DOES TRUNK POSITION CHANGE OVER TIME IN THE Y-BALANCE TEST IN PATIENTS WITH ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION?

by

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Chapter 1
INTRODUCTION

The anterior cruciate ligament (ACL) allows for stabilization of the knee when cutting and pivoting by preventing anterior and rotational motion of the tibia relative to the femur (Spindler & Wright, 2008). ACL injuries are a common injury among athletes and typically happen in non-contact situations associated with high external knee loads such as landing, decelerating, and of course cutting (Shimokochi & Shultz, 2008). Significant neuromuscular deficiencies and functional limitations are observed in both limbs following reconstruction surgery. These deficits are often observed right up until the latter stages of ACLR rehabilitation programs where athletes are reintroduced to high-risk athletic maneuvers in controlled environments (Hewett et al., 2002). Furthermore, although both limbs are affected post-surgery there is significant asymmetrical loading of the lower extremities across a variety of movements. One explanation for this asymmetry is loss in quadricep strength of the surgical side and presents in compensatory movement mechanisms (Chmielewski, 2011).

The primary goal for many athletes undergoing rehabilitation after ACLR is to return to their preinjury sports. Previous research has shown that 81% of athletes return to some form of sport post ACLR, and 55% of athletes return to competitive sport post ACLR. Patients who received ipsilateral semitendinosus and gracilis autograft (ISGA) also showed greater chances of returning to competitive level sports while those who underwent a bone-patellar tendon-bone (BPTB) graft had greater chance to return to their preinjury level sport (Ardern et al., 2014).

Return to sport is often guided by clinicians through assessing athletes' movement patterns and addressing abnormal movement. Functional movement tests allow clinicians to evaluate fundamental dynamic movement throughout three planes of motion simultaneously. Previous literature suggests that dynamic knee valgus measures may be predictive of ACL
injury and is often at the forefront of the measures analyzed (Hewett et al., 2005). The Y balance test (YBT) is a common clinical test that is part of rehabilitation of musculoskeletal injuries, including ACLR. It is used to assess dynamic balance, postural stability, and movement quality. It requires participants to reach in three directions; anterior (ANT), posterolateral (PL), and posteromedial (PM). Participants stand on an elevated footplate and with their foot push a rectangular block along plastic tubing in the three directions. The YBT is often used to analyze lower limb differences, it has been observed that ACLR individuals who were cleared for RTS have inferior YBT reach distances compared to mild lower limb injury groups and healthy control groups (Oleksy et al., 2021). Furthermore, no significant differences in YBT reach distance or composite scores have been found between sexes. (Maguire et al., 2021). Research suggests that the YBT may be a valid test to observe differences in balance and neuromuscular control at RTS for ACLR athletes (Kline et al., 2016; Oleksy et al., 2021). The YBT has been found to be indicative of performance outcomes in other functional movement assessments and patient reported outcome measures for ACLR athletes at RTS (Garrison et al., 2015; Kim et al., 2023).

Quadricep strength deficits are common after ACLR. These deficits begin after injury due to a combination of joint immobilization, muscle inhibition, and quadriceps avoidance strategies (Baugher et al., 1984; Chmielewski et al., 2001) which result in less quadriceps activity and strength; presumably to avoid shearing forces, and these deficits may be exacerbated with reconstructive surgery. It is important to have good quadricep strength post-ACLR for functional performance,(Palmieri-Smith & Lepley, 2015) symmetrical joint loading,(Lewek et al., 2002) knee stability,(Keays et al., 2003) and to slow the rate of osteoarthritis development.(Palmieri-Smith & Thomas, 2009) Approximately 80% of athletes do not meet the recommended quadriceps strength symmetry (LSI >90%) 6 months post ACLR surgery.(Cristiani et al., 2019) With decreased muscle strength compensation often
occurs resulting in altered movement patterns. Shi et al. investigated isokinetic thigh strength and knee biomechanics when side cutting in patients 1 year post ACLR surgery. They found that patients’ ACLR limbs had significantly decreased knee flexion angle and knee extension moment compared to their contralateral limb and the control group.

Patient reported outcome (PRO) measures can inform clinicians about the subjective progress of a patient as they progress through rehabilitation. Tegner and Marx scales are commonly used to estimate individuals’ current activity levels. Additionally, Tegner scale estimates the level of activity in patients before the injury occurred (Tegner & Lysholm, 1985). The International Knee Documentation Committee (IKDC) provides clinicians with an insight to how their patients’ knees are affecting their quality of life, by evaluating patients’ symptoms, functions and sports activity (Irrgang et al., 2001). The Knee Injury Osteoarthritis Outcome Score (KOOS) also assesses knee health quality of life. It evaluates knee symptoms and functions using 5 categories; pain, other symptoms, function in activities of daily living, function in sports and recreation, and knee related quality of life (Roos et al., 1998). The Tampa Scale for Kinesiophobia (TSK) assesses patients’ fear of disability. The Tampa Scale of Kinesiophobia - 11 (TSK-11) is a shorter 11 item questionnaire version of the TSK evaluating fear of reinjury. The TSK-11 has been validated for ACLR patient use in the early post operative phase (George et al., 2012). The ACL Return to Sport Index (ACL-RSI) scale is used to evaluate ACLR patients’ psychological responses in regards to their emotions, performance confidence, and risk in association with RTS (Webster et al., 2008).

Trunk control has been suggested to be an important variable in return to sport post ACLR and identifying those at increased risk of ACL injury (Zazulak et al., 2007). Significant deficits in neuromuscular control and proprioception can occur after ACL ruptures and these deficits are likely to be observed throughout the later stages of ACLR rehabilitation programs (Hewett, 2002). The trunk has been found to impact the dynamic stability of the
knee joint and increase the likelihood of knee injury. This is especially true during fast paced athletic movements due to high ground reaction force (GRF) aimed toward the body’s center of mass (COM) paired with insufficient neuromuscular control (Zazulak et al., 2007). When there is lateral trunk motion and increased knee load, the body responds by increasing hip adductor torque to stay in an upright position and reduce lower extremity forces (Hewett & Myer, 2011). This is particularly important when performing a single leg cutting or landing movement as the entire body must balance itself over one lower extremity limb (Hewett & Myer, 2011).

The core is also critical to performance on the YBT. Previous research observed that a core muscle exercise program resulted in significant improvements in YBT reach distances in all directions amongst youth soccer players (Kumahara et al., 2021). ACLR graft type has been seen to produce different trunk kinematics during single leg squats (SLS). ISGA grafts have previously shown greater forward trunk flexion and greater lateral trunk flexion over the ACLR limb compared to the BPTB graft and non-ACLR limbs (D. R. Bell et al., 2014). This demonstrates that trunk and knee outcomes are linked and an important area of study.

Although the YBT has been studied in relation to ACLR, it has not been studied extensively in relation to kinematic changes over time. Based on previous literature, impaired coordination and control of both the trunk and the lower extremity joints could potentially increase an athlete's susceptibility to injury. With further investigation this may prove to be a modifiable risk factor for ACLR athletes' susceptibility to reinjury or injury of the contralateral ACL. The research behind the trunk's association to the ACL for ACLR patients when performing functional movement tasks such as the YBT is quite limited, additionally trunk positioning changes over time appears to be absent from literature thus far.

The purpose of this study is to investigate trunk, hip, and knee kinetic and kinematic changes over time (month 4, month 5, month 6) when performing the YBT anterior direction
in ACLR patients undergoing rehabilitation. We hypothesize that trunk, hip, and knee kinetics and kinematics will differ between ACLR and non-ACLR limbs over time in the YBT anterior. The second purpose of this study is to investigate quadriceps strength changes over time (month 4, month 5, month 6) in ACLR patients undergoing rehabilitation. The third purpose of our study is to investigate the relationship between Patient Reported Outcome (PRO) measures and trunk, hip, and knee kinetic and kinematic measures at month 4, month 5, and month 6 post-surgery. We theorize that there will be a positive correlation between these variables and PRO measures.

**Research Questions:**

Aim 1: Determine if trunk, hip, and knee kinetics and kinematics changes over time (month 4, month 5, month 6) during the YBT anterior in patients undergoing rehabilitation after ACLR.

Aim 2: Determine if quadriceps strength changes over time (month 4, month 5, and month 6) in patients undergoing rehabilitation after ACLR.

Aim 3: Determine if PRO measures are correlated with trunk, hip, and knee kinematics and kinetics, and quadriceps strength measures at different time points in ACLR patients undergoing rehabilitation.

**Null Hypothesis:**

Aim 1a: H₀: YBT trunk, hip, and knee kinematics and kinetics will not significantly differ between limbs.

Aim 1b: H₀: YBT trunk, hip, and knee kinematics and kinetics will not significantly change over time.

Aim 2: H₀: Quadriceps strength will not change over time and will not significantly differ between limbs.
Aim 3: \( H_0: \) There will be no correlation between PRO measures and YBT trunk, hip, and knee and quadriceps strength measures of the ACLR limb.

**Research Hypotheses:**

**Primary Aims**

Aim 1a: YBT anterior direction trunk kinematics and kinetics will significantly differ between limbs. The non-ACLR limb will have reduced trunk flexion, trunk lateral lean, and trunk rotation. The non-ACLR limb will have increased knee flexion. The non-ACLR limb will have reduced hip flexion, increased knee extension moment and hip extension moment.

Aim 1b: YBT anterior direction trunk strategy will vary over time for ACLR limb. The ACLR limb will have reduced trunk flexion/trunk lateral lean/trunk rotation at month 6 compared to month 4. The ACLR limb will have increased knee flexion at month 6 compared to month 4. The ACLR limb will have reduced hip flexion. The ACLR limb will have increased knee extension moment and hip extension moment.

Aim 2: Quadriceps strength will increase over time (months 4,5,6) in both limbs. The healthy limb will be stronger than the ACLR limb.

Aim 3: There will be a correlation between PRO measures and YBT trunk, hip, and knee and quadriceps strength measures of the ACLR limb. There will be a positive correlation.

**Dependent Variables:**

Aim:

1a: Trunk forward flexion, Trunk lateral flexion, Trunk rotation, knee flexion, hip flexion, knee extension moment, hip extension moment.

1b: Trunk forward flexion, Trunk lateral flexion, Trunk rotation, knee flexion, hip flexion, knee extension moment, hip extension moment

2: Quadriceps Strength
3: PRO measures: IKDC score, Tegner score, ACL-RSI score

**Independent Variables:**

**Aim:**

1a: Healthy and ACLR limbs

1b: Time (months 4,5,6)

2: Time (months 4,5,6), Healthy and ACLR limbs

3: Trunk forward flexion, Trunk lateral flexion, Trunk rotation, knee flexion, hip flexion, knee extension moment, hip extension moment

**Delimitations:**

1. All testing was performed under the same laboratory conditions.

**Assumptions/Limitations:**

1. Participants performed to their best effort.

2. All participants completed surveys/questionnaires honestly.
Operational Definitions:

**ACLR:** Anterior Cruciate Ligament Reconstruction.

**COM:** Center of mass

**Healthy Limb:** The limb with no history of ACL injury, also referred to as non-ACLR.

**IKDC:** International Knee Document Committee 2000, self-reported knee function questionnaire used after knee injury.

**Injured Limb:** The limb that received ACL reconstruction surgery.

**VGRF:** Vertical ground reaction force

**Non-ACLR:** The limb with no history of ACL injury

**Normalized Reach Distance:** Reach distance (cm) divided by the length of the stance limb (cm), expressed as a percentage.

**PRO:** Patient Reported Outcome. Self-reported patient measurements recorded through questionnaires and surveys.

**ROM:** Range of Motion

**RTS:** Return to Sport

**Stance Limb:** The limb used for support during the single leg squat and support when reaching during the YBT.

**Torque:** Rotational force
Chapter 2

LITERATURE REVIEW

ACL injuries: Epidemiology

The anterior cruciate ligament (ACL) allows for stabilization of the knee when cutting and pivoting by preventing anterior and rotational motion of the tibia relative to the femur (Spindler et al., 2008). ACL injuries are a common injury among athletes and typically happen in non-contact situations associated with high external knee loads such as landing, decelerating, and of course cutting (Shimokochi & Shultz, 2008). In the general population the annual incidence rate of ACL tears is 68.6 per 100,000 person-years (Sanders et al., 2016). The implications of which puts U.S. healthcare system yearly costs at approximately $1 billion for ACL injuries (Griffin et al., 2000; Hewett & Bates, 2017).

ACL injuries: Risk Factors

There is no singular mechanism behind non-contact ACL injuries. Research has proposed several risk factors and theories behind ACL tears. These include anatomical risk factors, gender, hormonal risk factors, and environmental risk factors.

Anatomical factors

A meta-analysis conducted by Zeng et al. (2013) examined the effect of the intercondylar notch dimensions on ACL injury came to the conclusion that a narrow intercondylar notch is associated with ACL injury risk (Zeng et al., 2013). This is in agreement with the study carried out by Uhorchak et al. (2003). For this study researchers radiographed and measured femoral notches of 854 male and female military cadets, and then monitored subjects ACL injury occurrence over the course of 4 years. 29 subjects suffered complete ACL tears. It was observed that a small femoral notch may predispose athletes to non-contact ACL tears (Uhorchak et al., 2003). A retrospective study by Shen et al. (2018) also suggested that a narrow intercondylar notch may be used as a predictor for ACL injury.
(Shen et al., 2018). Uhorchak et al. (2003) also stated that generalized joint laxity was another significant contributing factor to both male and female ACL tears. They found that generalized joint laxity causes 2.7 times greater ACL injury risk. An increased Q-angle may be another anatomical ACL risk factor; it has been suggested that a large Q angle may increase knee valgus angular forces (Woodland & Francis, 1992). The Q-angle is formed by a line from the anterior-superior iliac spine to the central patella, and a second line from the central patella to the tibial tubercle (Alentorn-Geli et al., 2009). A smaller than average ACL and increased BMI (Uhorchak et al., 2003) have also been suggested as risk factors for ACL injury.

*Environmental factors*

Environmental factors such as weather conditions, playing surface, footwear, and sports equipment may also contribute to ACL injury risk. A retrospective study by Ruedl et al. (2011) investigated the interaction of extrinsic risk factors in female ACL injured recreational skiers. They found that snowfall increased skiers’ ACL injury risk 17-fold. They suggested that significant increase may be due to poor visibility, lighting, and increased slope friction associated with snowfall conditions. Although sunny conditions are associated with much less ACL injury risk than snowfall, they observed a higher ACL injury prevalence rate during sunny conditions due to an increased number of people on the slopes.

Playing surface is another environmental risk factor for ACL injury. In NCAA football players, the ACL injury rate on artificial grass has been found to be 1.39 times higher than that of natural grass (Dragoo et al., 2013). In Skiing, icy slopes, difficult (black) slopes, and snow fall have been found to significantly increase ACL injury risk. Moreover, lower ACL injury risk while skiing is associated with grippy, slushy snow, and moderate (red) slopes (Ruedl et al., 2011).
Footwear, specifically the shoe surface interface, has been noted as a possible ACL injury risk factor. Drakos et al. (2009) investigated the effects of shoe-surface interface in the development of ACL strain during a simulated cutting motion. They found that a natural grass-cleat combination produced less strain on the ACL than a turf-cleat shoe, turf-turf shoe, and an AstroTurf-turf shoe. It was suggested that this may be due to traction and/or the shock absorption properties of the shoes. A stiffer shoe like that of the AstroTurf-turf shoe allows for less vertical displacement of the foot than a more flexible shoe for the same vertical load, thus placing increasing pressure on joints (Drakos et al., 2009). Ski boot soles with increased abrasion at the toe and heel is also significantly associated with ACL injury risk (Ruedl et al., 2023). In relation to ski equipment, traditional skis have been found to have a higher ACL injury risk than carving skis; which are shorter and more sidecut than traditional skis (Ruedl et al., 2011). Longer skis have been shown to increase the risk of ACL injury in less skilled female skiers (Ruedl et al., 2023).

Female Athlete

Female athletes are at a greater risk of suffering ACL injury than their male counterparts in the same high-risk sports (Dewig et al., 2024). A systematic review with meta-analysis by Montalvo et al. (2019) revealed that 1 in 29 female athletes and 1 in 50 male athletes ruptured their ACL in a window spanning from a single sporting season to 25 years, making the incidence proportion of ACL injury among female athletes 1.5 times higher than male athletes (Montalvo et al., 2019). Moreover, it has been observed that high school female athletes are at 1.6-fold greater risk for ACL tears per athletic exposure compared to male athletes (Gornitzky et al, 2016). Female athletes demonstrate different maturation to males in terms of muscular strength and neuromuscular control. The absence of the which subjects females to the exposure of greater GRF’s and external knee abduction loads especially in sports where landing, pivoting, and deceleration are essential (Hewett et al., 2011).
**Hormonal factors**

It is known that hormone levels fluctuate across the menstrual cycle in females. It has been reported that ACL injury incidences are greater during the preovulatory phase (days 1-14) (Balachandar et al., 2017; Hewett et al., 2007; Ruedl et al., 2009). During the preovulatory phase estrogen levels are high, it has been noted that estradiol (form of estrogen) influences ligament strength and soft tissue tension negatively (Liu et al., 1996). The ACL has estrogen and progesterone receptors in its cells; synoviocytes, fibroblasts, blood vessel wall cells (Liu et al., 1996). This suggests that female sex hormones may influence the structure and composition of the ligament. The regulation of hormones through the use of oral contraception has not been found to increase or decrease ACL injury risk (D. R. Bell et al., 2011; Ruedl et al., 2009; Samuelson et al., 2017).

**Biomechanical Factors**

Although the aforementioned factors may play a role in an athlete suffering an ACL tear, they should not be the focus for injury prevention as they are non-modifiable risk factors. Therefore, we should turn our focus toward modifiable risk factors such as biomechanical and neuromuscular influences that can be amended with targeted preventative strategies and treatments.

The ACL can be placed under excessive stress by aberrant positions of the knee, hip and trunk. When joints are placed in a greater flexed position during landing tasks, it allows for more energy to be absorbed rather than transferring the impact to the knee (Alentorn-Geli et al., 2009). Foody et al. (2023) suggested that major tension created by increased quadriceps activity prior to landing paired with an unanticipated extended knee position subjects the ACL to greater risk of injury (Foody et al., 2023). Bakker et al. (2016) used an in vivo/computational/in vitro approach study measuring ACL strain in the sagittal plane during landing. They observed that decreased max knee flexion angle, decreased hip flexion angle at
maximum VGRF, increased hip extension moment, decreased hip angle ROM and velocity were all significantly associated with increased ACL strain. Moreover, that the variable combination of hip and trunk flexion angles at maximum GRF best predicted maximal ACL strain during jump landing (Bakker et al., 2016). Boden et al. (2009) using ACL injury videos, analyzed ankle and hip abnormalities during time of injury. They found that subjects who made contact with the ground flatfooted or by using their hindfoot, compensated for lack of ankle plantar-flexion by significantly increasing their hip flexion angle (Boden et al., 2009). This suggests that although increased flexion of the hip typically reduces risk of ACL injury, a more even distribution of flexion across the lower extremity joints is preferable.

ACL biomechanical risk factors are not confined to the sagittal plane. Females with increased dynamic knee valgus (position or motion of the distal femur toward and distal tibia away from the body’s midline) and high knee abduction loads during landing tasks are more susceptible to ACL injury (Hewett et al., 2005). This was also observed by Numata et al. (2018) where they used coronal plane two-dimensional motion analysis to evaluate the relationship between knee valgus angle and non-contact ACL. Dynamic knee valgus at hallux-ground contact and at maximal knee valgus was significantly greater in the injured group compared to the healthy control group (Numata et al., 2018).

Decreased internal and external hip rotation range of motion relative to body weight has also been suggested as a potential risk factor for ACL injury in athletes (Tainaka et al., 2014). A study by Chapell et al. (2007) that investigated the kinematics of a vertical stop-jump found that female subjects demonstrated increased internal hip rotation and decrease external rotation at the landing phase compared to males. Furthermore, they found that female subjects had increased knee internal rotation compared to male subjects (Chappell et al., 2007). Besier et al. (2001) also observed that cutting maneuvers performed without
adequate planning presented with increased internal-external knee rotation making the knee vulnerable to injury (Besier et al., 2001).

**ACL Injuries: Trunk**

ACL injury risk can be predicted by trunk displacement and frontal plane knee load in female athletes (Hewett et al., 2011). During active proprioception of the trunk, the muscle spindles are largely activated to reposition the trunk to a neutral position (Zazulak et al., 2007). When there is lateral trunk motion and increased knee load, the body responds by increasing hip adductor torque to stay in an upright position and reduce lower extremity forces (Hewett, 2011). This is particularly important when performing a single leg cutting or landing movement as the entire body must balance itself over one lower extremity limb (Hewett, 2011). Insufficient neuromuscular control matched with high VGRF aimed towards the body’s COM can negatively impact the dynamic stability of the knee and increase the risk of knee injury during fast paced athletic movements (Zazulak et al., 2007). A study by Frank et al. (2013) investigated the relationship between trunk motion, neuromuscular control of the lumbopelvic hip complex, and triplanar knee loads with ACL injury during sidestep cutting. They found that greater hip abduction and less trunk rotation in the new direction of travel was associated with increased internal knee varus moment. In addition, they observed that increased trunk flexion displacement and hip internal rotation moment was associated with a higher internal knee external rotation moment (Frank et al., 2013). This indicates that the trunk and hip biomechanics play a role in ACL loading mechanisms in the frontal and transverse planes. Moreover, it has been suggested that landing single legged with COM distanced more posterior from the base of support (unstable posture) may increase ACL injury risk due to the quadriceps strongly contracting upon landing to prevent falling backwards (Sheehan et al., 2012). It has been observed in healthy individuals performing drop jump landings that those who land with an extended trunk position place approximately
1.5-2 times greater load on the knee compared to those who land with a flexed trunk position (Kulas et al., 2008).

In recent years, trunk control has been suggested to also play a role in an athlete's ability to return to sport post ACLR and identifying those at increased risk of ACL injury (Zazulak et al., 2007). Significant neuromuscular control and proprioception deficits occur after ACL ruptures and these deficits are likely to be observed right up until the later stages of ACLR rehabilitation programs (Hewett et al., 2002).

**ACLR: Graft Types**

Instability, menisci damage, articular cartilage damage, and osteoarthritis are all anticipated injury progressions if ACL tears are left untreated (Spindler et al., 2008). Therefore, ACL reconstruction (ACLR) surgery and rehabilitation is the typical approach to regain joint stability and getting athletes back to their elected sport. The surgical method for ACL reconstruction involves repairing the ACL tear with a graft. The graft is drilled into the tibia and femur at ACL insertion points in order to imitate the normal anatomy and function of the ACL (Spindler et al., 2008). The patellar tendon or hamstring tendon may be used for the graft. Ipsilateral bone patellar tendon bone (BPTB) grafts have appeared to have a negative effect on knee extensor strength and knee extensor moment (Ageberg et al., 2009). Whereas the ipsilateral semitendinosus and gracilis (ISGA) graft preserves knee extension but also has its disadvantages of decreased knee flexion strength and tibial rotation control both of which are associated with hamstring weakness (Ageberg et al., 2009). Furthermore, it has been found that patients who have received BPTB reattain their quadriceps strength and meet return to play criteria at slower rates compared to ISGA (Smith et al., 2020). However, graft type has been shown to have minimal influence on the development of osteoarthritis in ACLR patients 10 years post-surgery (Pinczewski, L.A., 2007)(Frank & Jackson, 1997).
**ACLR: Post-Surgical Rehabilitation**

ACLR rehabilitation programs and return to sport timelines cannot be in a one size fits all box, but should be individualized based on graft type and in later stages be focused on preparing athletes to return to their chosen sport. Rehabilitation should be monitored by a trained professional such as an athletic trainer, as second ACL injuries could be minimized if significant muscle strength and endurance deficits still ensue post rehabilitation. Previous research has shown that 81% of athletes return to some form of sport post ACLR, and 55% of athletes return to competitive sport post ACLR (Ardern et al., 2014). Returning to sport post ACLR makes the patient susceptible to both ACL graft rupture and rupture of the contralateral ACL (Chmielewski, 2011). The incidence of a second ACL injury post ACLR is as high as 30%, with the greatest risk of retear occurring within the initial two years (Paterno et al., 2014).

*Early phase rehabilitation (0-3 months)*

The early phase of rehabilitation begins 1-day post-surgery and lasts approximately 3 months. Patients generally meet with their clinician 1-2 times per week in this phase. Their rehabilitation goals during this period are focused on graft healing, regaining flexion and extension range of motion (ROM), restoring quadriceps and hamstring strength, and adhering to their home exercise programs (HEP) and precautions such as weightbearing progressions, weaning from their post-operation extension brace, and reducing swelling (UW Health Sports Medicine, 2022).

*Late phase rehabilitation (4-6 months)*

Patients begin the late phase of rehabilitation once their goals are met for the early stage. Rehabilitation with their clinician is once every 2-4 weeks, we generally see most patients transition out of rehabilitation at this stage. In this phase their rehabilitation goals focus on continued strengthening of the quadriceps and hamstrings, movement quality,
conditioning and functional exercises such as running, agility drills, changing direction, landing tasks (UW Health Sports Medicine, 2022). During this period of 4-6 months, we tend to know very little about the changes that occur over time in the ACLR population as most of the literature with regards to ACLR is studied in the early phase of rehabilitation or when patients are preparing for RTS at around 9 months post-operation.

*Transition to sport (7-9)*

Between 7-9 months post-ACLR patients begin their transition back to their respective sports and have even less formalized rehab. Their goals for this stage are heavily focused on their ensuring they are confident with their sport specific movements e.g. cutting, have control of their movements, and most importantly perform these movements with good mechanics (UW Health Sports Medicine, 2022)

*Return to sport (~9 months)*

Patients may return to sport once they are cleared by their orthopedic surgeon and their physical therapist/ athletic trainer. In order to be cleared for return to sport, patients often must complete a battery of progressive tests. These tests require participants to have less than 10% asymmetry between limbs during and may include Biodex strength testing, force plate jumps and vertical hop tests, and horizontal hop tests (UW Health Sports Medicine, 2022).

*Quadriceps strength and associated mechanics*

The quadriceps function to extend the knee. Lower knee flexion angles (<30 degrees) with increased quadriceps forces have been shown to load the ACL, and instigate anterior shear force, anterior tibial translation, knee valgus rotation, knee valgus moment, and tibial internal rotation (Maniar et al., 2022). However, with greater knee flexion (>70 degrees) these forces influencing the ACL are reduced when paired with high quadriceps forces which are crucial for movements such as side cutting (Maniar et al., 2022).
Quadricep strength deficits are common post ACLR. These deficits begin after injury due to a combination of joint immobilization, muscle inhibition, and quadricep avoidance strategies (Baugher et al., 1984; Chmielewski et al., 2001) which result in less quadriceps activity and strength; presumably to avoid shearing forces, and may be exacerbated with reconstructive surgery. It is important to have good quadricep strength post ACLR for functional performance (Palmieri-Smith & Lepley, 2015), symmetrical joint loading (Lewek et al., 2002), knee stability (Keays et al., 2003), and to slow the rate of osteoarthritis development (Palmieri-Smith & Thomas, 2009).

Approximately 80% of athletes do not meet the recommended quadriceps strength symmetry (LSI >90%) 6 months post ACLR surgery (Cristiani et al., 2019). Inger Holm et al. (2000) investigated isokinetic quadricep strength in ACLR patients at 6, 12, and 24 months post-surgery. They found that there were significant quadriceps strength differences between the surgical and non-surgical limbs at each time point, with an average strength deficit of 10.4% (Inger Holm et al., 2000). Meanwhile, a similar study that investigated quadricep strength in male ACLR patients with BPTB graft at RTS (approximately 30 weeks post-surgery) observed a 33% average deficit in the ACLR limb compared to the non-ACLR limb (Thomas et al., 2013). Furthermore, a recent study found that quadriceps of ACLR (>6 months-post surgery) limbs showed greater quadriceps weakness, smaller recruitment thresholds, slower motor unit firing rates, and larger motor unit action potentials at high contractile intensities when compared to participants healthy contralateral limb and matched controls (Sherman et al., 2023). This suggests that ACLR may decrease the cortical excitability levels affiliated with the quadriceps motor unit function.

With decreased muscle strength compensation often occurs resulting in altered movement patterns. In a study by Bell et al. (2016) it was suggested that ACLR patients with weakened quadriceps may adapt by shifting the demand for strength away from the muscles
around the knee to those around the hip. They found that ACLR patients with diminished quadricep strength symmetry (LSI <85%) presented greater hip extension strength in both limbs compared to ACLR patients with sufficient quadricep strength symmetry (LSI>90%) and healthy controls (D. R. Bell et al., 2016). Quadriceps weakness as a result of ACLR is also associated with running gait adaptations specifically decreased peak knee flexion and decreased internal knee extension moment (Lewek et al., 2002). A study by Shi et al. (2022) investigated isokinetic thigh strength and knee biomechanics when side cutting in patients 1 year post ACLR surgery. They observed that the patients ACLR limb displayed decreased quadricep strength compared to their contralateral limb. In reference to side cutting, they found that ACLR limbs had significantly decreased knee flexion angle and knee extension moment compared to their contralateral limb and the control group. Furthermore, ACLR participants demonstrated greater knee abduction angles and knee external rotation angles at peak GRF of the ACLR limb than the contralateral limb and healthy control, suggesting an issue with rotational stability of the knee. No significant differences in hamstring strength were found between limbs in ACLR patients, and the control group.

Hamstring Strength and associated mechanics

The hamstring muscles function to flex the knee and extend the hip. The hamstrings also play a role in counteracting and reduction of ACL strain caused by quadricep forces (Draganich & Vahey, 1990). Hamstring strength decreases with ACLR surgery regardless of the surgical procedure (Cristiani et al., 2019). However, it has been reported that an ACLR using a hamstring autograft can reduce muscular strength of the hamstrings at least 1 year post-surgery (Samuelsson et al., 2009). Harput et al. (2015) investigated male isometric hamstring strength at 4, 8, and 12 weeks post hamstring graft ACLR surgery. They observed that hamstring strength increased over time for both in the ACLR limb and non-ACLR limb, with hamstring strength recovery at 76% after 12 weeks. Furthermore, a study by Thomas et
al. (2013) found that ACLR BPTB graft male athletes cleared for RTS (average 30 weeks) had 90% hamstring strength recovery. ACLR patients demonstrate decreased knee flexion and significantly greater hamstring forces at impact peak when running (Boggess et al., 2018). It is suggested that this may serve as a protection strategy by decreasing anterior translation of the knee which decreases load on the ACL (Boggess et al., 2018; MacWilliams et al., 1999).

**Bone mineral density**

With ACL injury bone integrity of the lower extremity is decreased and is not restored post ACLR even with expedited rehabilitation (Nyland et al., 2010). To increase bone mineral density (BMD) and bone mineral composition (BMC) of the proximal tibia and distal femur post ACLR, rehabilitation programs should be designed with dynamic loading exercises to increase osteogenesis of these bones (Turner & Robling, 2003). Knurr et al. (2023) investigated collegiate athletes’ longitudinal changes of BMD in quadricep performance and knee biomechanics during running over 2 years post-ACLR. They found that athletes with worse quadricep rate of torque development and peak knee extension moment (during running) in their surgical limb had BMD loss of 15% of the distal femur over the two years (Knurr et al., 2023). This suggests that bone loss after surgery of the ACLR limb may be reduced by restoring quadricep performance and knee biomechanics when running post-ACLR.

**Trunk**

Trunk forward flexion in ACLR individuals increases post-surgery during landing tasks. Research has shown that trunk forward flexion during landing reduces VGRF and quadriceps activity; reducing the amount of force and load placed on the ACL (Blackburn & Padua, 2009). Markström et al. (2018) found that ACLR individuals who received surgery >20 years ago have increased trunk forward flexion during take-off and landing phases of
single leg vertical hops when using their ACLR leg compared to their non-ACLR leg. Additionally, during the triple hop it has been observed that there are significant trunk forward flexion differences between the ACLR limb and the non ACLR limb throughout the first rebound, second rebound and final landing phases; with an approximately 11 degree greater trunk flexion in the first rebound phase of the ACLR limb compared to the non-ACLR limb (Kotsifaki et al., 2022).

Boggess et al. (2018) found that ACLR patients (approximately 34 weeks post-surgery) when running display greater trunk-pelvis lateral lean than healthy subjects; moving the trunk COM away from the pelvis trunk joint (Boggess et al., 2018). This was also seen in ACLR youth athletes during single leg landing; ACLR participants with low quadriceps strength presented with greater lateral excursion than the high quadriceps strength ACLR group and healthy controls (Fryer et al., 2019). This suggests that subjects may laterally flex their trunk to compensate for the reduction of muscular strength by shifting their weight away from the reconstructed limb to their non-ACLR limb.

**Y Balance Test**

The Y balance test is a common clinical test that is part of rehabilitation of musculoskeletal injuries, including ACLR. It is used to assess dynamic balance, postural stability, and movement quality. The Star Excursion Balance Test (SEBT) is the precursor of the Y balance test in assessing dynamic postural stability. The SEBT requires participants to reach in eight directions spaced 45 degrees apart on an even surface (Coughlan et al., 2012). The key difference between the tests is that there is a touch-down aspect of the SEBT test, where participants can support their weight through their reach foot touching the ground at the end of the excursion, consequently creating variability of foot pressure measures amongst subjects (Coughlan et al., 2012).
The Y-Balance Test requires participants to reach in three directions; anterior (ANT), posterolateral (PL), and posteromedial (PM). The reduced directions between the SEBT and YBT makes the YBT more convenient and time efficient for clinicians. Participants stand on an elevated footplate and with their foot push a rectangular block along plastic tubing in the three directions. Performance on this test is often measured by maximum reach distance divided by length of stance limb, and expressed as a percentage (Coughlan et al., 2007); with the lower test scores linked with increased risk of ACL injury.

\[
\% \text{ Max distance} (\%\text{MAXD}) = \frac{\text{excursion distance}}{\text{limb length}} \times 100 \quad (\text{Coughlan, 2007}).
\]

However, the validity of the test unaccompanied by other assessments with regards to it being used as a predictor of ACL injury, has been challenged in recent years (Lai et al., 2017). A study examining 2D lower extremity joint kinematics when executing the YBT ANT in healthy and ACLR adolescent females found no significant differences in reach distances or lower extremity kinematics between groups (Bulow et al., 2021). Furthermore, no relationships were found between lower extremity joint angles and YBT for anterior reach distances in the ACLR group (Bulow et al., 2021). Based on these observations, the researchers speculated that the ACLR participants may have applied movement strategies of the hip joint or trunk, which were not recorded in this study, to minimize knee movement and increase anterior reach distance (Bulow et al., 2021).

Hallagin et al. (2017) investigated the relationship between isokinetic quadriceps strength and YBT pre and post ACLR. They found that regardless of a significant decrease in quadriceps strength, participants were able to improve their YBT scores bilaterally. They suggested that neuromuscular control, hip strength, and overall lower extremity ROM may play an important role in these reach distances (Hallagin et al., 2017). Olesky et al. (2021) found in their study that the ACLR subject group who were cleared for RTS had inferior YBT reach distances in the anterior and posterior lateral directions compared to mild lower limb
injury and healthy control groups. They also suggested that these significant differences in performance between groups could be indicative that ACL ruptures may indefinitely disrupt movement patterns and neuromuscular control (Olesky et al., 2021). Kumahara et al. (2021) found that the application of a core muscle exercise program (plank, side plank, and Nordic hamstring extensions) performed for five minutes three times per week after 6 and 12 months showed significant improvements in maximum reach distance in all directions in the YBT amongst pediatric soccer players. It has been observed that in young active individuals, reach deficits in the Y balance test anterior direction when performed at 12 weeks post-surgery can be an indicator of poor performance in the single leg hop distance assessment when returning to sport (Garrison et al., 2015).

**Patient Reported Outcome Measures**

Patient reported outcome (PRO) measures can inform clinicians about the subjective progress of a patient as they progress through rehabilitation. A variety of PRO measures exist to capture the state of the patient. The Tegner and Marx scales are used to estimate individuals current activity levels. Additionally, Tegner scale estimates the level of activity in patients before the injury occurred (Tegner & Lysholm, 1985). Individuals with ACLR are less physically active compared with healthy matched controls, despite having similar physical activity levels on the Tegner and Marx scales (D. R. Bell et al., 2017).

The International Knee Documentation Committee (IKDC) provides clinicians with an insight to how their patients knees are affecting their quality of life, by evaluating patients symptoms, functions and sports activity (Irrgang et al., 2001). The IKDC is scored on a scale of 0-to-100 with greater knee function associated with a higher number. The IKDC has been found to be valid and reliable measure of symptoms, function, and sports activity in patients with different knee injuries including ACL injury (Irrgang et al., 2001). A worse IKDC score has been associated with a greater lateral trunk flexion in ACLR patients with BPTB graft
type during single leg squat performance (D. R. Bell et al., 2014). While ACLR patients with ISGA graft type, a higher IDKC score was associated with greater hip extension moment at peak knee flexion (D. R. Bell et al., 2014).

The Knee Injury Osteoarthritis Outcome Score (KOOS) also assesses knee health quality of life. It evaluates knee symptoms and functions using 5 categories; pain, other symptoms, function in activities of daily living, function in sports and recreation, and knee related quality of life (Roos et al., 1998). Bjornsen et al. (2023) observed KOOS in participants between 6 to 60 months post-ACLR. They found that KOOS quality of life scores improved with increasing time in both sexes, with males showing greater improvements over time than females (Bjornsen et al., 2023).

A study by Werner et al. (2018) evaluated athletes with similar preinjury physical activity levels on the Tegner scale that RTS and that did not RTS post ACLR. They found that despite no significant differences in functional performance measures, the athletes who did not RTS had produced lower scores on the IKDC and KOOS (Werner et al., 2018). This suggests that the evaluation of ACLR patient progress needs to be multidimensional in its approach by addressing both objective and subjective deficits to comprehensively gauge patients quality of life.

Tampa Scale for Kinesiophobia (TSK) assesses patients fear of disability. The Tampa Scale of Kinesiophobia - 11 (TSK-11) is a shorter 11 item questionnaire version of the TSK evaluating fear of reinjury. The TSK-11 is scored on a scale of 11 to 44 with higher scores denoting greater levels of kinesiophobia. The TSK-11 has been validated for ACLR patient use in the early post operative phase (George et al., 2012). High scores on the TSK-11 between 6 and 12 months post ACLR are associated with greater chance of persistent knee symptoms in reference to KOOS scores (Baez et al., 2023).
The ACL Return to Sport Index (ACL-RSI) scale is used to evaluate ACLR patients’ psychological responses in regards to their emotions, performance confidence, and risk in association with RTS (Webster et al., 2008). ACL-RSI score at 6 months has been observed to be a predictive variable for RTS at or above preinjury level at 12 months (Suzuki et al., 2023). In an adolescent ACLR cohort, participants who scored highly on the IKDC were likely to score highly on the ACLR-RSI, suggesting a relationship between knee function and psychological readiness at RTS (Fones et al., 2020). In ACLR adults, an ACLR-RSI score less than 60 has been associated with increased dynamic knee valgus during squatting, lower IDKC scores, and higher TSK-11 scores (Correa et al., 2023). A lower ACLR-RSI score between 6 and 12 months post ACLR is associated with greater odds of persistent knee symptoms in reference to KOOS scores (Baez et al., 2023).
Chapter Three

METHODOLOGY

Experimental Design:
This study follows a longitudinal, repeated measures study design. The purposes of this study are (1) to track and compare trunk, hip, and knee kinetic and kinematics changes during the YBT anterior direction over time (4-6 months) in ACLR patients undergoing rehabilitation. (2) To track and compare quadriceps strength changes over time (months 4,5,6) in patients undergoing rehabilitation. (3) Determine if there is a relationship between patient reported outcome (PRO) measures and trunk, hip, and knee kinematics and kinetics at each time point.

Participants
ACLR group subjects met the following criteria to be included in this study:
(1) underwent a primary unilateral ACLR (2) had been cleared by a physician or clinical rehabilitation specialist to participate in balance activities (3) were between 4-6 months post ACLR surgery (4) were between the ages of 14-25 years of age (5) had a stable knee with no episodes of giving way (6) had no history of multiple ligament reconstructions(MCL, PCL,LCL) (7) had not experienced an additional knee injury that required surgical repair (8) had no other lower extremity injury in the three months prior to the study.

Procedures
Patient Reported Outcome Measures
Once subjects signed informed consent, an interview was conducted to determine their rehabilitation type, time from surgery, and graft type. Participants completed the following surveys and questionnaires: Tampa Scale for Kinesiophobia (TSK-11), Tegner Activity Scale, Marx Activity Scale, International Knee Documentation Committee (IKDC)
Form, Knee Injury Osteoarthritis Outcome Score, and the ACL-Return to Sport after Injury Scale (ACL-RSI). Height and mass were also recorded.

Motion Analysis

Joint motion during the functional movement assessments was measured using an Electromagnetic Motion Tracking System. The sensors (trakSTAR sensors, Ascensions Technologies, Burlington, VT) are designed to analyze and capture human body movement. It provided kinematic analysis in this study. Participants performed the tests on force plates (Bertec Corporation, Columbus, Ohio) with the sensors attached to them. Vertical ground reaction force (VGRF) was collected by the force plates. The information from the force plates and sensors was collected by a main computer unit where it was synchronized, processed, and displayed. Sensors were placed on each subject over the spinous process C7, apex of sacrum, midpoint of lateral thigh, and tibia. The thigh and tibia sensors were placed on the leg in areas consisting of the least amount of muscle mass, in order to minimize potential artifact induced by muscle contraction. Double sided tape and elastic wrap secured the sensors to the body.

When the sensors were attached, the subjects were asked to stand in a neutral posture with their arms relaxed at their sides. The following bony landmarks were digitized in the following order using a mobile electromagnetic sensor attached to a stylus: spinous process of T12, medial femoral condyle, lateral femoral condyle, medial malleolus, left anterior iliac spine, and right anterior superior iliac spine. Digitized bony landmarks served to define the segment end points and joint centers of the lower extremity segments. The ankle joint center is located at the midpoint between the medial and lateral malleoli. Knee joint center is located at the midpoint between the lateral and medial femoral condyles. The hip joint center was determined by the Bell method (A. L. Bell et al., 1990). The method consist of estimating the hip joint center using the left and right anterior iliac spine as landmarks to mathematically
estimate the hip joint center. Once the subject was digitized, they were instructed to stand relaxed with their arms by their side for approximately 10 seconds, which allowed the computer to calibrate the participant’s neutral position. When calibrated, participants performed the functional movement assessments described below.

**Y Balance Testing**

To evaluate dynamic balance ability, participants performed a standardized balance assessment called the Y-Balance Test on both legs. It involved balancing on one leg while reaching for maximal distances with their opposite leg in three directions. The three directions were anterior, posteromedial, and posterolateral. The directions were indicated by tape on the ground. Participants started with both feet at the intersection point of the three lines, their hands were placed on their hips, their stance foot remained in the same start position, and their stance heel remained on the ground throughout the test. The maximal distances reached by the participants were marked for each trial in all directions. Participants completed four practice trials in all three directions, followed by three test trials in each direction for both limbs. The measurements recorded from the three test trials were averaged to obtain a representative value for each participant. As participants acted as their own controls (non-ACLR limb) normalization of leg length was not required for this study. Although participants performed the test in all directions, only the anterior direction was used for analysis in this study. Previous YBT studies have observed more significant findings in the anterior direction compared to the posterolateral and posteromedial directions (Garrison et al., 2015; Kim et al., 2023; Kline et al., 2016).

**Quadriceps Strength Testing**

To assess quadriceps strength a dynamometer was used. The subject was placed in a seated position with their test leg in 90° of knee flexion. The dynamometer was placed over the anterior aspect of the subjects shanks, just proximal to the ankle joint. The subject was
instructed to extend their knee with maximal effort. Subjects performed two test trials per testing period (month 4, month 5, month 6).

**Data Processing**

A right handed global reference system will be defined with the positive x-axis anterior, the positive y axis to the left of each participant. And the positive z axis in the superior direction. Euler angles will be used to calculate knee joint angle between the shank and the thigh, hip joint angles between the thigh and the pelvis, and trunk relative to the world, with orders of rotation: (1) Y axis representing sagittal plane (+flexion), (2) X axis representing frontal plane (+adduction), and (3) the Z axis representing transvers plane (+internal rotation). Kinematic data will be filtered using 4th order Butterworth filter with a cutoff frequency of 14.5 Hz. A customized MATLAB (The MathWorks, version R2022a) software program will be applied to the data.

**Statistical Analysis**

Statistical Package for the Social Sciences (SPSS) software will be used for statistical analysis. A repeated measures ANOVA (RMANOVA) will be applied to the primary dependent variable of trunk to determine whether there are significant differences between limbs (2 levels; healthy and ACLR) over time (3 levels; month 4, month 5, month 6). This process will be repeated replacing the primary dependent variable with secondary dependent variables of the hip, knee, and quadriceps strength. A Tukey post hoc test will be used when appropriate. To determine relationships between PRO variables and trunk, hip, knee and quadriceps strength variables a Pearson correlation coefficient test will be used. All significance will be set a-priori at P <0.05.
References


Appendix I

Abstract

Study Design: Longitudinal repeated-measures.

Objectives: (1) To track and compare trunk, hip, and knee kinetic and kinematic changes during the Y-Balance Test (YBT) anterior direction over time (months 4, 5, 6) in anterior cruciate ligament reconstruction (ACLR) patients undergoing rehabilitation. (2) To track and compare quadriceps strength changes over time (months 4, 5, 6) in patients undergoing rehabilitation. (3) Determine if there is a relationship between patient reported outcome (PRO) measures and trunk, hip, and knee kinematics and kinetics at each time point.

Background: Previous research has not investigated kinetic and kinematic changes over time in the YBT across months 4, 5, and 6 in ACLR populations; with investigation of trunk positionality during the YBT post-ACLR being quite limited. Understanding the coordination and control patterns occurring at the trunk, hip, and knee when performing the YBT may prevent patient susceptibility to subsequent ACL injuries.

Methods: 37 ACLR patients were included in this study. 18 participants had complete data sets for kinetic and kinematic variables of interest for the YBT anterior direction. 24 participants had complete data sets for quadriceps strength and PRO measures. Means and standard deviations were calculated for all variables. Repeated-measures ANOVA's were conducted for all the kinetic, kinematic and strength variables. Pearson correlation coefficient tests were used to compare PRO measures and performance variables.

Results: Time x limb interactions were observed for trunk lateral flexion (p =0.03, F = 4.05) and trunk rotation (p =0.01, F = 5.36). Time main effects were observed for knee flexion (p=0.04, F= 3.46) and quadriceps strength (p = 0.001, F = 6.84). Limb main effects (reconstructed < healthy) were observed for knee flexion (p = 0.01, F =13.6), knee extension moment (p =0.02, F = 6.8), hip flexion (p =0.01, F =20.8), and quadriceps strength (p = 0.01,
F =25.9). Month 4 Tegner scores were positively associated with quadriceps strength ($r^2 = 0.14$). Month 6 ACL-RSI was positively associated with hip extension moment ($r^2 = 0.22$).

**Conclusion:** ACLR patients’ YBT trunk movements post-ACLR are highly variable. Patients’ improvement in knee flexion and quadriceps strength do not follow a stepwise pattern in improvement over time. Our findings help to better understand the alterations that occur at the trunk, hip, and knee after ACLR.

**Key words:** Y-Balance Test, Trunk, ACLR
Introduction:

The anterior cruciate ligament is a commonly injured in non-contact athletic settings (Shimokochi & Shultz, 2008). In the general population the annual incidence rate of anterior cruciate ligament (ACL) tears is 68.6 per 100,000 person-years (Sanders et al., 2016) and on average costs the U.S. healthcare system $1 billion annually (Griffin et al., 2000; Hewett & Bates, 2017). Many individuals who suffer ACL injury opt for anterior cruciate ligament reconstruction (ACLR) to regain joint stability. After ACLR, the incidence of a second ACL injury is as high as 30% with greatest risk of retear occurring during the initial two years (Paterno et al., 2014).

Trunk control has been suggested to be an important variable in return to sport post ACLR and identifying those at increased risk of ACL injury (Zazulak et al., 2007). Research has shown that trunk forward flexion during landing reduces VGRF and quadriceps activity; reducing the amount of force and load placed on the ACL (Blackburn & Padua, 2009). Markström et al. (2018) observed that ACLR individuals who received surgery >20 years ago have increased trunk forward flexion during take-off and landing phases of single leg vertical hops when using their ACLR leg compared to their non-ACLR leg. Boggess et al. (2018) found that ACLR patients (approximately 34 weeks post-surgery) when running display greater trunk-pelvis lateral lean than healthy subjects; moving the trunk COM away from the pelvis trunk joint (Boggess et al., 2018). This was also seen in ACLR youth athletes during single leg landing; ACLR participants with low quadriceps strength presented with greater lateral excursion than the high quadriceps strength ACLR group and healthy controls (Fryer et al., 2019). This suggests that subjects may laterally flex their trunk to compensate for the reduction of muscular strength by shifting their weight away from the reconstructed limb to their non-ACLR limb.
The Y balance Test (YBT) is a common clinical test that is used as part of rehabilitation of musculoskeletal injuries including ACLR. The YBT assesses dynamic balance, postural control, and movement quality. The test requires participants to reach in three directions: anterior (ANT), posterolateral (PL), and posteromedial (PM). The core and trunk motion are crucial to YBT performance. Previous research observed a core muscle exercise program intervention resulted in significant improvements in YBT reach distances in all directions amongst youth soccer players (Kumahara et al., 2021). Furthermore, research suggests that the YBT may be a valid test to observe differences in balance and neuromuscular control at RTS for ACLR athletes (Kline et al., 2016; Oleksy et al., 2021). The YBT has also been found to be indicative of performance outcomes in other functional movement assessments and patient reported outcome measures for ACLR athletes at RTS (Garrison et al., 2015; Kim et al., 2023). With further investigation trunk control may prove to be a modifiable risk factor for ACLR athletes' susceptibility to reinjury or injury of the contralateral ACL.

Quadriceps strength deficits are common after ACLR. These deficits begin after injury due to a combination of joint immobilization, muscle inhibition, and quadriceps avoidance strategies (Baugher et al., 1984; Chmielewski et al., 2001) which result in less quadriceps activity; presumably to avoid shearing forces, and these deficits may be exacerbated with reconstruction surgery. It is important to have good quadriceps strength post-ACLR for functional performance (Palmieri-Smith & Lepley, 2015), symmetrical joint loading (Lewek et al., 2002), knee stability (Keays et al., 2003), and to slow the rate of osteoarthritis development (Palmieri-Smith & Thomas, 2009). Approximately 80% of athletes do not meet the recommended quadriceps strength symmetry (LSI ≥90%) 6 months post ACLR surgery (Cristiani et al., 2019). With decreased muscle strength compensation often occurs resulting in altered movement patterns. Shi et al. (2022) investigated isokinetic thigh strength and knee
biomechanics when side cutting in patients 1 year post ACLR surgery. They found that patients’ ACLR limbs had significantly decreased knee flexion angle and knee extension moment compared to their contralateral limb and the control group.

Patient reported outcome (PRO) measures can inform clinicians about the subjective progress of a patient as they progress through rehabilitation. A variety of PROs exist to help determine how a patient is recovering after surgery. Commonly used PRO’s include the Tegner Activity Scale is commonly used to estimate individuals’ current activity levels (Tegner & Lysholm, 1985), the International Knee Documentation Committee (IKDC) provides clinicians with an insight into subjective knee function of the patient (Irrgang et al., 2001), the ACL Return to Sport Index (ACL-RSI) scale which is used to evaluate ACLR patients’ psychological responses in regards to their emotions, performance confidence, and risk in association with RTS (Webster et al., 2008). These scales have been proven to provide valuable information and are linked with biomechanics. Together, these scales may provide critical information about how a patient is healing and progressing during rehabilitation.

The research behind the trunk's association to the ACL for ACLR patients when performing functional movement tasks such as the YBT is quite limited, additionally trunk positioning changes over time appears to be absent from literature. The primary purpose of this study was to track and compare trunk, hip, and knee kinetic and kinematic changes during the Y-Balance Test (YBT) anterior direction over time (months 4,5,6) in anterior cruciate ligament reconstruction (ACLR) patients undergoing rehabilitation. We hypothesized that trunk, hip and knee kinematics and kinetics would vary between ACLR and non-ACLR limbs over time in the YBT. The secondary purpose of this study was to track and compare quadriceps strength changes over time (months 4,5,6) and between limb differences in ACLR patients undergoing rehabilitation. We hypothesized that quadriceps strength would increase over time and that the non-ACLR limb would be stronger than the ACLR limb. The third
purpose of this study was to determine if there was a relationship between patient reported outcome (PRO) measures and trunk, hip, and knee kinematics and kinetics at each time point. We hypothesized that there would be positive correlations between our variables of interest and PRO measures.

**Methods**

This was a longitudinal repeated measures study. A total of 37 individuals were recruited for this study. A patient was considered for inclusion if the patient: 1) underwent a primary unilateral ACLR, 2) had been cleared by a physician or clinical rehabilitation specialist to participate in balance activities, 3) were between 4-6 months post ACLR surgery (4) were between the ages of 14-25 years of age, 5) had a stable knee with no episodes of giving way, 6) had no history of multiple ligament reconstructions(MCL, PCL, LCL), 7) had not experienced an additional knee injury that required surgical repair, 8) had no other lower extremity injury in the three months prior to the study.

*Instrumentation:* To assess lower extremity kinematics an electromagnetic tracking system (Ascension Technologies, Inc) controlled by MotionMonitor software (Innovative Sports Training Inc) was used. Force plates (Bertec Corporation) were used to collect ground-reaction forces which were synchronized to kinematics.

*Testing Procedures:* All testing was conducted in the Wisconsin Injury in Sport Laboratory. Subjects went through informed consent and an interview process to determine their rehabilitation type, time from surgery, and graft type. Subjects height and mass were also recorded. For PRO measures participants completed the Tegner Activity Scale, International Knee Documentation Committee (IKDC), and ACL-Return to Sport after Injury Scale (ACL-RSI) surveys at each testing period (month 4, month 5, month 6). Participants performed testing on the force plates with sensors attached. Sensors were placed on each subject over the spinous process C7, apex of sacrum, midpoint of lateral thigh, and tibia. The
thigh and tibia sensors were placed on the leg in areas consisting of the least amount of muscle mass, in order to minimize potential artifact induced by muscle contraction. Double sided tape and elastic wrap secured the sensors to the body. When the sensors were attached, the subjects were asked to stand in a neutral posture with their arms relaxed at their sides. The following bony landmarks were digitized in the following order using a mobile electromagnetic sensor attached to a stylus: spinous process of T12, medial femoral condyle, lateral femoral condyle, medial malleolus, left anterior iliac spine, and right anterior superior iliac spine. Digitized bony landmarks served to define the segment end points and joint centers of the lower extremity segments. The ankle joint center is located at the midpoint between the medial and lateral malleoli. Knee joint center is located at the midpoint between the lateral and medial femoral condyles. The hip joint center was determined by the Bell method (Bell et al., 1990). The method consists of estimating the hip joint center using the left and right anterior iliac spine as landmarks to mathematically estimate the hip joint center. Once the subject was digitized, they were instructed to stand relaxed with their arms by their side for approximately 10 seconds, which allowed the computer to calibrate the participant’s neutral position. When calibrated, participants performed the YBT. The participants balanced on one leg while reaching for maximal distances with their opposite leg in three directions. The three directions were anterior, posteromedial, and posterolateral. The directions were indicated by tape on the ground. Participants started with both feet at the intersection point of the three lines, their hands were placed on their hips, their stance foot remained in the same start position, and their stance heel remained on the ground throughout the test. The maximal distances reached by the participants were marked for each trial in all directions. Participants completed four practice trials in all three directions, followed by three test trials in each direction for both limbs. The measurements recorded from the three test trials were averaged to obtain a representative value for each participant. As participants acted as their own
controls (non-ACLR limb) normalization of leg length was not required for this study. Although participants performed the test in all directions, only the anterior direction was used for analysis in this study. Previous YBT studies have observed more significant findings in the anterior direction compared to the posterolateral and posteromedial directions (Garrison et al., 2015; Kim et al., 2023; Kline et al., 2016).

To assess quadriceps strength a dynamometer was used. The subject was placed in a seated position with their test leg in 90° of knee flexion. The dynamometer was placed over the anterior aspect of the subjects shanks, just proximal to the ankle joint. The subject was instructed to extend their knee with maximal effort. Subjects performed two test trials per testing period (month 4, month 5, month 6).

**Data Processing**

A right handed global reference system was defined with the positive x-axis anterior, the positive y axis to the left of each participant, and the positive z axis in the superior direction. Euler angles were used to calculate knee joint angle between the shank and the thigh, hip joint angles between the thigh and the pelvis, and trunk relative to the world, with orders of rotation: (1) Y axis representing sagittal plane (+flexion), (2) X axis representing frontal plane (+adduction), and (3) the Z axis representing transverse plane (+internal rotation). Kinematic data was filtered using 4th order Butterworth filter with a cutoff frequency of 14.5 Hz. A customized MATLAB (The MathWorks, version R2022a) software program was applied to the data.

**Statistical Analysis**

Statistical Package for the Social Sciences (SPSS) software was used for statistical analysis. A repeated measures ANOVA (RMANOVA) was applied to the primary dependent variable of trunk to determine whether there were significant differences between limbs (2 levels; healthy and ACLR) over time (3 levels; month 4, month 5, month 6). This process was
repeated replacing the primary dependent variable with secondary dependent variables of the
hip, knee, and quadriceps strength. A Tukey post hoc test was used when appropriate. To
determine relationships between PRO variables and trunk, hip, knee, and quadriceps strength
variables a Pearson correlation coefficient test was used. All significance was set a-priori at \( P < 0.05 \).

Results

A total of 37 participants were included in the study. A comparison of demographic
characteristics for all participants are shown in Table 1. 18 participants had complete data sets
for kinematic and kinetic variables of interest for aim 1. 24 participants had complete data
sets for quadriceps strength, IKDC, Tegner, and ACL-RSI for aim 2.

Repeated-measures ANOVAs were conducted to test the possible changes in the YBT
kinematic and kinetic variables at peak knee flexion and quadriceps strength over time and
between limbs. This data is shown in Table 2. For knee flexion, we observed a significant
main effect for time \( (P = 0.04, F = 3.46) \) with the post hoc analysis demonstrating that peak
knee flexion was greater at month 6 when compared to months 4 and 5. We also observed a
between limb difference with the reconstructed limb flexing less than the healthy limb \( (P =
0.01, F = 13.6) \). No time by limb interaction was observed for knee flexion (figure 4).

For knee extension moment we observed a significant main effect for limb \( (P = 0.02, F = 6.8) \) with the
post hoc analysis revealing that the healthy limb had greater knee extension moment
compared to the reconstructed limb (figure 5). Hip flexion differed between limbs \( (P = 0.01, F =
20.8) \) with the non-reconstructed limb having increased flexion in comparison to the
reconstructed (figure 6). Hip extension moment did not change over time or differ between
limbs (figure 7). Forward trunk flexion did not change over time nor differ between limbs
(figure 1). For lateral trunk flexion, we observed a significant time by limb interaction \( (P
= 0.03, F = 4.05) \). Post hoc analysis examining the interaction showed that participants’ trunk
lateral flexion differed in their month 6 reconstructed limb compared to month 4 reconstructed and non-reconstructed limbs, month 5 non-reconstructed limb, and month 6 non-reconstructed limb (Figure 2). For trunk rotation, a time by limb interaction ($P = 0.01$, $F = 5.36$) was observed. Post hoc analysis examining the interaction showed that participants trunk rotation for their non-reconstructed limb at month 5 is different to their trunk rotation in their month 4 non-reconstructed limb, month 5 reconstructed limb, and month 6 reconstructed limb (figure 3).

For quadriceps strength main effect for time ($P =0.001$, $F = 6.84$) and limb ($P=0.01$, $F = 25.9$) were observed. Quad strength in months 5 and 6 quadricep strength were greater compared to month 4. Participants had greater quadriceps strength in their healthy limb compared to their surgical limb (figure 8). No significant differences were observed when kinematic and kinetic variables were controlled for sex, age, and graft type (table 3). No statistically significant correlations were found between IKDC score and the YBT kinematic and kinetic data recorded as peak knee flexion across all time points ($p>0.05$) (table 4). There was a positive correlation between month 4 Tegner score and quadriceps strength ($r = 0.37$, $p = 0.03$), meaning that as Tegner score increased, so did quadriceps strength (figure 9). The month 6 ACL-RSI was correlated with hip extension moment ($r = 0.47$, $p= 0.03$) (figure 10). This means that as ACL-RSI increased so did hip extension moment.

**Discussion**

The findings of this study broaden our understanding of how the mechanics of the trunk, hip, and knee are altered after ACL reconstruction. Our results partially supported our hypotheses for our first aim in that trunk, hip, and knee kinematics and kinetics change over time and differ between reconstructed and non-reconstructed limbs during the YBT. The principal finding of this study was that we observed a time by limb interaction for lateral trunk flexion and trunk rotation. The secondary finding of this study we observed various
main effects for quadricep strength, knee and hip kinetic and kinematic variables for either
time or limb condition.

To our knowledge trunk adaptations following ACLR when performing the YBT have not
been previously examined. We hypothesized that the trunk motion would be limited/restricted
(reduced trunk flexion, lateral flexion, and trunk rotation) over time in patients with ACLR
specifically in the reconstructed limb. Our findings demonstrated no changes in trunk forward
flexion over time or between limbs. Direct comparison to previous literature is difficult since
we are the first to examine trunk motion over time and between limbs in the YBT in this
population. Previous studies have found that ACLR individuals, when performing single
legged landing tasks with their reconstructed limb, display greater trunk forward flexion
compared to when they landed on their non-reconstructed limb regardless of time (years)
since surgery (Markström et al., 2018). In contrast, our participants were in an extended trunk
posture, this is interesting as you would expect that with decreased quadriceps strength and
knee flexion angles post-surgery subjects would favor trunk flexion in their ACLR limb.

In regard to trunk lateral flexion, we observed a time by limb interaction. In month 6
reconstructed limb we observed significantly greater lateral trunk flexion over the stance limb
compared to month 4 time point of the reconstructed limb and all time points of the non-
reconstructed limb. For lateral trunk flexion, the non-ACLR limb for month 5 was
significantly different to month 4 non-ACLR, month 5 ACLR, and month 6 ACLR. The non-
ACLR limb for month 5 favored trunk rotation away from the stance limb. These findings are
important because in patients with ACLR, excessive lateral trunk flexion has been associated
with increased risk of re-injury during high knee loading tasks (Hewett & Myer, 2011).
Figure 3 shows the inconsistency found in trunk rotation direction in both limbs during the
time points. This lack of consistency in lateral trunk flexion and trunk rotation between limbs
may indicate the neuromuscular control and proprioception deficiencies that are associated
with ACL injuries. This could be problematic to individuals with ACLR as trunk motion can influence knee loading and potentially predispose patients to reinjury. Hewett and Myers (2011) explained that with lateral trunk flexion over the stance limb, VGRF may also shift laterally creating a larger moment arm relative to the knee joint, increasing knee abduction loading (knee valgus) during dynamic movements; a known risk factor of ACL injury. Similarly, an increase in trunk rotation towards the stance limb (externally) may subject the knee to increased internal rotation angles; another risk factor for ACL injury. However, it needs to be recognized that the YBT is a closed chained movement so forces at play (VGRF) will not be as high as with open chained movement such as side-cutting and landing tasks. Previous research has primarily investigated trunk movement in relation to open chained movements. For example, Boggess et al. (2018) observed that ACLR patients’ run with greater trunk flexion over their stance limb compared to healthy controls. Furthermore, Fryer et al. (2019) observed that ACLR youth athletes with insufficient quadriceps strength when performing a single leg landing display greater lateral excursion compared to groups with sufficient quadriceps strength. In a side step cutting task, Frank et al. (2013) found that having less trunk rotation in the new direction of movement paired with greater hip adduction in healthy individuals contributes to 81% of knee varus loading. Although our study did not investigate associations between trunk, hip and knee variables, we did see similar outcomes to previous research for some dependent variables of interest with regard to changes between limbs and changes over time. Our findings suggest that trunk kinematics after ACLR are highly variable.

The YBT has been shown to be useful in gauging patients’ future performance in other functional movements assessments and determining RTS. For example, Garrison et al. (2015) observed that performance deficits in the anterior direction of the YBT at 12 weeks post-ACLR is indicative of poor single leg hop performance at RTS. Furthermore, YBT anterior
direction performance deficits are associated with a lower Lysholm score, poorer carioca performance, and knee muscle strength deficits at 6 months post-ACLR (Kim et al., 2023).

We observed a main effect for time for both knee flexion and quadriceps strength, which partially agrees with our hypotheses. We hypothesized that we would see a continued improvement in each of the outcome measures each month. However, knee flexion at month 6 was greater than knee flexion at month 5 and month 4 in our study. Quadriceps strength was greater in months 5 and 6 compared to month 4. We expected quadriceps strength to improve over time due to patients participating in rehabilitation programs. So while we saw improvement, it was not as stepwise as we might have assumed. This could be for several different reasons. First, previous research has demonstrated that post-ACLR, knee flexion decreases which is often associated with loss of quadriceps strength. These strength deficits have shown to result in smaller knee flexion angles in the ACLR limb across a variety of open chained tasks such as the single leg hop, running, and side stepping (Lewek et al., 2002; Palmieri-Smith & Lepley, 2015; Shi et al., 2022). These decreases in quadriceps strength post-ACL injury and post-reconstruction surgery are attributed to a combination of factors including joint immobilization, muscle inhibition, and quadriceps avoidance strategies (Baugher et al., 1984; Chmielewski et al., 2001). Furthermore, prior studies that compared quadriceps strength at different time points post-surgery have observed strength differences averaging 10.4%-33% between limbs within the initial 2 years (Inger Holm et al., 2000; Thomas et al., 2013). Finally, in typical rehabilitation programs around month 4 post-ACLR patients begin the transition from focused strengthening exercises to more endurance based movements like walking and running when sufficient quadriceps strength is achieved. Subsequently, patients may not meet with their clinician as regularly. Therefore, we speculate that their home-based exercise program may not be adequately loaded for the stepped-progression we expected to see over time (Myer et al., 2006). We did consider the notion of
reduced patient compliance with their rehabilitation. However, a recent study which included 166 ACLR patients observed no differences in their rehabilitation adherence between month 3 and month 6 (Sonesson & Kvist, 2022).

When we factored in age, sex, and graft type in our analysis, the number of significant findings diminished. This suggests that the outcomes we observed initially may be influenced or explained more by these factors. This consequently impacts the accuracy of this study’s main results. However, our findings might have carried more weight if the study had greater statistical power, given that several p-values came close to falling below the 0.05 threshold; trunk forward flexion ($p = 0.051$), knee flexion ($p = 0.11$).

Our results partially fulfilled our hypothesis for aim 3. Overall, there were a lack of associations between our patient reported outcome measures and our kinetic, kinematic, and strength variables across all time points. We observed no associations for IKDC and our variables of interest. However, month 4 Tegner score was positively associated with quadriceps strength. This demonstrates that ACLR subjects who participate in more physical activity four months post-ACLR have better quadriceps strength. However, our $r^2$ value was quite low at 0.14, meaning only 14% of variance was explained by these variables.

The ACL-RSI score for month 6 was associated with hip extension moment. This positive correlation indicates that better psychological responses regarding knee function 6 months post-ACLR is associated with greater hip extension moment at peak knee flexion. Again, our $r^2$ value should be noted at 0.22, meaning approximately 1 in 5 patient’s ACL-RSI scores contribute to hip extension moment at month 6.

**Limitations and Future Research**

Our study has several limitations that should be noted. Only 18 of our patients had full data sets across the three time-points which impacted our final numbers for analysis.
Increasing our sample size would be beneficial in that it would increase our power. Additionally due to this sample size, we were unable to do more exploratory and informative subgroup analyses such as graft type, sex, and age. Due to the nature of our recruitment process post-operative rehabilitation was not standardized across participants. However, participants described their participation in standard ACL reconstruction rehabilitation protocols and self-reported high compliance with home exercise programs. Moreover, the lack of standardization of rehabilitation increases the external validity/generalizability of the study. Another limitation of this study is that we were unable to recruit and control for an individual or group of orthopaedic surgeons and their operative techniques. Ankle kinetics and kinematics were not recorded. It is possible that subjects may have altered their movement at the ankle joint when performing the YBT.

Future studies should investigate the foot and ankle. More research is needed for how these strategies at the trunk may influence the progression of knee osteoarthritis post-surgery. Additionally, how alterations in trunk kinematics may negatively impact the symmetrical deterioration of joints with ageing and consequently the longevity of the grafts through asymmetrical loading in ACLR populations. These findings in trunk provide clinicians with further insight into the biomechanics of their patients in the early stages of rehabilitation. Future studies should also investigate trunk biomechanics of ACLR individuals during various discrete closed skill exercises such as the YBT so that clinicians identify patient progress and safely proceed to introducing serial and continuous movements into patient rehabilitation programs effectively.

**Conclusion**

The results of this study show that ACLR patients’ trunk movement is highly variable when performing the YBT. When performing the YBT on their reconstructed limb, ACLR patients’ appear to have greater lateral trunk flexion over their stance limb. We observed
inconsistent trunk rotation direction overtime and between limbs. ACLR patients’ undergoing rehabilitation perform with greater knee flexion in both limbs at month 6 compared to month 4. Quadriceps strength in ACLR patients’ undergoing rehabilitation increases overtime between month 4 and month 6. Knee and hip kinetic and kinematic differences between limbs are present in ACLR patients’ during the YBT between months 4, 5, and 6. While we recommend additional research to support our findings, our findings will help better understand the alterations that occur at the trunk, hip, and knee after ACLR reconstruction and better define the movement strategies applied by ACLR patients’ when performing the YBT.
List of Tables:

Table 1: Participant Demographics. Data presented as mean ± sd or frequency.

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Female</th>
<th>Male</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>n = 37</td>
<td>n = 21</td>
<td>n = 16</td>
</tr>
<tr>
<td>Age (years)</td>
<td>19.3 ± 3.1</td>
<td>18.9 ± 3.1</td>
<td>19.9 ± 3.0</td>
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<tr>
<td>Height (cm)</td>
<td>174.2 ± 9.6</td>
<td>168.8 ± 7.7</td>
<td>181.3 ± 7.0</td>
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<tr>
<td>Mass (kg)</td>
<td>74.0 ± 16.7</td>
<td>69.2 ± 19.0</td>
<td>80.4 ± 10.6</td>
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<td>Graft</td>
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<td>1</td>
<td>1</td>
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</table>
Table 2: Uncontrolled kinematic data (degrees), kinetic data (Nm) and quadriceps strength (%body weight) – values are mean (±SD)

<table>
<thead>
<tr>
<th></th>
<th>Month 4</th>
<th>Month 5</th>
<th>Month 6</th>
<th>Interaction</th>
<th>Time Main Effect</th>
<th>Limb Main Effect</th>
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<td>Knee</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion</td>
<td>Reconstructed</td>
<td>58.7 ± 13.9</td>
<td>59.9 ± 15.2</td>
<td>62.0 ± 13.4</td>
<td>P = 0.83</td>
<td>P = 0.04*</td>
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<td>Healthy</td>
<td>66.5 ± 15.6</td>
<td>66.5 ± 15.7</td>
<td>70.0 ± 14.7</td>
<td>F = 3.46</td>
<td>F = 13.6</td>
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<tr>
<td>Extension Moment</td>
<td>Reconstructed</td>
<td>-73.2 ± 30.7</td>
<td>-72.3 ± 30.7</td>
<td>-79.7 ± 36.2</td>
<td>P = 0.73</td>
<td>P = 0.52</td>
</tr>
<tr>
<td></td>
<td>Healthy</td>
<td>-86.0 ± 20.9</td>
<td>-86.0 ± 36.8</td>
<td>-94.0 ± 49.8</td>
<td>F = 0.32</td>
<td>F = 0.67</td>
</tr>
<tr>
<td>Hip</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion</td>
<td>Reconstructed</td>
<td>-29.7 ± 16.1</td>
<td>-28.0 ± 17.6</td>
<td>-32.4 ± 14.6</td>
<td>P = 0.25</td>
<td>P = 0.74</td>
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<td>Healthy</td>
<td>-38.3 ± 17.7</td>
<td>-43.1 ± 18.5</td>
<td>-40.1 ± 15.8</td>
<td>F = 1.45</td>
<td>F = 0.3</td>
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<td>Extension Moment</td>
<td>Reconstructed</td>
<td>26.2 ± 43.3</td>
<td>21.4 ± 30.4</td>
<td>26.9 ± 37.8</td>
<td>P = 0.36</td>
<td>P = 0.84</td>
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<td>Healthy</td>
<td>28.6 ± 46.2</td>
<td>26.9 ± 37.8</td>
<td>21.6 ± 49.2</td>
<td>F = 1.06</td>
<td>F = 0.17</td>
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<tr>
<td>Trunk</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion (Y)</td>
<td>Reconstructed</td>
<td>-3.3 ± 10.1</td>
<td>-3.3 ± 9.7</td>
<td>-2.0 ± 10.1</td>
<td>P = 0.43</td>
<td>P = 0.34</td>
</tr>
<tr>
<td></td>
<td>Healthy</td>
<td>-5.6 ± 10.3</td>
<td>-1.4 ± 13.7</td>
<td>-2.7 ± 9.4</td>
<td>F = 0.87</td>
<td>F = 1.12</td>
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<td>Lateral Flexion (X)</td>
<td>Reconstructed</td>
<td>0.3 ± 7.6</td>
<td>1.5 ± 5.5</td>
<td>4.3 ± 10.9</td>
<td>P = 0.03‡</td>
<td>P = 0.28</td>
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<td>Healthy</td>
<td>0.2 ± 8.8</td>
<td>-2.4 ± 11</td>
<td>0.2 ± 7.7</td>
<td>F = 4.05</td>
<td>F = 1.33</td>
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<tr>
<td>Rotation (Z)</td>
<td>Reconstructed</td>
<td>3.5 ± 12.4</td>
<td>-2.4 ± 11.6</td>
<td>-0.7 ± 13.9</td>
<td>P = 0.01†</td>
<td>P = 0.67</td>
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<td>Healthy</td>
<td>-0.2 ± 13.6</td>
<td>5.4 ± 21.6</td>
<td>0.9 ± 14.8</td>
<td>F = 5.36</td>
<td>F = 0.41</td>
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<tr>
<td>Quadriceps</td>
<td>Reconstructed</td>
<td>0.395 ± 0.1</td>
<td>0.422 ± 0.1</td>
<td>0.444 ± 0.1</td>
<td>P = 0.47</td>
<td>P = 0.01*</td>
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<tr>
<td>Strength</td>
<td>Healthy</td>
<td>0.463 ± 0.1</td>
<td>0.501 ± 0.1</td>
<td>0.504 ± 0.1</td>
<td>F = 0.76</td>
<td>F = 6.84</td>
</tr>
</tbody>
</table>

*p<0.05:

Time Main Effects: Knee Flexion - M4: 62.6 ± 15.0°; M5:63.2 ± 15.6°; M6: 65.9 ± 14.4°; Post Hoc: Month 4 & 5 < Month 6
Quadriceps Strength - M4: 0.42 ± 0.1; M5: 0.46 ± 0.12; M6: 0.47 ± 0.1; Post Hoc Results: Month 4 < Months 5 & 6

Limb Main Effects: Knee Flexion- Reconstructed 60.21 ± 14.0°; Healthy: 67.66 ± 15.1°; Post Hoc: Reconstructed < Healthy
Knee Extension Moment - Reconstructed: -75.0 ± 29.5°; Healthy: -90.0 ± 37.3°; Post Hoc: Reconstructed < Healthy
Hip Flexion - Reconstructed: -30.01 ± 16.0°; Healthy:-40.51 ± 17.2°; Post Hoc: Reconstructed < Healthy
Quadriceps Strength (% body weight) Healthy: 0.42 ± 0.1; Reconstructed 0.49 ± 0.1; Post Hoc: Reconstructed < Healthy

†p<0.05, Trunk Rotation Time by Limb Interaction Post hoc: M5 healthy limb is different than M4 healthy, M5 reconstructed, M6 reconstructed.
‡p<0.05, Trunk Lateral Flexion Time by Limb Interaction - Post hoc: M6 reconstructed limb is different than M4 reconstructed, M4 healthy, M6 healthy, M5 healthy; M5 healthy limb differs from M5 reconstructed limb.
<table>
<thead>
<tr>
<th></th>
<th>Month 4</th>
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<th>Month 6</th>
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<th>Limb Main Effect</th>
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<tbody>
<tr>
<td><strong>Knee</strong></td>
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</tr>
<tr>
<td>Flexion</td>
<td>Reconstructed</td>
<td>58.7 ± 13.9</td>
<td>59.9 ± 15.2</td>
<td>62.0 ± 13.4</td>
<td>P = 0.11</td>
<td>P = 0.63</td>
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<td>66.5 ± 15.6</td>
<td>66.5 ± 15.7</td>
<td>70.0 ± 14.7</td>
<td>F = 2.35</td>
<td>F = 0.46</td>
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<tr>
<td>Extension Moment</td>
<td>Reconstructed</td>
<td>-73.2 ± 30.7</td>
<td>-72.3 ± 20.9</td>
<td>-79.7 ± 36.2</td>
<td>P = 0.55</td>
<td>P = 0.66</td>
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<td></td>
<td>Healthy</td>
<td>-86.0 ± 36.8</td>
<td>-88.9 ± 21.7</td>
<td>-94.0 ± 49.8</td>
<td>F = 0.63</td>
<td>F = 0.43</td>
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<tr>
<td><strong>Hip</strong></td>
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<td></td>
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</tr>
<tr>
<td>Flexion</td>
<td>Reconstructed</td>
<td>-29.7 ± 16.1</td>
<td>-28.0 ± 17.6</td>
<td>-32.4 ± 14.6</td>
<td>P = 0.14</td>
<td>P = 0.79</td>
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<td>-38.3 ± 17.7</td>
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<td>F = 2.1</td>
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<td>21.4 ± 30.4</td>
<td>26.9 ± 37.8</td>
<td>P = 0.16</td>
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<td>28.6 ± 46.2</td>
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<td>F = 2.0</td>
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<tr>
<td>Flexion (Y)</td>
<td>Reconstructed</td>
<td>-3.3 ± 10.1</td>
<td>-3.3 ± 9.7</td>
<td>-2.0 ± 10.1</td>
<td>P = 0.051</td>
<td>P = 0.34</td>
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<td></td>
<td>Healthy</td>
<td>-5.6 ± 10.3</td>
<td>-1.4 ± 13.7</td>
<td>-2.7 ± 9.4</td>
<td>F = 3.31</td>
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<td>Lateral Flexion (X)</td>
<td>Reconstructed</td>
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<td>1.5 ± 5.5</td>
<td>4.3 ± 10.9</td>
<td>P = 0.25</td>
<td>P = 0.70</td>
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<tr>
<td></td>
<td>Healthy</td>
<td>0.2 ± 8.8</td>
<td>-2.4 ± 11.0</td>
<td>0.2 ± 7.7</td>
<td>F = 1.46</td>
<td>F = 0.36</td>
</tr>
<tr>
<td>Rotation (Z)</td>
<td>Reconstructed</td>
<td>3.5 ± 12.4</td>
<td>-2.4 ± 11.6</td>
<td>-0.7 ± 13.9</td>
<td>P = 0.21</td>
<td>P = 0.98</td>
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<td>Healthy</td>
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<td>Quadriceps Strength</td>
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<td>0.444 ± 0.1</td>
<td>P = 0.38</td>
<td>P = 0.31</td>
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<tr>
<td></td>
<td>Healthy</td>
<td>0.463 ± 0.1</td>
<td>0.501 ± 0.1</td>
<td>0.504 ± 0.1</td>
<td>F = 1.00</td>
<td>F = 1.22</td>
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</table>
**Table 4:** IKDC scores relationship to variables of interest at different time points post-ACLR.

<table>
<thead>
<tr>
<th></th>
<th>Knee flexion</th>
<th>Knee Extension Moment</th>
<th>Hip Flexion</th>
<th>Hip Extension Moment</th>
<th>Trunk Y</th>
<th>Trunk X</th>
<th>Trunk Z</th>
<th>Quadriceps Strength</th>
</tr>
</thead>
<tbody>
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<td><strong>Month 4</strong></td>
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<td>-0.13</td>
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<td><strong>Month 6</strong></td>
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<td>0.14</td>
<td>-0.12</td>
<td>0.57</td>
<td>0.13</td>
<td>0.53</td>
<td>-0.25</td>
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</tbody>
</table>

**Table 5:** Tegner Activity Score relationship to variables of interest at different time points post-ACLR.

<table>
<thead>
<tr>
<th></th>
<th>Knee flexion</th>
<th>Knee Extension Moment</th>
<th>Hip Flexion</th>
<th>Hip Extension Moment</th>
<th>Trunk Y</th>
<th>Trunk X</th>
<th>Trunk Z</th>
<th>Quadriceps Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>P</td>
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*p<0.05, Correlation between Month 4 and Quadriceps Strength*
**Table 6:** ACL-RSI scores relationship to variables of interest at different time points post-ACLR.

<table>
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<th>Knee Extension Moment</th>
<th>Hip Flexion</th>
<th>Hip Extension Moment</th>
<th>Trunk Y</th>
<th>Trunk X</th>
<th>Trunk Z</th>
<th>Quadriceps Strength</th>
</tr>
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<tbody>
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<td>0.47</td>
<td>0.03*</td>
</tr>
</tbody>
</table>

*p<0.05, Correlation between Month 6 and Hip Extension Moment*
List of Figures:

Figure 1: Trunk forward flexion (degrees) changes over time (months) in ACLR and non-ACLR limbs.

![Trunk Forward Flexion Graph](image1)

Figure 2: Trunk lateral flexion (degrees) changes over time (months) in ACLR and non-ACLR limbs. M6 reconstructed limb is different than M4 reconstructed, M4 healthy, M6 healthy, M5 healthy; M5 healthy limb differs from M5 reconstructed limb.

![Trunk Lateral Flexion Graph](image2)
Figure 3: Trunk rotation (degrees) changes over time (months) in ACLR and non-ACLR limbs. M5 healthy limb is different than M4 healthy, M5 reconstructed, M6 reconstructed.

![Trunk Rotation Graph]

Figure 4: Knee flexion (degrees) changes over time (months) in ACLR and non-ACLR limbs.

![Knee Flexion Graph]
**Figure 5:** Knee extension moment (Nm) changes over time (months) in ACLR and non-ACLR limbs.

![Knee Extension Moment Graph]

**Figure 6:** Hip Flexion (degrees) changes over time (months) in ACLR and non-ACLR limbs.

![Hip Flexion Graph]
**Figure 7:** Hip extension moment (Nm) changes over time (months) in ACLR and non-ACLR limbs.

**Figure 8:** Quadriceps strength (% body weight) changes over time (months) in ACLR and non-ACLR limbs.
**Figure 9:** The relationship between Tegner scores and quadriceps strength at 4 months post-ACLR.

**Figure 10:** The relationship between ACL-RSI scores and hip extension moment at 6 months post-ACLR.
Figure 11: A – demonstrates direction of knee flexion (+); B – demonstrates direction of hip flexion (-); C – demonstrates direction of forward trunk flexion (+).
Figure 12: D – demonstrates direction of trunk rotation (+) away from the stance limb; E – demonstrates lateral trunk flexion (+) over the stance limb.
**Figure 13:** Gray – ‘With lateral trunk flexion over the stance limb the VGRF may also shift laterally creating a larger moment arm relative to the knee joint, increasing knee abduction loading (knee valgus)’. Black – Neutral trunk position over the stance limb the VGRF is more central thus creating a smaller moment arm relative to the knee.
References


