents an important step in identifying interventions capable of improving lower extremity biomechanics to reduce second ACL injury risk.

1.1 Statement of the Problem

ACL injuries occur frequently during athletic activity and hinder an individual’s ability to perform daily activities. ACL injuries produce immediate pain and swelling, impair quadriceps strength, and alter lower extremity biomechanics. Despite successful surgical and post-operative rehabilitation, patients are often faced with long-term strength deficits and abnormal biomechanics that purportedly contribute to future joint degeneration and may precipitate second ACL injury.

Improving long-term patient health and reducing the risk of subsequent ACL injury, following the initial injury, is imperative to reducing the financial burden that ACL tears place on the health care system and those who need it. One such mechanism by which to improve health may be to improve lower extremity biomechanics following ACL reconstruction. It has been demonstrated previously that plyometric exercise can improve lower limb biomechanics and reduce ACL injury risk. Employing a focused plyometric intervention following ACL reconstruction may have similar benefits for the patient.

1.2 Specific Aims and Hypotheses

Specific Aim 1: To determine the influence of a focused plyometric intervention following ACL reconstruction on vGRF and knee joint kinematics during landing.

Hypothesis 1.1: Patients who receive the plyometric intervention will demonstrate reduced vGRF and increased knee flexion angles upon landing compared to those not performing the plyometric intervention

Specific Aim 2: To determine the influence of a focused plyometric intervention following ACL reconstruction on muscular strength in the quadriceps and hamstrings.

Hypothesis 2.1: Patients who receive the plyometric intervention will demonstrate increases in muscular strength in the quadriceps and hamstrings compared to those not performing the plyometric intervention.

1.3 Limitations:

One of the main limitations on this study is the small population sample. Ideally, this study would be completed with a much bigger cohort so that if significant results are seen, they can be generalized more accurately to the general population. However, the sample size is based on and comparable to previous literature.

Another limitation is a lack of blinding. The same investigator will be supervising the intervention and collecting baseline and follow-up data. To minimize bias, the same instructions and feedback will be provided to all participants during testing, regardless of group.

1.4 Significance of the Study

With how common second ACL injuries are and with how devastating knee osteoarthritis is in patients after an ACL injury, it is necessary to try and reduce the risks for both. Unfortunately, current treatment strategies following ACL injury do not optimally protect against future injury or joint degeneration. If a focused plyometric program can mitigate these risks, then it should widely be accepted into the rehabilitation process as a part of the final program for return to activity.

CHAPTER 2: REVIEW OF THE LITERATURE

2.1 Introduction

The purpose of this literature review is to detail: 1) knee joint anatomy; 2) the function of the ACL; 3) the mechanism of ACL injury; 4) jump landing biomechanics; 5) ACL injury prevention strategies; 6) traditional rehabilitation following ACL reconstruction; and 7) second ACL injury incidence and risk factors.

2.2 Anatomy of the Knee

The knee joint complex is comprised of three joints: the tibiofemoral, the patellofemoral, and the proximal tibiofibular. This literature review will focus on the primary joint of the knee complex, the tibiofemoral joint.

The tibiofemoral joint is a hinge joint formed by the articulation of the tibia and femur. The distal femur is the most proximal part of the knee joint[9] and is covered in articular cartilage, which serves to allow weight bearing, shearing, and stress through the femoral condyles and the patella.[9] The femoral condyles are the most distal points of the femur and are separated by the intercondylar notch, inferiorly and posteriorly.[9] This intercondylar notch is the location of the attachment of the ACL superiorly.[9]

The femoral condyles meet with the medial and lateral tibial condyles to form the tibiofemoral joint.[9] While the tibia is a skinnier bone down the shaft towards the ankle, the proximal portion forms a much more expansive surface.[9] The medial tibial plateau is the most proximal surface of the tibia and has a slight concavity to meet with the convexity of the femoral condyle.[9] The lateral plateau is flat, bordering on convex.[9] The contact area on the medial plateau is larger than the lateral plateau, which is why there is more articular cartilage around the medial side than the lateral.[9] This assists in the greater amount of forces that are placed on the medial joint during functional weight bearing activities.[9] The intercodylar eminence is situated between the two condyles of the tibia.[9] Above this are the medial and lateral intercondylar tubercles, which serve as the attachment points of the ACL and posterior cruciate ligament (PCL).[9]

While this study focuses primarily on the ACL, it is also important to outline the 3 other main ligaments in the knee: the PCL, the medial collateral ligament (MCL), and the lateral collateral ligament (LCL). The word cruciate means, "cross-shaped." The ACL and PCL are named in accordance with this meaning as they form an "X" or cross when observing the knee anteriorly or posteriorly. The ACL runs from the posteromedial aspect of the lateral condyle of the femur to the anteromedial tibial plateau.[10] While some described the ACL's fiber bundle arrangement as a three-band system, most describe it as a two-bundle system.[9] Between the two attachment points, the ACL spirals on itself, which allows for a portion of the ligament to remain taut through the full range of knee flexion/extension motion.[9] While the knee is extended, the posterolateral band is tightened while the anteromedial band is slack.[9] In knee flexion, the posterolateral band is slack while the anteromedial band is taut. The PCL attaches to the proximal tibia on the posterior side and on the lateral portion of the medial femoral condyle.[9] The fiber bundle of the PCL has been seen as either a two-bundle system or four-bundle system, making it the wider of the two ligaments.[9] The PCL functions similarly to the ACL in that in both knee flexion and extension, part of the PCL remains taut and part remains slack. However, the PCL prevents posterior translation of the tibia on a fixed femur, while the ACL which prevents anterior tibial translation.[9]

The MCL and the LCL both serve as stabilizers during adduction and abduction movements, respectively.[9] It has been reported that 90% of all knee ligament injuries occur to the MCL, the ACL, or a combination of MCL and ACL.[9] The MCL is much more broad and flat than the LCL.[9] The MCL also has been found to have an anterior, superficial portion and a posterior, deeper portion that covers most of the medial side of the tibiofemoral joint.[9] Both of these portions attach proximally at the medial femoral epicondyle while the superficial portion attaches distally to the shaft of the tibia and the deeper portion attaches posteriorly to the tibial condyle.[9] The deeper portion also attaches to the medial meniscus.[9] The LCL runs from the lateral epicondyle of the femur to the head of the fibula.[9] Unlike the MCL, the LCL does not have any attachments to either of the menisci.[9]

Menisci are fibrocartilaginous disc located between the femoral condyles and the tibial plateau.[9] Each meniscus has its own unique shape and purpose in the function of the knee joint. The medial meniscus has more of a C shape and is larger in diameter than the lateral meniscus.[9] The medial meniscus also serves as an attachment point for the semimembranosus muscle.[9] This allows for some excursion of the meniscus during knee flexion.[9] The lateral meniscus is more circular in its shape and nearly forms a full ring.[9] Even though the medial meniscus has been shown to have a greater diameter than the lateral, the lateral covers a larger surface area of the tibia than the medial.[9] Seedhom found that the medial meniscus takes on only about 50% of the load while the lateral meniscus takes on about 70% of the load passing through the respective tibiofemoral compartments during weight bearing.[11]

The final aspect of the knee joint anatomy is the muscles that are involved with movement, specifically the quadriceps and hamstring muscles. The quadriceps are made up of four muscles; the rectus femoris, the vastus lateralis, the vastus medialis, and the vastus intermedius.[9] All four of these muscles insert at the quadriceps tendon and the patellar tendon.[9] Since all of these muscles insert at the same position, they all are responsible for the same action in the knee joint, knee extension.[9] The hamstrings, or the knee flexor group, are made up of the biceps femoris (long and short heads), the semimembranosus, and the semitendiosus.[9] Both the long and short head of the biceps femoris attach to the fibular head, the fascia of the lower leg, the LCL and the lateral capsule of the knee.[9] They are the most lateral of the hamstring muscles.[9] The semimembranosus and semitendinosus both arise at the same point as the long head of the biceps femoris at the ischial tuberosity.[9] Both of these muscle become tendons the further distally they travel.[9] The semimembranosus remains muscular longer than the semitendinosus and the semimembranosus attaches deeper than the semitendinosus does at the fascia of the lower leg.[9]

Both of these groups of muscles, the quadriceps and hamstrings, directly influence the amount of stress that is put on the ACL[9]. With the main actions of the knee, flexion and extension, being controlled by the quadriceps and hamstrings, the ACL is often times put into a weak position. Due to the quadriceps being an antagonist muscle to the ACL,[12] and the main action of the quadriceps being extension, the ACL has a great amount of stress put on it. Markolf et. Al[12] found that hamstrings were most effective in altering cruciate forces due to their function being knee flexion, the opposite of the quadriceps.

2.3 Anterior Cruciate Ligament Function

The primary function of the ACL is to limit anterior translation of the tibia relative to the femur.[10] As discussed previously, the ACL is comprised of two bundles. When the knee is in a more extended position, the posterolateral bundle is better able to resist anterior tibial translation. As the knee flexes, however, the anteromedial bundle dominates[13]. Additionally, the ACL may aid other static and dynamic stabilizers in the knee to limit abduction and rotation.[10] Surgical and cadaveric studies suggest that the posterolateral bundle provides more support to out of plane loads than the anteromedial bundle[14-16]. However, the role of the ACL in limiting knee abduction and rotational loads is controversial. The ACL may not limit frontal plane knee joint loading in the presence of intact collateral ligaments[17-21]. Further, the ACL does not resist frontal plane loads in a non-weightbearing state[22].

Not only is the ACL a stabilizer of the knee, it is also a sensory organ with a dense mechanoreceptor population.[23] One of the major functions of these mechanoreceptors is to initiate reflexes that help to limit injurious movements at the knee.[23] When an ACL is torn, there is damage to these mechanoreceptors. This damage leads to altered afference. When the signals that are transmitted from the knee to other surrounding musculature are altered, quadriceps function and knee joint biomechanics become impaired.[6] Even after the treatment process of surgery and rehabilitation, there is little consensus in the literature as to whether or not mechanoreceptor function is ever truly restored following ACL injury. This suggests that proprioceptive function may remain impaired due to the lack of restored function in the afferent and efferent pathways.

2.4 Mechanism of Anterior Cruciate Ligament Injury

ACL injuries are often classified as contact, meaning that the injury occurred because of direct contact between the injured person and another individual, or non-contact, wherein the injured person was untouched at the time of injury. An estimated 70% of these injuries are due to non-contact mechanisms.[1] Many hypotheses have been developed for what causes an ACL injury. The injury likely results from a combination of intrinsic and extrinsic factors.

Extrinsic factors may be related to the environment around the individual at the time of injury. Some of these extrinsic factors include where an event is being played, the type of surface being utilized, or what kind of footwear might be worn during the activity. In a 2010 study, Dowling[24] found that subjects had altered biomechanics at the knee when playing on a high-friction surface. The altered biomechanics included knee flexion angle, knee flexion moment, and knee valgus moment[24].

Intrinsic factors may be anatomical, hormonal, or biomechanical.[25] In recent research, factors such as femoral notch width at the anterior outlet have been shown to increase ACL injury risk.[26] Hewett[27] many other anatomical factors that can lead to a predisposition to an ACL injury. These include increased knee joint laxity, increased hamstrings flexibility, increased tibial translation, increased foot pronation and navicular drop, and a BMI level greater 1 standard deviation (SD) above the mean.[27]

Hormonal influences are purportedly why females are more likely to sustain an ACL injury than males performing similar activities.[4] Some research has shown that the luteal phase has a higher incidence rate of non-contact ACL injuries.[28,29] However, there is also research that has shown that ACL injuries are increased during the ovulatory phase due to the peak in estrogen and relaxin.[30]This discrepancy leads to a difficulty in determining which hormonal factor has the greatest impact on ACL injury risk. Because they can be modified, biomechanical risk factors for injury often receive a great deal of attention from researchers and clinicians. These risk factors include weakness in the quadriceps, a reduction in knee flexion angle, and a propensity towards increases in abduction postures and loads around the knee.[31] However, it is widely accepted that one of most common biomechanical positions that athletes injure their ACL in is a dynamic valgus position.[27] It is important that this valgus position in a very complex, 3-dimensional movement. In video analysis, we the tibia externally rotated, the knee close to full extension, the foot planted, and deceleration.[27]

2.5 Jump Landing Biomechanics

In healthy individuals, knee flexion excursion during landing is approximately 20-30 degrees, depending on gender.[32] Hip flexion angles have a similar range, varying upon gender, of 24-30 degrees.[32] Hip frontal plane data showed between 9.0 degrees of abduction and a neutral frontal lane position.[33] Knee frontal plane data showed between 12 degrees and 20 degrees of abduction.[33]

Once a patient has gone through an ACL-reconstructive surgery and rehabilitation process, we see the knee flexion angle drop by around 10-15 degrees (Unpublished data from our lab). Pre-injury, we know that there are some biomechanical risk factors that put people at risk for an ACL injury.[27] If a patient, male or female, demonstrates a greater dynamic knee valgus orientation, they may be at a higher risk of an ACL injury.[27]

Additionally, greater amounts of internal rotation at the knee and or hip may increase risk of an ACL injury.[27] Patients who have an ACL reconstruction surgery often have an imbalance in biomechanics related to the jump-landing movement. It is known that after an ACL injury, there is a distinct lack of quadriceps strength and activation in the involved leg.[34] This weakness causes there to be a disruption in the load bearing process in the knee.[34] This can be seen in the jump landing movement. When someone who has torn his or her ACL performs a jump landing, the lack of quadriceps activation causes the person to limit knee flexion and avoid eccentric use of the quadriceps to decelerate the landing process. This leads to a stiff-legged landing which brings more force through the knee instead of distributing it throughout the lower extremity.[35] When this disruption happens, there is a lack of shock absorption, which can lead to future ACL injury.[34]

2.6 Anterior Cruciate Ligament Injury Prevention

As previously stated, efforts to prevent ACL injury often focus on the biomechanical risk factors for injury as these are likely modifiable. In an attempt to improve knee flexion and eliminate stiff-legged landing, researchers have focused on reducing vGRF.[36] Hewett et al.[36] found a reduction of 22% in vGRF in a study completed on female athletes in jump sports (e.g., basketball and volleyball). The results in the study by Hewett et al.[36] suggest that neuromuscular training techniques may improve jump-landing, leading to a more efficient distribution of energy throughout the lower extremities. There are other studies that have used neuromuscular training techniques to reduce vGRF.[6] One of the main components of these studies is plyometric training.

2.6.1 Plyometric Training

Plyometric training has been demonstrated to improve jump performance.[37] While this is one benefit of plyometric training, the benefits towards biomechanical performance are also prevalent.[8] Myer showed a reduction in vGRF when comparing plyometric training to balance training.[8] However, while the benefits of plyometrics on improving landing biomechanics are well understood in a healthy population, a concentrated plyometric training protocol has not been tested on patients post-ACL reconstruction. If the hypothesis of this study proves true, it could change the ACL rehabilitation protocol to reduce re-injury risk and help protect against joint degeneration.

2.7 Post-ACL Reconstruction Rehabilitation

After surgery to repair the damaged ACL, patients are then advised to go through a relatively long rehabilitation process of physical therapy. The rehabilitation process has major focuses, as the time progresses, that are overarching goals for the patient. It is important to note that not all rehabilitation programs are the same and most of the programs vary due to physical therapists' methods and surgeons' recommendations. The following guideline is an overview of progression points used by Risberg.[6] Early on, it is important to make sure that the patient is treated in such a way that they have a decrease in their kinesiophobia.[38] From weeks 0-4, the physical therapist works with the patient to try and re-establish an independent activity level for daily living by having the rehabilitation focus on the sensorimotor aspect.[38] From weeks 5-26, the patient starts to transition from "patient" to "athlete."[38] This is done with a blending or resistance training and neuromuscular training that will help reestablish strength, balance, power, and endurance.[38] Once this has been accomplished, weeks 27-36 focus on sport-specific activities that will develop even more muscular control.[38] After week 36, the rehabilitation process begins to become patient-specific. If the athlete is progressing and, under the supervision or coaches or clinicians, shows a readiness to return to full activity, then he or she can be cleared to participate fully.[38] While this method has merit, this is not a standardized method that physical therapists and surgeons follow closely. A lack of standardized methodology, validated assessment methods and outcome measures, and careful and complete definitions of these terms is needed in the rehabilitation of patients post ACL-reconstruction.[39]

2.8 Second Anterior Cruciate Ligament Injury

Even though the precise mechanism of ACL injury is unknown, it is well understood that there is a high risk of re-injury to the same or contralateral limb following initial ACL injury. Paterno et al.[1] completed a longitudinal study looking at the re-injury rates of patients who sustained an ACL injury. The results of that study showed that an ACL injury makes someone 15 times more likely to sustain a second ACL injury.[1] The problem may lie within the surgical and rehabilitation processes. After surgery and rehabilitation, strength is often not restored to a level necessary to prevent re-injury.[40] This is also seen by the study done by Shelbourne[41] where the percent of athletes who were able to return to sport were between 62-74%, based upon whether or not they were a competitive college athlete or a recreational athlete. This reduction in strength leads to impaired biomechanics in the involved leg, especially in the muscles around the knee such as the quadriceps. When the quadriceps are not as strong, the patient starts to utilize compensatory biomechanical strategies to avoid using those muscles.[31] This leads to increased loads throughout other areas of the leg, which can lead to damage in the cartilage around the knee as well as increasing ACL re-injury rates.[31] In order to reduce re-injury rates and improve long-term joint health in these patients, post-operative rehabilitation must be enhanced to optimally restore strength and biomechanics.

CHAPTER 3: METHODS

3.1 Participants

Four adults with a history of ACL injury participated in this study. Each of these patients was: 1) between the ages of 18-30 years; 2) cleared to return to full activity without the use of a knee brace by their surgeon; 3) free of other orthopedic injuries to the lower extremities or low back in the previous six months; and 4) free of previous lower extremity surgery besides the ACL reconstruction. Participants were randomized into two groups, plyometric and control (n=2/group). This study was approved by the Institutional Review Board at UNC Charlotte. All participants provided written, informed consent prior to enrollment.

3.2 Procedures

The baseline measurement and follow up test were identical. Testing order was randomized prior to participant enrollment and maintained across both testing sessions for each individual.

3.2.1 Self-report surveys

All participants completed multiple subjective questionnaires during the initial and final testing sessions. These questionnaires included the Knee Injury and Osteoarthritis Outcome Score (KOOS), International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form, Tegner Activity Scale, Tampa Scale for

Kinesiophobia, and Patient Health Questionnaire-2 (PHQ-2)..The KOOS asks questions about symptoms during daily and sporting activities as well as knee-realted quality of life.[42] It is scored on a scale of 0-100 with 100 meaning no symptoms and 0 meaningextreme symptoms.[42] The IKDC is a tool that is used to measure changes in symptoms, function, and sports activity in patients treated for knee conditions.[43] It is scored on a scale of 0-100 with 0 meaning extreme limitations on activity and 100 meaning no limitations on activity.[43] The Tegner Activity Scale assesses the participant's physical activity level before and after injury.[44] It is scaled from 0-10 with 0 meaning the subject is living a sedentary lifestyle and 10 meaning that the subject is competing in sports at a national elite level.[44] The Tampa Scale for Kinesiophobia is used to assess fear of movement.[45] It is scaled from 17-68 with higher numbers indicating greater levels of kinesiophobia.[45] The PHQ-2 is used as a tool to screen for depression by inquiring about the frequency of depressed mood and anhedonia over the past two weeks.[46] It is scored on a scale of 0-6 with 0 meaning low frequency of depressed moods and 6 meaning high frequency of depressed moods.[46]

3.2.2 Biomechanics Assessment

Landing biomechanics were observed using a jump-landing task associated with the Landing Error Scoring System (LESS).[47] Participants stood atop a 30cm box placed 50% of the participant's height away from the force platform on which the participants were to land (Bertec, Columbus, Ohio; Figure 1).[33] The participants jumped forward from the box, landed with the target foot on the force platform, and immediately performed a vertical jump for maximal height.[33] Participants completed 3 successful trials of the jump-landing task for each limb, the order of which was randomized. Successful trials were defined as trials in which the participant's foot landed squarely within the center of the force platform. Participants were allowed sufficient practice trials prior to testing until they were familiar with the dynamic task.

Figure 1. The Landing Error Scoring System (LESS)

3.2.3 Muscle Strength Assessment

Quadriceps and hamstring strength were assessed concentrically (60°/s) using a Biodex isokinetic dynamometer (System 3, Biodex, Inc., Shirley, NY) (Figure 2).[48] Participants were seated on the dynamometer with their arms crossed over their chests, their hips flexed to 85° and the fulcrum of the dynamometer aligned with the knee joint center.[48] Participants were instructed to extend and flex the knee through the full, available range of motion.[48] Next, participants performed a single set of 5 repetitions. The peak torque from repetitions 2-5 was extracted and normalized to participant body mass (Nm/kg) for statistical analysis.[48] All strength assessments were performed bilaterally. Participants received verbal and visual feedback during testing to encourage maximal effort.

Figure 2. Representative figure of muscle strength testing.

3.2.4 Functional Performance Tasks

All of our subjects completed multiple functional performance tasks during their baseline and follow-up sessions. These tasks included the broad jump, bilateral single leg hop, and a gait test to determine normal walking speed. The broad jump and single leg hops were measured with measuring tape that served as a line of reference for the jumps. During the broad jump and single leg hop tasks, the subjects were given a practice trial of each before performing three repetitions of each movement. In these three movements, the subjects were instructed to jump out as far as possible while landing with both feet sticking to the spot where they originally landed. If the either of the subject's feet moved following landing, the trial was not counted and they were asked to repeat it.

The gait test was performed using the Microgate OptoGait system for gait analysis. Subjects were instructed to walk through the LED transmitting bars at what they consider a normal walking speed. The example that was given to all of our subjects, who were all students was, “Walk at the speed to which you would normally walk to class.”

3.3 Interventions

3.3.1 Plyometric Intervention

The plyometric group will complete a 4-week plyometric intervention (3 days/week; 12 sessions total).[8] Each session will start with a five-minute dynamic warm-up. Participants will then complete the intervention consisting of a series of exercises of gradually increasing complexity (Appendix A). The exercises for each week will be completed once with rest built in during periods of explanation for the next exercise. Following each session, the patients will complete a cool down regiment consisting of lower extremity (e.g., hamstrings, quadriceps, calves) and lower back stretching.

3.3.2 Control Intervention

Participants in the control group will not receive any intervention. This is consistent with the standard of care for patients cleared for full activity following ACL reconstruction.

3.4 Statistical Analysis

The independent variables for this study consisted of group (intervention or control) and time (pre- and post-intervention). The primary dependent variable was vGRF during the jump-landing task. Secondary dependent variables included quadriceps and hamstrings strength. Data was analyzed using 2x2, mixed models, repeated measures ANOVAs. T-tests were utilized in the presence of significant interactions. The alpha level was set at <0.05. All analyses were completed in SPSS (v21, IBM Corporation, Armonk, NY).

CHAPTER 4: RESULTS

4.1 Self-Reported Outcomes

Four participants completed this study. There were no differences in demographics between groups (Table 1). Responses for all patient-reported surveys can be found in Table 2 and Appendix B. KOOS QOL was greater in the control compared to the plyometric group both prior to and following the intervention (*P*=0.046). No other survey outcomes were different between groups.

Table 1. Participant demographics. Data are mean ± standard deviation unless otherwise noted.

	Plyometric (n=2)	**Control (n=2)**	***P*-value**
% female	100	50	
Age (years)	21.00±0.00	20.50±0.71	0.423
Height (cm)	175.26±0.00	176.53±19.76	0.936
Body mass (kg)	72.72±12.86	70.00±18.65	0.869

Table 2. Patient-reported survey results. Data are mean ± standard deviation.

	Plyometric		Control	
	Pre	**Post**	**Pre**	**Post**
KOOS Pain	97.00±4.24	93.00±5.66	97.00±4.24	100.00±100.00
KOOS Symptoms	62.50±2.12	60.50±4.95	66.00±2.83	67.50±4.95
KOOS ADL	100.00±0.00	98.50±2.12	100.00±0.00	100.00±0.00
KOOS Sport/Rec	75.00±0.00	85.00±14.14	100.00±0.00	97.50±0.35
KOOS QOL	78.00±4.24	78.00±4.24	97.00±4.24	97.50±4.24
IKDC	83.9±6.51	83.90±9.76	96.6±3.25	95.45±1.63
Tegner Activity Scale	6.00±1.41	----	7.00±1.41	----
Tampa Scale of Kinesiophobia	32.00±1.41	32.00±1.41	29.50±0.71	29.50±3.53
PHQ-2	1.00±1.41	0.00±0.00	0.00±0.00	0.00±0.00

KOOS: Knee Osteoarthritis Outcomes Survery, ADL: Activities of Daily Living, Rec: Recreation, QOL: Quality of Life, IKDC: International Knee Documentation Committee, PHQ-2: Patient Health Questionnaire

4.2 Vertical Ground Reaction Force

There was a significant group by time interaction for involved limb vGRF (*P*=.019; Appendix C). Post-hoc analyses revealed that there were no differences between the control group and plyometric group at baseline (*P*=0.325) or follow-up (*P*=0.417) time points. Additionally, there were no differences in the involved limb vGRF within either the control (*P*=0.152) or the plyometric group (*P*=0.102) between baseline and follow-up. For the involved limb, there was a significant time main effect such that vGRF was lower at follow-up (*P*=0.040). There was no group main effect to report for the involved limb (*P*=0.923). For the uninvolved limb vGRF there were no significant interactions (*P*=0.633) or main effects (time *P*=0.149, group *P*=0.868) to report.

4.3 Muscular Strength Assessment

There were no significant group by time interactions for knee extension strength in the involved (*P*=0.283; Appendix D) or uninvolved (*P*=0.457) limbs. There were no time (involved: *P*=0.061; uninvolved: *P*=0.658) or group (involved: *P*=0.274; uninvolved: *P*=0.194) main effects for knee extension strength in either limb.

For knee flexion strength, there were no significant interactions in the involved (*P*=0.184) or uninvolved (*P*=0.057) limbs. Regardless of group, knee flexion strength was lower at baseline compared to follow-up for the involved (*P*=0.032) but not uninvolved (*P*=0.555) limbs. There were no group main effects for either limb (p-values here).

4.4 Functional Performance Tasks

There were no significant group by time interactions for broad jump (*P*=0.563; Appendix E). There were no time (*P*=0.564) or group (*P*=0.125) main effects for broad jump.

There were no significant group by time interactions for single leg forward hop in the involved (*P*=0.856) or the uninvolved (*P*=0.384) limbs. There were no time (involved: *P*=0.601; uninvolved: *P*=0.710) or group (involved: *P*=0.605; uninvolved: *P*=0.434) main effects for single leg forward hop in either limb.

There were no significant group by time interactions for gait speed (*P*=0.979). There were also no time (*P*=0.429) or group (*P*=0.750) main effects for gait speed.

CHAPTER 5: DISCUSSION

Aberrant biomechanics persist following ACL reconstruction and may contribute to the risk of second ACL injury. Plyometric exercises reduce initial ACL injury risk and may, therefore, be beneficial post-operatively to reduce risk of subsequent injury. The purpose of this study was to determine the influence of a focused plyometric intervention following ACL reconstruction on vGRF and muscular strength in the quadriceps and hamstrings. We observed improvements in involved limb vGRF and knee flexion strength at follow-up.

5.1 Vertical Ground Reaction Force

Participants demonstrated a decrease in the vGRF in the involved limb at follow-up regardless of group assignment. Closer examination of our individual participant data reveals that the observed time main effect was driven by changes in the plyometric group, as both of these participants reduced their vGRF following testing while the same was not true of control participants. Previous studies have shown that a reduction in vGRF is common in healthy adults following plyometric intervention.[8,36] One study examined reducing vGRF in female patients after an ACL reconstruction and the subjects in that study saw a 22% reduction in vGRF.[36] These significant changes prove the trends that we saw, in our smaller sample size, of vGRF being reduced after plyometrics. Considering that greater vGRF during landing is associated with increased risk of ACL injury,[49] the ability to reduce vGRF is important to injury prevention.

Though it is known that higher vGRFs are associated with greater injury risk, it is unknown by how much participants must decrease their vGRF to reduce injury risk. Each of the plyometric group participants demonstrated a substantial reduction in vGRF (45.5% and 36.77% respectively) following the intervention. We feel that such large reductions in vGRF are likely associated with positive reductions in injury risk and demonstrate great potential for our intervention.

5.2 Muscle Strength

Participants in the intervention group demonstrated an increase in knee flexor strength in the involved limb (13.9% and 9% respectively) at follow up but no significant increase in the uninvolved limb at follow up. Improving muscle strength after ACL reconstruction is imperative; [48] however, there were no significant changes in knee extensor strength, in the involved or uninvolved limbs, at follow up. A possible cause for the increases in knee flexor muscle strength, and not knee extensor muscle strength, could be the specificity of the plyometric program design. The focus was put on the landing aspect during each of the movements and feedback was provided to the subjects on “landing soft” in order to provide the reduction in vGRF that was seen. This also means that there was more emphasis on the part of the movement where the hamstrings were contracting concentrically and the quadriceps were contracting eccentrically. As muscle strength was measured concentrically in our study, it makes sense that only changes in knee flexor strength were observed. A different plyometric program focused on maximal movements, which emphasized the concentric contraction of the quadriceps.[50] This study found improvements in knee extensor strength rather than knee flexor strength.[50] A previous study with a similar plyometric program, focusing upon landing and biomechanics, provided increases in knee flexion torques.[3651] This is important for ACL prevention efforts due to risk of injury with weak hamstrings.[36,52] If an athlete has weak hamstrings, then there is greater strain put onto the quadriceps, eccentrically, during the landing task. Without the concentric contribution of strengthened hamstrings, the energy distribution is skewed and there is potential for greater risk of injury.[52]

5.3 Functional Performance Tasks

The intervention we created did not produce any statistically significant differences in any of the functional tasks the participants performed. However, our participants realized improvements in different tasks. One of our plyometric subjects saw a 20% broad jump distance increase, 23% uninvolved limb single leg hop distance increase, and 23% involved limb single leg hop distance increase. These sorts of increases were not seen with our other plyometric subject. The subject who saw increases played competitive volleyball, but had not completed plyometrics recently before our intervention. This subject's body could have responded better due to their history of completing similar tasks. Plyometrics have generally been proven to improve performance in functional movements such as the broad jump and single leg hop.[8,53] Even though this intervention was not designed for performance improvement, some of our individual data was trending towards improvements.

5.5 Limitations

Presently, we are underpowered to observe statistical significance between groups and over time. However, this study is part of an ongoing investigation and the results reported presently are preliminary. This study would have also benefitted greatly from access to a 3D motion capture analysis system to allow for synchronous kinematic data collection from which inferences about strategies used to reduce vGRF could be determined.

5.6 Conclusion

This study serves as the first step in determining what role focused plyometric interventions may have in the rehabilitation process for patients who have undergone ACL reconstruction. The results we found so far show trends such as reduction in vGRF and improvements in knee flexor strength. If these trends hold up, upon completion of a larger study, then this intervention could demonstrate the need for more intensive plyometric exercise as part of post-operative rehabilitation.

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APPENDIX A: PLYOMETRIC INTERVENTION

PLYOMETRIC EXERCISE	TIME	REPETITIONS
Week 1		
Line Jumps	15 seconds	
Line Jumps with Vertical		8
Squat Jumps	15 seconds	
Tuck Jumps	15 seconds	
Lunge Jumps	15 seconds	
Box Jumps		8
AP Barrier Jumps	15 seconds	
Broad Jump with Vertical		8
Box Drop with Vertical		8
Week 2		
Line Jumps	20 seconds	
Line Jumps with Vertical		10
Squat Jumps	20 seconds	
Tuck Jumps	20 seconds	
Lunge Jumps	20 seconds	
Box Jumps		10
AP Barrier Jumps	20 seconds	
Broad Jump with Vertical		10
Box Drop with Vertical		10
Week 3		
Squat Jumps	20 seconds	
Tuck Jumps	20 seconds	
Single Leg Forward Hop, Bilateral		8 per side
Single Leg Box Drop, Bilateral		8 per side
Broad Jump+Box Jump+Box Drop+Vertical Jump		8
Box Drop+Vertical Jump+Sprint		8
Broad Jump+Box Jump+Box Drop+Cut Movement		8 per side
Week 4		
Squat Jumps	20 seconds	
Tuck Jumps	20 seconds	
Single Leg Forward Hop, Bilateral		8 per side
Single Leg Box Drop, Bilateral		8 per side
Broad Jump+Box Jump+Box Drop+Vertical Jump		10
Box Drop+Vertical Jump+Sprint		10
Broad Jump+Box Jump+Box Drop+Cut Movement		8 per side

APPENDIX B: PATIENT-REPORTED OUTCOME FIGURES

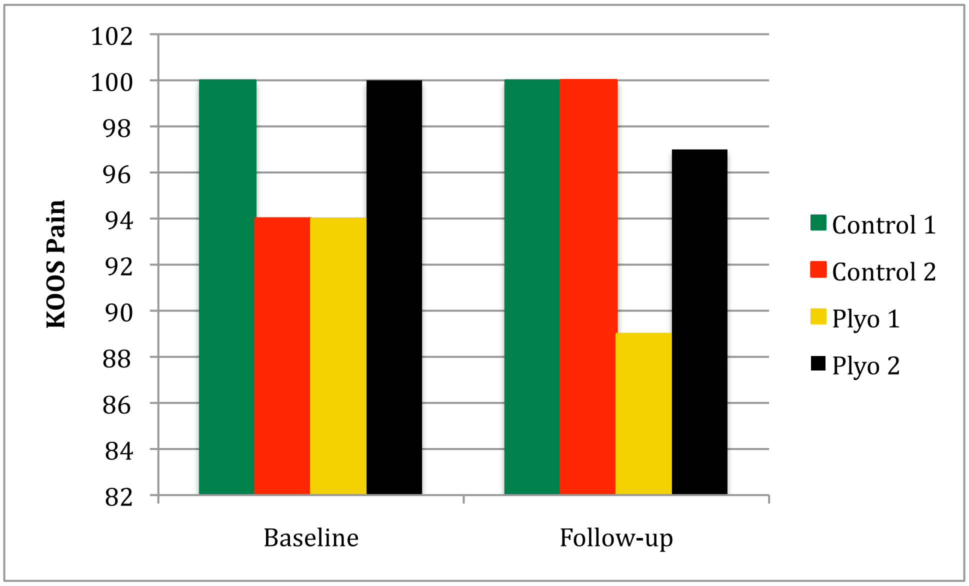

Figure B1: Knee Osteoarthritis Outcome Score (KOOS) Pain

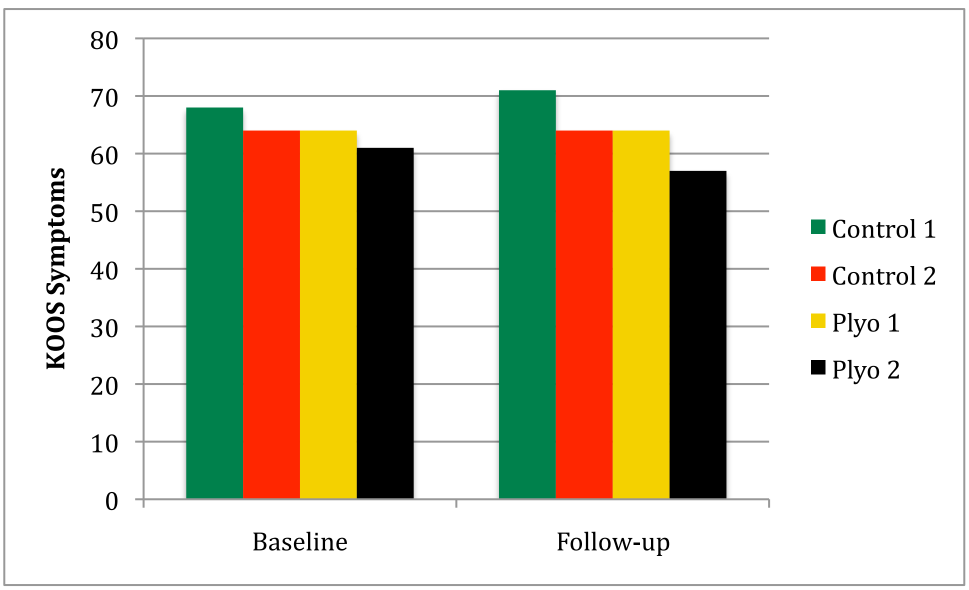

Figure B2: Knee Osteoarthritis Outcome Score (KOOS) Symptoms

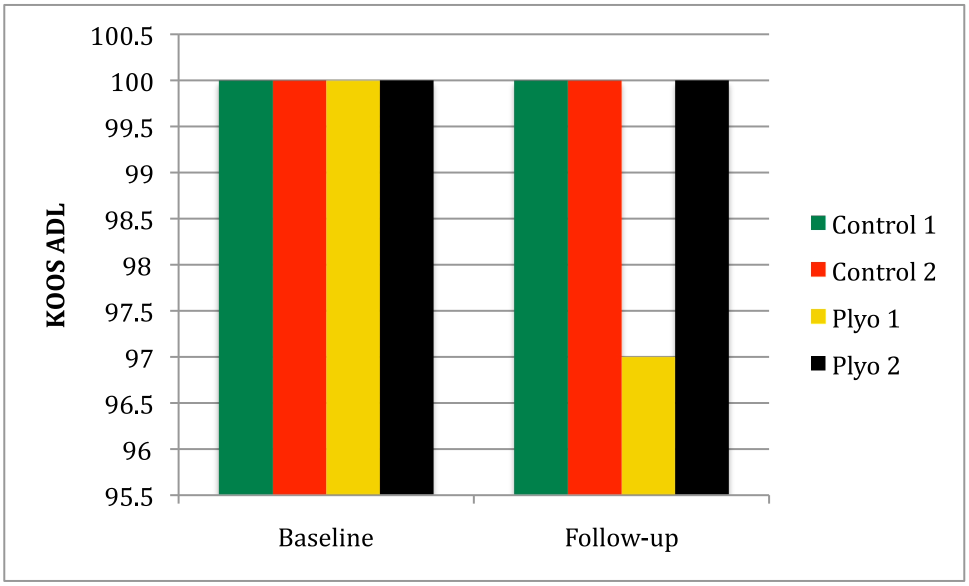

Figure B3: Knee Osteoarthritis Outcome Score (KOOS) Activities of Daily Living (ADL)

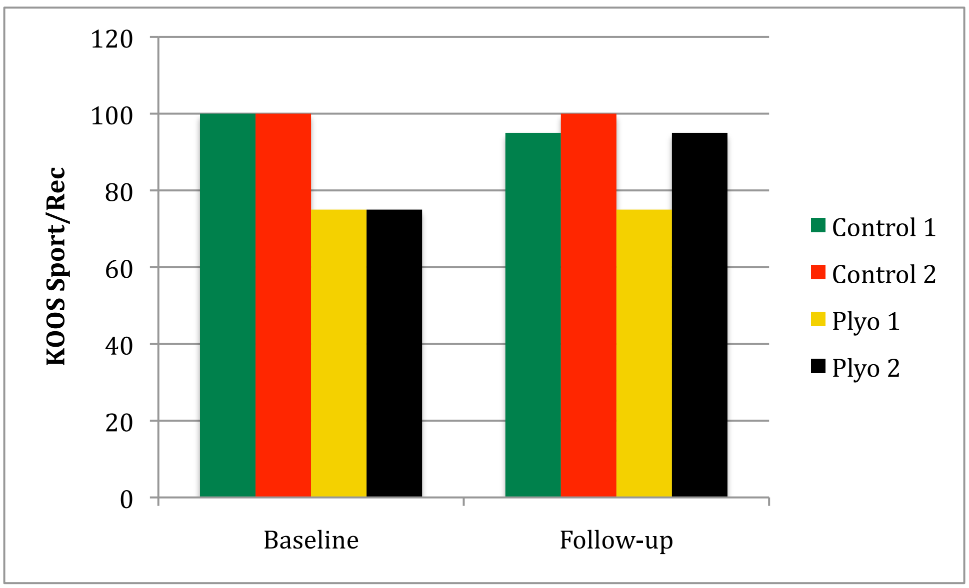

Figure B4: Knee Osteoarthritis Outcome Score (KOOS) Sports and Recreation

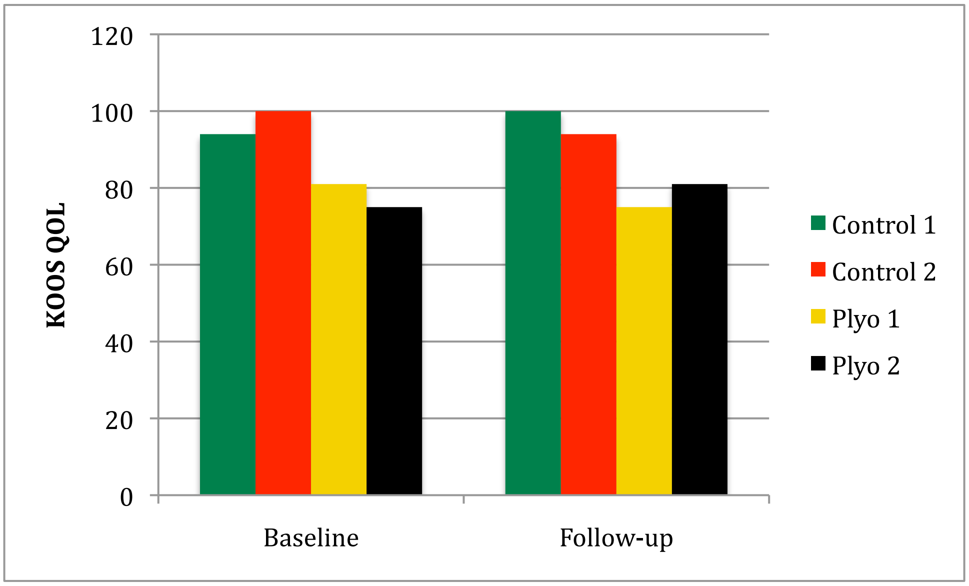

Figure B5: Knee Osteoarthritis Outcome Score (KOOS) Quality of Life (QOL)

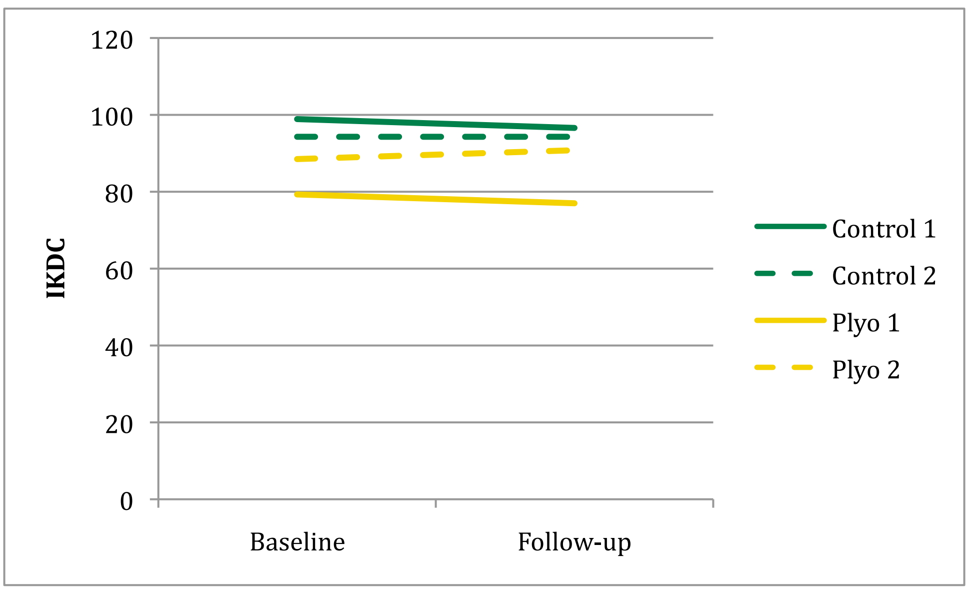

Figure B6: International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form

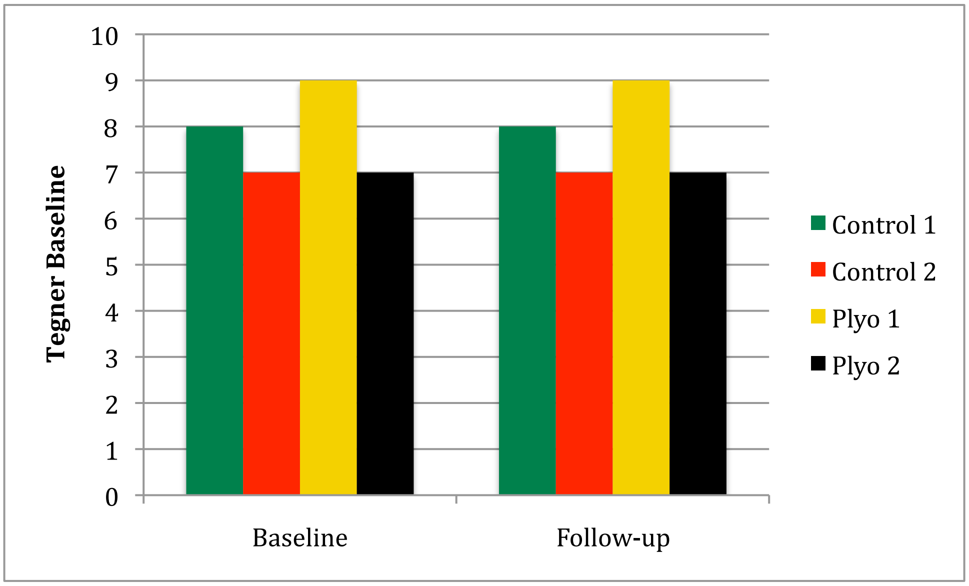

Figure B7: Baseline Tegner Activity Scale

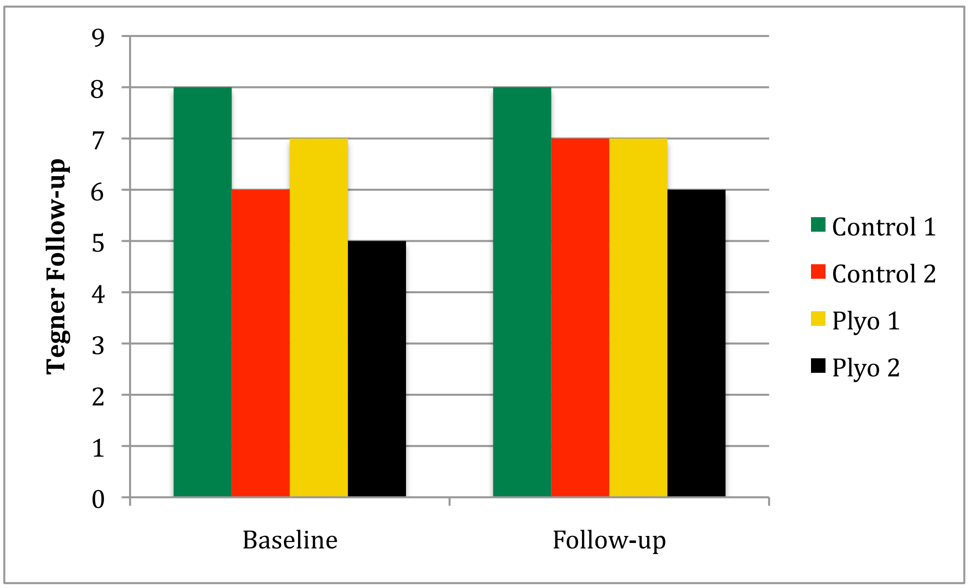

Figure B8: Follow-up Tegner Activity Scale

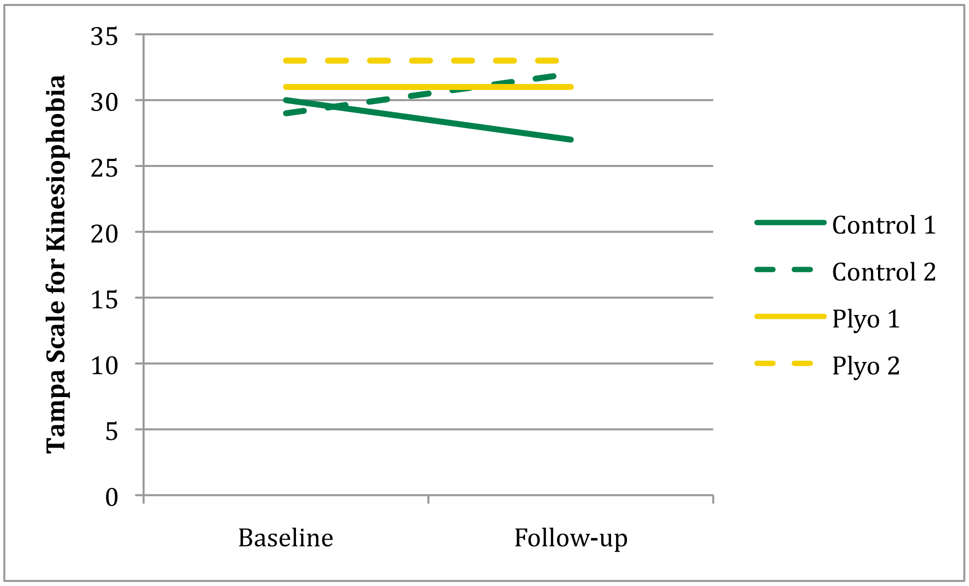

Figure B9: Tampa Scale for Kinesiophobia

APPENDIX C: VERTICAL GROUND REACTION FORCE FIGURES

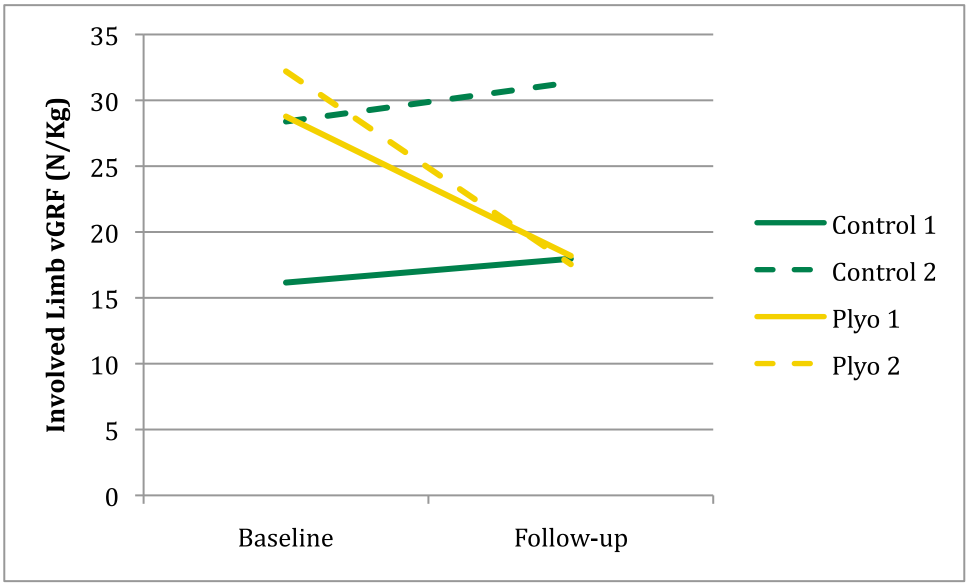

Figure C1: Involved Limb Vertical Ground Reaction Force

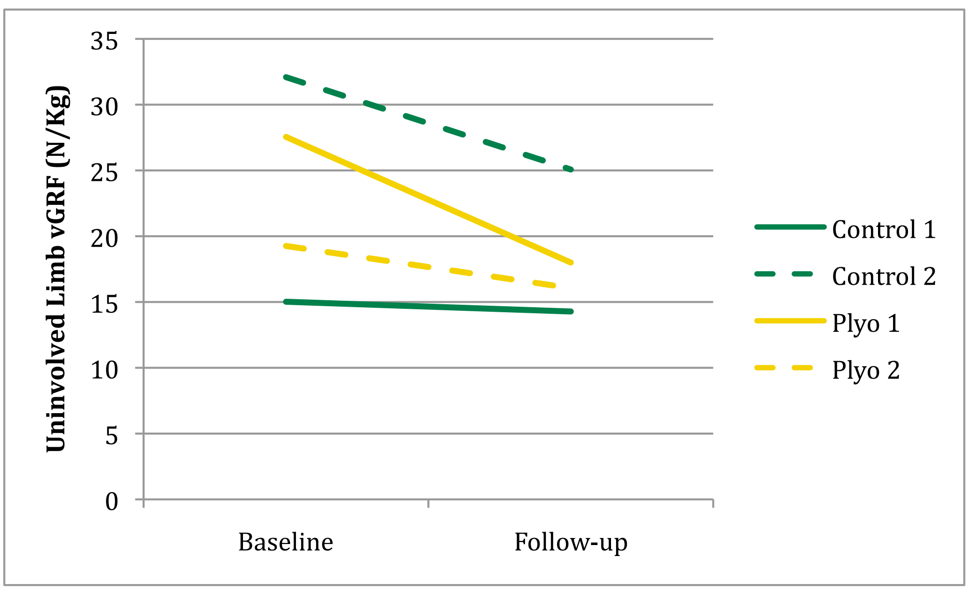

Figure C2: Uninvolved Limb Vertical Ground Reaction Force

APPENDIX D: MUSCLE STRENGTH FIGURES

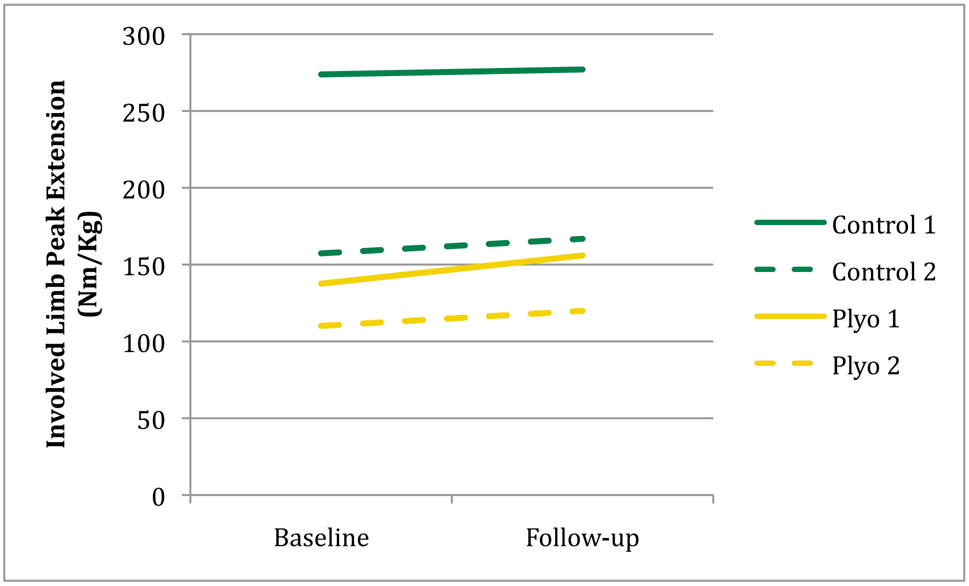

Figure D1: Involved Limb Peak Extension

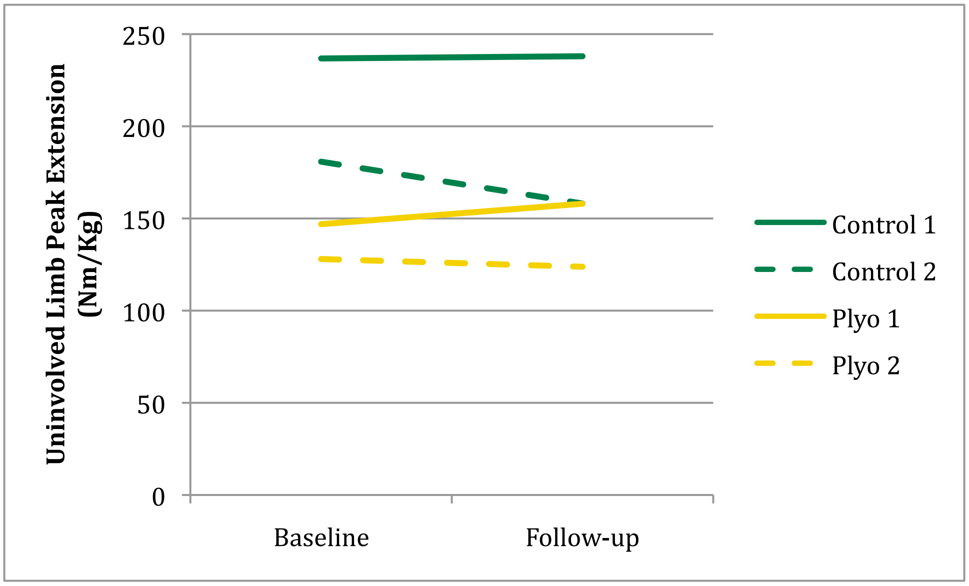

Figure D2: Uninvolved Limb Peak Extension

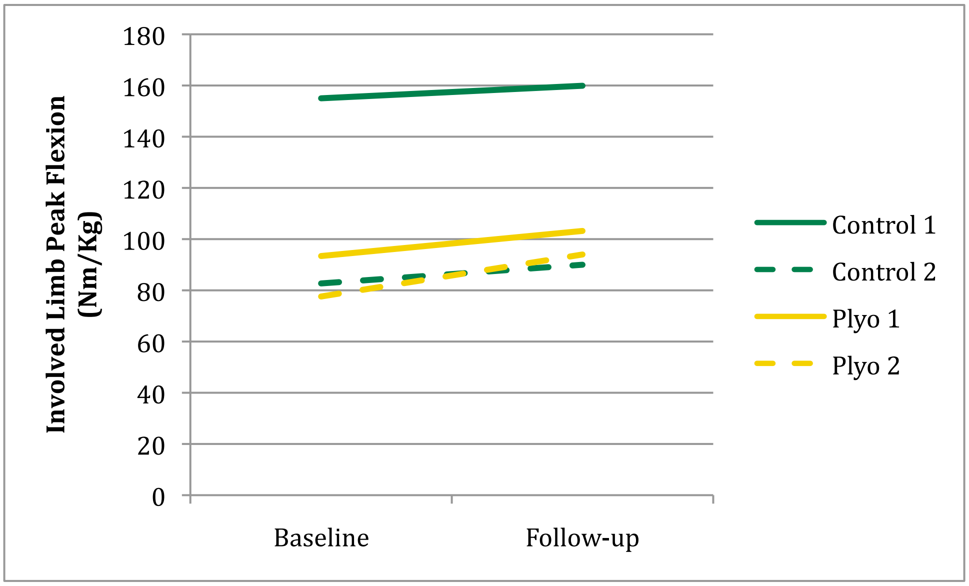

Figure D3: Involved Limb Peak Flexion

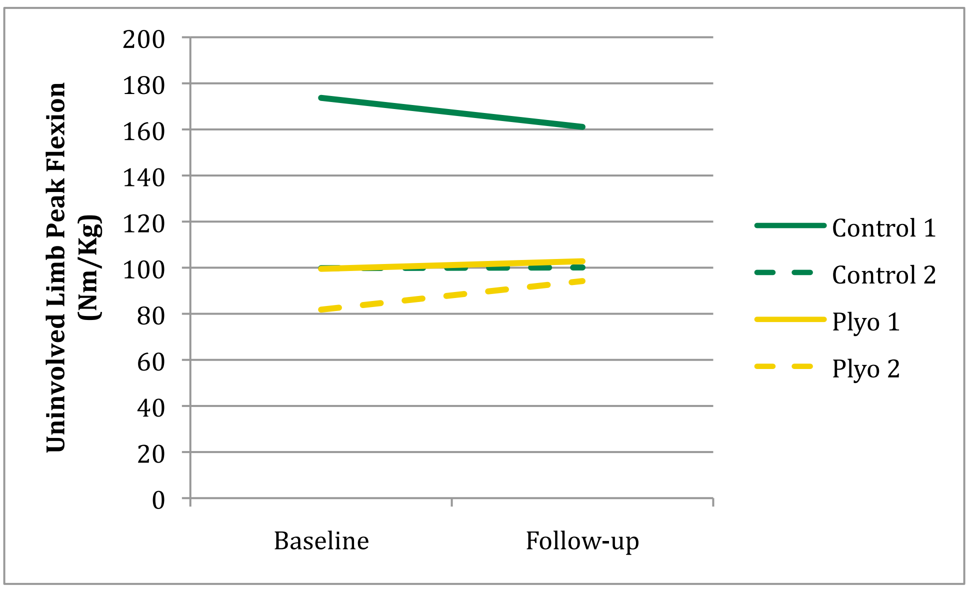

Figure D4: Uninvolved Limb Peak Flexion

APPENDIX E: FUNCTIONAL PERFORMANCE OUTCOME FIGURES

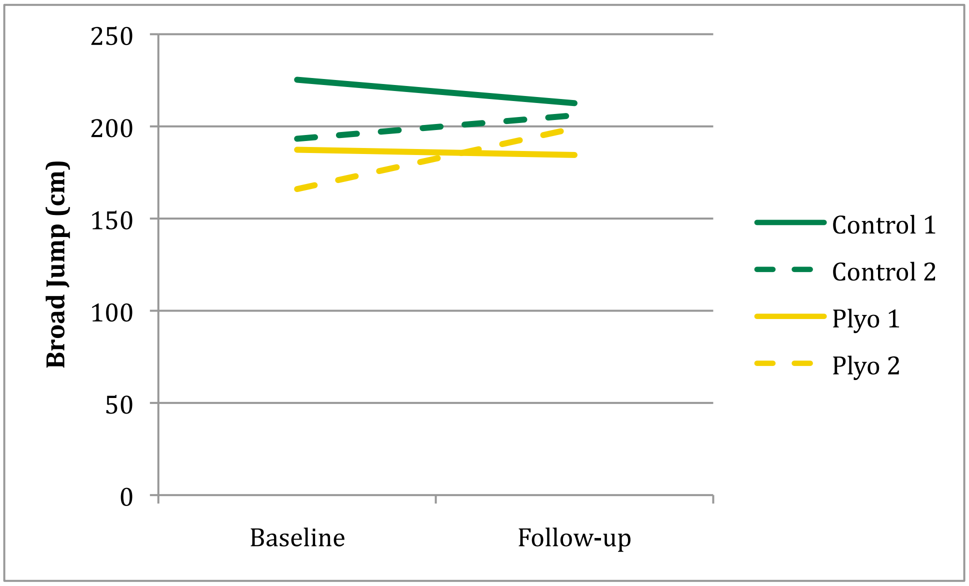

Figure E1: Broad Jump Distance

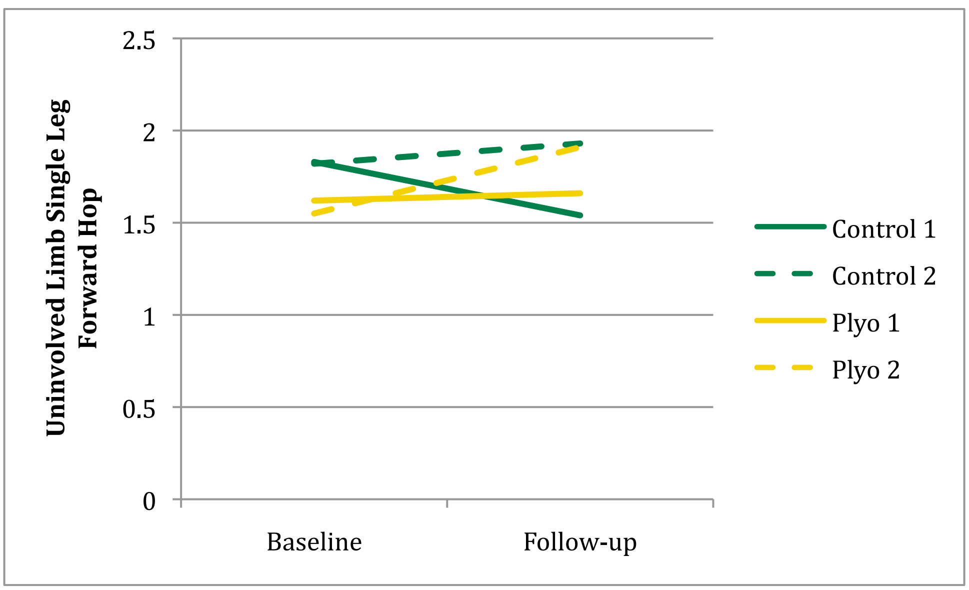

Figure E2: Involved Limb Single Leg Forward Hop Distance

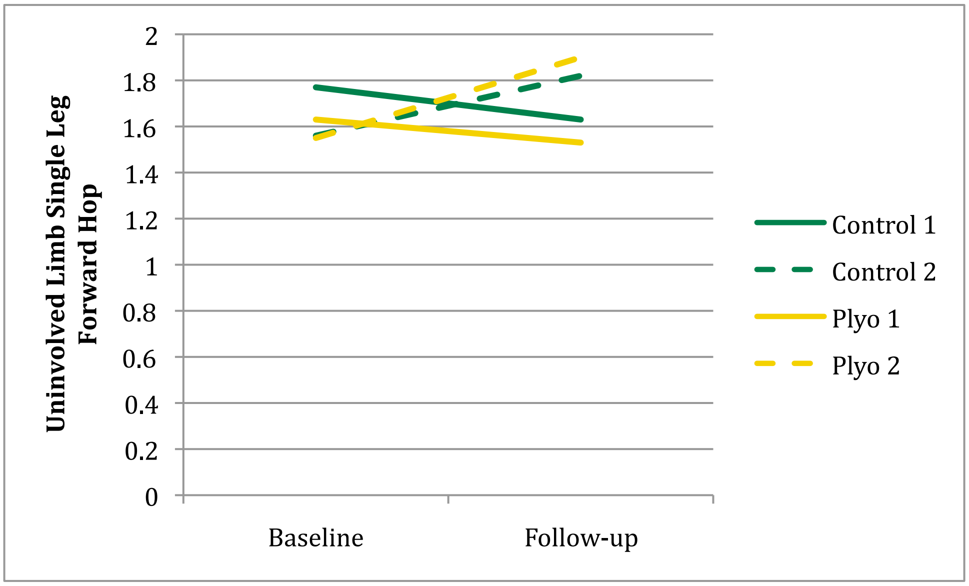

Figure E3: Uninvolved Limb Single Leg Hop Distance

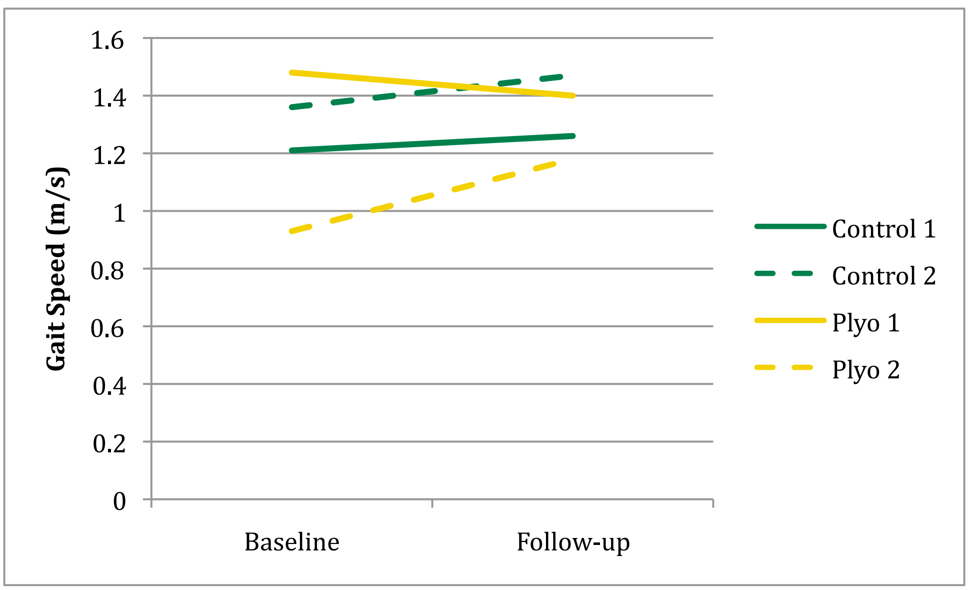

Figure E4 Gait Speed