The Effect of Fatigue on Lower Extremity Biomechanics and Balance in Anterior Cruciate Ligament Reconstructed Individuals

Christine M. Gilsdorf, LAT, ATC*; Darin Padua, PhD, ATC*; William E. Prentice, PhD, ATC, PT, FNATA*; Benjamin M. Goerger, MS, ATC*; Barnett Frank, MA, ATC*

*****_University of North Carolina, Chapel Hill_

Anterior Cruciate Ligament (ACL) injury is common in athletes frequently requiring invasive surgery and arduous rehabilitation, with the athlete commonly not returning to their previous level of activity. About 70% of ACL injuries are associated with a non-contact mechanism that involves a jump landing, cutting or pivoting maneuver (Agel, Arendt et al. 2005). The non-contact mechanism of injury stems from a degradation in the body's neuromuscular control of the lower extremity creating adverse joint biomechanics in the knee (Borotikar, Newcomer et al. 2008). Insufficient neuromuscular control (NMC) of the body during jumping, landing, cutting and pivoting maneuvers, has the potential to result in biomechanics that put the ACL at risk of rupture (Olsen, Myklebust et al. 2004).

Of the individuals who undergo ACLR, the likelihood of sustaining a second ACL injury to either the reconstructed knee or contralateral knee has been reported to range from 6 to 20% (Salmon, Russell et al. 2005; Wright, Dunn et al. 2007; Shelbourne, Gray et al. 2009). In a study by Paterno et al, individuals that had previous history of ACLR are 15 times at greater risk to incur a second injury as compared to a healthy population (Paterno, Rauh et al. 2012). In particular, female athletes had a second ACL injury rate of 16 times that of healthy female controls (Paterno, Rauh et al. 2012). Females also had a re-injury rate that was 4 times that of the re-injury rate of male ACLR participants (Paterno, Rauh et al. 2012). These results are very concerning of clinicians and sport staff served with the duty of rehabilitation of these ACL injured athletes. ACLR individuals may possess specific neuromechanical factors that are different than individuals who never injure their ACL.

Residual postural control deficits after ACLR may also account for increased risk for ACL injury. Postural stability while balancing on a single leg is significantly different in ACLR individuals compared to healthy individuals (Zouita Ben Moussa, Zouita et al. 2009). ACLR individuals with postural stability deficits in single leg stance on their involved limb are twice as likely to sustain a second ACL injury than individuals without postural stability deficits (Paterno, Schmitt et al. 2010).

The literature suggests that fatiguing physical activity produces deficits in balance in a healthy population (Corbeil, Blouin et al. 2003; Gribble and Hertel 2004; Wilkins, Valovich McLeod et al. 2004; Yaggie 2004). These altered control strategies have been suggested to increased risk non-contact ACL injury in healthy individuals (Chappell, Herman et al. 2005; McLean, Fellin et al. 2007; Benjaminse, Habu et al. 2008). Although the effects of fatigue on balance have been well documented, no literature has examined the effects of fatiguing exercise on balance in an ACL injured population.

The purpose of this study is to investigate the effects of fatigue on balance in females with ACLR. We hypothesize that in a fatigue state, female ACLR individuals exhibit balance deficits associated with increased risk of ACL injury, which may provide insight to elements that contribute to the high rate of re-injury. A greater understanding of the effects of fatigue on postural stability will direct clinicians to implement rehabilitation programs that mitigate the risk of injury.

METHODS

Participants

This study was a repeated measures design with all participants belonging to an ACLR group. A total of 14 female ACLR participants (age= 19.64±1.5 years; height = 163.52±6.18cm; weight = 62.6±13.97kg) were used in this study. Inclusion criteria were that all participants: were female, exercised for at least 30 minutes at least 3 sessions per week, and were between the ages of 18 and 30 years old. Exclusion criteria included: participants that are not cleared by their physician to participate in exercise, a history of bilateral ACL injury or injury to the MCL, PCL, LCL or meniscus in the contralateral knee, participants more than 6 years post ACLR, having any lower extremity injury episodes in the past 6 months that has left them unable to participate in physical activity for more than 3 consecutive days, and participants with a history of more than one ACL injury.

Instrumentation

Kinematic data were collected using an electromagnetic motion tracking system (trakSTAR; Ascension Technologies Inc, Burlington VT) was used to record kinematic data. All kinematic data were sampled at 140Hz . Kinetic data, including ground reaction force and center of pressure (COP) were sampled at 1,400 Hz with a non-conductive force plate (Type 4060-08 Bertec Corporation, Worthingtion, OH).

Procedures

All participants reported for a single testing session for data collection, lasting approximately 1.5 hours. Before participation individuals read and signed an informed consent document approved by the institution's human subjects review board. Participants also completed an active population questionnaire and a physical activity readiness questionnaire (PAR-Q) (Shephard 1988). To ascertain ACL injury and surgical history and graft type, a questionnaire was completed by all subjects (Table 1-2). The Marx and Tegner Activity scales were also completed by all subjects to ascertain subject's physical activity levels. (Table 3 & 4) (Marx, Stump et al. 2001) (Hambly 2011). . To determine post-surgical knee functional outcomes the participants were given a Knee Injury and Osteoarthritis Outcome Scale (KOOS) questionnaire (Table 5) (Roos and Lohmander 2003).

Participant's height and mass was measured with a stadiometer and digital scale, and was recorded prior to collection of biomechanical data. Each participant performed 5 minutes of light stationary bike warm up followed by 5 minutes of light stretching prior to testing. Immediately after warm-up, electromagnetic sensors were attached to the shank and thigh of both legs as well as the sacrum using double-sided tape, a Velcro belt and secured with pre-wrap and athletic tape. After the participants were digitized, testing protocol began.

Data Collection

A global axis system was defined based on a right-hand coordinate system with the positive *x*-axis corresponding with the anterior direction, positive *y*-axis corresponding with the lateral direction, and positive *z*-axis corresponding with superior direction. Local coordinate systems for the shank, thigh, and pelvis segments will correspond with that of the global axis system. The shank segment was digitized using a movable sensor, indicating the medial and lateral femoral epicondyles, medial and lateral malleoli and right and left anterior superior iliac spine. The ankle joint center was defined as the midpoint between the medial and lateral malleolus, knee joint center as the midpoint between the medial and lateral femoral epicondyle, and hip joint center estimated from the right and left anterior superior iliac spine using the Bell Method (Bell, Pedersen et al. 1990). The three non-colinear points of the ankle joint center, knee joint center, and shank sensor defined the shank segment. The thigh segment was defined by the knee joint center, hip joint center and thigh sensor. The pelvis was defined by the left anterior superior iliac spine, right anterior superior iliac spine and sacrum sensor.

Joint motion at the knee was defined as the motion of the shank segment relative to the thigh segment using an Euler sequence of Y, X’, Z’’; joint motion of the hip was defined as motion of thigh relative to the motion of the pelvis using an Euler sequence of Y, X’, Z”. Sagittal plane motion (+ flexion, - extension) was defined about the *y*-axis, frontal plane motion (+ varus, - valgus) defined about the *x*-axis, and transverse plane motion (+ internal rotation, - external rotation) defined about the *z*-axis.

Double Leg Jump Landing

The jump-landing task was preformed with a 30cm box placed at a distance equal to half the participants’ height from the leading edge of the force plate. Participants were instructed to jump from the box to the force plate, landing with two feet. Then upon landing, participants were instructed to jump as high as possible (Padua, Marshall et al. 2009). A successful jump landing trial is only when the participant had landed two feet and with the specified foot (left or right) on the force plate. Participants were allowed 3 practice jumps to familiarize themselves with the task. A total of 10 successful trials were collected, 5 with the right leg landing on the force plate and 5 with the left leg landing on the force plate.

Single Leg Balance Test

Participants completed a single leg balance test on the force plate to assess balance. After the jump-landing each participant completed the single leg balance assessment with eyes closed while standing unshod on the center of the force plate, instructed to stand as still as possible. Participants were instructed to place hands on hips for the duration of the balance task. Each participant balanced on a single leg for 20 seconds while center of pressure (COP) data were collected. Trials were repeated if the participant touched down with the non-stance foot, took hands off their hips, or opened their eyes. A total of 6 successful trials were collected, 3 while standing on the right foot and 3 while standing on the left foot.

Intervention

Fatigue Protocol

The fatigue protocol was adopted from a similar study by Padua et. all (Padua, Arnold et al. 2006). Participants performed repeated squatting motions with the weighted bar through a knee flexion range of 0° to 60°. The bar for each participant was weighted to approximately 30% of the participants' mass in pounds. Knee range of motion during the fatigue protocol was controlled as participants were instructed to come to a knee extended position (0°) when moving upwards then lightly touch their gluteals to a mechanical block that was set at a height to achieve 60° of knee flexion when moving downwards. Frequency of the squatting motion during the fatigue protocol was controlled using the beat of a digital metronome as subjects perform repeated weighted squats at a frequency of 50 beats per minute, or approximately 25 squats per minute. Each beat represented the beginning and bottom of each squat during the squat cycle. One squat cycle was defined as the period of time when the participant moved from an upright standing position (0° knee flexion) to the squatting position (60° knee flexion), and back to the upright standing position (two beats of the digital metronome). Participants were instructed to maintain a constant rate of movement for both the downward and upward motion of the squat. The relative loading and movement frequency had been selected from pilot testing.

The fatiguing exercise was terminated when participants fell four squat cycles behind the 50 squats per minute set pace or failed to complete two sequential squat cycles. The need to come into full knee extension and lightly touch the range of motion block when moving into knee flexion, even at the cost of falling behind the set cadence was emphasized to the subjects in order to maintain a constant, even motion. Participants continued to exercise until verbally instructed to stop when the investigator had observed that they met stop criteria. After stop criteria was met, the participant reported a Borg perceived rate of exertion rating (Borg 1970).

Data Processing

All data was recorded using the Motion Monitor Software version 9 (Innovative Sports Technology, Chicago, IL), exported from Motion Monitor, and then reduced using Matlab Software (2011 The MathWorks, Inc.). Hip and knee joint angles were identified at initial contact (time when vertical ground reaction force exceeds 10 N) as well as the peak angle and displacement during the loading phase. The loading phase was defined as the time from initial contact until 50% of the entire stance phase (time from initial contact until vertical ground reaction force drops below 10 N). Peak internal joint moments at the hip and knee as well as peak proximal anterior tibial shear force and vertical ground reaction force were identified during the loading phase. Joint moments were normalized to the product of body mass (kg) and height (m). Anterior tibial shear force and vertical ground reaction force data were normalized to body mass (kg). All moments were reported as a positive value. Data were collected for each trial and the arithmetic mean was calculated across three trials for each variable.

Postural sway path and velocity were quantified during the first 13 seconds of each single leg balance trial. The arithmetic mean was then calculated for each postural sway variable across the three trials.

Statistical Analysis

Paired samples t-tests were performed to compare pre-fatigue and post-fatigue data for each dependent variable. An a priori alpha level for this study was set at α = 0.05. All variables were analyzed on the levels of pre-fatigue and post-fatigue. All statistical analyses were performed using SPSS 19.0.

RESULTS

Seventy-one percent of participants in this study reported a non-contact mechanism of injury, and the remaining participants reported contact with another player at the time of injury. All demographic means and standard deviations as well as Marx Scale, KOOS and Tegner Activity Scale ratings are reported in Table 1-6. Participants Borg ratings were 16.42 $\pm$ 1.88. Time to fatigue for all participants was 7.85 $\pm$ 4.23 minutes.

Joint Angles at Initial Contact

Paired-samples t-tests were conducted to compare joint angles at initial ground contact between the pre-fatigue and post-fatigue conditions. There was a significant difference in hip flexion angle at initial contact between the pre-fatigue and post-fatigue conditions ($t = -2.823$, $p = 0.014$) as hip flexion significantly decreased from pre-fatigue to post-fatigue (Figure 1). There was no significant difference between pre-fatigue and post-fatigue joint angles at initial contact for hip adduction ($t = -0.610$; $p = 0.552$), hip rotation ($t = 0.059$; $p = 0.954$), knee flexion ($t = 1.197$; $p = 0.253$), knee valgus ($t = 0.554$; $p = 0.589$), and knee rotation ($t = 0.479$; $p = 0.640$). Means, standard deviations, and effect sizes are reported in Table 7.

Peak Joint Angles During Loading Phase

Paired-samples t-tests were conducted to compare peak joint angles during the loading phase between the pre-fatigue and post-fatigue conditions. There was no significant difference between pre-fatigue and post-fatigue peak joint angles during the loading phase for hip flexion ($t = -1.461$; $p = 0.168$), hip adduction ($t = 0.510$; $p = 0.619$), hip abduction ($t = -0.379$; $p = 0.711$), hip external rotation ($t = 0.277$; $p = 0.786$), hip internal rotation ($t=0.362$; $p = 0.723$), knee flexion ($t = 1.131$; $p = 0.278$), knee valgus ($t = 0.413$; $p = 0.686$), knee varus ($t = 0.601$; $p = 0.558$), knee internal rotation ($t = 0.611$; $p = 0.552$), and knee external rotation ($t = -0.468$; $p = 0.648$). Means, standard deviations, and effect sizes are reported in Table 8.

Joint Displacement During Loading Phase

Paired-samples t-tests were conducted to compare joint displacement during the loading phase between the pre-fatigue and post-fatigue conditions. There was a significant difference in hip flexion displacement during the loading phase between the pre-fatigue and post-fatigue conditions ($t = 2.231$, $p = 0.044$) as hip flexion displacement significantly increased from pre-fatigue to post-fatigue (Figure 2). There was no significant difference between pre-fatigue and post-fatigue joint displacement during the loading phase for hip adduction ($t = 1.126$; $p = 0.281$), hip abduction ($t = 0.645$; $p = 0.530$), hip internal rotation ($t = 1.526$; $p = 0.151$), hip external rotation ($t = 0.568$; $p = 0.580$), knee flexion ($t = 0.034$; $p = 0.973$), knee valgus ($t = 0.196$; $p = 0.848$), knee internal rotation ($t = 0.070$; $p = 0.945$), and knee external rotation ($t = -1.206$; $p = 0.249$). Means, standard deviations, and effect sizes are reported in Table 9.

Peak Kinetics During Loading

Paired-samples t-tests were conducted to compare external joint moments, proximal anterior tibial shear force (ATSF) and vertical ground reaction force (VGRF) during the loading phase between the pre-fatigue and post-fatigue conditions. External hip flexion moment during the loading phase between the pre-fatigue and post-fatigue conditions approached significance ($t = 2.141$; $p = 0.052$) (Figure 3). There was no significant difference between pre-fatigue and post-fatigue peak kinetics during the loading phase for hip extension moment ($t = 0.991$; $p = 0.340$), hip adduction moment ($t = 0.872$; $p = 0.399$), hip abduction moment ($t = -0.951$; $p = 0.359$), hip internal rotation moment ($t = -0.883$; $p = 0.393$), hip external rotation moment ($t = 0.568$; $p = 0.580$), knee flexion moment ($t = -1.095$; $p = 0.293$), knee extension moment ($t = 0.442$; $p = 0.666$), knee valgus moment (t = -0.221; p = 0.829), knee varus moment (t = 1.266; p = 0.228), knee internal rotation moment (t = 0.616; p = 0.549), knee external rotation moment (t = -0.540; p = 0.598), proximal ATSF (t = 0.956; p = 0.357), and VGRF (t = -0.837; p = 0.418). Means, standard deviations, and effect sizes are reported in Table 10.

Postural Stability

Paired-samples t-tests were conducted to compare COP velocity and COP sway path between the pre-fatigue and post-fatigue conditions. There was a significant difference in COP velocity and COP sway path between the pre-fatigue and post-fatigue conditions (t = -3.947; p = 0.002 and t = -3.925; p = 0.002 respectfully) as COP velocity and COP sway path significantly increased from pre-fatigue to post-fatigue (Figure 4,5). Means, standard deviations, and effect sizes are reported in Table 11.

DISCUSSION

The results of this study indicate that in the fatigue condition, female ACLR participants exhibited a significant increase in COP path and COP velocity, indicating poorer postural stability. Participants also had a significant decrease in hip angle at IC, significantly greater hip flexion displacement and greater internal hip flexion moment during the loading phase. Deficits in postural stability have been a suggested risk factor for sustaining an ACL injury (Corbeil, Blouin et al. 2003; Gribble and Hertel 2004; Yaggie 2004; McLean and Samorezov 2009; Zouita Ben Moussa, Zouita et al. 2009). Decrease in postural stability is associated with altered kinematics at the hip and ankle, which would agree with our findings of a significant decrease in hip flexion angle at IC, larger hip flexion displacement, and greater external hip flexion moment during the loading phase (Corbeil, Blouin et al. 2003; Gribble and Hertel 2004; Wilkins, Valovich McLeod et al. 2004; Benjaminse, Habu et al. 2008; McLean and Samorezov 2009; Paterno, Schmitt et al. 2010; Webster and Gribble 2010). It has also been shown that altered biomechanics at the hip indicate change in trunk stability, which is an indicator of decreased postural control and are identified as risk factors for ACL injury (Salmon, Russell et al. 2005; Hewett, Torg et al. 2009; McLean and Samorezov 2009; Webster and Gribble 2010; Delahunt, Prendiville et al. 2012)

While our study examined balance in an ACL injured population, another injured population that has been extensively researched in regard to balance are individuals with history of ankle injury(Gribble and Hertel 2004; Gribble, Hertel et al. 2004; Wikstrom, Tillman et al. 2006; Gribble, Hertel et al. 2007; Gribble and Robinson 2009; de Vries, Kingma et al. 2010; Gribble, Taylor et al. 2010). While our findings of a decrease in postural control is similar in many of these studies, it is difficult to directly compare implications of injury and fatigue because the ankle and knee are vastly different joints. Isolated fatigue of the ankle musculature has been shown to decrease postural stability in healthy individuals, although isolated fatigue of lower extremity muscle groups are not thought to increase injury risk. This suggests that central mechanisms of fatigue may be responsible, as suboptimal neural drive from the central nervous system can produce inadequate muscular corrections to postural sway (Gandevia 2001; McLean and Samorezov 2009). Balance is a complex and integrated central processing of several sensory systems, so exact mechanisms of fatigue in our study are hard to delineate.

Our study did not investigate ankle biomechanics, but previous studies have suggested that after fatigue, the ankle adopts a stiffer landing strategy to maintain overall vertical stiffness of the limb (Padua, Arnold et al. 2006). This is perhaps to spare reliance of fatigued structures to stabilize the knee joint on less fatigued musculature. Changes in hip biomechanics along with changes in ankle biomechanics could indicate compensatory movement patterns to protect the knee joint when in a fatigued state (Padua, Arnold et al. 2006; Webster, Santamaria et al. 2012). This could be an explanation of why knee joint kinematics and kinetics were not significantly different pre to post fatigue. A limitation of this study is that muscle activation of the lower extremity musculature and ankle biomechanics were not measured, so recruitment patterns indicating compensatory biomechanics cannot be directly inferred.

Participants had a significant decrease in postural stability as demonstrated by the significantly higher COP velocity and longer COP path after fatigue (Figures 4, 5), suggesting that when females with history of ACLR are fatigued they have less postural stability. Several studies support the notion of deficits in postural stability after fatigue in healthy individuals (Corbeil, Blouin et al. 2003; Gribble and Hertel 2004; Wilkins, Valovich McLeod et al. 2004; Yaggie 2004). Non-fatigued individuals with history of ACLR also exhibit deficits in postural control (Paterno, Schmitt et al. 2010; Webster, Santamaria et al. 2012). Poor postural control has also been suggested as a risk factor for subsequent ACL injury (Paterno, Schmitt et al. 2010). In our study, assuming that ACLR individuals already possess poorer postural control, the effect of fatigue may be compounded. This is potentially particularly troubling for ACLR individuals, as this added decrease to postural control likely contributes to their increased susceptibility to incur a second ACL injury (Paterno, Schmitt et al. 2010; Paterno, Rauh et al. 2012).

The effect of fatigue on balance in healthy subjects has been widely investigated. Research suggests that fatigue has a greater effect on the muscular component of postural control than the sensory system, or vision (Corbeil, Blouin et al. 2003). Performance of healthy subjects on the Balance Error Scoring System, a clinical tool used to assess postural control, has shown to be negatively affected by fatigue (Wilkins, Valovich McLeod et al. 2004). The frequency of muscular corrections for changes in sway greatly increases post fatigue, with changes in sensory input occurring at the peripheral level (Corbeil, Blouin et al. 2003). If muscular corrections become more numerous, it can be interpreted that these larger and faster excursions make the individual less stable, and less likely to correct biomechanical deviations that may put increased strain on the ACL (Hirokawa, Solomonow et al. 1992; Markolf, Burchfield et al. 1995). This agrees with our finding of significant increases in COP velocity and COP area, indicating decrease in postural control after fatigue. Fatigue in the lower extremity can affect postural stability greater the more proximal the fatigued muscle groups exist (Gribble and Hertel 2004). Fatigue at the hip and knee affects medial and lateral postural stability more than localized fatigue at the ankle in static stance (Gribble and Hertel 2004). This could be because the muscles at the hip and knee are much larger than at the ankle, and are less able to produce finer adjustments in posture because of an increased recruitment of motor units to maintain force output when fatigued (Gribble and Hertel 2004). If our fatigue protocol did indeed fatigue the hip musculature more so than the knee musculature, then the increases in COP velocity and COP path could be due to the hip musculature not being able to make the appropriate postural adjustments to maintain postural stability. If this is true, hip muscular fatigue may account for greater changes in postural stability than isolated fatigue of the knee musculature. Our findings would then agree with Gribble 2004 study on isolated muscle fatigue and balance, that fatigue in more proximal muscle groups having a greater effect on postural stability. Our findings of significant change in hip flexion at IC and hip joint displacement could also indicate a poorer neuromuscular control at the hip, which could be due to increased fatigue in the muscle group.

Our sample was heterogeneous in that many participants had concomitant ligament and meniscal pathology with the original ACL injury, but we believe that our sample mirrors prospective studies in which second ACL injury often accompanied injury to other knee structures(Paterno, Schmitt et al. 2010; Paterno, Rauh et al. 2012). Our sample was also similar in that 71% represented a non-contact mechanism of injury, which was similarly reported in other epidemiological studies (Agel, Arendt et al. 2005). This study also utilized participants that were similar in years post ACLR as other descriptive ACL studies (Paterno, Ford et al. 2007; Shelbourne, Gray et al. 2009; Paterno, Schmitt et al. 2010).

Limitations of this study were largely due to small sample size, as well as the heterogeneity of the participant's knee injury history. We only collected unilateral data, so any correlation or differences in contralateral limb kinematics and kinetics were unknown. Also, because data were only collected from female ACLR individuals, it is unknown if the effect of fatigue would cause similar changes to hip biomechanics and postural sway in healthy individuals. All COP values are an approximation, and it is inferred that this correlates with deficits of trunk and postural stability. Our fatigue protocol consisted of a stationary squatting task, which may have fatigued the hip extensors but did not fatigue the musculature effecting the knee to the same extent. This could account for the lack of significant changes in frontal and transverse plane biomechanics at the knee. Another limitation is that we did not collect muscle activation during the fatigue protocol, so differences in muscle recruitment and reliance between the hip and knee musculature cannot be directly inferred.

Further research on the effect of fatigue on ACLR individuals could include collecting bilateral data for a jump-landing task to assess for asymmetries in hip and knee biomechanics. Also including data on ankle biomechanics could be useful in developing a biomechanical profile of ACLR individuals. Use of a control group to investigate group interaction pre and post fatigue would also be helpful in comparing ACLR individuals to a healthy population. Clinical implications for a decrease in postural stability could be addressed by adding balance training in a fatigued state for ACLR rehabilitation protocol.

CONCLUSION

Results from this study indicate that female ACLR individuals have significantly greater COP velocity and COP area after fatigue. These results suggest that when female ACLR individuals are fatigued, they have poorer postural stability, which increases their risk of second ACL injury. Central mechanisms of fatigue may be responsible for injury as they have been suggested to produce deficits in postural control and have been linked to lower extremity injury history (McLean and Samorezov 2009; Paterno, Schmitt et al.

2010). Future research should include bilateral jump landing data as well as a healthy control group to analyze a group by fatigue status effect.

Table 1. ACLR History

	Months from Injury to Surgery	Years Post-ACLR	Weeks From Surgery to post-ACLR Rehab	Years since RTP
MEAN	1.64	2.92	0.89	2.36
SD	1.28	1.41	1.67	1.52

Table 2. Graft Type (%)

Hamstring	0.64
Patellar Tendon	0.29
N/A	0.07

Table 3. Marx Scale*

	Running	Cutting	Deceleration	Pivoting
MEAN	3.07	2.86	2.86	2.93
SD	0.92	1.35	1.10	1.21

*Marx Scale

4 = 4 or more times in a week

3 = 2 or 3 times in a week

2 = one time in a week

1 = one time in a month

0 = less than one time in a month

Table 4. Tegner Activity Scale

	Before	Currently
MEAN	8.86	7.71
SD	1.10	1.59

Table 5. KOOS

MEAN	94.39
SD	2.86

Table 6. Demographics

	Age	Height (cm)	Weight (kg)
MEAN	19.64	163.52	62.60
SD	1.50	6.18	13.97

Table 7. Joint Angle at Initial Contact	**Pre-Fatigue Mean**	**SD**	**Post-Fatigue Mean**	**SD**	**P-Value**	**Effect Size**
Hip Flexion*	40.98	9.79	36.75	8.61	0.014	0.46
Hip Adduction	7.44	9.69	6.89	9.57	0.552	0.06
Hip Rotation	3.17	8.43	3.08	9.84	0.954	0.01
Knee Flexion	30.24	7.24	28.03	6.49	0.253	0.32
Knee Valgus	3.12	5.78	2.78	6.66	0.589	0.05
Knee Rotation	5.08	7.19	6.08	11.56	0.64	-0.11

Table 8. Peak Joint Angle During Loading	Pre-Fatigue		Post-Fatigue			
	Mean	**SD**	**Mean**	**SD**	**P-Value**	**Effect Size**
Hip Flexion	86.17	20.86	84.23	19.56	0.168	0.10
Hip Adduction	10.44	10.84	10.77	10.69	0.619	-0.03
Hip Abduction	5.06	10.18	4.81	9.62	0.711	0.03
Hip Internal Rotation	1.01	8.97	0.44	10.94	0.786	0.06
Hip External Rotation	16	12.07	15.47	14.78	0.723	0.04
Knee Flexion	103.15	17.45	100.87	14.21	0.278	0.14
Knee Valgus	10.09	9.51	9.49	10.04	0.688	0.06
Knee Varus	0.1	7.56	0.96	8.83	0.558	-0.10
Knee Internal Rotation	6.79	6.93	7.74	10.12	0.552	-0.11
Knee External Rotation	8.66	12.08	9.22	13.25	0.648	-0.04

Table 9. Joint Displacement During Loading	Pre-Fatigue		Post-Fatigue			
	Mean	**SD**	**Mean**	**SD**	**P-Value**	**Effect Size**
Hip Flexion*	45.19	14.1	47.48	14.21	0.044	-0.16
Hip Adduction	3	2.85	3.88	2.98	0.281	-0.30
Hip Abduction	2.38	1.97	2.08	2.07	0.53	0.15
Hip Internal Rotation	2.16	3.24	2.64	4.06	0.58	-0.13
Hip External Rotation	12.82	10.09	12.39	9.78	0.151	0.04
Knee Flexion	72.89	14.16	72.84	13.03	0.973	0.00
Knee Valgus	6.97	5.6	6.71	5.79	0.848	0.05
Knee Varus	3.22	3.98	3.74	5.11	0.655	-0.11
Knee Internal Rotation	1.71	2.78	1.66	2.8	0.249	0.02
Knee External Rotation	13.73	12.72	15.3	14.33	0.945	-0.12

Table 10. Peak Kinetics During Loading	Pre-Fatigue Mean	SD	Post-Fatigue Mean	SD	P-Value	Effect Size
Hip Extension	1.93	1.44	2.21	1.69	0.34	-0.18
Hip Flexion	1.66	0.68	1.91	0.62	0.052	-0.38
Hip Adduction	0.56	0.66	0.62	0.79	0.399	-0.08
Hip Abduction	1.03	0.8	1.15	1	0.359	-0.13
Hip Internal Rotation	0.31	0.29	0.28	0.32	0.393	0.10
Hip External Rotation	0.51	0.45	0.53	0.49	0.82	-0.04
Knee Extension	1.78	0.51	1.8	0.45	0.666	-0.04
Knee Flexion	0.8	0.14	0.13	0.23	0.293	3.62
Knee Valgus	0.48	0.37	0.5	0.44	0.829	-0.05
Knee Varus	0.34	0.23	0.39	0.34	0.228	-0.18
Knee Internal Rotation	0.54	0.46	0.57	0.5	0.549	-0.06
Knee External Rotation	0.23	0.29	0.24	0.32	0.598	-0.03
Proximal ATSF	8.18	2.16	7.91	1.67	0.357	0.14
VGRF	23.18	6.38	24.19	5.95	0.418	-0.16

Table 11. Postural Sway	**Pre-Fatigue**		**Post-Fatigue**			
	Mean	**SD**	**Mean**	**SD**	**P-Value**	**Effect Size**
COP Velocity*	5.18	0.96	6.2	1.72	0.002	-0.76
COP Sway Path*	102.54	19.36	124	34.51	0.002	-0.80

Figure 1.

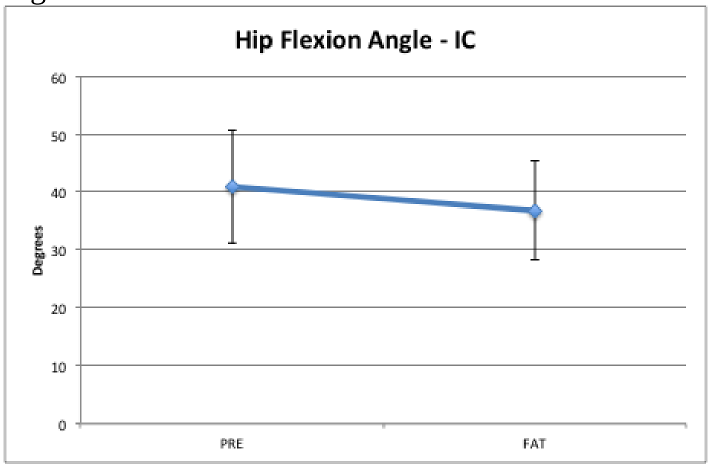


Figure 2.

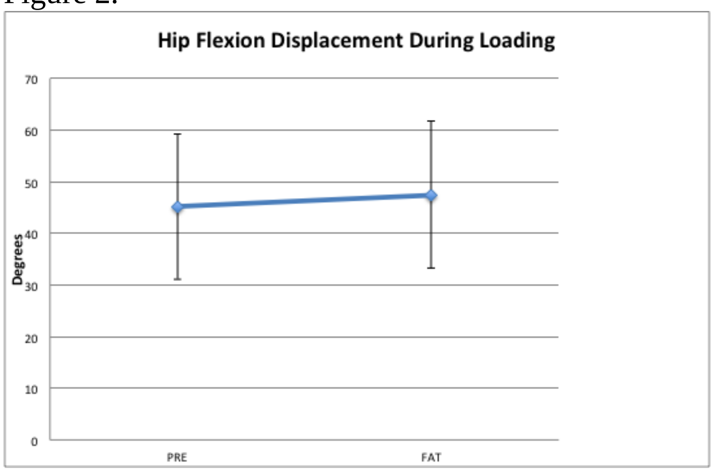


Figure 3.

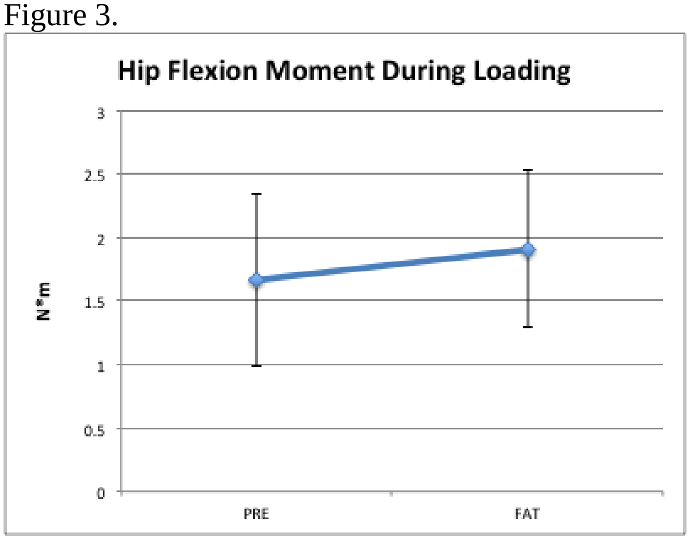


Figure 4.

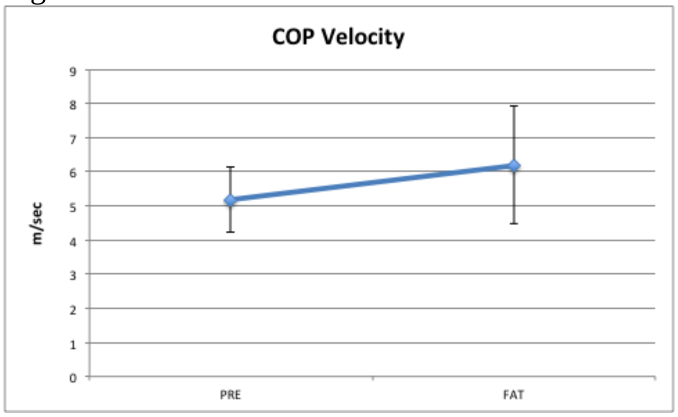
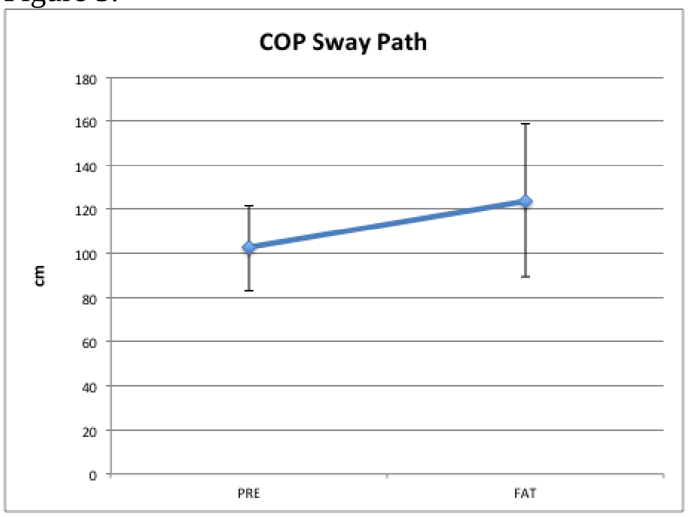


Figure 5.



References:

Agel, J., E. A. Arendt, et al. (2005). "Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review." Am J Sports Med **33**(4): 524-530.

Bell, A. L., D. R. Pedersen, et al. (1990). "A comparison of the accuracy of several hip center location prediction methods." Journal of biomechanics **23**(6): 617-621.

Benjaminse, A., A. Habu, et al. (2008). "Fatigue alters lower extremity kinematics during a single-leg stop-jump task." Knee Surg Sports Traumatol Arthrosc **16**(4): 400-407.

Borg, G. (1970). "Perceived exertion as an indicator of somatic stress." Scandinavian journal of rehabilitation medicine **2**(2): 92-98.

Borotikar, B. S., R. Newcomer, et al. (2008). "Combined effects of fatigue and decision making on female lower limb landing postures: central and peripheral contributions to ACL injury risk." Clinical biomechanics **23**(1): 81-92.

Chappell, J. D., D. C. Herman, et al. (2005). "Effect of fatigue on knee kinetics and kinematics in stop-jump tasks." Am J Sports Med **33**(7): 1022-1029.

Corbeil, P., J. S. Blouin, et al. (2003). "Perturbation of the postural control system induced by muscular fatigue." Gait Posture **18**(2): 92-100.

de Vries, J. S., I. Kingma, et al. (2010). "Difference in balance measures between patients with chronic ankle instability and patients after an acute ankle inversion trauma." Knee Surg Sports Traumatol Arthrosc **18**(5): 601-606.

Delahunt, E., A. Prendiville, et al. (2012). "Hip and knee joint kinematics during a diagonal jump landing in anterior cruciate ligament reconstructed females." Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology.

Gandevia, S. C. (2001). "Spinal and supraspinal factors in human muscle fatigue." Physiological reviews **81**(4): 1725-1789.

Gribble, P. A. and J. Hertel (2004). "Effect of hip and ankle muscle fatigue on unipedal postural control." J Electromyogr Kinesiol **14**(6): 641-646.

Gribble, P. A. and J. Hertel (2004). "Effect of lower-extremity muscle fatigue on postural control." Arch Phys Med Rehabil **85**(4): 589-592.

Gribble, P. A., J. Hertel, et al. (2007). "Chronic ankle instability and fatigue create proximal joint alterations during performance of the Star Excursion Balance Test." Int J Sports Med **28**(3): 236-242.

Gribble, P. A., J. Hertel, et al. (2004). "The Effects of Fatigue and Chronic Ankle Instability on Dynamic Postural Control." J Athl Train **39**(4): 321-329.

Gribble, P. A. and R. H. Robinson (2009). "Alterations in knee kinematics and dynamic stability associated with chronic ankle instability." J Athl Train **44**(4): 350-355.

Gribble, P. A., B. L. Taylor, et al. (2010). "Bracing does not improve dynamic stability in chronic ankle instability subjects." Phys Ther Sport **11**(1): 3-7.

Hambly, K. (2011). "The use of the Tegner Activity Scale for articular cartilage repair of the knee: a systematic review." Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA **19**(4): 604-614.

Hewett, T. E., J. S. Torg, et al. (2009). "Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and

knee abduction motion are combined components of the injury mechanism." Br J Sports Med **43**(6): 417-422.
Hirokawa, S., M. Solomonow, et al. (1992). "Anterior-posterior and rotational displacement of the tibia elicited by quadriceps contraction." The American journal of sports medicine **20**(3): 299-306.
Markolf, K. L., D. M. Burchfield, et al. (1995). "Combined knee loading states that generate high anterior cruciate ligament forces." Journal of orthopaedic research : official publication of the Orthopaedic Research Society **13**(6): 930-935.
Marx, R. G., T. J. Stump, et al. (2001). "Development and evaluation of an activity rating scale for disorders of the knee." The American journal of sports medicine **29**(2): 213-218.
McLean, S. G., R. E. Fellin, et al. (2007). "Impact of fatigue on gender-based high-risk landing strategies." Med Sci Sports Exerc **39**(3): 502-514.
McLean, S. G. and J. E. Samorezov (2009). "Fatigue-induced ACL injury risk stems from a degradation in central control." Med Sci Sports Exerc **41**(8): 1661-1672.
Olsen, O. E., G. Myklebust, et al. (2004). "Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis." Am J Sports Med **32**(4): 1002-1012.
Padua, D. A., B. L. Arnold, et al. (2006). "Fatigue, vertical leg stiffness, and stiffness control strategies in males and females." Journal of athletic training **41**(3): 294-304.
Padua, D. A., S. W. Marshall, et al. (2009). "The Landing Error Scoring System (LESS) Is a valid and reliable clinical assessment tool of jump-landing biomechanics: The JUMP-ACL study." Am J Sports Med **37**(10): 1996-2002.
Paterno, M. V., K. R. Ford, et al. (2007). "Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction." Clin J Sport Med **17**(4): 258-262.
Paterno, M. V., M. J. Rauh, et al. (2012). "Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport." Clin J Sport Med **22**(2): 116-121.
Paterno, M. V., L. C. Schmitt, et al. (2010). "Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport." Am J Sports Med **38**(10): 1968-1978.
Roos, E. M. and L. S. Lohmander (2003). "The Knee injury and Osteoarthritis Outcome Score (KOOS): from joint injury to osteoarthritis." Health and quality of life outcomes **1**: 64.
Salmon, L., V. Russell, et al. (2005). "Incidence and risk factors for graft rupture and contralateral rupture after anterior cruciate ligament reconstruction." Arthroscopy **21**(8): 948-957.
Shelbourne, K. D., T. Gray, et al. (2009). "Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft." Am J Sports Med **37**(2): 246-251.
Shephard, R. J. (1988). "PAR-Q, Canadian Home Fitness Test and exercise screening alternatives." Sports medicine **5**(3): 185-195.

Webster, K. A. and P. A. Gribble (2010). "Time to stabilization of anterior cruciate ligament-reconstructed versus healthy knees in National Collegiate Athletic Association Division I female athletes." J Athl Train **45**(6): 580-585.

Webster, K. E., L. J. Santamaria, et al. (2012). "Effect of Fatigue on Landing Biomechanics after Anterior Cruciate Ligament Reconstruction Surgery." American Journal of Sports Medicine.

Wikstrom, E. A., M. D. Tillman, et al. (2006). "Measurement and evaluation of dynamic joint stability of the knee and ankle after injury." Sports Med **36**(5): 393-410.

Wilkins, J. C., T. C. Valovich McLeod, et al. (2004). "Performance on the Balance Error Scoring System Decreases After Fatigue." J Athl Train **39**(2): 156-161.

Wright, R. W., W. R. Dunn, et al. (2007). "Risk of tearing the intact anterior cruciate ligament in the contralateral knee and rupturing the anterior cruciate ligament graft during the first 2 years after anterior cruciate ligament reconstruction: a prospective MOON cohort study." Am J Sports Med **35**(7): 1131-1134.

Yaggie, J. A., W.J (2004). "Effects of Lower Extremity Fatigue on Indices of Balance." J Sport Rehabil **13**: 312-322.

Zouita Ben Moussa, A., S. Zouita, et al. (2009). "Single-leg assessment of postural stability and knee functional outcome two years after anterior cruciate ligament reconstruction." Ann Phys Rehabil Med **52**(6): 475-484.