Preliminary Analysis of a Randomized Parallel Trial: A 10-Week Training Program Comparing Traditional and Single-Foot Elevated Full Squats in ACL Injured Persons

by

Liane Marie Yolande Jean

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

Faculty of Physical Education and Recreation
University of Alberta

Abstract

Quadriceps atrophy and weakness is a common sequela following ACL injury. Restoring quadriceps function, defined as coordination, size and strength, is imperative for individuals to return to activity to the same level prior to injury. Current rehabilitation programs are unable to fully restore quadriceps function. Therefore, the purpose of this study was to investigate differences in quadriceps strength, kinetics and function during multi-joint tasks between traditional and single-foot elevated squats after a 10-week training program emphasizing full depth squats. A randomized parallel trials research design was employed. ACL injured persons, prior to surgery were randomly assigned to a traditional (n=10) or single-foot elevated (n=10) group. The traditional group performed plate squats with both feet on the ground, the single-foot elevated group performed plate squats with the non-involved limb placed on a 5 cm platform. Maximal isometric knee extensor strength was measure between 15°-75° of knee flexion. Motion analysis was used to measure ankle, knee and hip extensor work during sit-to-stands, vertical jumping and landing. ANOVA and cohen's d effect sizes were used to compare between the involved and non-involved limb and from pre- to post-intervention. Maximal isometric knee extensor strength increased at all knee flexion angles. Further, knee extensor asymmetry between 30°-75° knee flexion was eliminated post-intervention. Knee extensor work increased in the involved limb post-intervention in the traditional (d=0.25) and single foot elevated group (d=0.38). However, the non-involved limb also had an increase in knee extensor work in the traditional (d=0.36) but not the single-foot elevated group (d=-0.02). Resulting in larger knee extensor work asymmetry performed in the traditional squat group (d=0.85) post intervention, but reduced asymmetry in the single-foot elevated group (d=0.67). Concluding, full depth squats was successful at increasing knee extensor strength in both groups. Single-foot elevated squats provided a motor learning effect that transferred to sit-to-stands.

Preface

This thesis is original work by Liane Jean. The research project, of which this thesis was a part, received research ethics approval from the University of Alberta Research Ethics Board under the name "Comparison of Normal and Single-Foot Elevated Squats in ACL Injured Persons", No Pro000589914, approved September 16, 2016. All participants provided written consent, in the case of participants under the age of 18 parental consent was provided.

Acknowledgement

I would like to thank my supervisor, Dr. Loren Chiu for his guidance on completing this research project. Without his help this project and my thesis would not have been possible. I would also like to thank Dr. Chiu for assisting in training participants.

I would like to thank the National Strength and Conditioning Association for providing funding for this project.

I would like to thank Sarah Hudson and Lauren Vincent for their help in training participants and collecting data.

I would like to acknowledge and thank all the participants who volunteered their time and effort.

Content

List of Tables

List of Figures

List of Abbreviations

ACL - Anterior cruciate ligament

NJM - Net joint moment

SFE - Single-foot elevated

%1RM - Percentage of one-repetition maximum

Chapter 1: Introduction

Rationale

Quadriceps muscle atrophy is a common sequela in individuals following anterior cruciate ligament (ACL) injury, regardless of whether reconstructive surgery is performed [1]. Sport and recreation involve activities such as running, jumping and landing; in these activities, the quadriceps act at the knee to generate energy during propulsion [2] and absorb energy during impact [3]. Thus, restoring quadriceps strength and mass are a primary objective in rehabilitation and return to activity training for ACL injured individuals. However, to date rehabilitation approaches have been unable to optimally improve the quadriceps' functional capabilities – defined as coordination, muscle strength, volume, cross-sectional area – after ACL injury [4].

Magnetic resonance imagining has shown ACL injured individuals have quadriceps muscle atrophy. Muscle size, quantified as volume and cross-sectional area, is different between: 1) the involved and non-involved limbs, and 2) copers versus non-copers [5, 6]. Copers are those individuals who are able to maintain a higher level of strength, stability and functional abilities after injury. However, differences in muscle size are specific to individual quadriceps muscles. The rectus femoris has no difference in volume and cross-sectional area in the involved limb compared to the non-involved limb [1, 5, 6]. Further, there are no differences in rectus femoris volume and cross-sectional area between copers and non-copers. However, the vasti demonstrate marked loss in total volume and cross-sectional area in the involved limb, particularly in non-copers. Vasti atrophy is associated with deficits in knee extension strength [7]. Deficits in knee extension strength and quadriceps size can persist for several years after ACL reconstruction and rehabilitation [8, 9]. Moreover, quadriceps weakness is believed to contribute to the use of compensatory strategies during functional tasks [10, 11]. For example, Salem et al. [11] demonstrated reduced knee extensor and increased hip extensor net joint moment in the involved limb during bilateral squat exercise. The combination of quadriceps weakness and compensatory strategies may contribute to the low levels of return to activity and high incidences of re-injury in ACL injured persons.

Increasing quadriceps muscle strength has been found to increase the success rate for individuals returning to sport or other physical activities. Mikkelsen et al. [12] reported twice as many patients were successful at returning to activity when leg extension exercises were added to a program of closed kinetic chain exercises. However, this success rate was still only 50%, indicating a large proportion of individuals who were still unable to return to the same level of activity prior to the ACL injury. While quadriceps strength plays a key role in return to activity, leg extension exercise may not be ideal for restoring quadriceps function. Leg extension exercise targets the rectus femoris muscle as opposed to the vasti muscles [13]. Following 12 weeks of leg extension exercise training, greater relative changes in anatomical cross-sectional area, muscle thickness and angle of pennation occur in the rectus femoris as opposed to the vasti muscles [14]. Therefore, leg extension exercises may be more effective in eliciting adaptations in the rectus femoris versus the vasti. As ACL injured persons have atrophy of the vasti but not rectus femoris in the involved limb, exercises targeting the vasti may provide better functional outcomes [1, 5, 6]. Accordingly, rehabilitation programs must focus on increasing strength, volume and cross sectional area of the vasti muscles.

Closed kinetic chain exercises have been used to target and improve strength in the vasti muscles in a healthy population [13, 15]. Although the squat exercise is successful in increasing the strength of the vasti muscles in a healthy population, the shift in mechanical effort from the knee extensors to the hip extensors observed by Salem et al. [11] in ACL injured limbs suggest that typical squat exercise is likely inappropriate for training the quadriceps in persons recovering from ACL injury. Other variations of squat exercise, including single-leg variations have also been found to be sub-optimal for restoring quadriceps function [16], which is due to the same compensatory strategy described by Salem et al [11, 17].

Recently, our laboratory has investigated a novel variation of squat exercise, where the foot of one limb is placed on an elevated platform. During single-foot elevated squats, knee extensor net joint moment, vastus lateralis and vastus medialis EMG activity increase in the non-elevated limb compared to a traditional bilateral squat where both feet are on the same ground level [18]. These parameters indicate that greater stress is placed on the vasti of the non-elevated limb. Therefore, as single-foot elevated squats increase the stress placed on the vasti of the non-elevated side, it can be hypothesized that greater adaptations in the quadriceps muscles of the non-elevated side will occur through training with this exercise. Thus, the single-foot elevated squat should be studied in ACL injured persons to increase vasti muscle volume and cross-sectional area, strength and functional performance in the involved limb.

Purpose and Hypothesis

The purpose of this study is to investigate differences in lower extremity strength, kinetics and function during multi-joint tasks between traditional and single foot-elevated squats after a 10-week training program. Specific aims of this investigation include 1) comparing quadriceps strength in the involved limb between the traditional and single-foot elevated squats, 2) compare knee and hip extensor moments in the involved limb during multi-joint tasks between traditional and single-foot elevated squats and, 3) investigate the transfer of strength during vertical jumping and landing mechanics between traditional and single-foot elevated squats. It is hypothesized that 1) single-foot elevated squats will be more effective at increasing isometric quadriceps strength in the involved limb at 75˚, 60˚, 30˚ and 15˚ of knee flexion, 2) single-foot elevated squats will be more effective at increasing knee and hip extensor moments in the involved limb during multi-joint tasks and, 3) single-foot elevated squats will increase the functional abilities of the quadriceps during vertical jumping and landing by increasing knee extensor work in the involved limb.

Significance

This study investigated the effects of traditional and single-foot elevated full squats in persons with ACL injuries. To the authors' knowledge, this is the first study to investigate knee extensor strength using full squats in persons with ACL injuries. Further, it is the first study to investigate traditional and single-foot elevated squats to increase knee extensor work symmetry in persons with ACL injuries.

Literature Review

Mechanism of ACL Injuries

Anterior cruciate ligament (ACL) ruptures are common among young active individuals. The ACL is a stabilizing intracapusular ligament of the knee joint, originating on the anterior intercondylar area of the tibial plateau and inserting posterior and superior to the medial side of the lateral femoral condyle [19]. The ACL prevents anterior translation and medial rotation of the tibia relative to the femur. Therefore, the ACL acts as a stabilizer at the knee by restricting extreme ranges of motion. Risk factors associated with ACL injuries can be divided in four main categories: biomechanical, environmental, anatomical and hormonal. Biomechanical and environmental can be explained further by categorizing the injuries into non-contact and contact mechanisms. Contact injuries occur due to physical contact with another individual or object other than the ground. Non-contact injuries are believed to occur due to faulty movement patterns. Movement patterns associated with ACL injuries include sudden decelerations while running, pivoting or landing [19]. ACL injuries commonly occur during these movements when the knee is fully extended, and the ligament is stretched. The specific motions that may injure the ACL are anterior tibial translation, valgus knee collapse and excessive internal or external tibial rotation. Several, anatomical factors, such as posterior tibial slope, intercondylar notch width and tibial torsion may predispose an individual to an increased risk of non-contact injury [20, 21].

Women have a higher incidence of non-contact ACL injury than men; furthermore women have a higher re-injury rate then men [22]. Although there are distinct differences in the rate of ACL injuries between men and women, the consequences of injury appear to be homogenous between sexes [23]. These consequences include quadriceps atrophy, compensatory movement strategies and knee instability. Therefore, approaches to rehabilitation and return to activity are not different for men and women. Instead these approaches are designed to target the specific deficits that result from the injury.

Current Approaches to Rehabilitation

Rehabilitation Pre-Reconstructive Surgery

The goal of pre-surgical rehabilitation is to increase function so that the individual is able to tolerate the stressors of inactivity post-surgery [24]. Pre-rehabilitation focuses on regaining the strength and functional outcomes of the quadriceps muscles before reconstruction surgery. ACL injured persons who participate in pre-rehabilitation have higher quadriceps strength up to two years after reconstruction than individuals who only participate in postoperative rehabilitation [25]. Further, functional measures such as, single leg hop tests transfer over to postoperative rehabilitation [26]. Inclusively, pre-rehabilitation has a higher rate of ACL injured persons returning to sport then ACL injured persons not participating in pre-rehabilitation [27].

However, a pre-rehabilitation program implemented by Logerstedt, Lynch [28] still had 23% of ACL injured persons that were not able to regain quadriceps strength and functional abilities 6 months after reconstruction surgery. These findings are alarming because most return to activity programs occur 6 months after reconstruction surgery. Therefore, future research should focus on the optimal method to regain quadriceps strength, particularly for this population, which is hypothesized to be noncopers.

Rehabilitation Post-Reconstructive Surgery

Optimally, post-surgical rehabilitation programs should restore normal range of motion of the knee joint and regain strength of the atrophied muscles while not producing excessive swelling or strain on the ACL graft [29]. However, to date there is no consensus on the optimal rehabilitation of ACL injuries. Currently, rehabilitation programs implement an accelerated program that includes single- and multi-joint exercises [26]. Common multi-joint exercises include parallel squats, leg presses and single leg squats. Leg extensions are the most common single-joint exercise. Regardless of the approach, these rehabilitation programs are not effective at regaining full strength and size of the quadriceps muscles in the majority of individuals [4]. This suggests the current exercises are inappropriate to restore quadriceps function.

Despite rehabilitation efforts many persons with ACL injuries are not able to return to activity at the same level prior to injury [12]. This is, in part, due to large strength differences of the quadriceps between the involved and the non-involved limb. Research has demonstrated that individuals with less then 10% difference in knee extensor strength perform similar to individuals without ACL injuries. Individuals with more than 15% asymmetry have reduced performance and have difficulty returning to activity [30]. Most persons that have difficulty returning back to activity report decreases in knee function and fear of re-injury [12]. Overall, this suggests that rehabilitation programs must focus on regaining quadriceps strength in order for persons to return to activity.

Consequences of Injury

The quadriceps primary function is to generate knee extensor moments during functional movement tasks. Locomotion such as, walking and running, and sporting activities, such as jumping and landing require strong quadriceps. The quadriceps are necessary to propel the body forward during locomotion, vertically during jumping and to absorb energy during landing [2, 3, 31]. ACL injured persons commonly display decreased performance; which is correlated with the inability of the quadriceps to generate moments during functional tasks [30]. Therefore, restoring quadriceps function is imperative for return to activity. A common consequence of ACL injuries is a loss in quadriceps size and strength. Decreases in size and strength will result in decreased functional abilities of the quadriceps.

Magnetic resonance imaging techniques have revealed a loss in total quadriceps volume and cross-sectional area [1, 5, 6] in the involved versus non-involved limb in ACL injured persons. Atrophy occurs specifically to the vasti muscles, while the rectus femoris maintains its volume and cross-sectional area. Due to anatomical differences, the rectus femoris and vasti do not react homogenously to the injury. The rectus femoris is a biarticular muscle, originating on the pelvis and inserting on the tibia. This gives rectus femoris the ability to flex the hip and extend the leg. The vasti muscles are monoarticular, originating on the femur and inserting on the tibia; making the vasti the primary extensors of the knee. Atrophy of the vasti muscles will cause a decrease in knee extensor strength [7]. Interestingly, this appears to affect some joint angles, 15°-40°, more than others [32].

ACL injured persons experience a decrease in strength between the involved and non-involved limb; decreases in strength can last several years after injury [9, 30-34]. Persistent quadriceps weakness causes compensatory strategies among ACL injured persons. Quadriceps weakness compromises basic locomotion such as walking and running [31]. During walking, persons with quadriceps weakness are not able to control the descent of the leg during heel strike [7], Resulting in a decrease in initial and peak knee flexion angles during gait. Further, this strategy is believed to increase the risk of arthritis in the knee joint [31].

Compensatory strategies are also seen during sporting tasks. ACL injured persons have demonstrated compensatory strategies when completing bilateral tasks such as squatting, jumping and landing. During bilateral squats ACL injured persons avoid loading the involved knee by increasing load at the hip, resulting in a decrease in knee extensor moment and an increase in hip extensor moment in the involved limb [11]. Interestingly, the ground reaction force is distributed evenly among limbs, but differently across joints. Similar strategies are found in other sporting tasks such as jumping and landing [23, 35, 36]. When landing from a jump, ACL injured persons also increase trunk angle [36]. This strategy decreases the moment arm at the knee, consequently decreasing the loading at the knee and decreases stability [36]. Altogether, compensatory strategies lead to a decrease in ACL injured persons able to return to activities to the same level prior to injury.

Quadriceps size, strength and compensatory strategies are magnified in non-copers. Non-copers experience greater losses in volume and cross-sectional area of the vasti than copers, while the rectus femoris size remains similar in both non-copers and copers [1, 5]. This demonstrates that only one of the quadriceps muscles continues to act similarly in both groups. Larger decreases in vasti size lead to larger asymmetries in quadriceps strength in non-copers, whereas copers demonstrate similar isokinetic strength to healthy individuals after rehabilitation [32]. Copers also have a higher rate of return to activity at the same level prior to injury [26], suggesting that an increase in quadriceps strength will result in greater functional outcomes. In contrast, non-copers have a decrease in quadriceps strength and a decrease rate of individuals returning to activity [26]. Accordingly, impaired quadriceps function is detrimental for return to activity.

Quadriceps Inhibition

The ACL provides the spinal cord with information on joint movement and load at the knee; rupture of the ACL disrupts this pathway. It is hypothesized that this causes arthrogenic muscle inhibition [4, 37]. Arthrogenic muscle inhibition is the inability to completely activate the muscle, ultimately decreasing the excitability of the quadriceps. Arthrogenic muscle inhibition is suggested to cause muscle weakness that ultimately leads to a decrease in quadriceps size. However, arthrogenic muscle inhibition appears to decrease over time and does not explain persistent quadriceps weakness [38]

Long-term quadriceps weakness in ACL persons is proposed to be limited to peripheral factors [38]. Voluntary quadriceps muscle activation is similar in the involved and non-involved limb of ACL persons [38, 39]. This means that the central nervous system is capable of activating both limbs similarly. Therefore it is hypothesized that persistent quadriceps weakness is a consequence of quadriceps atrophy rather than inability to activate the quadriceps. Indeed, functional outcomes, such as quadriceps strength, are increased two years after surgery when quadriceps strength is increased before reconstruction of the ACL [40]. This indicates that quadriceps strength is restored more efficiently when asymmetries between limbs are reduced within a timely period.

Quadriceps Atrophy

Persistent quadriceps atrophy may be attributed to the type and techniques of exercises implemented during rehabilitation. Common exercises include leg extensions and squat variations. Although, single-joint exercises such as knee extension increase quadriceps strength, they preferentially loads the rectus femoris as opposed to the vasti muscles [13]. A 12-week training program, emphasizing leg extension exercise resulted in greater increases in cross-sectional area, muscle thickness and angle of pennation in rectus femoris compared to the vasti muscles [14]. As rectus femoris maintains its cross-sectional area and volume in the involved and non-involved limb [1, 5, 6], leg extension exercise is likely not optimal for ACL injured persons. Alternatively, exercises should target the vasti muscles.

Bilateral squat variations target the vasti muscles in a healthy population [15, 41]. Loading of the vasti muscles is increased with increasing knee flexion [42]. Relative muscular effort of the knee extensors is greatest above 120° of knee flexion [43], implying that full squats are necessary to train the vasti muscles. A longitudinal training study has confirmed this [41]. However, rehabilitation programs have used partial squats as opposed to deep squats [26], which limits the effectiveness of the exercise in increasing vasti strength. Further, ACL injured persons demonstrate compensatory strategies during tasks, by transferring the load from the knee extensors to the hip extensors [11]. This suggests that traditional squatting exercises may not be appropriate to elicit vasti adaptations in ACL injured persons, although it is not clear if this is a result of the compensatory strategies or using partial squats or both. Single leg squats have demonstrated similar compensatory strategies, decreased moment at the knee and increased moment at the hip in the involved limb compared to healthy controls [17]. Demonstrating that single leg squats use similar compensatory strategies as bilateral squats. Further, after a 16-week rehabilitation single leg squats did not increase knee extensor strength [16].

Optimizing Squat Exercise

To optimize squat exercise, how the exercise is performed should be considered. Jean et al. [18] have proposed specific criteria for squats to be performed to overcome unilateral quadriceps atrophy and weakness. These include: 1) full squats with knee flexion angles above 120° and 2) single foot elevation, where the non-involved limb is placed on a 5 cm platform. The rationale for criteria 1 is that this will increase the relative effort of the quadriceps muscles compared to partial squats [42]. The rationale for criteria 2 is that this will increase the loading of the involved limb compared to the non-involved limb in ACL injured persons [44].

Deep Squats

The terminal position of a deep squat is defined as maximum knee flexion, approximately 120-140°. Deep, as opposed to partial, squats are imperative to increase quadriceps strength, as relative muscular effort of the quadriceps increases with increasing knee flexion angle [42, 43]. Electromyography of the vasti muscles increases with squat depth and peaks during the terminal position, whereas electromyography of the rectus femoris remains relatively stable throughout the movement [15]. This suggests that the vasti muscles are used to control the descent of the squat and to extend the leg during the ascent, the rectus femoris is most likely used as a stabilizer muscle. Therefore, deep squats have the potential to elicit adaptations in the quadriceps by increasing the relative effort and moreover, greater adaptations are likely to occur in the vasti muscles then rectus femoris.

Additionally deep squats have the ability to increase performance during multi-joint tasks. After a 10-week training program, individuals who performed deep squats were able to increase countermovement jump performance, whereas individuals who performed shallow squats were not [45]. Furthermore, performing deep squats over shallow squats have demonstrated the ability to increase strength in other training tasks, such as knee extension [41]. Suggesting that training with deep squats allows a transfer of strength to occur across multi-joint and strength related tasks. Therefore, deep squats are beneficial for ACL injured persons returning to activity because they increase strength of the quadriceps and transfer the strength to increase performance.

However, some have questioned the safety of performing deep squats in an ACL injured population. When performing deep squats the leg must rotate forward in order to engage the knee extensors [46]. Consequently, many question the safety of this technique and believe that it is better to prevent the leg from rotating forward. However, restricting leg rotation decreases the knee extensor net joint moment (NJM) [47]. As a result, this practice reduces the effectiveness of the exercise, thus, allowing the leg to rotate forward is necessary to elicit adaptations in the quadriceps [46].

Further, ACL strain decreases with an increase in knee flexion, with minimal to no strain occurring past 90° of knee flexion during weight bearing tasks such as squatting. Interestingly, there is an increase in ACL strain during non-weight bearing tasks, such as leg extensions, further advocating the use of squat exercise [48]. Biceps femoris activity increases with squat depth, contributing to posterior tibiofemoral shear forces, which has been suggested to protect the ACL [49]. Moreover, deep squats do not increase anterior-posterior translation of the ACL [8]. In fact, weightlifters commonly perform deep squats and have an increase in cross-sectional area of the ACL [50] and low rates of knee injuries [51]. This suggests that deep squats have the potential to increase strength of the ACL and decrease the rate of injuries. Overall, the evidence indicates that ACL injured persons can perform deep squats safely.

Single Foot Elevated Squats

Generally, deep squats are sufficient to increase quadriceps size and strength in a healthy population, however ACL persons display compensatory strategies - shifting the load from the knee extensors to the hip extensors – in their involved limb [11].

Therefore, a single foot elevated squat, with the non-involved limb elevated is proposed to preferentially load the involved limb of ACL persons [44].

Persons with hemiplegia experience unilateral quadriceps weakness, which contributes to similar compensatory strategies as ACL persons during multi-joint movement tasks [52, 53]. Compensatory strategies include, increased loading of the non-involved limb and decreased loading of the involved limb; and a decrease in knee extensor NJM and an increase in hip extensor NJM in the involved limb. Consequently, exercise modifications have been implemented to counter these movement strategies. To increase load and knee extensor moment Roy, Nadeau [53] placed the involved limb posteriorly with 15° of dorsiflexion during sit-to-stand tasks. Similar results were found by Brunt, Greenberg [52], when elevating the non-involved limb during sit-to-stand tasks persons were able to increase vertical ground reaction force and knee extensor NJM of the involved limb. Further, electromyography of the quadriceps in the involved limb increases when the non-involved limb is elevated. Both strategies used a forced use technique to preferentially load the involved limb.

Single foot elevated squats resulted in higher vertical ground reaction forces, increased electromyography of the quadriceps and increased knee extensor NJM in the non-elevated limb in healthy persons [18]. Further, single foot elevated squats eliminate the knee extensor NJM asymmetry between limbs [44].Inclusively, single foot elevated squats, where the non-involved limb is elevated, would be able to simultaneously increase vertical ground reaction force, electromyography of the vasti and knee extensor moment in the involved limb. Altogether eliciting greater adaptations in the vasti muscles that could ultimately lead to an increase in size and strength of the quadriceps.

Strength Testing

Currently, differences in quadriceps strength of ACL injured persons between a) the involved and non-involved limb and at b) different knee flexion angles are monitored through isokinetic or isometric maximal leg extension. Both isokinetic and isometric leg extension reveal strength differences between the involved and non-involved limb, with non-copers having larger strength differences in the involved limb [32]. Measuring quadriceps strength between limbs at different knee flexion angles may provide a larger insight to where strength differences occur. When using isokinetic testing at 60°/s strength differences are larger at 40°-15° of knee flexion [32]. However, these strength deficits may be representative of the strength of rectus femoris. According to the length-tension relationship, rectus femoris is on the descending limb during shallow knee flexion angles, meaning the differences seen in Eizten et al (2010) may be representative of the strength of the rectus femorsis as opposed to the vasti muscles. Contrary, isometric testing reveals larger strength differences at larger knee flexion angles, 90°-70° [54]. These differences may be more representative of the strength of the vasti muscles based on their length-tension relationship. Nonetheless, regardless of whether isometric or isokinetic testing is used, quadriceps strength should be assessed at multiple joint angles.

Chapter 2: 10–Week Training Program: Traditional and Single-Foot Elevated Full Squats in ACL Injured Persons

Methods

Introduction

The quadriceps are important for activities of daily living as well as sport performance tasks. The quadriceps propel the body forward during walking and running [31], vertically during jumping [2] and absorb impact during landing [3]. Persons with ACL injuries experience quadriceps atrophy and weakness [1]. Current rehabilitation programs are unable to fully restore quadriceps strength after an ACL injury, whether reconstruction surgery is performed or not [4]. Restoring quadriceps function is imperative for persons with ACL injuries to return to activity at the same level prior to injury.

Quadriceps atrophy, cross-sectional area and volume, is limited to the vasti muscles, whereas rectus femoris is able to maintain cross-sectional area and volume after an ACL injury and reconstruction surgery [5, 6]. Vasti atrophy is correlated with quadriceps weakness [7]. Further, quadriceps weakness can persist several years after the injury, despite rehabilitation or reconstruction surgery [8, 9].This may, in part, be due to the use of a quadriceps avoidance strategy in their involved limb that shifts the quadriceps moment to a hip extensor moment during strengthen exercises, such as bilateral and unilateral squats [11, 17]. This strategy may impair the effectiveness of squatting exercises on increasing quadriceps strength.

A novel exercise where the non-involved limb is placed on a 5 cm platform during squatting is proposed to increase quadriceps size and strength in ACL injured persons [44]. The 5 cm platform results in an increase in vertical ground reaction force in the involved limb. Consequently increasing knee extensor NJM, further it creates knee extensor NJM symmetry between limbs. The single-foot elevated squat could lead to long-term increases in size and strength of the quadriceps in the involved limb.

Therefore, the purpose of this study was to investigate differences in lower extremity strength, kinetics and function during multi-joint tasks between traditional and single foot-elevated squats after a 10-week training program. Specific aims of this investigation included 1) comparing quadriceps strength in the involved limb between the traditional and single-foot elevated squats, 2) comparing knee and hip extensor moments in the involved limb during multi-joint tasks between traditional and single-foot elevated squats and, 3) investigating the transfer of strength during vertical jumping and landing mechanics between traditional and single-foot elevated squats. It was hypothesized that 1) single-foot elevated squats would be more effective at increasing isometric quadriceps strength in the involved limb at 75˚, 60˚, 30˚ and 15˚ of knee flexion, 2) single-foot elevated squats would be more effective at increasing knee and hip extensor moments in the involved limb during multi-joint tasks and, 3) single-foot elevated squats would increase the functional abilities of the quadriceps during vertical jumping and landing by increasing knee extensor work in the involved limb.

Trial Design

A 10-week training program was implemented to compare traditional and single-foot elevated squats in ACL injured persons. Participants were randomized into the traditional or single-foot elevated squat group. A parallel trials research design was employed using a 1:1 allocation ratio. Isometric knee extensor strength, kinetics and function were measured pre- and post-intervention to compare the involved and non-involved limb between groups.

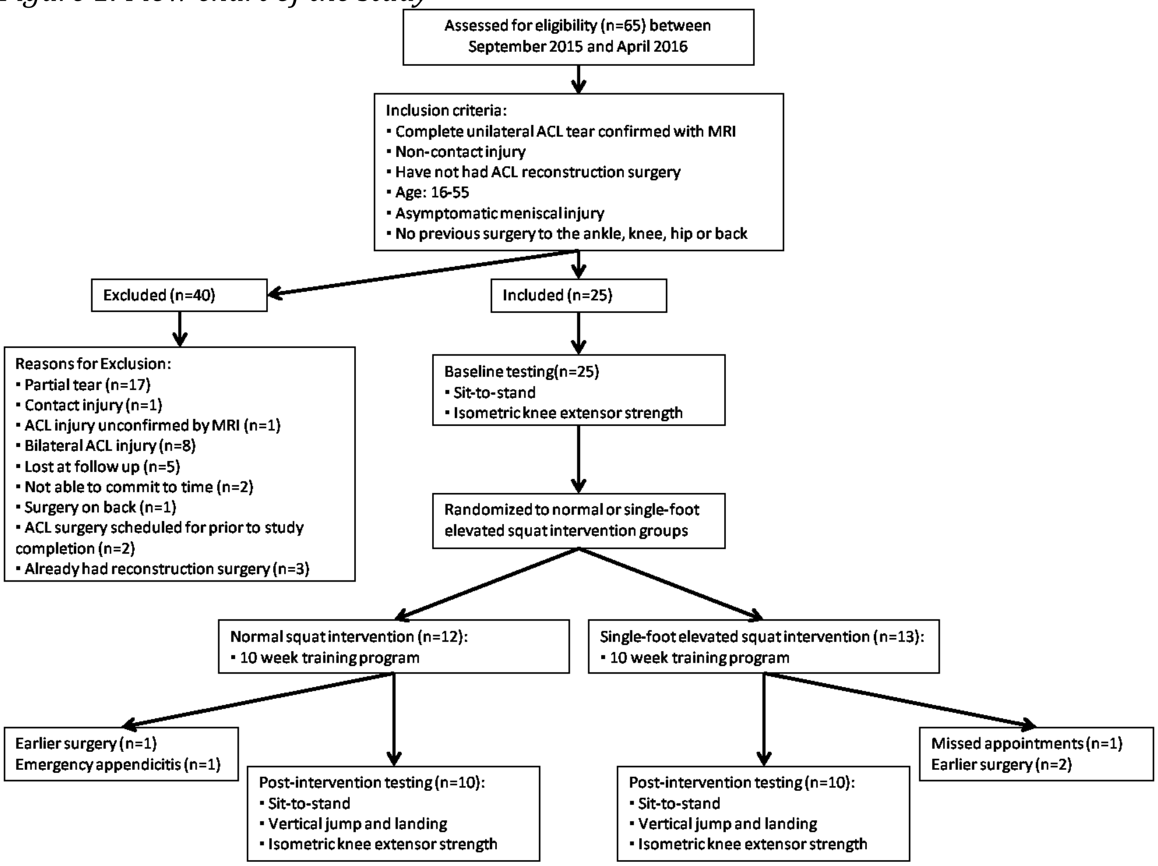
Subjects

Twenty ACL injured, men (n=11) and women (n=9) were recruited to participate in the study. Posters at fitness facilities around the city and physiotherapists from the Glen Sather Sports Medicine Clinic were used to recruit potential participants. All participants had a full unilateral, non-contact ACL injury and had not had surgery. Participants were randomly assigned to either traditional or single-foot elevated squat training groups. Random assignment was determined using 5 sets of 8 blocks. Exclusion criteria were: partial ACL tear, mechanism of injury included contact, previous ACL injury to the opposite knee, symptomatic menisci injury, prior injury to the ankle, knee, hip or back that required surgery (Figure 1). 65 potential participants were assessed for eligibility; 25 were eligible for baseline testing and

20 participants completed the program (10 traditional group, 10 single-foot elevated group). In the traditional squat group one participant's income was depended on physical fitness, therefore they were expedited for surgery; they completed 6 weeks of the training program before their surgery. In the single-foot elevated group, one participant was under the age of 18 and one participant was a varsity athlete, as a result both were expedited for surgery; they both completed 5 weeks. Participants that received early surgery had a decision to continue the program until two days before their surgery or dropout, all participants continued the program. One participant in the single-foot elevated group missed two consecutive weeks of training due to time commitment issues, they completed 4 weeks. Participants over 18 provided written informed consent while participants under 18 provided written assent and their parents provided written informed consent. The study protocol was approved by a University of Alberta Research Ethics Board.

Effect size differences in ACL injured persons between their involved and non-involved limbs were 0.98 and 0.72 standard deviations for knee extensor peak torque and torque at 15° of knee flexion, respectively [32]. Peak knee extensor NJM during bilateral squats had effect size differences of 0.88 standard deviations between the involved and non-involved limbs of ACL injured persons [11]. A 0.75 standard deviation effect size has over 80% power to reach statistical significance when alpha is 0.05 if there are 16 participants per group. Therefore, a minimum of 32 participants are required. The results presented only have 10 participants per group, a total of 20 participants; therefore the data presented only represents the preliminary results of an ongoing study.

Figure 1: Flow chart of the study



Experimental Protocol

Participants reported to the laboratory on two separate occasions for testing, once before and once after the training intervention. A member of the research team supervised all exercise sessions. Participants began the 10-week, 3days/week training program within one week of baseline testing. Post-intervention testing was performed within one week of the last training session. Participants were asked to refrain from physical activity 24 hours before testing. A block-periodized program, neuromotor (2 weeks), hypertophy (4 weeks) and strength (4 weeks) was implemented A teaching progression of the squat exercise was implemented to ensure that all participants were able to perform a full depth squat. Progression included; maximal voluntary quadriceps activation (weeks 1-4), sit-to-stands (weeks 1-5), plate squats (traditional or single-foot elevated; weeks 2-10) and front squats (weeks 5-10). Accessory exercises included: deadlifts, calf raises, glute bridges, leg lowers, weighted crunch and spread leg sit-ups. A warm up of static stretching was performed before each session. Stretches targeted the hip flexors, quadriceps, adductors, piriformis, hamstrings and calves; each stretch was held twice for 30 seconds. Rolling out was performed at the end of each session focusing on the feet, calves, quadriceps, hamstrings and IT bands. The only difference between groups was the plate squats; participants either performed the plate squat in the traditional condition with both feet on the ground or in the single-foot elevated condition with the non-involved limb placed on a 5 cm platform. Details of the training program are provided in Appendix A.

Experimental Measurements

On both testing days participants completed three sets of five repetitions of sit-to-stands while their kinetics and kinematics were recorded using a three-dimensional motion analysis system. Sit-to-stands were done on an armless, backless seat at a height equal to the length of their tibia. Participants crossed their arms over their chest holding their shoulders throughout the test. The feet were placed underneath the pelvis and their entire foot remained in contact with the floor. Participants were instructed to minimize forward truck lean while performing the task. Two minutes of rest was given between sets to prevent fatigue.

For the sit-to-stands, retroreflective markers were placed on bony landmarks (L5/S1; and bilateral iliac crests, femoral trochanters, medial and lateral femoral epicondyles, medial and lateral malleoli, medial, lateral and posterior calcaneus, base of the 1st and 5th metatarsal heads) and tracking clusters each consisting of four retroreflective markers were placed bilaterally on the thigh and leg segments. Marker trajectories were recorded using seven optoelectronic cameras (ProReflex MCU240, Qualisys; Gothenberg, Sweden) sampling at 120 Hz. Ground reaction forces were measured by two force platforms (OR6-6, AMTI; Watertown, MA), one under each foot, sampling at 1,200 Hz.

Following sit-to-stand trials, participants performed maximal isometric knee extensor contractions at four different knee flexion angles, approximately 15°, 30°, 60° and 75°. Participants were seated in a custom built dynamometer similar to that described in Bryanton et al. [42]. For each repetition the participant was instructed to contract as hard as possible for 3 seconds. The involved and non-involved limbs were alternated until all angles were performed. Loud verbal encouragement was given. Two minutes of rest was given between trials to prevent fatigue. As the dynamometer lever angle and knee flexion angle may not match, knee flexion angle was manually measured using a digital goniometer for each trial.

Force data from the dynamometer was sampled at 500 Hz using a 12-bit analog-to-digital convertor (USB-6000, National Instruments; Austin, TX). Custom software was written using LabVIEW software (National Instruments; Austin, TX) and used for data collection and to calculate moment of force. The dynamometer was capable of measuring the static inertial characteristics of the limb segment, allowing participant-specific gravity corrections to be made for the different testing angles.

Sit-to-stands and maximal isometric knee extensor strength testing were duplicated during post-testing, with the addition of vertical jumping and landing after the sit-to-stands. Six maximal counter-movement jumps were performed using the same three-dimensional motion analysis system as the sit-to-stands with one to three minutes of rest between jumps to prevent fatigue. Participants wore running shoes during vertical jumping and landing so markers on the calcaneus were replaced with tracking clusters, each consisting of three retroreflective markers on the outside of the shoe.

Vertical jumping and landing was not tested pre-intervention due to safety concerns. The mechanism of many ACL injuries includes valgus knee collapse when landing from a jump, which has been related to quadriceps weakness [55]. Further, ACL injured persons experience additional quadriceps weakness after their injury [4]. Therefore, it was deemed as unsafe to perform vertical jumping and landing prior to strengthening the quadriceps.

Data Processing and Reduction

Visual 3D software was used to process motion analysis data. Motion and force data were digitally low-pass filtered using a fourth-order recursive Butterworth with a 6 Hz cut-off frequency. Joint angles were defined as motion of the proximal segment relative to the distal segment using a XYZ Cardan sequence. Ankle, knee and hip extensor NJM were calculated using inverse dynamics. Ankle, knee and hip extensor power were calculated as the product of NJM and joint velocity.

Initiation of the sit-to-stand was defined as the time the pelvis' center of gravity acceleration in the vertical axis increased above zero. The end of the repetition was defined as the time when the angular velocity of the pelvis in the sagittal plane reached zero. Initiation of the vertical jump was defined as the time when the center of gravity position of the pelvis in the vertical axis lowered from the standing position. The time of peak knee flexion was defined to demarcate the eccentric and concentric phases of the jump. Right and left vertical ground reaction force data were used to define the take-off time when the feet were no longer on the force plate. Landing was defined as the moment the feet touched the force plates and ended at left and right peak knee flexion angle.

Isometric knee extensor moment data were digitally low-pass filtered using a fourth-order recursive Butterworth with a 5 Hz cut-off frequency. The peak moment was determined for each trial. The trial with the highest moment at each of the joint angles was used to evaluate knee extensor strength. To account for differences in knee flexion angle, strength curves were determined by plotting moment (y-axis) versus angle (x-axis) and fitted with a 2nd order polynomial. Angle-specific maximum knee extensor moment was predicted from each participants curve for knee flexion angles between 15°-75° at 15° intervals.

An asymmetry index between the involved and non-involved limb of isometric knee extensor strength was calculated using:

$$\frac{Involved - NonInvolved}{NonInvolved} = AsymmetryIndex$$

Statistical Analyses

Three-way (group [2] by limb [2] by time [2]) multivariate ANOVA with repeated measures on the limb and time factors were used to find differences in isometric knee extensor strength and sit-to-stands kinetics. Two-way (group [2] by limb [2]) multivariate ANOVA with repeated measures on the limb factor were used to find differences in vertical jumping and landing kinetics.

For post hoc comparisons, Cohen's d effect size was used to examine the magnitude of differences in the involved versus the non-involved limb both at pre- and post-intervention; and the change from pre- to post-intervention in both the involved and non-involved limbs. . Effect sizes were interpreted as: 0.2-0.49 – small, 0.5-0.79 – moderate and >0.8 – large [56].

Results

Participant Characteristics
Participant characteristics are provided in table 1.

Table 1: Participant characteristics

	Traditional Group (n=10)	Single-Foot Elevated Group (n=10)
Age (years)	23.4±4.2	27.3±5.0
Dominant Limb	Left: 0/Right: 10	Left: 3/Right: 7
Involved Limb	Left: 3/Right: 7	Left: 5/Right: 5
Height – Pre (m)	1.74±0.08	1.74±0.09
Height – Post (m)	1.74±0.08	1.74±0.09
Body Mass – Pre (kg)	78.26±16.84	79.44±16.89
Body Mass – Post (kg)	78.61±15.46	79.41±15.07

Isometric Strength Testing
The limb by time by group interaction for knee extensor strength was not significant at 15° (p=0.58), 30° (p=0.60), 45° (p=0.43), 60° (p=0.75) and 75° (p=0.93). The limb by time interactions were significant at 45° (p=0.007), 60° (p=0.005) and 75° (p=0.02). At 15°, a large effect size difference was found between the involved and non-involved limbs pre-intervention and a moderate effect size difference post-intervention. At 30°, 45°, 60° and 75° moderate effect size differences were observed pre-intervention and trivial effect size differences post-intervention. At 75°, a moderate effect size difference was observed pre-intervention and a small effect size difference post-intervention.

Figure 2: Isometric knee extensor strength of the traditional group.

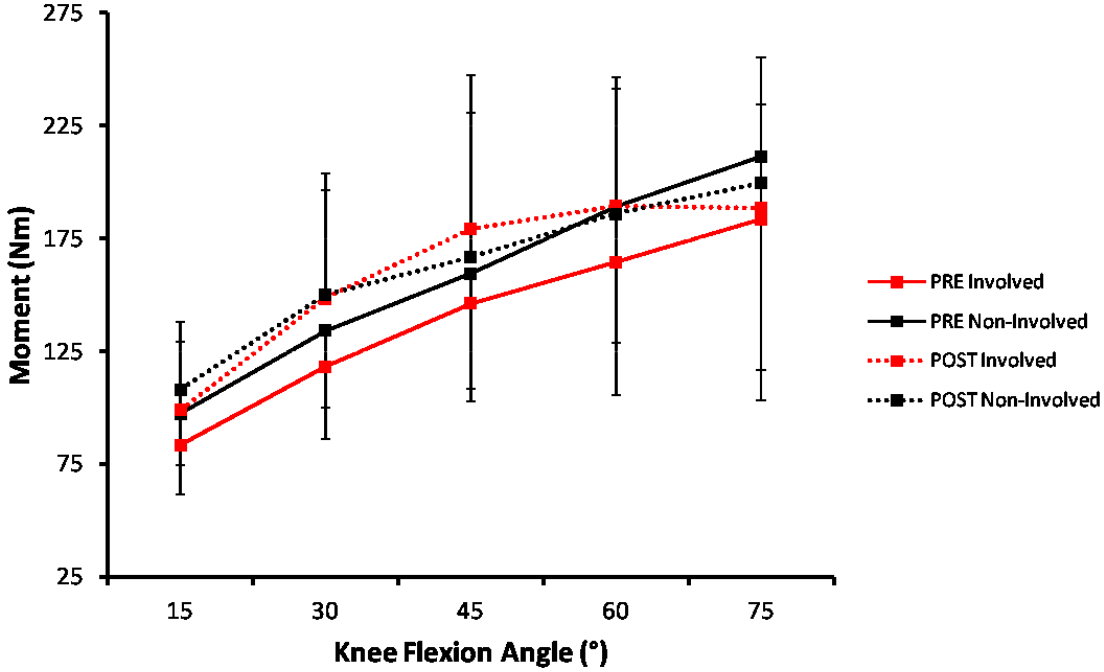
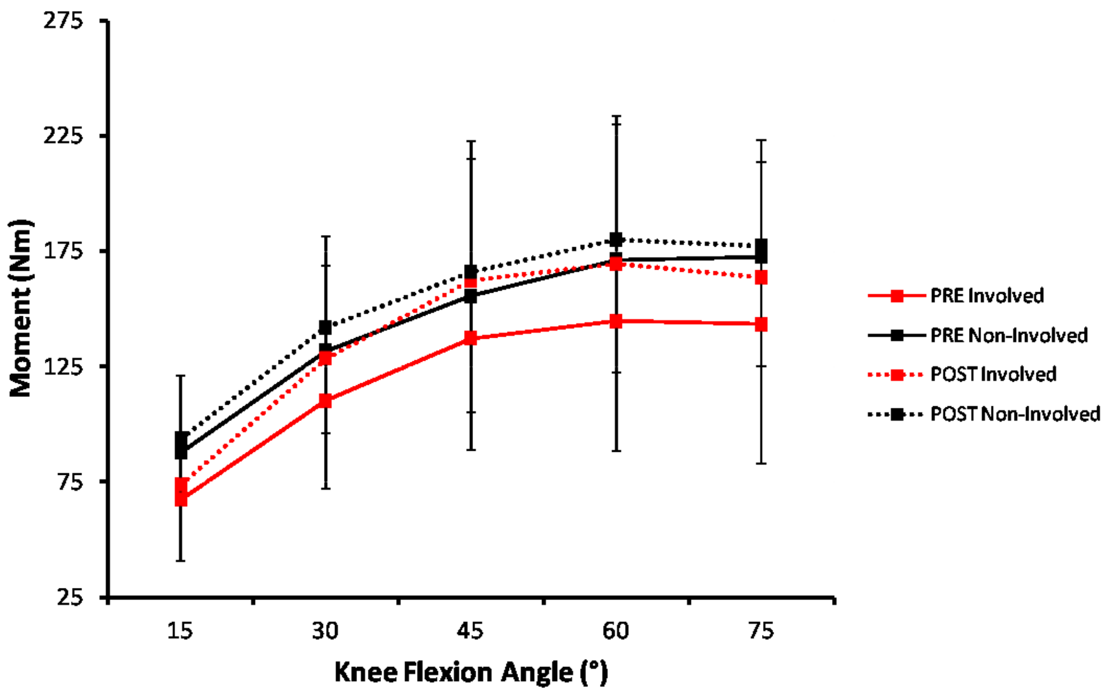


Figure 3: Isometric knee extensor strength of the single-foot elevated group.



Asymmetry indexes provide confirmation of greater differences pre-intervention versus post-intervention between the involved and non-involved limbs. Pre-intervention, the traditional group had an asymmetry index of -14% and -11% at 15° and 75° of knee flexion; the single-foot elevated group had a larger asymmetry index of -22% and -18%. Post-intervention both groups decreased asymmetry between limbs; the traditional group had an asymmetry index of -5% and -4%, the single foot elevated group -16% and -7%.

The reduced differences between the involved and non-involved limbs was due to increases in strength in the involved limb. The involved limb had small effect size increases in strength from pre to post-intervention at 15°, 60° and 75° and large effect size increases at 30° and 45°.

Sit to Stand

Joint angles are presented in table 2.

Table 2: Joint angles during sit-to-stand At Seat-Off. Positive values indicate ankle plantarflexion, knee flexion and hip extension

	Traditional Group (n=10)	Single-Foot Elevated (n=10)
Involved Ankle (°)		
Pre	-25.77±5.67	-26.29±7.03
Post	-27.01±6.36	-28.27±4.87
Non-Involved Ankle (°)		
Pre	-27.33±5.27	-27.17±8.37
Post	-27.99±4.46	-26.09±15.57
Involved Knee (°)		
Pre	96.92±5.08	100.49±6.97
Post	98.92±5.43	101.52±5.72
Non-Involved Knee (°)		
Pre	99.09±5.58	100.19±7.44
Post	99.38±5.34	101.52±6.56
Involved Hip (°)		
Pre	-65.81±11.35	-64.64±10.69
Post	-62.96±10.85	-62.90±9.99
Non-Involved Hip (°)		
Pre	-66.86±9.69	-64.52±9.74
Post	-62.83±9.70	-63.01±10.25

The limb by time by group (p=0.26) and limb by time (p=0.91) interactions for total work were not significant. There was no difference for total work between limbs (p=0.15) (Figure 4). Limb by time by group (p=0.28) and limb by time (p=0.46) interactions for knee extensor work were not significant. Significant limb (p=0.004) and time (p=0.04) effects for knee extensor work were observed (Figure 5). The knee extensors performed less work in the involved limb pre-intervention; the effect size difference was moderate in the traditional (d=0.65) and large in the single-foot elevated (d=0.92) groups. Post-intervention, the traditional group had increased knee extensor work in the involved (d=0.25) and non-involved limbs (d=0.36), resulting in a large effect size difference between limbs (d=0.85). The single-foot elevated group increased knee extensor work in the involved (d=0.38) but not non-involved (d=-0.02) limbs, resulting in a moderate effect size difference between limbs (d=0.67).

Figure 4: Total work during sit-to-stands

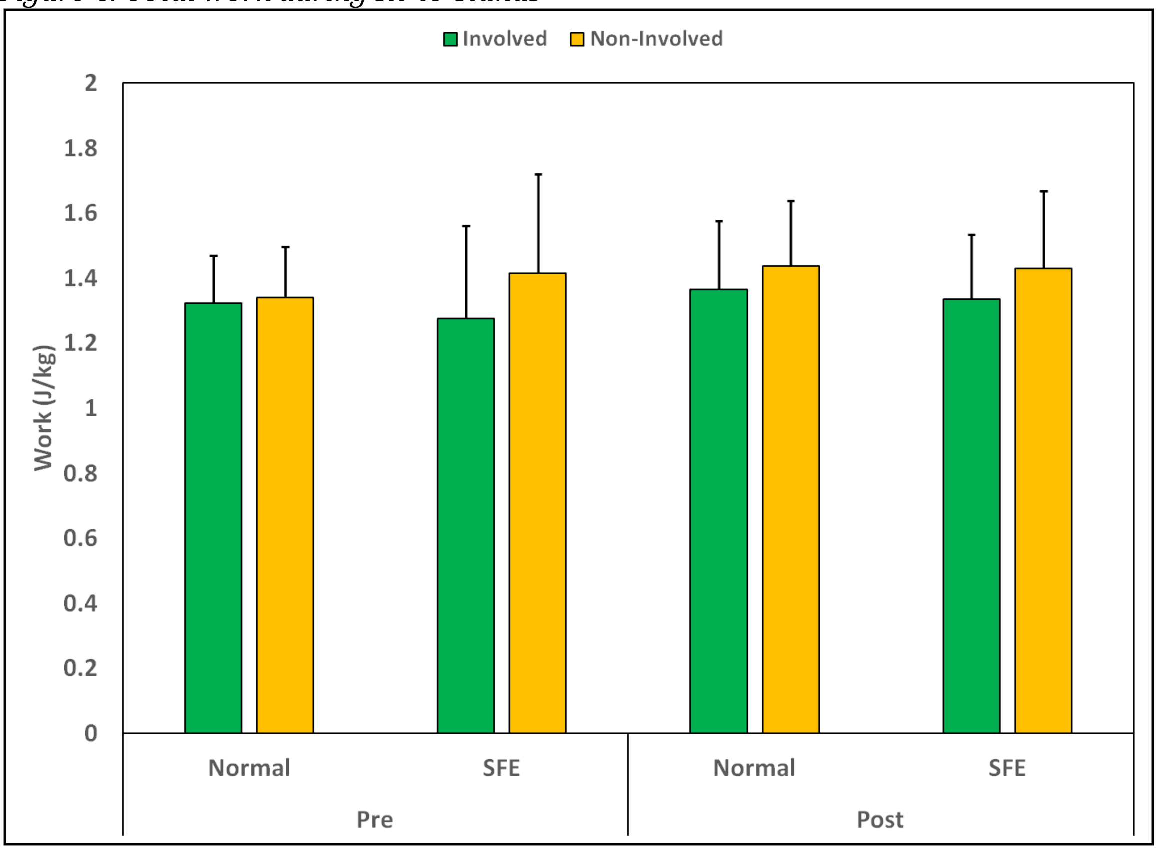
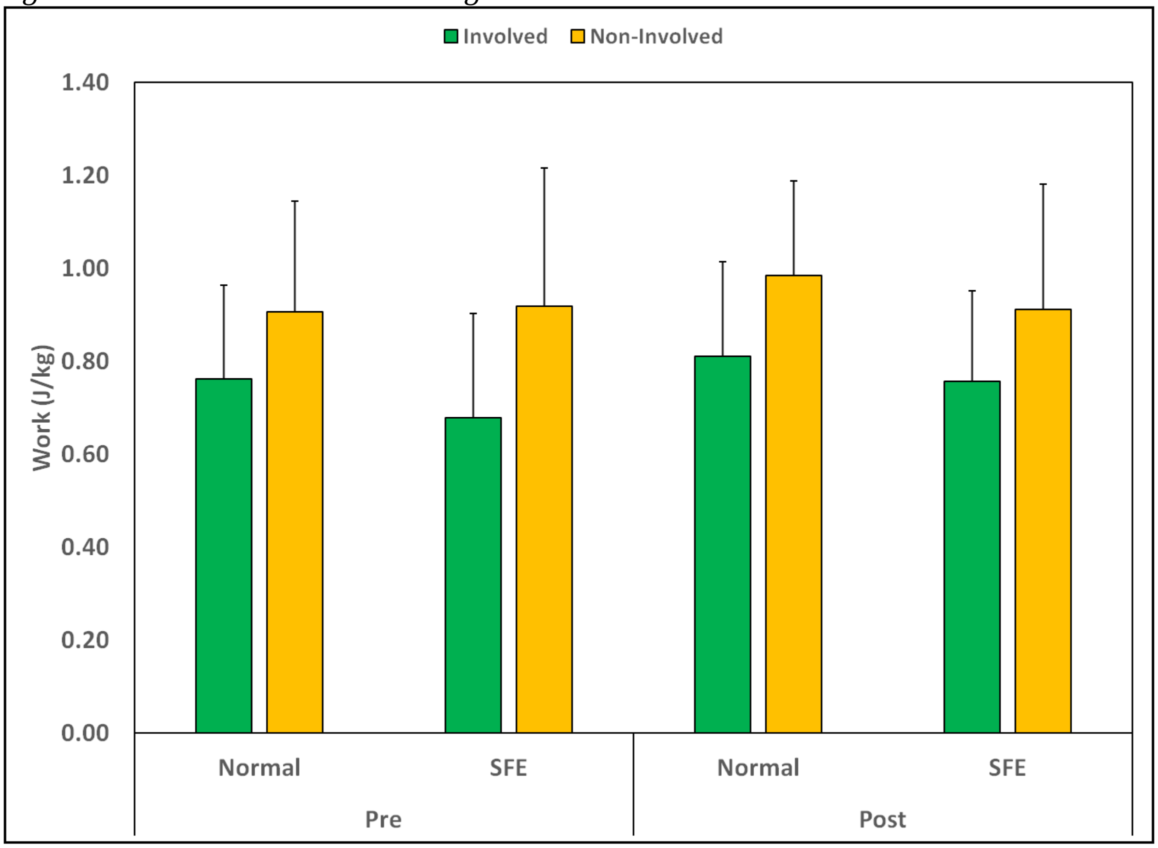
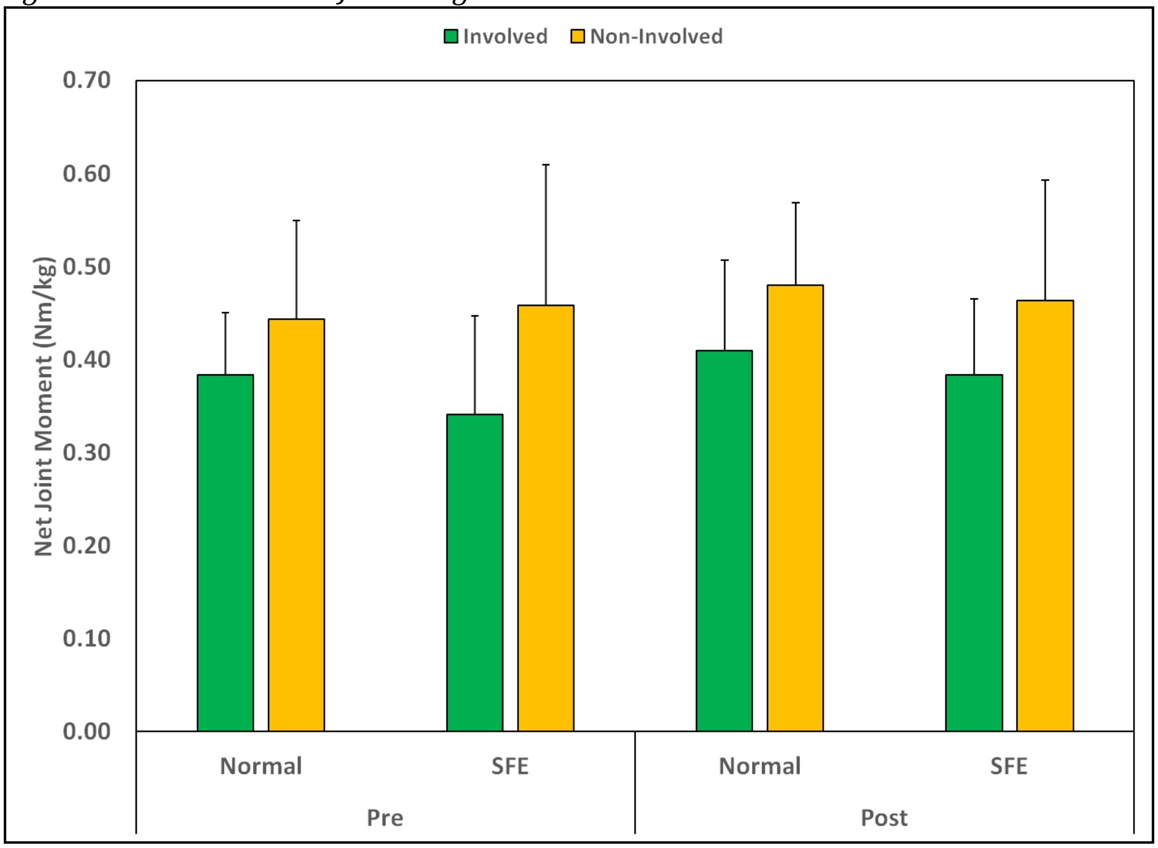


Figure 5: Knee extensor work during sit-to-stands



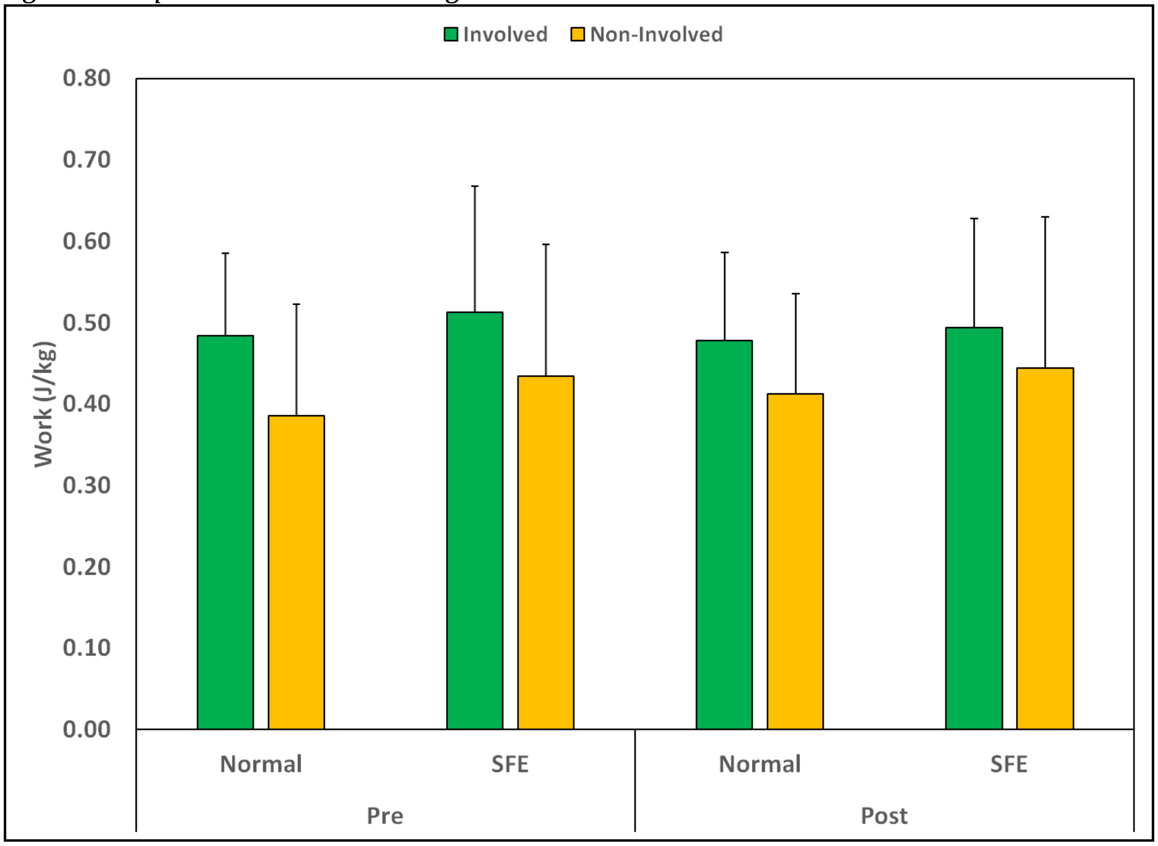
The increases in knee extensor work were due to increases in average knee extensor NJM (Figure 6). Pre-intervention, average knee extensor NJM was lower in the involved limb for both traditional (d=0.69) and single-foot elevated (d=0.92) groups. The traditional group had increased average knee extensor NJM in both their involved (d=0.31) and non-involved (d=0.38) limbs, resulting in moderate effect size difference between limbs (d=0.76) post-intervention. Knee extensor NJM increased in the involved (d=0.45) but not the non-involved (d=0.03) limbs in the single-foot elevated group, resulting in a moderate effect size difference between limbs (d=0.75).

Figure 6: Knee extensor NJM during sit-to-stands



The limb by time by group interaction for hip extensor work was not significant (p=0.993), however, the limb by time interaction approached significance (p=0.15) (Figure 7). The hip extensors performed more work in the involved limb compared to the non-involved limb in both the traditional (d=0.83) and single-foot elevated (d=0.56) groups pre-intervention. While the hip extensors continued to perform more work in the non-involved limb post-intervention, the effect size differences were smaller in both the traditional (d=0.56) and single-foot elevated (d=0.31) groups.

Figure 7: Hip extensor work during sit-to-stands



Similar results were found for the average hip extensor NJM. Pre-intervention average hip extensor NJM was larger in the involved limb in the traditional (d=0.60) and single-foot elevated (0.49) groups. Differences in average hip extensor NJM between the involved and non-involved limbs were smaller post-intervention in the traditional (d=0.43) and single-foot elevated (0.23) groups.

Vertical Jump

The limb by group interaction was significant for total eccentric work (p=0.018) but not concentric work (p=0.158). The involved limb performed more eccentric work in the traditional group (d=0.25) and less in single-foot elevated group (d=0.35). There was a significant limb effect for total concentric work (p=0.02). The involved limb performed less work compared to the non-involved limb in the single-foot elevated group (d=0.42). This difference was trivial in the traditional group (d=0.17)

Significant limb by group interactions for eccentric (p=0.009) (Figure 8) and concentric (p=0.03) (Figure 9) knee extensor work were observed. Knee extensor work was similar between limbs during the eccentric phase (d=0.07), but lower in the involved limb during the concentric phase (d=0.30) in the traditional group. The involved limb performed less knee extensor work than the non-involved during the eccentric (d=0.75) and concentric (d=0.66) phases. The average knee extensor NJM between was smaller in the non-involved limb for the traditional (d=0.29) and single-foot elevated (d=0.55) groups.

Figure 8: Eccentric knee extensor work during vertical jumping

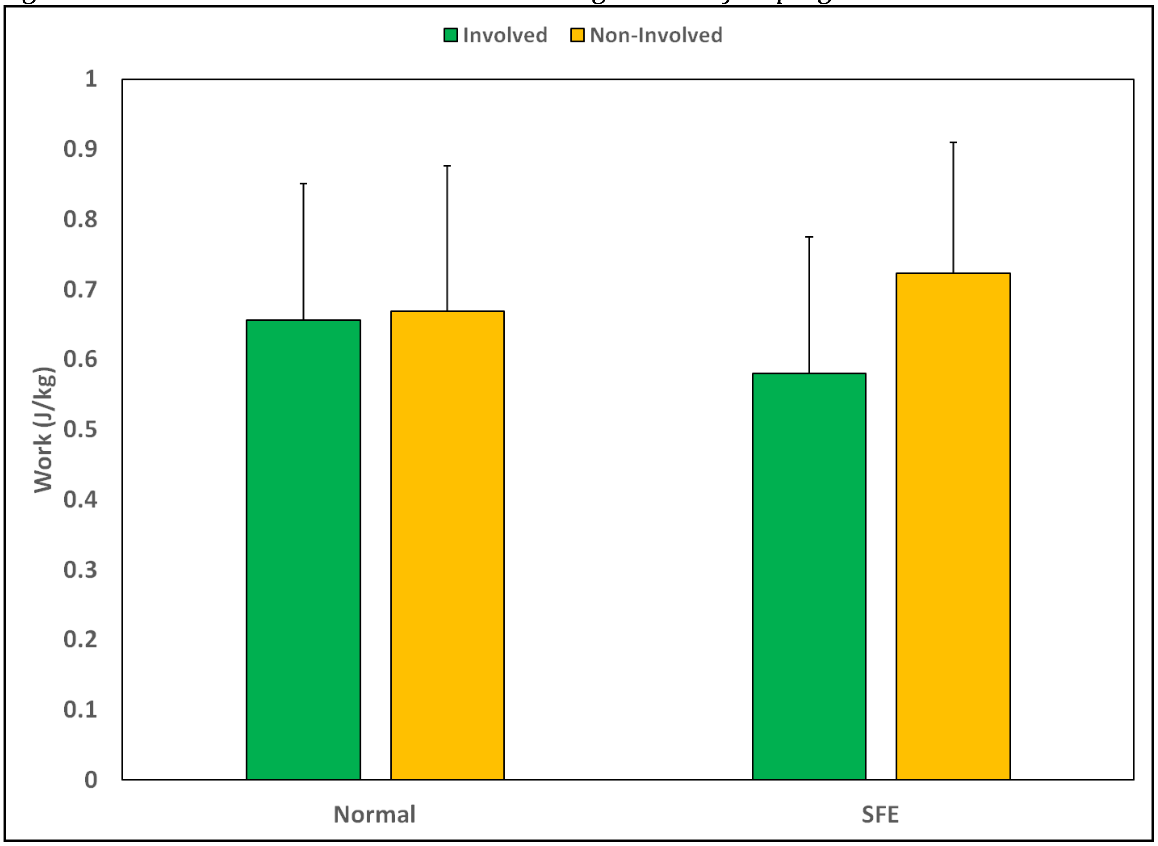
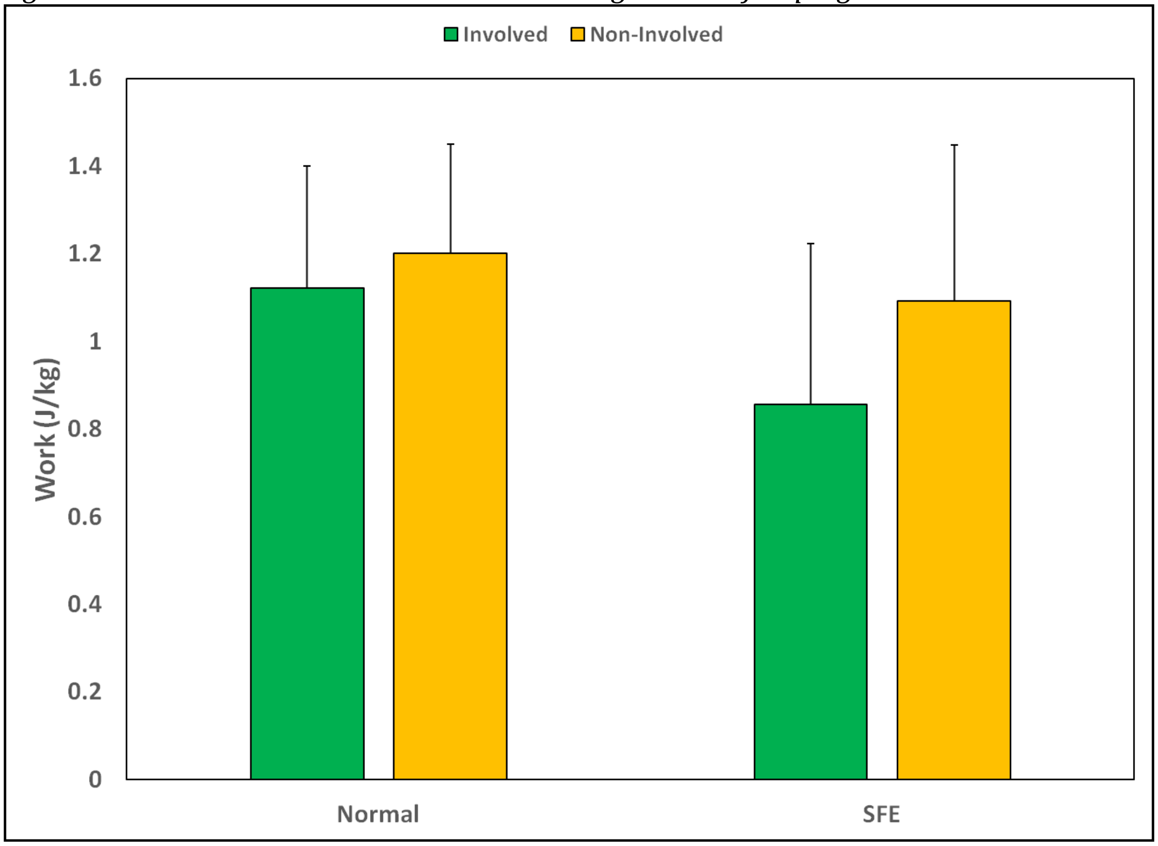


Figure 9: Concentric knee extensor work during vertical jumping

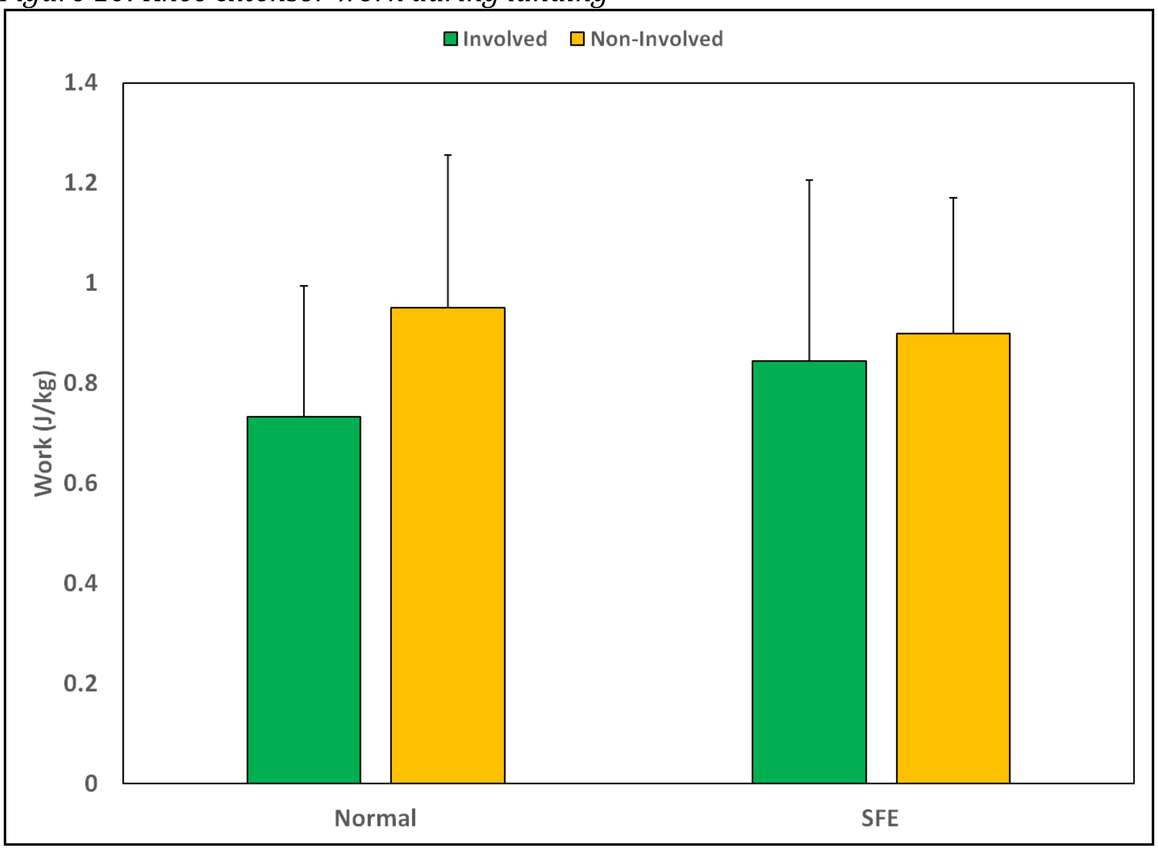


The limb by group interaction was not significant for hip extensor work during the eccentric (p=0.71) or concentric (p=0.29) phases. Limb by group interaction was not significant for ankle plantar flexor work during the eccentric (p=0.40) or concentric (p=0.19) phases. The limb effect was not significant for hip extensor work (p=0.58) or ankle plantarflexor work (p=0.34).

Landing

The limb by group interaction was not significant for total work performed during landing (p=0.72). The limb by group interaction for knee extensor work approached significance (p=0.06). The traditional group performed less knee extensor work in their involved limb (d=0.77) compared to their non-involved limb. The single-foot elevated group had only a trivial difference in knee extensor work (d=0.17) group (Figure 10). The smaller knee extensor work in the traditional group's involved limb can be explained by the smaller knee extensor NJM (d=0.79). Only a small difference was observed between involved and non-involved limb knee extensor NJM in the single-foot elevated group (d=0.23).

Figure 10: Knee extensor work during landing



The limb by group interaction was not significant for either hip extensor (p=0.27) or ankle plantarflexor (p=0.35) work during landing. The limb effect was not significant for either hip extensor (p=0.18) or ankle plantar flexor (p=0.85) work during landing.

Discussion

As expected, knee extensor strength was lower in the involved limb at all knee flexions angles pre-intervention. Following the 10-week exercise program, both groups increased knee extensor strength in the involved limb. At 30°, 45° and 60°, trivial differences between limbs post-intervention were observed, while moderate and small differences were observed at 15° and 75°, respectively. These data suggest that the exercise intervention was effective for reducing and even eliminating knee extensor strength asymmetries at multiple joint angles. Previous research has found that typical rehabilitation programs are ineffective for substantially reducing knee extensor strength deficits in the involved limb of ACL injured persons [8, 9, 32].

Exercises used in ACL rehabilitation programs to target knee extensor strength include squats, lunges, leg press and knee extension [26]. While most programs recommend unilateral and or bilateral squat exercises, these are performed only through a partial range of motion. Training programs in healthy participants comparing full depth to partial squats demonstrate increases in vertical jump height, isometric knee extensor torque and quadriceps size in groups that perform full depth squats [41, 45]. Individuals training with partial squats do not increase strength or function in any task other than partial squats [41, 45]. Consequently, full depth squats elicit adaptations that can transfer strength to multi and single-joint tasks. Full squats provide adequate tension to stimulate strength adaptations whereas partial squats do not [57].

Relative muscular effort is defined as the muscle force required to perform a task relative to the maximum force that the muscle can produce. Quadriceps relative muscular effort during squats increase with an increase in knee flexion angle [42]. Rehabilitation programs recommend squats be performed to 90° of knee flexion [16, 26]. Relative muscular effort of the quadriceps is considerably higher between 105° - 119° of knee flexion compared to 90°-104° [42]. Further, knee extensor NJM is significantly higher between 135°-149° of knee flexion when compared to 105°-119° [58]. Electromyography of the vastus lateralis and medialis was also larger at higher knee flexion angles [58]. This may, in part, be the cause of unsuccessful rehabilitation programs for ACL injured persons [4, 28, 32]. Further, Quadriceps weakness can persist several years after rehabilitation [8, 9] and return to activity to the same level prior to injury is dependent on quadriceps strength [12]. Therefore, full depth squats should be performed to increase strength and hypertrophy in ACL injured persons.

In the sit-to-stand there were no differences in the total work performed by the involved and non-involved limbs. However, the involved limb performed less knee extensor work and more hip extensor work. Similarly, knee extensor NJM was lower and hip extensor NJM was higher in the involved limb. These mechanics indicate the presence of compensatory muscle strategy, also referred to as a quadriceps avoidance strategy. This strategy has been observed in walking, squatting, vertical jumping and landing [2, 11, 31, 35, 36]. In the traditional group, knee extensor work increased in both the involved and non-involved limbs. Consequently knee extensor work asymmetry increased between the involved and non-involved limb following the exercise program. In contrast, knee extensor work only increased in the involved limb in the single-foot elevated group. As a result, knee extensor work asymmetry between the involved and non-involved limbs was smaller after the exercise program.

The different changes in knee extensor work during sit-to-stand in the traditional and single-foot elevated groups following the exercise program cannot be explained by strength differences as both groups had similar increases in knee extensor strength. Moreover, it should be considered that the single-foot elevated squat was only performed for the plate squat exercise. The heavier loaded front squats, which would be expected to have the greatest strengthening effect, were identical for both groups. Thus, it can be hypothesized that the single-foot elevated squat elicited a change in motor coordination facilitating increased utilization of the knee extensors in the involved limb.

Knee extensor NJM is reduced in the involved limb during multi and single-joint tasks of ACL injured persons [11, 17, 35, 36]. In the current study, participants that performed traditional squats increased knee extensor strength but maintained knee extensor asymmetry during sit-to-stands. Thus, it may be hypothesized that a change in motor coordination occurred as a result of injury that cannot be addressed solely be restoring strength. Single-foot elevated squats increase vertical ground reaction force in the non-elevated limb, resulting in an increase in ankle plantarflexor, knee extensor and hip extensor NJM [18]. Thus, this modified squat mechanically forces individuals to increase knee extensor NJM in the involved limb [44]. It may therefore be hypothesized that knee extensor symmetry during single-foot elevated squats elicits a motor learning effect that transfers to sit-to-stands. These results suggest that the combination of quadriceps strength training and motor coordination training can decrease compensatory mechanisms, such as quadriceps avoidance strategy in ACL injured persons.

During vertical jumping knee extensor work was similar between limbs in the traditional group, but was less in the involved limb in the single-foot elevated group. Vertical jumping requires large knee extensor work and NJM [2]. Overall, the traditional group had larger quadriceps strength pre- and post-intervention than the single-foot elevated group. Further they eliminated quadriceps strength asymmetries between limbs following the exercise program. This suggests that they had enough strength to perform vertical jumps with knee extensor symmetry, which was required due to the large demands of vertical jumping, in contrast to the low demands of sit-to-stands. The single-foot elevated group still had minor strength asymmetries after the exercise program and was not able to perform the vertical jump with equal knee extensor work. However, the single-foot elevated group was able to land with equal knee extensor work. Landing is a less demanding task that requires less knee extensor work than vertical jumping. The single-foot elevated group was able to perform landing with similar knee extensor work because it was a less demanding task and they had sufficient strength to perform the task. Contrarily, the traditional group landed with less knee extensor work symmetry than the single-foot elevated group. Both sit-to-stands and landing require less knee extensor work. The traditional group had larger knee extensor strength than the single-foot elevated group. Therefore it was not necessary for the traditional group to perform landing with equal knee extensor work.

Unfortunately vertical jumping and landing was not performed before the exercise program. Therefore, changes in performance due to the intervention were not measured. However, it was not possible to safely perform vertical jumping and landing before the exercise program as large quadriceps strength asymmetries existed.

Experimental Considerations and Limitations

A limitation of the study was vertical jumping and landing were only tested post-intervention. A comparison in knee extensor work performed across time was not feasible as many of the participants were not strong enough pre-intervention to perform the task safely. Therefore, only comparisons between groups were made. Previous research on jumping and landing in persons with ACL injury show a shift in knee extensor NJM to hip extensor NJM in the involved limb [35, 36]. This strategy is similar to the quadriceps avoidance strategy used during strengthening exercises [11, 17]. Considering participants used a quadriceps avoidance strategy during sit-to-stands, pre-intervention it is reasonable to believe that participants would have used a similar strategy if vertical jumping and landing was also performed pre-intervention. This suggests that reductions in asymmetry may be the result of the training program. Nonetheless, further research is required to investigate changes in knee extensor work after full depth squat training in ACL injured persons.

Another limitation is the length of the training program. Although this study eliminated strength differences at some knee flexion angles after 10-weeks, the single-foot elevated group still had asymmetries between limbs. A longer program, >10-weeks, may be necessary to eliminate all strength asymmetries. Other studies, less then 10-weeks were also not able to eliminate strength asymmetries between limbs [26].

Future Directions

The present study used a 10-week training program to increase quadriceps strength in ACL injured persons. Full depth front squats, with progressively heavier loads, were effective at increasing quadriceps strength in both the involved and non-involved limbs. Although the single-foot elevated group increased quadriceps strength in their involved limb they had larger strength asymmetries pre-intervention and were not able to eliminate asymmetries at all knee flexion angles. Therefore, a longer training period (>10 weeks) may be necessary to eliminate larger strength asymmetries between limbs.

Future studies should consider the height of the platform relative to the height of the tibia. The center of gravity displacement is increased with a larger tibia and decreased with a shorter tibia. An individual with a longer tibia may have relatively smaller effects using the same height platform as an individual with a shorter tibia. Thus, the height of the platform relative to height of the tibia should be examined further.

Conclusion

Full squats increase quadriceps strength in ACL injured persons. In contrast to previous research, which has only used partial squats in this population, a full depth squat program was effective for reducing or eliminating strength deficits in the involved limb. Both groups increased knee extensor work in their involved limb during sit-to-stands. However, the traditional group also had an increase in knee extensor work in the non-involved limb. This created larger knee extensor work asymmetries during sit-to-stands after the exercise program in the traditional group. In contrast, the single-foot elevated squat group had no changes in knee extensor work in their non-involved limb, resulting in reduced knee extensor work asymmetry during sit-to-stands. Altogether, full depth squats restore quadriceps strength in ACL injured persons and single-foot elevated squats may contribute to addressing motor coordination deficits resulting from quadriceps weakness.

References

1. Williams, G.N., et al., *Quadriceps weakness, atrophy, and activation failure in predicted noncopers after anterior cruciate ligament injury.* The American journal of sports medicine, 2005. **33**(3): p. 402-407.
2. Chiu, L. and G.J. Salem, *Potentiation of vertical jump performance during a snatch pull exercise session.* J Appl Biomech, 2012. **28**(6): p. 627-35.
3. Moolyk, A.N., J.P. Carey, and L.Z. Chiu, *Characteristics of lower extremity work during the impact phase of jumping and weightlifting.* The Journal of Strength & Conditioning Research, 2013. **27**(12): p. 3225-3232.
4. Palmieri-Smith, R.M., A.C. Thomas, and E.M. Wojtys, *Maximizing quadriceps strength after ACL reconstruction.* Clinics in sports medicine, 2008. **27**(3): p. 405-424.
5. MacLeod, T.D., L. Snyder-Mackler, and T.S. Buchanan, *Differences in neuromuscular control and quadriceps morphology between potential copers and noncopers following anterior cruciate ligament injury.* journal of orthopaedic & sports physical therapy, 2014. **44**(2): p. 76-84.
6. Williams, G.N., et al., *Quadriceps femoris muscle morphology and function after ACL injury: a differential response in copers versus non-copers.* Journal of biomechanics, 2005. **38**(4): p. 685-693.
7. Serrão, P.R.M., et al., *Men with Early Degrees of Knee Osteoarthritis Present Functional and Morphological Impairments of the Quadriceps Femoris Muscle.* American Journal of Physical Medicine & Rehabilitation, 2015. **94**(1): p. 70-81.
8. Panariello, R.A., S.I. Backus, and J.W. Parker, *The effect of the squat exercise on anterior-posterior knee translation in professional football players.* The American journal of sports medicine, 1994. **22**(6): p. 768-773.
9. Seto, J.L., et al., *Assessment of quadriceps/hamstring strength, knee ligament stability, functional and sports activity levels five years after anterior cruciate ligament reconstruction.* The American journal of sports medicine, 1988. **16**(2): p. 170-178.
10. Puniello, M.S., C.A. McGibbon, and D.E. Krebs, *Lifting strategy and stability in strength-impaired elders.* Spine, 2001. **26**(7): p. 731-737.
11. Salem, G.J., R. Salinas, and F.V. Harding, *Bilateral kinematic and kinetic analysis of the squat exercise after anterior cruciate ligament reconstruction.* Archives of physical medicine and rehabilitation, 2003. **84**(8): p. 1211-1216.
12. Mikkelsen, C., S. Werner, and E. Eriksson, *Closed kinetic chain alone compared to combined open and closed kinetic chain exercises for quadriceps strengthening after anterior cruciate ligament reconstruction with respect to return to sports: a prospective matched follow-up study.* Knee Surgery, Sports Traumatology, Arthroscopy, 2000. **8**(6): p. 337-342.
13. Ema, R., et al., *Inferior muscularity of the rectus femoris to vasti in varsity oarsmen.* International journal of sports medicine, 2014. **35**(4): p. 293-297.
14. Ema, R., et al., *Inhomogeneous architectural changes of the quadriceps femoris induced by resistance training.* European journal of applied physiology, 2013. **113**(11): p. 2691-2703.

15. Robertson, D.G.E., J.-M.J. Wilson, and T.A. St Pierre, *Lower extremity muscle functions during full squats.* Journal of applied biomechanics, 2008(24): p. 333-9.
16. Tagesson, S., et al., *A comprehensive rehabilitation program with quadriceps strengthening in closed versus open kinetic chain exercise in patients with anterior cruciate ligament deficiency a randomized clinical trial evaluating dynamic tibial translation and muscle function.* The American journal of sports medicine, 2008. **36**(2): p. 298-307.
17. Bell, D., et al., *Squatting Mechanics in People With and Without Anterior Cruciate Ligament Reconstruction: The Influence of Graft Type.* American Journal of Medicine, 2014: p. 1-9.
18. Jean, L.M., et al., *Squat variation for preferential unilateral quadriceps loading*, in *20th Congress of the European College of Sport Science*. 2015: Malmö, Sweden.
19. Neumann, D.A., *Kinesiology of the musculoskeletal system: foundations for rehabilitation*. 2013: Elsevier Health Sciences.
20. Todd, M.S., et al., *The relationship between posterior tibial slope and anterior cruciate ligament injuries.* The American journal of sports medicine, 2010. **38**(1): p. 63-67.
21. Uhorchak, J.M., et al., *Risk factors associated with noncontact injury of the anterior cruciate ligament a prospective four-year evaluation of 859 west point cadets.* The American journal of sports medicine, 2003. **31**(6): p. 831-842.
22. Paterno, M.V., et al., *Incidence of second ACL injuries 2 years after primary ACL reconstruction and return to sport.* The American journal of sports medicine, 2014. **42**(7): p. 1567-1573.
23. Castanharo, R., et al., *Males still have limb asymmetries in multijoint movement tasks more than 2 years following anterior cruciate ligament reconstruction.* Journal of Orthopaedic Science, 2011. **16**(5): p. 531-535.
24. Shaarani, S.R., et al., *Effect of prehabilitation on the outcome of anterior cruciate ligament reconstruction.* The American journal of sports medicine, 2013. **41**(9): p. 2117-2127.
25. Grindem, H., et al., *How does a combined preoperative and postoperative rehabilitation programme influence the outcome of ACL reconstruction 2 years after surgery? A comparison between patients in the Delaware-Oslo ACL Cohort and the Norwegian National Knee Ligament Registry.* British journal of sports medicine, 2015. **49**(6): p. 385-389.
26. EItzEn, I., et al., *A progressive 5-week exercise therapy program leads to significant improvement in knee function early after anterior cruciate ligament injury.* journal of orthopaedic & sports physical therapy, 2010. **40**(11): p. 705-721.
27. Hartigan, E.H., et al., *Preoperative predictors for noncopers to pass return to sports criteria after ACL reconstruction.* Journal of applied biomechanics, 2012. **28**(4): p. 366.
28. Logerstedt, D., et al., *Symmetry restoration and functional recovery before and after anterior cruciate ligament reconstruction.* Knee Surgery, Sports Traumatology, Arthroscopy, 2013. **21**(4): p. 859-868.

29. Beynnon, B.D., et al., *Anterior cruciate ligament strain behavior during rehabilitation exercises in vivo.* The American Journal of Sports Medicine, 1995. **23**(1): p. 24-34.
30. Schmitt, L.C., M.V. Paterno, and T.E. Hewett, *The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction.* journal of orthopaedic & sports physical therapy, 2012. **42**(9): p. 750-759.
31. Lewek, M., et al., *The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction.* Clinical Biomechanics, 2002. **17**(1): p. 56-63.
32. Eitzen, I., et al., *Anterior cruciate ligament–deficient potential copers and noncopers reveal different isokinetic quadriceps strength profiles in the early stage after injury.* The American journal of sports medicine, 2010. **38**(3): p. 586-593.
33. Benjuya, N., D. Plotqin, and I. Melzer, *Isokinetic profile of patient with anterior cruciate ligament tear.* Isokinetics and exercise science, 2000. **8**(4): p. 229-232.
34. LoPresti, C., et al., *Quadriceps Insufficiency following Repair of the Anterior Cruciate Ligament*.* Journal of Orthopaedic & Sports Physical Therapy, 1988. **9**(7): p. 245-249.
35. Oberländer, K.D., et al., *Reduced knee joint moment in ACL deficient patients at a cost of dynamic stability during landing.* Journal of biomechanics, 2012. **45**(8): p. 1387-1392.
36. Oberländer, K.D., et al., *Knee mechanics during landing in anterior cruciate ligament patients: A longitudinal study from pre-to 12months post-reconstruction.* Clinical Biomechanics, 2014. **29**(5): p. 512-517.
37. Palmieri-Smith, R.M. and A.C. Thomas, *A Neuromuscular Mechanism of Posttraumatic Osteoarthritis Associated with ACL Injury.* Exercise & Sport Sciences Reviews, 2009. **37**(3): p. 147-153.
38. Krishnan, C. and G.N. Williams, *Factors explaining chronic knee extensor strength deficits after ACL reconstruction.* Journal of Orthopaedic Research, 2011. **29**(5): p. 633-640.
39. Chmielewski, T.L., et al., *A prospective analysis of incidence and severity of quadriceps inhibition in a consecutive sample of 100 patients with complete acute anterior cruciate ligament rupture.* Journal of orthopaedic research, 2004. **22**(5): p. 925-930.
40. Eitzen, I., I. Holm, and M. Risberg, *Preoperative quadriceps strength is a significant predictor of knee function two years after anterior cruciate ligament reconstruction.* British journal of sports medicine, 2009. **43**(5): p. 371-376.
41. Bloomquist, K., et al., *Effect of range of motion in heavy load squatting on muscle and tendon adaptations.* European journal of applied physiology, 2013. **113**(8): p. 2133-2142.
42. Bryanton, M.A., et al., *Effect of squat depth and barbell load on relative muscular effort in squatting.* The Journal of Strength & Conditioning Research, 2012. **26**(10): p. 2820-2828.

43. Bryanton, M.A., et al., *Quadriceps effort during squat exercise depends on hip extensor muscle strategy.* Sports Biomechanics, In Press.
44. Jean, L.M. and L.Z. Chiu, *Unilateral Quadriceps Loading During Full Squat Exercise With and Without Single-Foot Elevation in ACL Injured Persons*, in *Gait and Clinical Movement Analysis Society* 2016: Memphis, TN.
45. Hartmann, H., et al., *Influence of squatting depth on jumping performance.* The Journal of Strength & Conditioning Research, 2012. **26**(12): p. 3243-3261.
46. Chizewski, M.G. and L.Z. Chiu, *Contribution of calcaneal and leg segment rotations to ankle joint dorsiflexion in a weight-bearing task.* Gait & posture, 2012. **36**(1): p. 85-89.
47. Fry, A.C., J.C. Smith, and B.K. Schilling, *Effect of knee position on hip and knee torques during the barbell squat.* The Journal of Strength & Conditioning Research, 2003. **17**(4): p. 629-633.
48. Escamilla, R., et al., *Cruciate ligament loading during common knee rehabilitation exercises.* Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 2012: p. 0954411912451839.
49. Markolf, K.L., et al., *Effects of applied quadriceps and hamstrings muscle loads on forces in the anterior and posterior cruciate ligaments.* The American journal of sports medicine, 2004. **32**(5): p. 1144-1149.
50. Grzelak, P., et al., *Hypertrophied cruciate ligament in high performance weightlifters observed in magnetic resonance imaging.* International orthopaedics, 2012. **36**(8): p. 1715-1719.
51. Calhoon, G. and A.C. Fry, *Injury rates and profiles of elite competitive weightlifters.* Journal of athletic training, 1999. **34**(3): p. 232.
52. Brunt, D., et al., *The effect of foot placement on sit to stand in healthy young subjects and patients with hemiplegia.* Archives of physical medicine and rehabilitation, 2002. **83**(7): p. 924-929.
53. Roy, G., et al., *Side difference in the hip and knee joint moments during sit-to-stand and stand-to-sit tasks in individuals with hemiparesis.* Clinical Biomechanics, 2007. **22**(7): p. 795-804.
54. Hsiao, S., et al., *Changes of muscle mechanics associated with anterior cruciate ligament deficiency and reconstruction.* The Journal of Strength & Conditioning Research, 2014. **28**(2): p. 390-400.
55. Nilstad, A., et al., *Association Between Anatomical Characteristics, Knee Laxity, Muscle Strength and Peak Knee Valgus During Vertical Drop-Jump Landings.* journal of orthopaedic & sports physical therapy, 2015. **45**(12): p. 998-1005.
56. Cohen, J., *A Power Primer.* Psychology Bulletin, 1992. **112**(1): p. 155-159.
57. Fry, A.C., *The Role of Resistance Exercise Intensity on Muscle Fibre Adaptations.* Sports Medicine, 2004. **34**: p. 663-679.
58. Chiu, L.Z., G.L. VonGaza, and L.M. Jean, *Net Joint Moments and Muscle Activation in Barbell Squats Without and With Restricted Anterior Leg Rotation.* Journal of sports sciences, 2016: p. 1-9.

Appendix A:

Stretches
* To be completed prior to every exercise session

Stretch	**Time (seconds)**	**Repetitions**
Adductors	30	2
Calves	30	2
Hamstrings	30	2
Hip Flexors	30	2
Piriformis	30	2
Quadriceps	30	2

Rolling out
* To be completed at the end of training sessions

Muscle
Feet
Calves
Hamstrings
Quadriceps
IT Band

Intensity is given as weight in kilograms or as a % of one-repetition maximum (%1RM)

Week 1 - Neuromotor

Monday

Exercise	Intensity	Sets*Repetitions
Quad Activation	-	5*5
Sit to Stand	-	5*3
Calf Activation	-	3*6
A1 - Leg Lowers A2 - Glute Bridges A3 - Calf Raises	- - -	3*5 3*6 3*6

Wednesday

Exercise	Intensity	Sets*Repetitions
Quad Activation	-	5*5
Sit to Stand	-	5*3
Calf Activation	-	3*6
A1 - Leg Lowers A2 - Glute Bridges A3 - Calf Raises	- - -	3*5 3*6 3*6

Friday

Exercise	Intensity	Sets*Repetitions
Quad Activation	-	5*5
Sit to Stand	-	5*3
Calf Activation	-	3*6
A1 - Leg Lowers A2 - Glute Bridges A3 - Calf Raises	- - -	3*6 3*6 3*6

Week 2 - Neuromotor

Monday

Exercise	Intensity	Sets*Repetitions
Quad Activation	-	5*5
Sit to Stand	-	5*5
Calf Activation	-	3*8
A1 - Leg Lowers A2 - Glute Bridges A3 - Calf Raises	- - -	3*6 3*8 3*6

Wednesday

Exercise	Intensity	Sets*Repetitions
Quad Activation	-	5*5
Sit to Stand	-	5*6
Plate Squat	10 kg	3*3
A1 - Leg Lowers A2 - Glute Bridges A3 - Calf Raises	- - -	3*6 3*8 3*6

Friday

Exercise	Intensity	Sets*Repetitions
Quad Activation	-	5*5
Sit to Stand	-	5*6
Plate Squat	10 kg	3*3
A1 - Leg Lowers A2 - Glute Bridges A3 - Calf Raises	- - -	3*8 3*8 3*8

Week 3 - Hypertrophy

Monday

Exercise	Intensity	Sets*Repetitions
Quad Activation	-	5*5
Sit to Stand	-	5*5
Plate Squat	10 kg	3*5
A1 - Leg Lowers	-	3*8
A2 - Glute Bridges	-	3*8
A3 - Calf Raises	-	3*8

Wednesday

Exercise	Intensity	Sets*Repetitions
Quad Activation	-	5*5
Sit to Stand	-	5*5
Plate Squat	10 kg	3*5
A1 - Leg Lowers A2 - Glute Bridges A3 - Calf Raises	- - -	3*8 3*10 3*8

Friday

Exercise	Intensity	Sets*Repetitions
Quad Activation	-	5*5
Sit to Stand	-	5*5
Plate Squat	10 kg	3*6
A1 - Leg Lowers A2 - Glute Bridges A3 - Calf Raises	- - -	3*10 3*12 3*10

Week 4 - Hypertrophy

Monday

Exercise	Intensity	Sets*Repetitions
Quad Activation	-	5*5
Sit to Stand	-	5*5
Plate Squat	10 kg	3*8
A1 - Leg Lowers	-	3*12
A2 - Glute Bridges	-	3*12
A3 - Calf Raises	-	3*10

Wednesday

Exercise	Intensity	Sets*Repetitions
Sit to Stand	-	5*5
Plate Squat	10 kg	3*8
Deadlift Morning	-	5*5
A1 - Leg Lowers A2 - Glute Bridges A3 - Calf Raises	- - -	3*12 3*12 3*12

Friday

Exercise	Intensity	Sets*Repetitions
Sit to Stand	-	3*8
Plate Squat	10 kg	4*8
Deadlift Morning	-	5*5
Deadlift	70%1RM	4*3
A1 - Leg Lowers A2 - Calf Raises	- -	4*12 4*12

Week 5 - Hypertrophy

Monday

Exercise	Intensity	Sets*Repetitions
Sit to Stand	-	3*8
Plate Squat	15 kg	5*6
Front Squat NH	50%1RM	4*5
A1 - Psoas Sit Up A2 - Glute Bridges A3 - Calf Raises	- - 5 kg	3*6 3*12 3*10

Wednesday

Exercise	Intensity	Sets*Repetitions
Sit to Stand	-	3*10
Plate Squat	15 kg	5*6
Front Squat	60%1RM	5*5
Deadlift	80%1RM	4*3
A1 - Crunch A2 - Calf Raises	5 kg 5 kg	3*5 3*10

Friday

Exercise	Intensity	Sets*Repetitions
Sit to Stand	-	3*5
Plate Squat	15 kg	5*8
Front Squat	80%1RM	5*5
A1 - Psoas Sit Up	-	4*6
A2 - Glute Bridges	-	4*12
A3 - Calf Raises	5 kg	4*10

* NH = No hands

Week 6 - Hypertrophy

Monday

Exercise	Intensity	Sets*Repetitions
Plate Squat	15 kg	5*6
Front Squat	80%1RM	5*3
A1 - Psoas Sit Up A2 - Glute Bridges A3 - Calf Raises	- - 5 kg	3*6 3*12 3*10

Wednesday

Exercise	Intensity	Sets*Repetitions
Plate Squat	15 kg	5*6
Front Squat	85%1RM	5*3
Deadlift	85%1RM	4*3
A1 - Crunch A2 - Calf Raises	5 kg 5 kg	3*5 3*10

Friday

Exercise	Intensity	Sets*Repetitions
Plate Squat	15 kg	5*6
Front Squat	85%1RM	4*4
A1 - Psoas Sit Up A2 - Glute Bridges A3 - Calf Raises	- - 5 kg	4*6 4*12 4*12

Week 7 - Strength

Monday

Exercise	Intensity	Sets*Repetitions
Plate Squat	15 kg	3*5
Front Squat	85%1RM	5*5
A1 - Psoas Sit up A2 - Glute Bridges A3 - Calf Raises	- - 5 kg	3*8 3*12 3*12
Plate Squat	15 kg	3*8

Wednesday

Exercise	Intensity	Sets*Repetitions
Plate Squat	15 kg	3*5
Front Squat	87%1RM	5*3
Deadlift	87%1RM	4*3
A1 - Crunch A2 - Calf Raises	5 kg 5 kg	3*5 3*12

Friday

Exercise	Intensity	Sets*Repetitions
Plate Squat	15 kg	3*5
Front Squat	87%1RM	5*3
A1 - Psoas Sit up A2 - Calf Raises	- 7 kg	4*8 4*12
Plate Squat	15 kg	3*10

Week 8 - Strength

Monday

Exercise	Intensity	Sets*Repetitions
Plate Squat	15 kg	3*5
Front Squat	87%1RM	4*4
A1 - Psoas Sit up A2 - Glute Bridges A3 - Calf Raises	- - 7 kg	3*12 3*12 3*12
Plate Squat	15 kg	3*10

Wednesday

Exercise	Intensity	Sets*Repetitions
Plate Squat	15 kg	3*5
Front Squat	87%1RM	5*4
Deadlift	87%1RM	3*5
A1 - Crunch A2 - Calf Raises	5 kg 7 kg	3*8 3*10

Friday

Exercise	Intensity	Sets*Repetitions
Plate Squat	15 kg	3*5
Front Squat	90%1RM	5*3
A1 - Psoas Sit up A2 - Calf Raises	- 7 kg	4*12 4*12
Plate Squat	15 kg	3*12

Week 9 - Strength

Monday

Exercise	**Intensity**	**Sets*Repetitions**
Plate Squat	15 kg	3*5
Front Squat	90%1RM	5*3
Front Squat	75%1RM	5*5
A1 - Psoas Sit up A2 - Calf Raises A3 - Glute Bridges	- 9 kg -	3*12 3*12 3*12

Wednesday

Exercise	**Intensity**	**Sets*Repetitions**
Plate Squat	15 kg	3*5
Front Squat	90%1RM	5*4
Deadlift	90%1RM	3*3
A1 - Crunch A2 - Calf Raises	5 kg 9 kg	3*12 3*12

Friday

Exercise	**Intensity**	**Sets*Repetitions**
Plate Squat	15 kg	3*5
Front Squat	93%1RM	5*3
Front Squat	75%1RM	3*8
A1 - Crunch A2 - Psoas Sit up	5 kg -	4*12 4*12

Week 10 - Strength

Monday

Exercise	Intensity	Sets*Repetitions
Plate Squat	15 kg	3*5
Front Squat	93%1RM	5*3
Front Squat	75%1RM	3*10
A1 - Psoas Sit up A2 - Calf Raises A3 - Glute Bridges	- 9 kg -	3*12 3*12 3*12

Wednesday

Exercise	Intensity	Sets*Repetitions
Plate Squat	15 kg	3*5
Front Squat	93%1RM	5*4
Deadlift	93%1RM	3*3
A1 - Crunch A2 - Calf Raises	10 kg 9 kg	3*8 3*12

Friday

Exercise	Intensity	Sets*Repetitions
Plate Squat	15 kg	3*5
Front Squat	95%1RM	5*3
Front Squat	75%1RM	3*8
A1 - Crunch A2 - Calf Raises	10 kg 9 kg	2*8 2*12