

GROUND REACTION FORCE PROFILES IN
ACL RECONSTRUCTED FEMALE
ATHLETES

by

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ABSTRACT

GROUND REACTION FORCE PROFILES IN ACL RECONSTRUCTED FEMALE ATHLETES

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Injury to the anterior cruciate ligament (ACL) has become a global topic of research, as the number of injuries is staggering and continues to increase each year because the underlying elements contributing to this injury have yet to be fully grasped. It is estimated that 80,000 – 250,000 ACL injuries occur annually in female athletics.(45) As a result, an estimated number of 100,000 ACL reconstructions are performed annually.(2) The uncertainty involving the contributing causes of this injury has naturally ushered uncertainty involving the treatment of the injury, i.e. surgical repair and subsequent rehabilitation. Although considerable gains toward improving surgical procedure and rehabilitation have been achieved over the last

decade, there exists much debate as to the proper criteria-based rehabilitation for return to pre-injury activity level.

Current “accelerated” rehabilitation now consists of immediate weightbearing, aggressive restoration of ROM, strength and functional progression based upon certain criteria, and a quick return to play for athletes. (88;96;101;123;125) However, ipsilateral and contralateral ACL injuries, as well as early onset of osteoarthritis have become a significant occurrence: studies have shown that there is a 10-12% risk of reinjury to the ipsilateral or contralateral limb and a 59%-100% chance of developing osteoarthritis 7-15 years after an ACL disruption. (15;46;65;67;90;91;104;107;108; 112;113)

One of the contributing causes to the reinjury rate and osteoarthritis is the absence of applicable guidelines for criteria-based progression through an ACL rehabilitation program suitable to various age groups and activity levels. According to current rehabilitation protocol, return to full participation is most commonly granted at 4-7 months after a subjective evaluation based on knee range of motion (ROM) measurements, eccentric/concentric strength ratios, graft stability, subjective medical opinion(s), and the athlete’s perceived ability to play at his/her previous level.(13;82;92) Because dynamic, high-impact movements are a major component to athletics, static measurements, eccentric/concentric comparisons, and functional jump tests for time or distance may not adequately take into account an individual’s interaction with the ground. We believe the examination of an individual’s dynamic

interaction with the ground may provide a better method to assess ACL's functional stability under game condition.

The ground reaction force profiles of two healthy, young female athletes, at six months post ACL reconstruction, were evaluated as they performed a series of jump-landing tasks in order to determine if there was a significant (>10%) asymmetry in force attenuation between limbs. The subjects were assessed for time to peak force, impact force, peak force magnitude, peak knee flexion, and impulse in the vertical direction.

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CHAPTER 1

INTRODUCTION

1.1 Background

Injury to the anterior cruciate ligament (ACL) has become a global topic of research, as the number of injuries is staggering and continues to increase each year because the underlying elements contributing to this injury have yet to be fully grasped. At this point, we are in mere possession of collective educated guesses posed by distinguished members of the scientific community. The uncertainty involving the contributing causes of this injury has naturally ushered uncertainty involving the treatment of the injury, i.e. surgical repair and subsequent rehabilitation. Although considerable gains toward improving surgical procedure and rehabilitation have been achieved over the last decade, there exists much debate as to the proper criteria-based rehabilitation for return to pre-injury activity level.

In the past, ACL rehabilitation guidelines included prolonged immobilization, non-weight bearing ambulation, and slow progression to activity- up to 12 months- with documented unsuccessful attempts to return an athlete to previous activity level.(96;125) Therapy consisted of protected kinetic chain exercises designed to protect graft stability, prevent hyperextension, and develop quadriceps strength.(96;125) Current rehabilitation techniques emphasize functional training that address neuromuscular control and proprioception.(88;96;123;125) Accelerated rehabilitation now consists of immediate weightbearing, aggressive restoration of ROM, strength and functional progression based

on certain criteria, and a quick return to play for athletes. (88;96;101;123;125) There have been documented cases of return to play as early as 90 days post reconstruction.(101) Thus, athletes are able to return to play much earlier than before due to advances in rehabilitation methods. However, ipsilateral and contralateral ACL injuries have become a significant occurrence.(15;104;107) Studies have shown that there is a 10-12% risk of reinjury to the ipsilateral or contralateral limb.(15;104;107) Not only has reinjury become a problem, but, there is also an issue of a severe risk of early onset osteoarthritis associated with an ACL deficiency. Fifty-nine percent of patients who undergo an ACL disruption and maintain a normal meniscus show evidence of osteoarthritis 7-15 years post operatively, while 60% to 100% of patients who undergo an ACL disruption concomitant with a meniscectomy develop osteoarthritis as early as 7 years post reconstruction. (46;65;67;90;91;108;112;113)

One of the contributing causes to the reinjury rate and osteoarthritis is the absence of applicable guidelines for criteria-based progression through an ACL rehabilitation program suitable to various age groups and activity levels. According to current rehabilitation protocol, return to full participation is most commonly granted at 4-7 months after a subjective evaluation of an athlete's performance ability by her physician and a physical therapist or certified athletic trainer. This evaluation is typically based on knee range of motion (ROM) measurements, eccentric/concentric strength ratios, graft stability, subjective medical opinion(s), and the athlete's perceived ability to play at his/her previous level.(13;82;92) While these parameters have been standard markers for a successful rehabilitation program, they do not simulate the stresses of a 'game situation' in any regard. In a review of ACL treatment literature, Beynnon et al.(13) suggest that it

may not be adequate to use only anterior-posterior knee laxity measurements as an outcome to judge the success/failure of an ACL reconstruction and that the dynamic measurements that include weight bearing and muscle contraction conditions may be necessary to gain insight into the underlying biomechanics of the tibiofemoral joint.(13) Because dynamic, high-impact movements are a major component to athletics, static measurements, eccentric/concentric comparisons, and functional jump tests for time or distance may not adequately take into account an individual's interaction with the ground. We believe, the examination of an individual's dynamic interaction with the ground may lend a condition more suitable to better estimate his/her performance under game condition.

Therefore, the purpose of this study was to examine ground reaction force profiles of female athletes at six months post ACL reconstruction to examine the merit of current rehabilitation protocols and the effectiveness of a standard return to play decision at six months.

1.1.1 Purpose

The purpose of the study was to evaluate the ground reaction force profiles of two, healthy young females who were six months post ACL reconstruction, as they performed a series of jump-landing tasks in order to determine if there is a significant (>10%) asymmetry in force attenuation between limbs. The subjects were assessed for time to peak force, impact force, peak force magnitude, peak knee flexion, and impulse in the vertical direction.

1.2 Definition of Terms

1) ACL: One of the two cruciate ligaments of the knee, located in the intercondylar notch of the femur. It attaches proximally on the posteromedial aspect of the lateral condyle of the femur and distally on the anterior portion of the intercondylar surface of the tibia. Primary function is to restrict anterior movement of the tibia relative to the femur and to provide resistance to valgus, varus, and tibial rotation.

2.) Valgus: Condition of outward deviation in alignment from the proximal to the distal end of a body segment. With regards to the knee, the distal portion of the tibia is deviated outward, resulting in a knock-kneed appearance.

3.) Varus: Condition of inward deviation in alignment from the proximal to the distal end of a body segment. With regards to the knee, the distal portion of the tibia is deviated inward, resulting in a bowlegged appearance.

4.) Tibial Rotation: Proximal segment of the tibia twisting on the midline axis, internally or externally, relative the distal portion of the femur.

5) Impulse: Area under the force-time curve which represents the stress on a joint at each time point of a human movement; equal to force magnitude times time.

6) Braking and Propulsion: Portions of the ground reaction curve where the body is decelerating or accelerating, respectively.

7) Kinematics: The branch of dynamics concerned with the description of motion by the use of position, velocity and acceleration; an accurate description of human movement without acknowledging the causes of motion.

8) Kinetics: The branch of dynamics concerned with the forces that cause or tend to cause motion.

9) Center of Mass: Point where gravity is said to act on a given system; not always the geometric center.

10) Center of Pressure: Point on a body where the pressure acts, causing a force and no moment about the point; point on the foot at which the ground reaction force acting on the entire area of the foot, can be resolved into a vector. Can also be said that it represents the neuromuscular response to imbalances of the body's center of gravity.

11) Inertia: Resistance to action or to change; tendency of a body to maintain its current state of motion, whether motionless or moving with a constant velocity.

12) Ground Reaction Forces (GRF): The reaction to the force the body places on the ground during movement; based on Newton's Third Law of Motion.

13) Torque: Vector that measures the tendency of a force to rotate an object about an axis; rotary effect of a force. Equal to the force magnitude times the lever arm (perpendicular distance from point of rotation to force application).

14) Newton's First Law of Motion: "Law of Inertia;" A body will maintain a state of rest or constant velocity unless acted on by an external force that changes the state.

15) Newton's Second Law of Motion: Force applied to a body causes an acceleration of that body of a magnitude proportional to the force, in the direction of the force, and inversely proportional to the body's mass.

16) Newton's Third Law of Motion: For every action, there is an equal or greater reaction.

1.3 Delimitations

The delimitations of the study are: 1) Two healthy female subjects in the age group of 17-19 years of age. 2) All subjects have undergone their first ACL reconstruction. 3) All subjects are within six months of the ACL reconstruction operation.

1.4 Assumptions

The study assumed the following: 1) All subjects accurately completed the health history questionnaire. 2) All subjects performed the jump-landing tasks to the best of their ability. 3) All subjects completed a designated ACL rehabilitation program with a certified physical therapist. 4) All subjects shared the goal of full integration into athletic participation after six months post operation.

1.5 Limitations

The study had some limitations that need to be considered. First and foremost, subject recruitment with such a specific group is very difficult. Access to multiple medical clinics or development of a multi-center prospective study would be ideal for this study. Since subjects are recruited from various doctor's offices and physical therapists, there is no control for a subject's specific program of rehabilitation.

All jump tasks were performed in a controlled laboratory environment. A subject's psychological condition can be affected in this setting. For one, a game condition in which most ACL injuries occur cannot be replicated. Also, if a subject is aware of what the desired outcome or measurement is, conscious awareness increases within the subject so that they perform the task to their ideal standards.

There were also several limitations within our laboratory. The subject's footwear and ground surfaces of the laboratory do not replicate that of their respective sport. Also, the lab only contained one force plate, so data from each leg was obtained by the subject landing on the force plate with the desired leg, and off the force plate with the uninvolved leg. This could affect the degree by which the subject balances force during the landing and thus, the magnitude measured. Also, GRF data was not collected pre-injury so there lacks a method to determine whether an asymmetry existed pre-injury.

Activity level of the athlete pre- and post-operation is another consideration. Some athletes may train to be sport ready in six months, while others may not. Since subjects were only recruited from the Dallas/Ft. Worth area, the sample might not be fully representative of the entire population.

CHAPTER 2
REVIEW OF LITERATURE

2.1 ACL Injury

The number of females participating in sports has increased approximately 800% since the inclusion of Title IX of the Educational Amendments in 1972. (110) College scholarships and opportunities to play professional sports have increased significantly for female athletes over the last three decades. The CDC in 2000 reported that women represent more than 33% of college athletes and 37% of U.S. Olympians.(1) With the recent renewal of Title IX, these numbers are expected to maintain at the present level or even increase.

With the increasing number of female athlete participation, there has been a concomitant increase in documented injuries. One injury in particular has become the focus of advanced research and academic debate from clinicians and researchers across the globe: damage to the anterior cruciate ligament (ACL) in the knee. The ACL is the primary restraint to anterior displacement of the tibia relative to the femur & acts as a restraint to internal-external rotation, varus-valgus angulation, any possible combinations thereof, and is thus vital to consistent knee stability.(13) Injury to this ligament facilitates many short-term and long-term physiological consequences such as painful joint degradation, meniscal and chondral surface damage, chronic instability and arthritis, and long-term disability. (13;57;91;92;111) There are also more imminent psychological consequences such as the potential loss of athletic participation for the season, loss of

scholarship funding, and lowered academic performance. (57) Along with individual ramifications, there are severe economic ramifications: in 2006, Hewett et al.(57) alluded to an estimated cost of ACL surgical reconstruction and rehabilitation at \$17,000-\$25,000 per injury; and the estimated annual cost has been projected in excess of \$2 billion. (46;50;61)

In addition to the staggering cost of ACL reconstruction, the number of such occurrences across all female athletes shares a similar alarming numerical characteristic. Huston et al.(61) estimated that 10,000 ACL injuries occur annually in female intercollegiate athletics and 25,000 occur at the level of high school athletics. The enigma of higher rates of ACL injury in females when compared with males has been well documented. (6;10;14;15;24;25;28;37;44;46;53;56;57;61;78;82;85;80;86;129;133) According to Arendt et al.(7), ACL injuries are two to three times more likely to occur in female athletes engaged in soccer or basketball when compared to males. Powell and Barber-Foss reported a 3-4 times greater incidence of injury for girls compared to boys at the high school level, and also reported that girls had a higher rate of reinjury.(98) In another study of high school injuries, Messina et al.(85) reported a four times higher rate of ACL injuries in female basketball players as compared to male basketball players. According to an examination of statistics from the National Collegiate Athletic Association (NCAA), Hutchinson and Ireland(62) found that women sustained ACL injuries at a rate two times that of men in soccer and nearly four times in basketball. In other studies comparing collegiate athletes, Malone et al.(82) and Pearl(94) both reported an eight times greater risk of ACL injury to female basketball players as compared to male basketball players. When comparing recreational athletes, Lindenfeld and

colleagues(78) compared ACL injury rates between male (0.87/100 player-hours) and female (0.29/100 player-hours) soccer players and concluded that females were at a greater risk. Arendt and Dick(6) confirmed the disproportionate injury risk in basketball and soccer athletes in 1995. Studies conducted by DeHaven and Lintner(28) and Chandy and Grana(20) reported similar outcomes for high school athletes. In two separate extensive reviews of ACL injury literature, Beynon et al.(13) alluded to a range of 2.4 to 9.7 and Hewett et al.(57), alluded to a range of 4 to 6 times greater occurrence rate of female ACL injuries when compared to male. Therefore, there is conclusive evidence to support the theory that female athletes are at a greater risk of injuring their ACL: sports-related ACL injuries occur 2-9 times more frequently for females as compared to males.

2.1.1 Risk Factors

The majority of ACL injuries sustained are noncontact (occur in the absence of external forces from another body). (6;13;14;57;84;91;92) Athletes that incur the predominance of ACL injuries participate in sports that require rapid postural adjustments such as cutting, pivoting, jumping and deceleration maneuvers. (15;38;51;57) In 2002, Yu et al.(131) performed a comprehensive analysis of ACL literature and reported a re-categorization of risk factors with a delineation of four types of variables: anatomic, environmental, hormonal and biomechanical. Studies examining anatomic risk factors have focused on intercondylar notch width, volume of the ligament, the angle between the patellar tendon and tibial shaft, navicular drop and subtalar joint pronation. Studies involving environmental factors are limited to playing surfaces and/or shoe surface interface, and exposure and performance information. Hormonal risk factors involve the phase of the menstrual cycle. The biomechanical factors are the least

understood and involve kinetics and kinematics of the lower limb. They have the most potential and can be improved through training, as determined by a 1999 National Institutes of Health/American Academy of Orthopaedic Surgeons sponsored conference

During the 2005 Hunt Valley Meeting II, a conference dedicated solely to the issue of ACL injuries in female athletes, a similar conclusion was reached. Based on the body of evidence reviewed, researchers from this meeting concluded that there is convincing evidence suggesting that neuromuscular interventions and heightened awareness of the biomechanics of injury reduces ACL injury risk in female athletes.(51) However, the specifics of exercises and sequence, intensity and duration, and timing for neuromuscular training remain elusive. To elucidate intervention training at an early age, the authors also emphasize the need for more randomized controlled trials between institutions, various geographic areas of the country, age groups, and gender for all high-risk sports, followed by a careful analysis of the prevention programs' effect on dynamic knee stability, performance, and overall injury rates.(51)

Hewett et al.(57) performed another comprehensive review of ACL literature in 2006 and divided injury mechanisms into two categories: extrinsic and intrinsic mechanisms. The extrinsic mechanisms addressed contact with another player versus noncontact ACL injuries; motion perturbations; the effects of bracing; and shoe-surface interaction.(57) The intrinsic mechanisms were subcategorized as anatomical; hormonal; neuromuscular; prior injury; and biomechanical.(57) Anatomical mechanisms listed in this study and not included in the aforementioned study performed by Yu et al.(131) were static alignment, increased muscle flexibility, biomechanical and neuromuscular changes during puberty, and effects of body mass and age. The hormonal risk factors addressed

were those pertaining to the effects of estrogen on the ACL and neuromuscular function, and the effect of oral contraceptives on injury. Neuromuscular risk factors included agonist-antagonist relationships, increased anterior shear, altered magnitude and timing of muscle activation, preactivation of protective muscle groups, decreased proprioception, imbalanced medial-lateral muscle firing patterns, and increased fatigue. Finally, the biomechanical risk factors pertain to body position and joint loading and are described as sagittal, coronal, and transverse plane mechanisms involving the kinematics and kinetics of the hip, knee, and ankle.

2.1.1.1 Biomechanical Risk Factors

Biomechanical risk factors may provide the key to a deeper understanding of noncontact ACL injuries. They also represent a hopeful candidate for the prevention of such impairment as they can be modified through training.(51;56;57) Biomechanical risk factors involve the study of kinematic and kinetic variables applied to dynamic motion, as well as neuromuscular characteristics. Kinematic variables (velocity, acceleration, etc.), describe movement without involving the forces that cause them while kinetic variables (forces and torques), describe the forces that cause or oppose movement. Neuromuscular characteristics involve a large number of descriptive factors as they pertain to muscle function during an athlete's performance. There are a plethora of studies examining the aforementioned factors as a contributing risk towards ACL injury.(4;5;9;12;13;16-18;22;26;34;39;42;47;48;51;57;59;65;70-74;76;87;92;95;106;107;114;119;121;122;127;128;130;134)

Griffin et al.(51), in their paper based on the proceedings of the second Hunt Valley Meeting, described injury biomechanics as the evaluation of kinematic and kinetic

variables about the hip, knee and ankle, and categorized them as dynamic factors. According to the authors, the primary factors influencing a knee's loading pattern include center of gravity and postural adjustment to rapid changes in the external environment: thus, ACL tears are thought to be a result of unsuccessful adjustments to postural changes resulting in abnormal dynamic loading across the knee.(51) Dynamic loading was defined as intersegmental loads transmitted across a joint that change with time and flexion angle and were divided into neuromuscular (reaction time, balance, etc.) and muscular (endurance, absolute strength, etc.) factors.(51) Those factors that were found to have a negative effect on muscle control were fatigue, decreased torsional stiffness, muscle imbalance, unanticipated cutting, and straight posture landing. Those with a positive effect were listed as anticipation or preparation for cutting; maximum co-contraction of the muscles crossing the knee to increase stiffness; muscle and gait training, agility drills, and plyometrics with the goal to decrease time to peak torque for voluntary contraction.

It is also important to examine muscular characteristics during dynamic activities because as the knee-joint position changes, moment arms of the different muscles and tibiofemoral joint contact position also change and affects ACL biomechanics.(13) Several studies have attempted to examine muscle function during dynamic activities, (i.e., running and jumping), and compared the results between men and women, athletes and nonathletes. It has been shown in these studies that increased hamstring strength, increased knee stiffness, and increased endurance of the muscles crossing the knee are associated with the least anterior tibial translation, while high levels of quadriceps activity, hamstring weakness, decreased stiffness, and muscle fatigue are associated with

more anterior tibial translation.(51) In 2000, Shultz and colleagues(109) carried out a study of neuromuscular response characteristics of the knee with a functional perturbation. They concluded that weightbearing postures revealed significant differences in firing patterns and activation times as compared to previous studies involving seated postures. In another study published in 2001, Fleming et al.(39) measured ACL strain in vivo and reported that ACL strain increased during the transition from non-weightbearing to weightbearing and that weightbearing increased ACL strain during anterior shear and internal/external rotation loading conditions. ACL strain rates measured from other investigations were documented highest with the knee near full extension and with quadriceps or isometric hamstring contraction and lowest with the knee flexed less than 50° and with hamstring or isometric quadriceps contraction.(13;51) Results also demonstrate that peak ACL strain occurred at the smallest knee flexion angle.(51)

Griffin et al.(51) also alluded to a study performed by Bahr and Krosshaug(8) which proposes that an ACL injury description should include a minimum of four elements: vital aspects of the playing situation, athlete and opponent behavior, gross biomechanical characteristics, and detailed biomechanical characteristics. The playing situation includes sports-specific details, the athlete and opponent behavior includes action and interaction with the opponent, the gross biomechanical description includes whole-body biomechanics while the detailed biomechanical description involves joint/tissue biomechanics.(51) Based upon athlete interviews and videotapes of the injury, the position of the knee during injury displays tibial rotation, apparent knee valgus, foot pronation, and a relatively extended knee and hip.(51) An informative description such as the one suggested by Bahr and Krosshaug(8) would identify detailed components of the

ACL injury event, which would ideally lead to a greater understanding through the comparison of each descriptive element of the injury event.

In a comprehensive analysis of ACL injuries in female athletes, Hewett et al.(57) defined biomechanical risk factors as pertaining to body position and joint loading and described as sagittal, coronal, and transverse plane mechanisms involving the kinematics and kinetics of the hip, knee, and ankle. Investigators from this study documented a common body position similar to that of Griffin et al.(51): externally rotated tibia; knee near full extension; foot pronated; and a deceleration of momentum followed by valgus collapse.(57) They also alluded to a study performed by Teitz et al.(115) which pointed out that ACL injury occurred most often when the center of mass of the body is behind and away from the base of support. The biomechanical risk factors from this study were described according to their planal mechanisms: sagittal, coronal, and transverse.

Sagittal mechanisms include anterior shear components such as knee and hip flexion. There is no consensus as to whether female athletes land and cut with greater knee flexion than males; knee flexion moments were similar.(57) Based on the authors' examinations, knee flexion angle at landing was not predictive of ACL injury risk. The authors alluded to another examination performed by Hewett et al.(56) in which the differences in sagittal plane hip torques between female athletes who sustained ACL injury and those who were uninjured were reported, with the peak external hip moment being greater in the ACL injured. In other studies that were reviewed, Zazulak et al.(132) reported decreased gluteus maximus activity in females compared to males; Devita et al.(32) found that during a soft landing, lower extremity muscles absorbed 19% more of the body's kinetic energy, with hip extensor eccentric contraction responsible for 22%

total kinetic energy; and Decker et al.(27) reported higher ground reaction forces at the lower extremity in females during landing due to the decreased use of hip musculature.

Coronal mechanisms involve abduction/adduction moments at the hip and knee, as well as ankle eversion/inversion. Physiological dynamic valgus torques on the knee can significantly increase anterior tibial translation and load on the ACL.(57) Knee abduction moments and angles have been found to be significant predictors of future ACL risk.(57) A study conducted by Ford et al.(42) reported female athletes exhibiting a greater knee abduction angle when preparing to execute a cutting maneuver compared with males with no difference in flexion, as well as increased rectus femoris firing and decreased gluteal muscle firing in females. Another investigation from Ford et al.(41) reported dominant versus nondominant differences in hip stabilization during landing: women landed with greater external hip adduction moments and decreased hip flexion angles on the dominant side. It has also been reported that hip abduction strength was a significant predictor of initial contact and peak knee valgus angles during a drop-landing task and that female athletes who are at a higher risk of ACL injury demonstrated decreased hip muscle activation during single-limb landing tasks when compared to males.(92) It is thought that increased side-to-side differences and dynamic coupling between kinetic segments combined with decreased activation of the hip musculature could increase the risk of valgus knee positioning and subsequently ACL injury.(57) The increased ability to decelerate from landing and to control dynamic valgus might be related to hip muscle strength and recruitment.(57) It is possible that women have difficulty controlling the hip, especially during adduction due to the fact that they display greater external hip adduction moments during landing.(57) Ankle eversion is also a

potential factor for the gender disparity among ACL injury, as greater maximum ankle eversion during cutting is displayed in females when compared to males performing the same task and there is a near-linear correlation between foot eversion and tibial internal rotation.(57)

Transverse mechanisms contributing to ACL injury include rotational motions and torques about the lower extremity joints. An increased internal-external and varus-valgus knee moment during unanticipated knee movement has been reported and suggested as a potential for noncontact knee injuries.(57) It has also been shown that female athletes demonstrate a greater hip internal rotation max angular displacement than males during landing as well as differences in lower extremity valgus during unanticipated cutting.(57) Such rapid, unanticipated changes of direction are often cited as a common ACL injury mechanism and it is speculated that the limited time to make postural adjustments during these unanticipated situations in high-risk sports contribute to ACL injury.(57)

2.2 ACL Rehabilitation

ACL rehabilitation has made considerable gains in last decade. In the 1980's, traditional ACL rehabilitation included limited knee extension through immobilization at 30°, which eventually progressed to full hyperextension by the early 1990's; restricted weightbearing with brace for 6-8 weeks post-operation; protected kinetic chain exercises; low predictability to high level sports; and activity restriction for 1 year post reconstruction.(96;125) Thus, the traditional ACL rehabilitation protocol once included prolonged immobilization, non-weight bearing, slow progression to activity, and unsuccessful attempts to return an athlete to their previous activity level.

Current rehabilitation guidelines now include maintenance of full extension and ROM throughout rehabilitation progression; similar bilateral strength (within 10-15% of the contralateral limb), as measured by eccentric/concentric strength ratios and peak torque; closed kinetic chain exercises; functional stability and proprioception training with emphasis on neuromuscular control; subjective criteria-based progression; and early return to activity.(88;96;125) Therefore, this same rehabilitation now emphasizes immediate motion, early weight bearing, functional testing, criteria-based progression and accelerated return to sports participation for athletic patients. One case study performed by Roi et al.(101), documented a Serie A Italian soccer player's progression through an aggressive rehabilitation program with an outcome of return to full participation in 90 days. This, however, is an extreme case as return to play is more commonly granted at 4-7 months post reconstruction. An ACL therapy guideline proposed by Wilk et al.(123) outlines their current rehabilitation guidelines based on eight factors that they feel should be taken into account when rehabilitating a female athlete: hip musculature to stabilize the knee; retrain neuromuscular pattern hamstring control; control valgus moment; control hyperextension; high-speed training, focusing on hamstrings; neuromuscular reaction; less-developed thigh musculature; poorer muscular endurance. These factors account for the inherently different shape of a female's body compared to a male and are based on the body of evidence supporting the various risk factors that make a female athlete more susceptible to an ACL injury. Their rehabilitation program design for an athlete emphasizes an aggressive progression through functional rehabilitation, based on subjective criteria, with the ultimate goal of return to sport.

With the progression of “aggressive” and “accelerated” rehabilitation for ACL and the desire to return to sport quicker, it has become apparent that the athlete is more susceptible to dire physiological and psychological consequences. Studies have shown that injury to the ACL, isolated or combined with damage to the meniscus, leads to radiographic changes of the knee that suggest osteoarthritis in 60% to 90% of subjects 10 to 15 years after the index of injury.(46;67;90;91;108;112;113) Meniscal injury in conjunction with ACL disruption is reported to occur from 15% to 40% of the time and becomes much higher with chronic ACL deficiency.(77) During a 7-year prospective study conducted by Jomha et al.(65) in 1999, 66% of patients who had an acute ACL reconstruction concomitant with a meniscectomy developed radiographic evidence of osteoarthritis, where 11% of those with uninjured meniscus were affected. Within the same study, 100% of another group that underwent ACL reconstruction and meniscectomy had radiographic evidence of osteoarthritis, while 50% with normal menisci had osteoarthritis.(65)

Along with severe joint degradation side effects, athletes are facing an increasing risk of reinjury. Salmon et al.(104) in a clinical study evaluating 612 patient follow-up, 5 years after and ACL reconstruction, reported that 12% (72/612) of the patents sustained a reinjury, with 39 occurring on the ipsilateral limb and 35 occurring on the contralateral limb. Shelbourne et al.(107) documented a similar finding where 1/38 patients suffered a reinjury on the ipsilateral side and 1/26 endured one contralaterally. Boden et al.(15) reported a 10% occurrence of contralateral ACL injury. Considering that one of the single best predictors for ACL injury is prior ACL injury and the lack of objective data demonstrating that ACL injury is prevented by reconstruction, there exists a need for an

appropriate criteria-based progression through rehabilitation based upon objective measurements.(57;88)

A review of the ACL rehabilitation literature conducted by Risberg et al.(100) revealed the following: immediate weight-bearing after ACL reconstruction is useful; rehabilitation programs must be monitored by a physical therapist; supporting evidence exists for the use of closed chain kinetic exercises at knee joint motions of less than 60° and open kinetic chain exercises with knee flexion angles of less than 40° to increase quadriceps muscle strength without increasing ACL and patellofemoral joint strain; and lastly, there is evidence that high intensity neuromuscular electrical stimulation in addition to volitional exercises significantly improves isometric quadriceps strength. Myer et al.(88) describe ACL rehabilitation as being divided into two stages, early and late; where the early phase utilizes stringent criteria-based guidelines for ROM and progression to full weight bearing and exercise selection and the later phases are more with general categorizations of appropriate exercises and progressions without specific milestones for when it is safe to introduce high-risk and high joint loading activities. The investigators also mention the current lack of objective criteria to reliably determine how and when to progress a patient through the aforementioned end stage rehabilitation and suggest that progression should be based on variables that determine functional stability and neuromuscular control.

An appropriate ACL rehabilitation must also take into account the various biomechanical effects on the ACL deficient limb and include many stipulations regarding the application of stress on the musculature at specific knee angles due to the effects on the newly attached ACL. For instance, Beynnon et al.(13) summarized the following

regarding the tibial-femoral relationship during a squat from an extended position to a flexed position of 90° in an ACL-deficient knee: an anterior subluxation of the lateral tibial plateau occurred relative to the femur compared to the normal knee, while in the medial compartment, tibiofemoral motion remained unchanged relative to the normal side; and the absolute position of the lateral tibial plateau was displaced anteriorly relative to the femur by 5mm. Concomitant with decreased biomechanical strength of the ACL graft relative to the native ligament, athletes who undergo reconstruction may demonstrate decreased muscular strength, joint position sense, postural stability and force attenuation.(88) It has also been demonstrated that ACL reconstruction failed to restore normal rotational kinematics during running.(13) These ongoing biomechanical deficits that contribute to neuromuscular performance during athletics may limit the dynamic support and compromise the weakened graft.(88)

There is one biomechanical deficit in particular that may significantly increase an athlete's risk of injury: the inability to attenuate forces evenly between limbs during a lower extremity dynamic maneuver.(57;88) Side-to-side imbalances in neuromuscular strength, flexibility and coordination, as well as decreased activation of the hip musculature, could increase valgus knee positioning and risk of ACL injury.(57) Athletes who demonstrate side-to-side differences in biomechanical measures during a drop vertical jump are at an increased risk of ACL injury when compared to subjects with more symmetrical lower extremity biomechanics.(56) Current evaluations recommend that the jump landing force bilateral symmetry be within 10%.(88) An improved ability to attenuate force on a single limb and to regenerate and redirect motion may be relevant to a reduction in injury risk during athletic participation.(88) Therefore, rehabilitation

criteria for ACL injury should address side-to-side differences in neuromuscular characteristics and force attenuation, as it may decrease the risk of injury once athletes are allowed unrestricted return to play.

Thus, the ultimate goal of our biomechanical evaluation is addressing side-to-side imbalances through the measurement and comparison of lower limb force attenuation.

CHAPTER 3

METHODS

Athletic activity is considered to be dynamic, i.e. displays non-linear inflections of joint angles, joint velocities, and musculoskeletal forces. Dynamic motion is described by kinematic and kinetic variables. Kinematic variables describe movement independent of the forces that cause the movement and include linear and angular displacements, velocities, and accelerations. The displacement data can be measured in terms of any anatomical landmark: center of gravity of body segments, key anatomical prominences, or centers of rotation of joints. Kinetic variables describe the forces, both internal and external, that cause the movement. Kinetics also include the examination of force moments produced by muscles crossing a joint, mechanical power flowing to or from those muscles, and the energy changes in the body resulting from this power flow.

There are three forces acting on each segment which can be analyzed: gravitational force- force of gravity acting downward through the center of mass and equal to mass times the acceleration due to gravity; ground reaction/external force- forces applied to the body and measured using a force transducer (e.g., force plate); and muscle and ligament force- net effect of muscle activity at a joint calculated in terms of net muscle moments or torques. The ground reaction force measured by the force plate is three-dimensional and therefore contains three components: a vertical component plus two shear components acting parallel to the surface of the plate. The parallel forces acting perpendicular to the vertical force can be shear or frictional. Shear forces will

accelerate an object's center of mass in the horizontal direction, while friction, which represents opposition to an object's inertia, will decelerate an object's center of mass in the horizontal direction. Shear and friction represent movement in the anterior-posterior and medio-lateral direction. These joint reaction forces can be estimated through the use of inverse dynamics- determining joint forces and torques from the measured, respective acceleration.

The net effect of muscle and ligament activity at a joint can be estimated in terms of net muscle moments, about the joint's axis of rotation. The disturbance of equilibrium between the external and internal forces at a joint produces rotation action at the joint. This rotation occurs about a designated axis, individual to each joint. The rotation of a body segment about its axis is a key component in our every day movement. The force capable of producing these joint rotations about their axes is termed torque or moment.

As an athlete hits the ground during a jump-landing, the body must absorb the ground's reaction force. This force is absorbed and produces torque at the ankle, knee, and hip. Inadequate absorption of force leads to an altered generation of torque, which may lead to altered kinematics of landings. The inability to attenuate forces and subsequent alterations of torque and kinematics in the kinetic chain leaves the ACL more vulnerable to a risk of reinjury or to joint surface damage.

Jump-landings are activities which predominately utilize the lower extremity. Therefore, an effective biomechanical analysis of a human body performing such an activity would entail measurement of ground reaction forces, the use of kinetic and kinematic data from the lower extremity segments, and the calculation of joint reaction force using dynamics.

3.1 Design

This study is a pilot study design involving two female subjects, ages 17 and 19 years. Subjects' individual data will be compared between their uninvolved and involved limbs to show the relative involvement of the rehabilitated limb in attenuating ground reaction forces. For the purposes of this study, the rehabilitated limb will be referred to as the involved limb, while the contralateral, non-operative limb will be referred to as the uninvolved limb. The average peak vertical force will be compared between subjects to show the relative difference in the amount of force per body weight each subject generates upon performing a dynamic maneuver. Both subjects are collegiate soccer players and at the 6-month return to play mark in their rehabilitation. Therefore, they should ideally display relative contributions to vertical GRF within 10%, of their uninvolved limbs.

3.2 Subjects

Two, healthy female subjects volunteered for participation in this study. Subject 1 was 5.25 months post ACL reconstruction on her right limb, right-dominant, 17 years of age, 64 inches in height, and weighed 130 pounds. Subject 2 was 6 months post ACL reconstruction on her right limb, right-dominant, 19 years of age, 63 inches in height, and weighed 166 pounds. All subjects signed a University Institutional Review Board for Human Subject Research approved informed consent and filled out a health and athletic history questionnaire. Subjects were excluded if they had undergone any prior lower extremity operations, or had any outstanding medical condition that would prevent them from full participation. The subjects who participated in the study had completed their

ACL rehabilitation and were released by their overseeing medical professional to full participation of sport.

3.3 Experimental Protocol

The subjects were scheduled for one, sixty-minute laboratory session. They first signed an informed consent (UTA IRB approved) and filled out a health and athletic history questionnaire. Subjects were then assessed for joint hypermobility according to the Beighton test for hypermobility. They were then instructed to change into spandex shorts to prevent excessive marker movement and ensure accurate marker placement and stability. For the biomechanical assessment, sixteen reflective markers were placed on the subject's lower extremities to designate joint centers: the femoral lateral epicondyle; the lateral malleolus; the heel; the first metatarso-phalangeal joint; the shank; the thigh; the anterior sacroiliac joint; and the posterior sacroiliac joint. This marker set defined three body segments used for biomechanical analysis of the lower extremity: foot, shank, and the thigh. Anthropometric data were then measured on the subject and input into the data collection software. This data included ankle width (defined as the distance between the later and medial malleolus), knee width (distance between the femoral condyles), and limb length (distance from anterior sacroiliac marker to lateral malleolus marker) for each limb, as well as the subject's height and weight.

Subjects were then introduced into the laboratory set-up and protocol before practicing each of the three conditions until they were comfortable with the maneuvers. Maximal distances for the single leg hop were estimated and marked for the involved and uninvolved leg. Given that each of the subjects had recently finished rehabilitation for an injury, the condition order was kept the same for each subject in order of decreasing

exertion: single-leg hop; max height jump; and platform landing. For the single-leg hop, the subject hopped for maximal distance, beginning and ending with the same leg, and landing on the force plate. For the max height jump, the subject began on a 6 inch platform, 6 inches from the force plate and proceeded to jump down on the force plate then immediately perform a maximal height jump. The platform landing condition was initiated with the subject standing on a six inch platform, six inches from the force plate. Subjects were instructed to dangle the leg being tested over the force plate before 'falling' off the platform and landing on the force plate. Each of the above procedures were repeated seven times for the involved and uninvolved leg. It was assumed that each subject gave maximal effort and did not favor one limb over the other due to landing with one foot on the force plate and one foot off.

3.4 Data Collection, Processing and Analyses

Force and torque data were collected using an AMTI force plate (model OR6-7-1000) comprised of strain gauges attached to load cells at the four corners of the platform. This arrangement allows for the simultaneous measurement of forces and torques in three dimensions. The raw force and moment signals were collected at a sampling frequency of 1080 Hz and amplified by a high-gain amplifier before undergoing further analysis. From this, an accurate measure of the ground reaction force along the Z direction was obtained. Ground reaction force data were presented as %BW.

The biomechanical reflective marker configuration was collected using a 6 MCam2 camera Vicon® 460 Motion Capture system. Cameras tracked with a resolution of 1.3 megapixels at a frame rate of 120 Hz. The DLT method, as set forth by Kwon(72), was used to transpose the two-dimensional camera data, to the three-dimensional

reference (object-space) frame used for our calculations. The raw force and motion data were then digitized using the Workstation® software and converted from c3d file format to txt file format using a conversion program written with Visual Basic® 6.0. The final force and motion data were calculated using a Visual Basic® 6.0 lower extremity kinetic analysis program.

3.5 Statistical Analysis

Since this study is of a pilot study design, we understand that an $n = 2$ gives us very low statistical power. This study is pilot in nature and will continue as a multi-center study, for those with access to a greater subject recruitment pool. Data will be compared to test for statistical significance and clinical significance. A paired student's t-test will be used to determine significant differences between the subjects' involved and uninvolved leg. An unpaired t-test will be used to determine significant differences in force magnitude between subjects. All data will be averaged and reported as mean \pm standard deviation. The means for peak vertical force during the jump landing and max height condition will be compared between subjects using an unpaired t-test. Statistical significance level will be set at $p < 0.05$. Clinical significance, within the scope of this study, will be defined as a bilateral force asymmetry greater than 10%.

CHAPTER 4

RESULTS

4.1 Jump Landing

The time to peak force in the vertical direction, normalized peak vertical GRF, normalized peak medial and lateral GRF, normalized peak braking GRF, and peak knee flexion were averaged from the trials for each subject, over the span of the jump landing condition. The average time to peak vertical force, as well as peak forces in all directions were compared within each subject through statistical analysis, with a significance level of $p < 0.05$. Raw data from each subject are shown in the form of vertical GRF curves. Averaged peak vertical GRF was then compared as a relative percentage contribution of each limb to the total summation of forces for both limbs during the jump landing, (greater than 10% of the contralateral limb was considered clinically significant). The 'involved limb' refers to the right leg for both subjects. Subject 1 displayed a non-statistically significant difference (Table 4.1) in the peak GRF from all components, as well as bilateral vertical GRF symmetry within 6% for the average peak vertical GRF (Figure 4.1). Subject 2 sustained a significantly higher peak vertical GRF for the uninvolved leg compared with the involved leg (Table 4.2). Clinically, Subject 2 displayed bilateral vertical GRF symmetry within 10% for the average peak vertical GRF (Figure 4.2). When comparing averaged peak vertical GRF for each limb between subjects, Subject 2 displayed a significantly higher magnitude of normalized GRF than Subject 1 for each limb (Figure 4.3).

Table 4.1 Subject 1 GRF Profile for Jump Landing

	UNINVOLVED	INVOLVED
TPT Vertical (ms)	9 ± 6	7 ± 6
Max Vertical (%BW)	150 ± 30	132 ± 40
Max Lateral (%BW)	1 ± 1	0 ± 0
Max Medial (%BW)	20 ± 5	15 ± 2
Max Braking (%BW)	40 ± 11	41 ± 18
Max Knee Flexion (Deg)	105 ± 4	109 ± 4

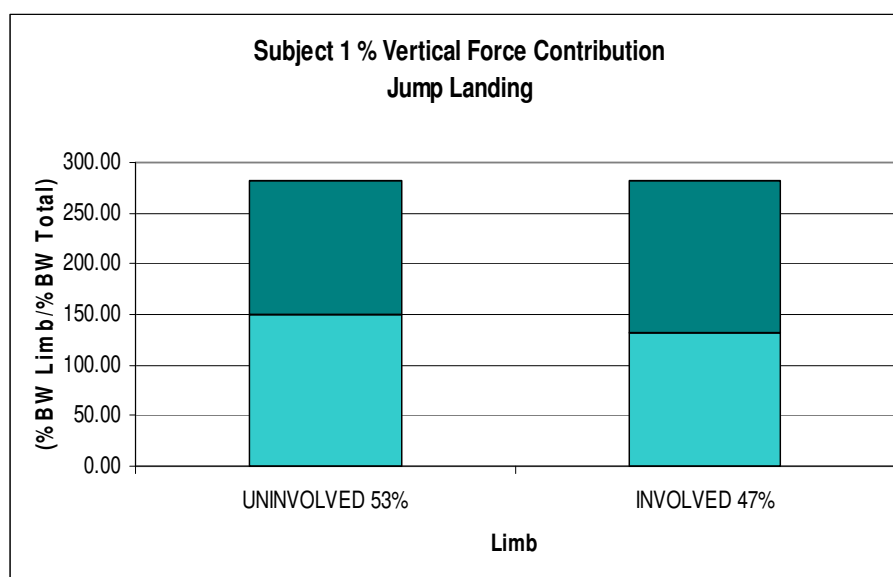


Figure 4.1 Subject 1: Percent Contribution of Each limb to the Vertical GRF for the Jump Landing.

Table 4.2 Subject 2 GRF Profile for Jump Landing

	UNINVOLVED	INVOLVED
TPT Vertical (ms)	5 ± 0	5 ± 1
Max Vertical (%BW)	281 ± 20*	227 ± 35
Max Lateral (%BW)	17 ± 2	16 ± 8
Max Medial (%BW)	0 ± 0	3 ± 8
Max Braking (%BW)	48 ± 9	41 ± 8
Max Knee Flexion (Deg)	80 ± 2	77 ± 6

* p<0.05

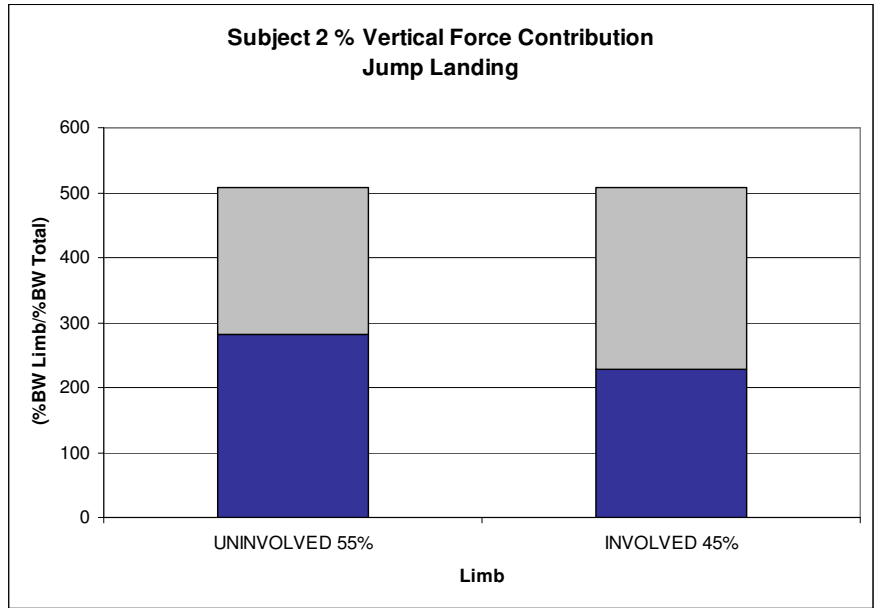
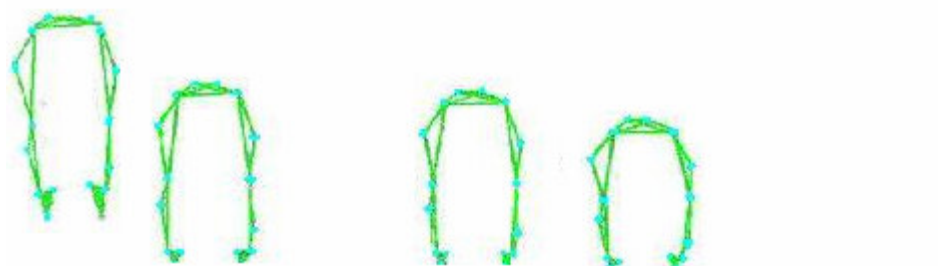
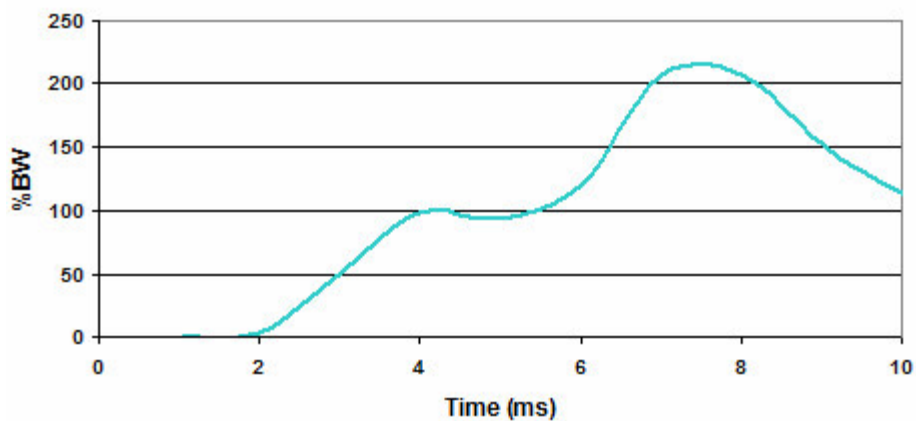


Figure 4.2 Subject 2: Percent Contribution of Each limb to the Vertical GRF for the Jump Landing.



Subject 1 Vertical GRF Involved Limb Jump Landing



Subject 2 Vertical GRF Involved Limb Jump Landing

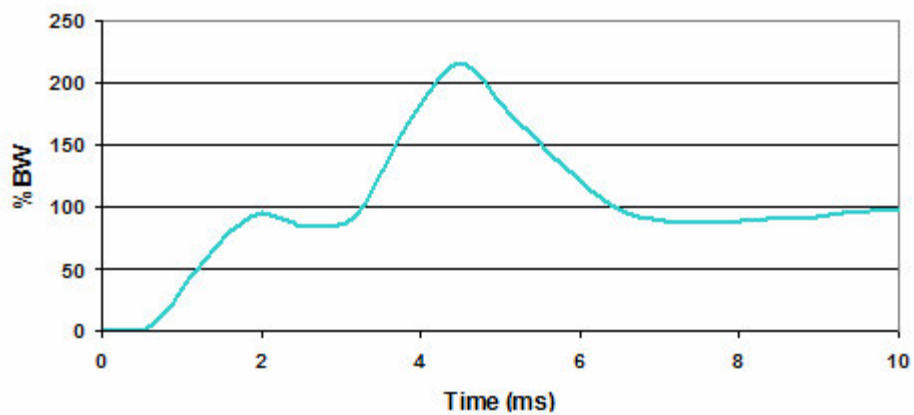


Figure 4.3 Comparison of Vertical GRF between Subjects during Jump Landing. (Stick Figures shown at Take-Off, Foot Contact, Peak Vertical GRF, and Peak Knee Flexion).

4.2 Single Leg Hop

The time to peak force in the vertical direction, normalized peak vertical GRF, normalized peak medial and lateral GRF, normalized peak braking GRF, and peak knee flexion were averaged from the trials for each subject, over the span of the single leg hop landing condition. Raw data from each subject are shown in the form of GRF curves for each component (vertical, medial/lateral, and braking/propulsion). Subject 1 showed a statistically significant difference in average peak braking GRF, with no other significant differences in peak forces or knee flexion (Table 4.3, Figures 4.4 & 4.5) Subject 2 displayed statistically significant differences for average peak vertical GRF, average peak braking GRF, and average peak medial GRF, with no other statistically significant differences in peak forces or knee flexion (Table 4.4, Figure 4.6).

Table 4.3 Subject 1 GRF Profile for Single Leg Hop

	UNINVOLVED	INVOLVED
TPT Vertical (ms)	6 ± 1	5 ± 1
Max Vertical (%BW)	295 ± 28	297 ± 44
Max Lateral (%BW)	15 ± 3	9 ± 5
Max Medial (%BW)	10 ± 4	11 ± 4
Max Braking (%BW)	124 ± 3*	114 ± 3
Max Knee Flexion (Deg)	70 ± 11	68 ± 11

* p<0.05

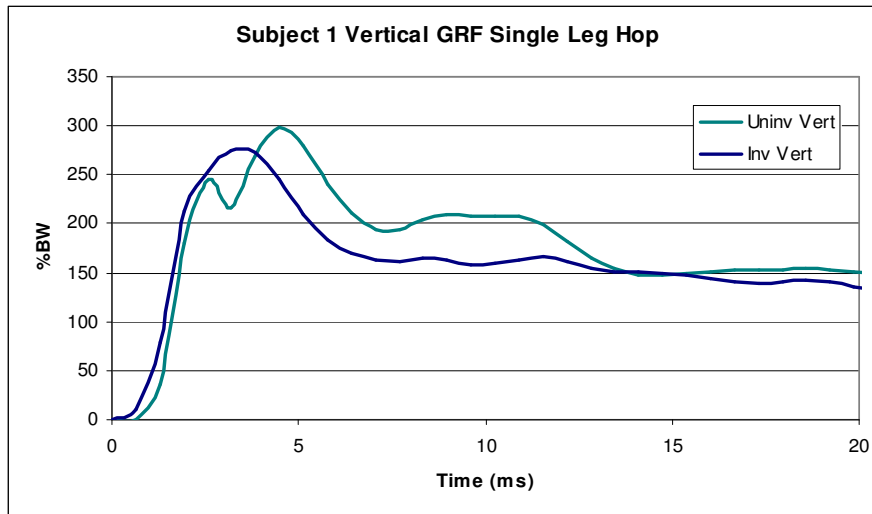


Figure 4.4 Subject 1: Vertical GRF Comparison for the Single Leg Hop.

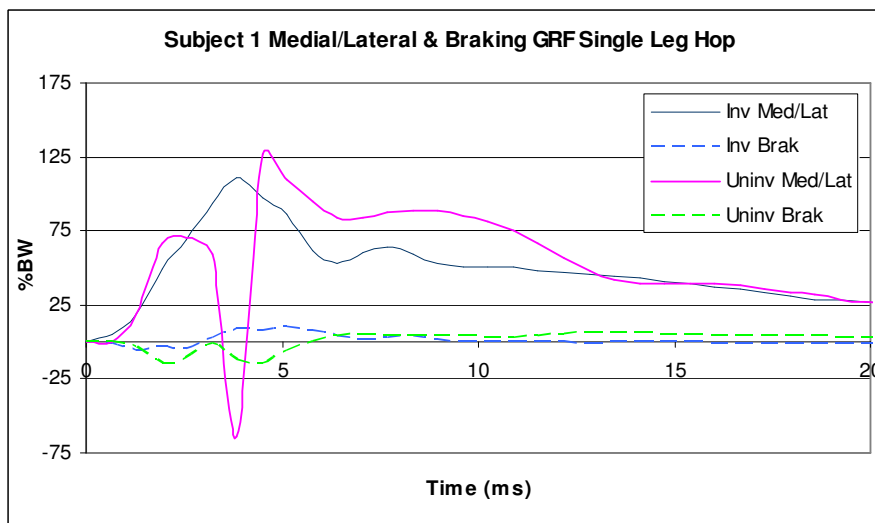
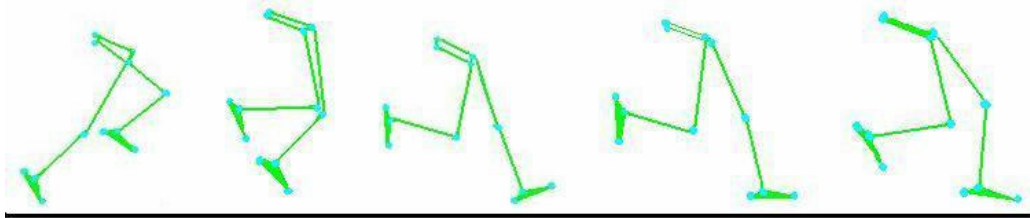


Figure 4.5 Subject 1: Medial/Lateral & Braking GRF Comparison for the Single Leg Hop.

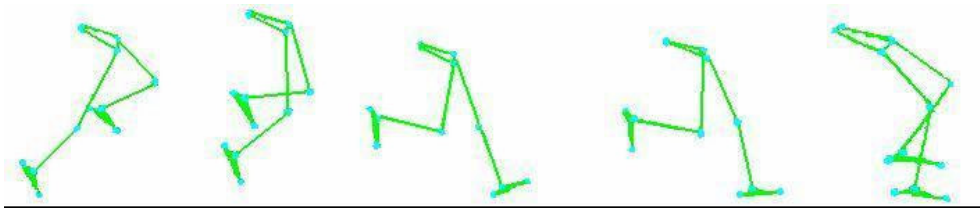
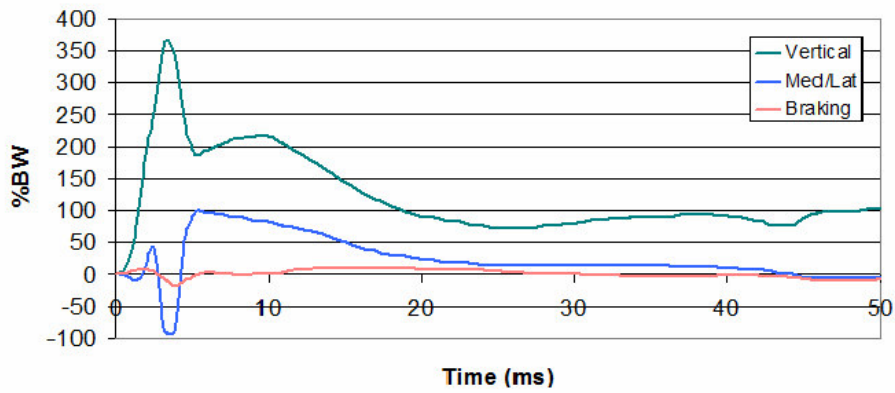
Table 4.4 Subject 2 GRF Profile for Single Leg Hop

	UNINVOLVED	INVOLVED
TPT Vertical (ms)	5 ± 0.8	5 ± 0.8
Max Vertical (%BW)	367 ± 20*	301 ± 34
Max Lateral (%BW)	8 ± 2	38 ± 39
Max Medial (%BW)	31 ± 10*	95 ± 7
Max Braking (%BW)	96 ± 2*	17 ± 4
Max Flexion (Deg)	64 ± 7	67 ± 6

* p<0.05



Subject 2 GRF Profile Uninvolved Limb Single Leg Hop



Subject 2 GRF Profile Involved Limb Single Leg Hop

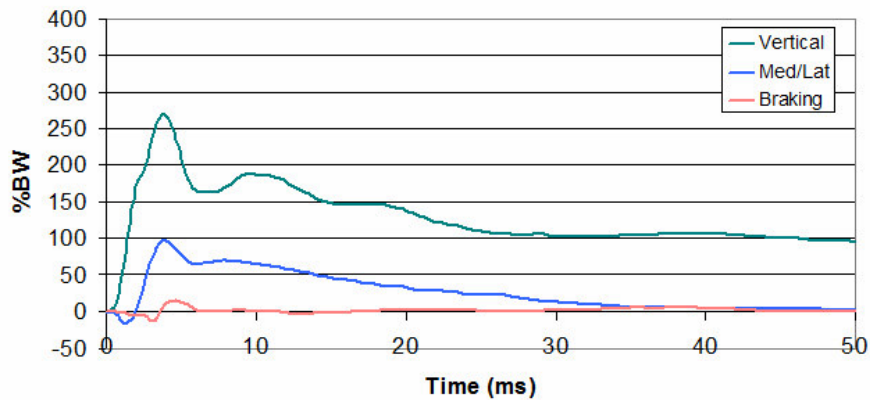


Figure 4.6 Subject 2: GRF Profile Comparisons between Limbs during Single Leg Hop. (Stick Figures shown at Take-Off, Max Height, Heel Strike, Peak Vertical GRF, and Peak Knee Flexion).

4.3 Max Height Jump

The time to peak force in the vertical direction, normalized peak vertical GRF, normalized peak medial and lateral GRF, normalized peak braking GRF, and max knee flexion were averaged from the trials for each subject, over the span of the max height jump condition. Raw data from each subject are shown in the form of vertical GRF curves. Averaged peak vertical GRF was then compared as a relative percentage contribution of each limb to the total summation of forces for both limbs during the max height jump conditions (greater than 10% of the contralateral limb was considered clinically significant). Subject 1 showed a statistically significant difference in average peak vertical GRF. (Table 4.5, Figure 4.7). The relative asymmetry between limbs was clinically significant for peak vertical GRF (within 20% of uninjured limb) and is displayed in Figure 4.8. Subject 2 showed no statistically significant differences in averaged peak GRF between limbs, however, her total relative magnitude of peak vertical GRF was significantly higher than Subject 1's (Figures 4.9 & 4.10). Also, Subject 2's total relative magnitude of peak vertical GRF during the max height jump condition was significantly less than her vertical GRF generated during the jump landing condition (Figures 4.3 & 4.9).

Table 4.5 Subject 1 GRF Profile for Max Height Jump

	UNINVOLVED	INVOLVED
TPT Vertical (ms)	6 ± 1	6 ± 1
Max Vertical (%BW)	180 ± 36*	121 ± 10
Max Lateral (%BW)	16 ± 2	10 ± 5
Max Medial (%BW)	19 ± 3	16 ± 3
Max Braking (%BW)	25 ± 8	30 ± 12
Max Knee Flexion (Deg)	104 ± 4	101 ± 5

* p<0.05

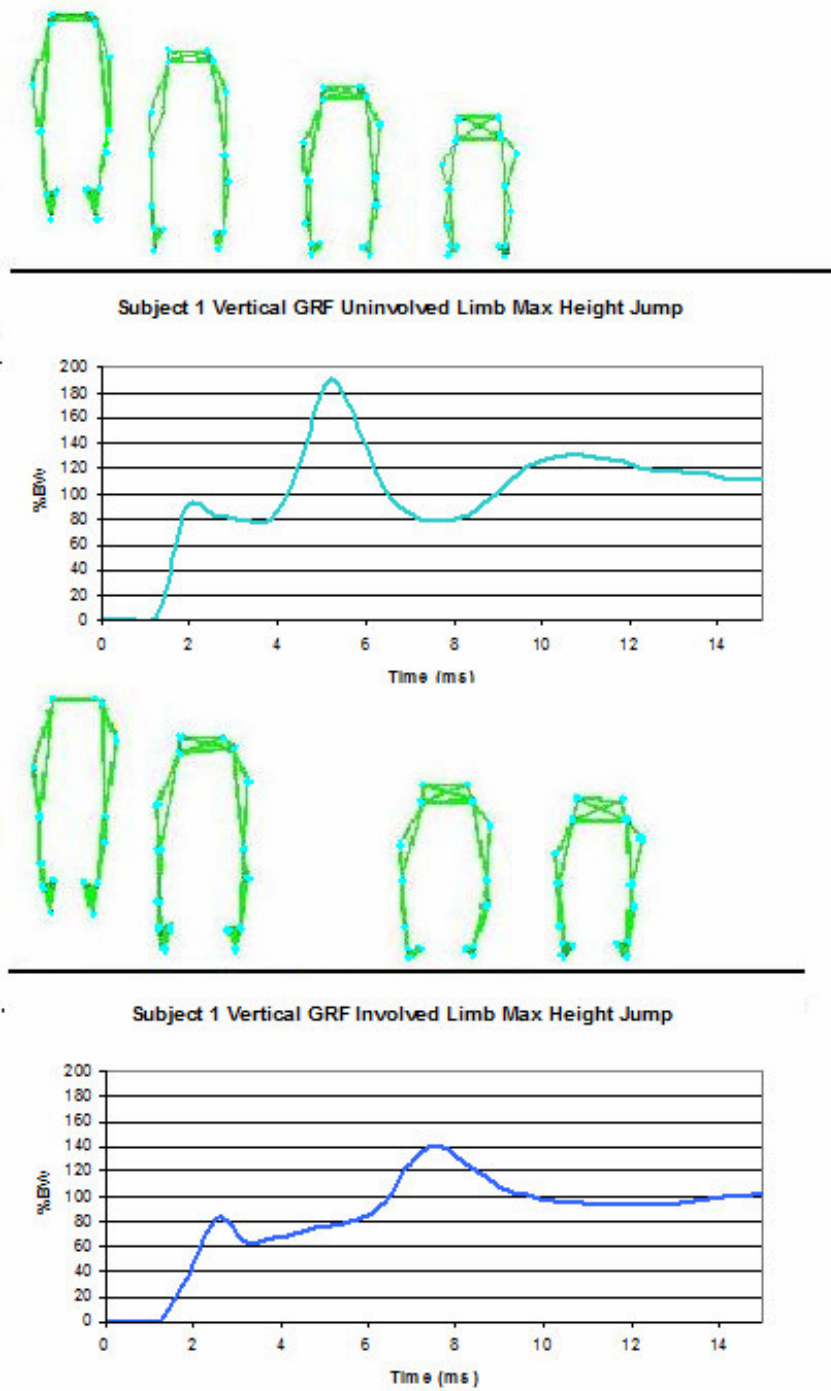


Figure 4.7 Subject 1: Vertical GRF Comparison during Max Height Jump. (Stick Figures shown at Take-Off, Foot Contact, Peak Vertical GRF, and Peak Knee Flexion).

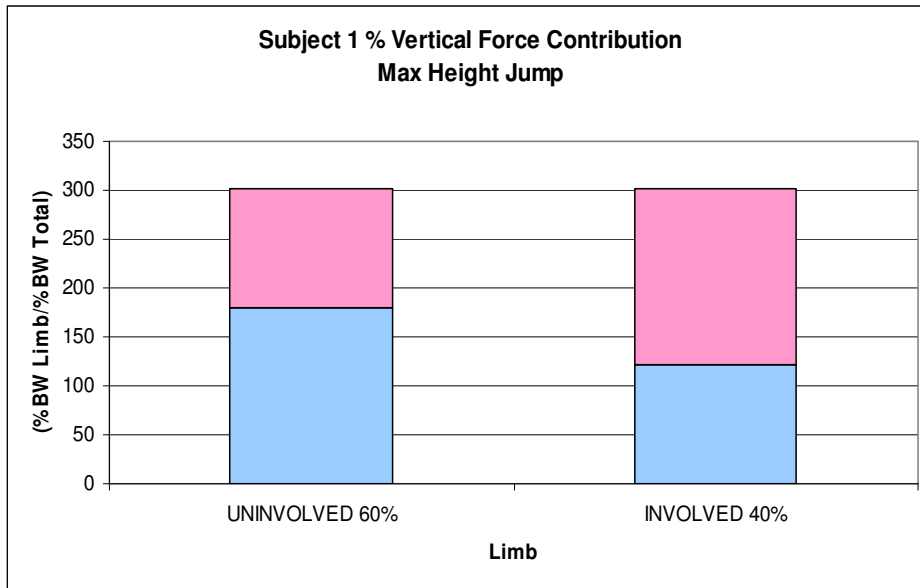


Figure 4.8 Subject 1: Percent Contribution of Each Limb to the Vertical GRF for the Max Height Jump.

Table 4.6 Subject 2 GRF Profile for Max Height Jump

	UNINVOLVED	INVOLVED
TPT Vertical (ms)	7 ± 0.5	6 ± 0.5
Max Vertical (%BW)	182 ± 27	182 ± 41
Max Lateral (%BW)	14 ± 5	15 ± 3
Max Medial (%BW)	2 ± 2	0.5 ± 0.9
Max Braking (%BW)	25 ± 8	20 ± 3
Max Knee Flexion (Deg)	95 ± 1	96 ± 1

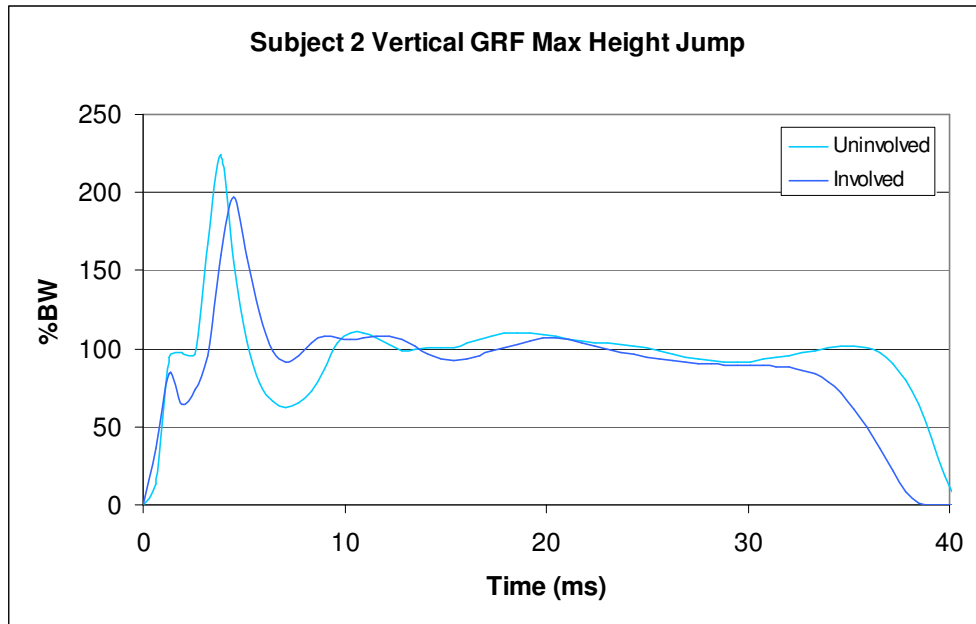


Figure 4.9 Subject 2: Vertical GRF Comparison for the Max Height Jump.

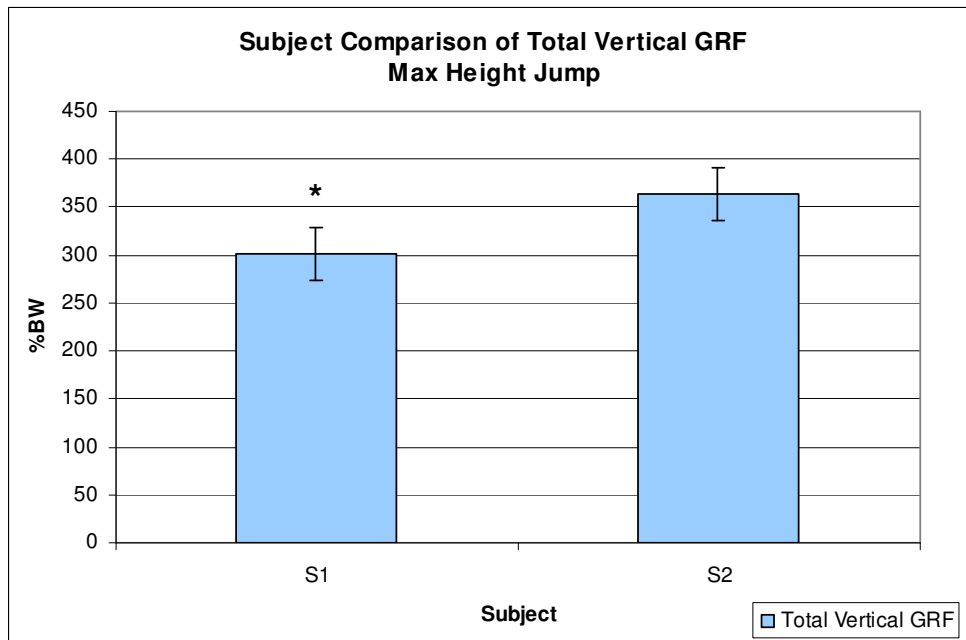


Figure 4.10 Comparison of Vertical GRF between Subjects during Max Height Jump. *Indicates sig. diff between subjects, $p < 0.05$.

CHAPTER 5

DISCUSSION

The purpose of this study was to evaluate the ground reaction force profiles of two, healthy young females who were six months post ACL reconstruction to determine if there was a significant (>10% of the uninvolved limb) asymmetry in force attenuation between limbs. The subjects' rehabilitation progression, estimated by their GRF profile, was evaluated based upon the objective phase progression criteria set forth by Myer et al.(88) The last two stages of the four stages outlined (see Fig. 5.1) are the focus of this study since these are the final stages leading to release for full athletic participation and represent the rehabilitation stage of our subjects (6 months post-op, released to sport). Stages 3 and 4 offer a guide to functional, objective rehabilitation progression and full integration into sport based on addressing the issue of bilateral force attenuation symmetry between the athlete's involved and uninvolved limbs.(88;96;123) Goals of stage 3 include: improvement of single-limb power production; improvement of lower extremity muscular endurance; and improvement of lower extremity biomechanics during plyometric activities. Criteria for progression to stage 4 includes: single-limb hop for distance within 15% of uninvolved side; single-limb crossover triple hop for distance within 15%; single-limb timed hop over 6 meters w/in 15%; single-limb vertical power hop within 15%; and a reassessment of tuck jump to 15% improvement and/or an 80-point score. Goals of stage 4 include equalizing ground reaction force attenuation strategies between limbs; improving confidence and

stability with high intensity change of direction activities; improving and equalizing power endurance between limbs; and using safe biomechanics (increased knee flexion and decreased knee abduction angles) when performing high-intensity plyometric exercises. The criteria for clearance to full athletic participation are: drop vertical jump landing force bilateral symmetry within 15% of the uninvolved; modified agility T-test time within 10%; single-limb average peak power test for 10 seconds within 15%; and reassessment of tuck jump with a 20% point improvement from initial test score or perfect 80 point score. The stringent exit criteria were designed to ensure adequate strength, power, agility, symmetry and stability prior to participation in high-risk activities.(88)

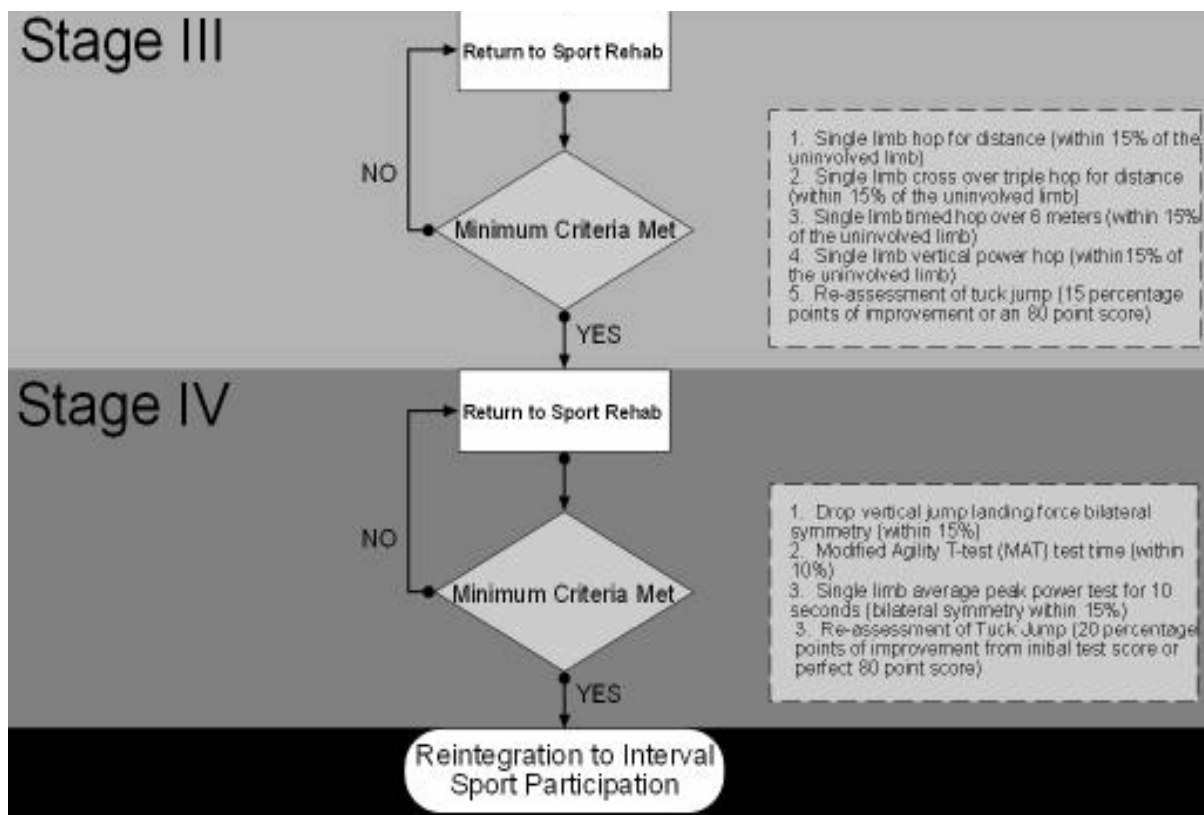


Figure 5.1 Return-to-Sports Activities Post ACL Reconstruction, Myer et al.(88)

Subject 1, at the time of our evaluation, was 5.25 months post-operative, three weeks away from the 'six month return to play' mark. For the jump landing condition, Subject 1 displayed a GRF profile of bilateral vertical force symmetry within 10% of the involved leg with no significant differences in medial/lateral GRF and max knee flexion (Figure 4.1). For the single leg hop condition, Subject 1 showed bilateral vertical force symmetry within 10% of the involved leg with no significant differences in medial/lateral GRF or max knee flexion, but a statistically significant difference in braking between the involved and uninvolved limb. The uninvolved limb showed a higher average magnitude of braking GRF than the involved limb with a 10% difference in vertical GRF production, (124% BW compared to 114% BW, Figure 4.5), even though the absolute magnitude of vertical GRF production was not significantly different (295% BW compared to 297% BW). This suggests that this subject has an improved ability to decelerate her center of mass on the uninvolved limb. The ability to decelerate and thereby control the center of mass is a key component to performing successful jump landings and unanticipated cutting maneuvers, where ACL injury risk is highest. Although these results were statistically significant, Subject 1's absolute difference between the involved and uninvolved limb was still within 10%. For the max height jump condition, Subject 1 showed a significant difference in magnitude of peak vertical GRF, (180% BW, uninvolved limb compared to 121% BW, involved limb, Figure 4.7), as well as a clinically significant bilateral force asymmetry within 20% (Figure 4.8). While the subject showed no significant differences in force attenuation during the jump landing, when asked to perform a more high-impact maneuver, the subject displayed a significant difference in her ability to absorb vertical force on her uninvolved limb. This

provides evidence for the need to address the subject's ability to decelerate during a high-impact landing on the involved limb through plyometric or other applicable high-impact training exercises.

Based on Subject 1's GRF profile, we feel it is appropriate to presume that she can be categorized as being in stage 4 of the rehabilitation outline from Meyer et al.(88) Using data from her GRF profile, we can show that she has met at least two of the four stipulations for progression to full integration into sport and address those where she may be weakest. Subject 1 exhibits bilateral force symmetry within 15% during the low impact jump landing, (criteria 1), bilateral force symmetry within 15% during the single leg hop which suggests an ability to perform a modified agility T-test, (criteria 2), but a bilateral force asymmetry within 20% during the high impact jump landing, suggesting a weakened ability to attenuate forces during high-impact activity. This deficit may manifest in the single-limb average peak power test and the tuck jump assessment, (criteria 3 & 4), as these exercises rely on an athlete's ability to repetitively attenuate forces during a high-impact landing. Although it is assumed she has only met two of the four criteria for progression, the subject has only completed 5.25 months of accelerated rehabilitation. Based on our results, the criteria set forth by Myer et al.(88) and the assumption that her rehabilitation program will address an improved ability to attenuate forces during high-impact training, it may be assumed that at 6 months she will be ready for full sport integration.

Subject 2, at the time of our evaluation was 6 months post ACL reconstruction, had completed an accelerated rehabilitation program, and had been released for full athletic integration back to a Division I soccer team. For the jump landing condition,

Subject 2 displayed bilateral vertical force symmetry within 10% of the uninvolved limb with a significant difference in vertical GRF magnitude between limbs, (281% BW, uninvolved limb compared to 227% BW, involved limb, Figure 4.2), and with no significant differences in medial/lateral GRF and max knee flexion. Also, Subject 2 generated a significantly higher magnitude of force per body weight when compared with Subject 1, (508% BW, Subject 2 compared to 282% BW, Subject 1, Figure 4.3). This suggests that Subject 2 had a smaller impulse and landed with less knee flexion. This is supported by our data: Subject 2 had an average time to peak vertical GRF 2-4 seconds less than Subject 1 and landed on average with 20-32 degrees less knee flexion. Although Subject 2's relative contribution to vertical force was within 10% of the contralateral limb, she displayed a significantly higher peak vertical GRF on her uninvolved limb. The reason for the bilateral force symmetry existing within 10% in spite of the significant difference in magnitude can partially be explained by the fact that Subject 2 generated significantly higher vertical GRF, especially when compared to Subject 1 (Figure 4.3), therefore the relative contribution of each limb is smaller due to the larger magnitude of total force generated. For the single leg hop condition, Subject 2 displayed a significant difference in peak vertical GRF, average peak braking GRF, and average peak medial GRF magnitude between limbs, (Table 4.4 & Figure 4.6). These data suggest that Subject 2 displayed a significant inability to decelerate and maintain stability when landing on her involved limb and therefore, an inability to maintain her center of mass over her base of support. She also displayed significant discrepancies in bilateral force symmetry. The ability to adjust to rapid postural changes through center of mass maintenance as well as bilateral force symmetry, are key components to the

reduction of ACL injury risk. (51;57;88;115) For the max height jump condition, Subject 2 displayed bilateral vertical force symmetry within 10%, with no significant differences in peak vertical GRF magnitude, medial/lateral GRF, and peak knee flexion. Subject 2 displayed a significantly higher magnitude of peak vertical GRF than Subject 1 for this condition as well, (364% BW, Subject 2 compared to 301% BW, Subject 1, Figure 4.10). However, the magnitude of vertical GRF generated by Subject 2 during this condition was significantly less for both limbs than that generated during the jump landing (364% BW compared to 508% BW for jump landing, Figures 4.3 & 4.9). We would expect a higher generation of GRFs during the high-impact jump landing when compared to the low impact jump landing, as was the case with Subject 1, (301% BW compared to 282% BW for jump landing, Figures 4.7 & 4.9) therefore, this provides further evidence that Subject 2 displayed a significant inability to attenuate forces during a low-impact landing.

Based on Subject 2's GRF profile, we feel it is appropriate to presume that she can be categorized as being in stage 3 of the rehabilitation outline from Meyer et al.(88) Using the information obtained from her GRF profile, we show that she has not only failed to meet the criteria for stage 4 progression to sport but also failed to meet all of the criteria for progression into stage 4. Subject 2 showed significant differences in vertical GRF attenuation during a low-impact landing; significant differences in vertical, medial and braking GRF attenuation during a single leg hop landing; and significantly less vertical GRF magnitude for the high-impact landing when compared to the low-impact landing. These results suggest an inability to decelerate the center of mass as well as attenuate and redirect forces on the involved limb. Since the criteria for progression from

stage 3 to stage 4 are based on functional, comparative measurements between limbs, (single hop for distance, time and power), we feel that based on Subject 2's biomechanical deficits, she would be unable to adequately perform these tasks. Therefore, it is recommended that Subject 2's rehabilitation incorporate exercises which address these force attenuation and landing deceleration asymmetries between limbs before progression to stage 4 and sport specific training.

Based on the results, we believe that the GRF profile can not only be used as a tool for progression throughout the phases of accelerated rehabilitation using objective, criteria-based guidelines, but also as an aid in determining whether or not an athlete is ready for return to sport, even after functional measurements have been performed and deemed acceptable. Based upon Subject 1's GRF profile and the criteria guidelines set forth by Myer et al.(88), we were able to assess her current functional ability and address the specific weaknesses that need to be addressed in her ongoing rehabilitation. Subject 1 displayed bilateral force symmetry during the low-impact landing and no significant differences between limbs in force attenuation during the single leg landing but she did show significant force attenuation asymmetry during the high-impact landing. Based on this data, we were able to show not only that there was a deficit, but also why. It is the job, then, of the rehabilitation specialist to address these deficits during an athlete's rehabilitation progression.

Subject 2 has been released to full participation in a Division I collegiate soccer program and we assume that in order for this to occur, she met all of the functional criteria guidelines used by her rehabilitation professional. However, based upon her GRF profile, there were significant biomechanical deficits manifested through asymmetries in

landing force attenuation and a decreased ability to decelerate from a landing on her involved limb that the functional criteria used for her rehabilitation did not address. Based upon previous studies, we know that these biomechanical deficits predispose an athlete to re-injury and osteoarthritis, therefore, premature return to athletic participation has severe ramifications.(15;46;51;57;65;67;77;88;90;91;104;107;108;112;113) The main concerns in accelerated rehabilitation guidelines should include the safe and healthy return of an athlete to her desired activity level, with a minimal risk of the aforementioned occurrences. We have sufficient evidence from our study to show that these concerns are not ideally being addressed and that the current guidelines used for Subject 2, for integration to full athletic participation, were inadequate in the attempt to address post-operative biomechanical deficits.

We have provided preliminary evidence for a need to develop functional tests based on measuring and identifying biomechanical deficits and the collective efforts of a medical team inclusive of orthopaedic surgeons, rehabilitation professionals, and biomechanists in order to address the current limitations and ramifications of accelerated ACL rehabilitation. Previous studies have alluded to the current lack of objective criteria-based guidelines for ACL rehabilitation progression, as well as the inefficiency of current functional tests to assess an ACL's functional stability.(9;88;96;114) It has been shown that when used in isolation, functional tests have a low sensitivity and that there is a lack of an absolute gold standard for functional scoring due to the varying strengths and weaknesses of such tests.(96) Tegner et al.(114) showed that there was a significant difference between symptomatic ACL deficient subjects and the normal controls but no significant difference between symptomatic ACL deficient and ACL reconstructed

patients during a single leg hop, figure-of-eight run, spiral staircase run and indoor slope run. They also found that a substantial number of ACL deficient subjects achieved scores within normal ranges for the functional tests.(114) Barber et al.(9) found that over 90% of the symptomatic ACL deficient patients achieved normal scores on the shuttle runs due to a lower running velocity in both directions. We must question whether such functional assessments conducted with the primary goal of measuring ACL stability is truly accurate, considering that a person with no ACL can achieve a passing score. Such studies provide evidence for the idea proposed by Phillips et al.(96) and supported by our study: functional tests tend to be global in their measurement in that they do not indicate which component in knee function might be negatively affecting performance. For instance, a patient performs a single hop to within only 15% of the contralateral limb's distance or a tuck jump assessment to within 20% of the contralateral limb's: a functional test measures to what extent the activity can be performed, but it does not address the why and how if it cannot be executed successfully. There are subjective ideas as to why a patient cannot perform a single hop to within 10% of the uninvolved limb or within 20% during a tuck jump assessment: but until studies are performed correlating the so-called 'sensitivity' of ACL functional stability measurements to biomechanical properties, little evidence is provided for objective criteria. In order to effectively rehabilitate an athlete, these questions, must be addressed.

With the understanding that not every rehabilitation clinic has access to a high speed motion analysis camera system and/or force plates, there is an ongoing need for correlative studies to be performed with the ultimate goal of addressing a functional test or test(s) that, when administered, can not only measure the extent of performance but

address why it could not be performed successfully. An effective evaluation involving a biomechanical analysis can provide the answers, as demonstrated by our study. More studies, however, ideally involving larger subject populations and multi-center cooperation, need to be performed to elucidate our current theory.

APPENDIX A

STATEMENT OF INFORMED CONSENT

THE UNIVERSITY OF TEXAS AT ARLINGTON
DEPARTMENT OF KINESIOLOGY

INFORMED CONSENT

PRINCIPAL INVESTIGATOR: Ashley McGavern

TITLE OF PROJECT: Ground Reaction Force Profiles in ACL Reconstructed Female Athletes

This Informed Consent will explain about being a research subject in an experiment. It is important that you read this material carefully and then decide if you wish to be a volunteer.

PURPOSE:

The purpose of this study is to investigate the ground reaction force profiles during three different jump landing movements. During this study I will be filmed while jumping and landing on the force platform. The force platform will measure the force that I apply to the ground during the landings.

The specific purposes of this research study are as follows:

1. Compare the ground reaction force profiles of a six month post-operative ACL reconstruction female athlete between the involved and non-involved leg.

DURATION

In this study I will be scheduled for a one hour appointment. The first thirty minutes will consist of a health history, injury history, joint hypermobility determination, marker placement, and a practice session in which I will practice the three conditions: max height jump, single leg hop, and landing from a 6 inch platform. I will be required to wear spandex shirt and shorts to eliminate movement of clothing during the activity. 1 cm markers will be placed over my toe, ankle, knee, hip joints on the right and left sides of my body. Six video cameras will track the locations of the markers. The marker locations will then be used to compute the position of my body segments during the jump landing motions. I will be asked to do 7 trials of each of the three conditions, aforementioned, for my involved and uninvolved leg. Only trials in which I land with my desired foot on the center of the force plate will be saved for further analysis.

The total number of subjects participating is 20.

PROCEDURES

The procedures, which will involve you as a research subject, include:

1. To be included in this study, you will report to the Biomechanics Laboratory (Room 150) in the Activities Building and fill out a health history and injury history questionnaire. If you have had a sprain, ligament tear or fracture to either leg in the last six months, excluding the injury you were recruited for, you will be excluded from the study.
2. At the appointment I will be required to complete a health history questionnaire. If I have had more than one injury to either leg requiring surgical attention I will be excluded from the study.
3. During the appointment I will practice the three jump-landing conditions: max height jump, single leg hop, and landing from a 6 inch platform. I will be asked to change into the spandex shirt and shorts. Then the 1 cm markers will be placed on my right and left toe, ankle, heel, lower leg and hip body landmarks. I will be asked to do 7 trials of each of the three conditions, max height jump, single leg hop, and 6 inch platform landing. During each landing condition, the force plate will compute how much force I apply against the ground. Only trials in which I land with my desired foot on the center of the force plate will be saved for further analysis.

POSSIBLE RISKS/DISCOMFORTS

The possible risks and/or discomforts of your involvement are comparable to running for exercise, I could slip or trip.

Throughout the tests you will be monitored by laboratory personnel trained in CPR and First Aid. Emergency (911) will be called for any emergency situations.

POSSIBLE BENEFITS

The possible benefits of your participation are:

1. Improved understanding of the ability of an athlete to return to full participation in their desired sport, with less risk of re-injury.

ALTERNATIVE PROCEDURES / TREATMENTS

There are no alternative procedures or courses of treatment. **However, you can elect not to participate in the study at any time with no negative consequences.**

CONFIDENTIALITY

Every attempt will be made to see that your study results are kept confidential. A copy of the records from this study will be stored in (Office of Dr. Mark Ricard, ACT 220) for at least three (3) years after the end of this research. The results of this study may be published and/or presented at meetings without naming you as a subject. Although your rights and privacy will be maintained, the Secretary of the Department of Health and Human Services, the UTA IRB, and personnel particular to this research (Mark Ricard, Kinesiology Department) have access to the study records. Your records will be kept completely confidential according to current legal requirements. They will not be revealed unless required by law, or as noted above.

FINANCIAL COSTS

The possible financial costs to you as a participant in this research study are:

1. There should be no financial costs to you as a participant unless you incur medical treatment outside the UTA covered costs.

CONTACT FOR QUESTIONS

If you have any questions, problems or research-related medical problems at any time, you may call Ashley McGavern at 504-296-2761 (mcgavern@uta.edu) or at the Biomechanics Laboratory 817-272-7146.

You may call the Chairman of the Institutional Review Board at 817-272-1235 for any questions you may have about your rights as a research subject.

VOLUNTARY PARTICIPATION

Participation in this research experiment is voluntary. You may refuse to participate or quit at any time. You may quit by calling Ashley McGavern, whose phone number is 504-296-2761. You will be told immediately if any of the results of the study should reasonably be expected to make you change your mind about staying in the study.

VOLUNTARY PARTICIPATION

By signing below, you confirm that you have read or had this document read to you. You will be given a signed copy of this informed consent document. You have been and will continue to be given the chance to ask questions and to discuss your participation with the investigator.

You freely and voluntarily choose to be in this research project.

PRINCIPAL INVESTIGATOR: _____ DATE

SIGNATURE OF VOLUNTEER DATE

ASSENT:

By signing below, you confirm that you have read or had this document read to you. You have been informed about this study's purpose, procedures, possible benefits and risks, and you have received a copy of this form. You have been given the opportunity to ask questions before you sign, and you have been told that you can ask other questions at any time. You understand that since you are under 18 years of age that your parent(s)/legal guardian(s) have consented for your participation.

You voluntarily agree to participate in this study. By signing this form, you are not waiving any of your legal rights. Refusal to participate will involve no penalty or loss of benefits to which you are otherwise entitled, and you may discontinue participation at any time without penalty or loss of benefits, to which you are otherwise entitled.

SIGNATURE OF PATIENT/LEGAL GUARDIAN DATE

SIGNATURE OF MINOR VOLUNTEER DATE

APPENDIX B

HEALTH HISTORY QUESTIONNAIRE

THE UNIVERSITY OF TEXAS AT ARLINGTON
DEPARTMENT OF KINESIOLOGY
HEALTH STATUS QUESTIONNAIRE

Name _____ Date _____

Home Address _____

Work Phone _____ Home Phone _____

Person to contact in case of emergency _____

Emergency Contact Phone _____ Birthday (mm/dd/yy)____/____/____

Gender _____ Age _____(yrs) Height _____(ft)_____(in) Weight _____(lbs)

A. JOINT-MUSCLE STATUS (✓Check areas where you have problems or meet criteria)

Do you currently have any problems with your:

- Knee
- Thigh
- Lower Leg
- Ankle

If any checked, please explain: _____

DECISION-MAKING CRITERIA:

1. If an individual checks ***two or more*** of the areas above this response by itself would preclude the subject from participation in this study.

Do you have metal plates or screws in your:

- Knee
- Thigh
- Lower Leg
- Ankle

If any checked, please explain: _____

DECISION-MAKING CRITERIA:

1. If an individual checks **two or more** of the areas for metal implants, this response by itself would preclude the subject from participation in this study. No subjects will be included if they have metal implants.

B. HEALTH STATUS (✓Check if you currently have any of the following conditions)

- | | |
|---|--|
| <input type="checkbox"/> High Blood Pressure | <input type="checkbox"/> Acute Infection |
| <input type="checkbox"/> Heart Disease or Dysfunction | <input type="checkbox"/> Hypersensitivity to Needles |
| <input type="checkbox"/> Peripheral Circulatory Disorder | <input type="checkbox"/> Edema |
| <input type="checkbox"/> Allergic Reactions to Medication
please describe_____ | <input type="checkbox"/> Others That You Feel We Should Know
about_____ |
| <input type="checkbox"/> Allergic Reactions to Any Other Substance
about_____ | |

DECISION-MAKING CRITERIA:

1. If an individual checks **two or more** of the Health Status Conditions above, this response by itself would preclude the subject from participation in this study.
2. If an individual checks **one** of the Health Status Conditions above and the potential subject feels comfortable participating in the experiment despite their problem denoted above, the subject can be included in this study.
3. If an individual checks **other** and the other description cannot be classified into one of the above categories, this response by itself would preclude the subject from participation in this study.

C. CURRENT MEDICATION USAGE (List the drug name and the condition being managed)

<u>MEDICATION</u>	<u>CONDITION</u>
_____	_____
_____	_____
_____	_____

DECISION-MAKING CRITERIA:

1. Taking certain medications does not preclude a subject from participating in this study.
2. However, if an individual indicates that he/she is currently taking medications that treat a condition that aligns with two or more of the conditions listed in sections A, B, C, and/or E, this response by itself would preclude the subject from participation in this study.
3. If no medications are listed, the subject can be included in this study.

APPENDIX C

ATHLETIC HISTORY QUESTIONNAIRE

ATHLETIC AND INJURY HISTORY QUESTIONNAIRE

PRINCIPAL INVESTIGATOR: Ashley McGavern

TITLE OF PROJECT: Ground Reaction Force Profiles in ACL Reconstructed Female Athletes

1. Previous to this injury, have you incurred any injuries that have not required surgical intervention, particularly to the ankle or foot?

2. Do you have a history of neurological disorders of any type? (ex. seizures, epilepsy...) If yes, please give a description of your symptoms and approximate frequency and length of occurrence.

3. Did you participate in gymnastics, ballet, or some form of acrobatics/dance class at any point in your life? If yes, please list activity and approximate length of participation.

4. To your best knowledge, do any of your immediate family members have a ligament/cartilage injury history?

5. You will be measured for joint laxity: (A Beighton Score of $\geq 5/9$ will be considered positive for generalized joint hypermobility)

Beighton Score = _____

1. L Passive Dorsal Flexion of Pinky Beyond 90 deg: _____
2. R Passive Dorsal Flexion of Pinky Beyond 90 deg: _____
3. L Passive Apposition of Thumb to Forearm Flexors: _____
4. R Passive Apposition of Thumb to Forearm Flexors: _____
5. L Hyperextension >10 deg of Elbow: _____
6. R Hyperextension >10 deg of Elbow: _____
7. L Hyperextension >10 deg of Knee: _____
8. R Hyperextension >10 deg of Knee: _____
9. Forward Flexion of Trunk, Knees Straight, Palms to Ground: _____

APPENDIX D

SAMPLE ACL REHABILITATION PROTOCOL

ANTERIOR CRUCIATE LIGAMENT ALLO/AUTOGRAFT RECONSTRUCTION (Criteria Based)

This protocol is designed to progress through phases based on meeting certain criteria and not strictly on time. Approximate time frames are included with each phase but are not absolute. It is designed for allografts and autograft patellar tendon and hamstring grafts. It does not change if there is a concomitant meniscal repair. There are a few time-based exceptions:

- No full range open chain knee extensions until 10 weeks post-op
- No land running until >10 weeks for autograft patellar tendon and >12 weeks for hamstring/allograft
- No agilities until at least 18 weeks post-operative and after successful completion of 4 – 6 week straight plane running program
- No hamstring curls for 6 weeks with a concomitant posterior horn medial meniscal repair
- Weight-bearing may be restricted initially with concomitant articular pick or drilling and will be determined by physician based on size of lesion

Phase I – Protective Phase (~Day 1 –7)

Gait:	WBAT with immobilizer and 2 crutches
ROM:	PROM/AAROM to tolerance for flexion/extension Prone hangs/heel props (10 min) for extension ROM PROM for flexion at end of bed using opposite leg
Strength:	Quadricep sets emphasizing VM (use E-stim if necessary) SLR's X 4 planes (in immobilizer if significant quadricep lag)
Proprioception:	Weight shifts without immobilizer
Progress Criteria:	>90° flexion; extension within 5° of opposite leg Fair/Good quad set (VL solid and some recruitment of VM) SLR with < 5° quadricep lag

Phase II – Early Mobility (~Day 8 – 20)

Gait:	First wean from immobilizer when good quad control and no lag Then wean off crutches when no limp or increase in pain/effusion
-------	---

ROM: Progress to heel slides for flexion ROM
 Continue prone hangs/heel props (add weight if necessary)
 Initiate stationary cycle when >110° flexion
 Initiate HS/ITB/Calf stretching
 Initiate 1 leg retrograde walking on treadmill for extension ROM
 Patellar mobilizations/scar massage/massage to ITB and quads

Strength: Continue quad sets and SLR's (no resistance)
 Initiate closed chain TKE's in standing with theraband
 Initiate bilateral calf raises on floor

Proprioception: Continue weight shifts
 Initiate single leg stance (SLS) on floor

Progress Criteria: >110° flexion and extension within 5° of opposite side
 Good quadricep set (solid VM/VL recruitment)
 SLR without a quad lag
 Independent gait without assistive device and without a limp
 ≤ 1+ effusion

Phase III - Controlled Mobility (~Week 3 – 6)

Gait: Client should be independent without limp/quad avoidance gait

ROM: Continue heel slides and prone hangs until equal to opp. side
 Add quadricep stretch when appropriate

Strength: D/C quad sets and SLR's in clinic
 Calf raises (2 leg floor→2leg step→1 leg floor→1 leg step)
 Initiate: Shuttle/leg press (high reps/low resistance for endurance)
 Mini-squats (0 - 45°) and progress with dumbbells
 Forward/lateral step-ups (6"→8"→10"→12")
 Hamstring curls (light resistance if HS graft)
 T-band resisted sidestepping for hip abductors

Proprioception: Begin and progress through proprioception progression
 Slide board

Testing at 6 wks: KT 2000 (15 and 20 lbs)

Progress Criteria: ROM (within 10 -15° flex and full ext. equal to opposite side)

Stable KT at 6 wks
< Trace effusion
No or very mild patello-femoral symptoms

Phase IV - Advanced Strengthening/Proprioception (~Week 7 – 10)

Gait: Initiate water running if > 8 weeks
ROM: Continue ROM and flexibility as necessary
Strength: Continue to progress previous exercises
Initiate leg press (<90° flexion)
Initiate open chain knee extension with the last 40° of ext. blocked
Isokinetic (high speed/high reps)
Isotonic (light weights/high pad on tibia)
Proprioception: Continue to progress through program increasing challenges
Progress Criteria: ROM WFL (within 5° flexion and full ext. equal to opposite side)
No effusion
Progressing without PF symptoms in strength/proprioception

Phase V - Plyometric/Running (~Week 11 – 12)

Gait: Water running → treadmill as outlined initially
ROM: Continue flexibility as necessary
Strength: Continue all strengthening progressing to full range knee ext.
Proprioception: Continue to increase challenges
Plyometrics: Bounding on shuttle (2 legs → 1 leg working on landing form)
10 – 12” step jumps both forward and lateral progressing from 2
leg landing to 1 leg landing concentrating on proper technique
Testing at 12 wks: KT 2000 (15, 20, 30 lbs and manual max)
Isokinetic strength test (full ROM at 60 and 180°/sec)
Progress Criteria: Stable KT (< 3 mm side to side difference)
Biodex deficit of < 40% in quadriceps and hamstrings
No effusion
No PF symptoms

Phase VI - Independent Running/Agility (~Week 12 – 6 months)

Gait:	Initiate independent straight running program for 4 – 6 wks
ROM:	Counsel on appropriate stretching for warm-up/cool-down
Strength:	Counsel on appropriate strengthening program at gym based on biodex results
Agility:	Initiate independent 4 – 6 week agility/sport specific program after successful completion of straight running program

Criteria for Return to Play (~5 – 6 months post-op)

1. Physician release
2. Stable KT (< 3mm side to side difference with firm end point)
3. Full ROM
4. No effusion
5. Satisfactory strength (> 85% compared to opposite leg)
6. Successful completion of proprioception/running/agility programs

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BIOGRAPHICAL INFORMATION

Ashley L. McGavern was born and raised in Zephyrhills, FL. She attended the Tulane University of Louisiana for her undergraduate tenure where she majored in Biomedical Engineering. She then attended the University of Texas at Arlington, where she obtained a Master of Science in Exercise Physiology, with a concentration in Biomechanics. She will be attending the University of Sydney in July to commence her doctoral program in Biomechanics and Tissue Analysis. Her research interests include the understanding and prevention of knee injuries, three-dimensional shape variations of the knee between sexes, and the effect of high-tibial osteotomies on gait and cartilage volume.