AN ABSTRACT OF THE DISSERTATION OF

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Although female athletes are at greater risk of non-contact knee injuries than men, the factors that contribute to these injuries are not well understood. One important question is whether intense exercise influences the risk of knee injury, both acutely and over the following days. The purpose of this study was thus to evaluate the acute and delayed effects of an intense bout of exercise on risk factors associated with knee injury in women and men.

Fifteen each of healthy young women and men performed two testing sessions, 44-52 hours apart. In each session, biomechanical data were collected during execution of sets of 10 drop vertical jumps. An initial set of drop vertical jumps was compared to a set performed immediately after an intense exercise bout on the first day and to a set performed on the second day to determine the acute and delayed effects of fatigue, respectively. A two-way repeated measures ANOVA was used to determine the effect of the exercise bout on risk factors associated with knee injury during the jump task in women and men.

Intense exercise had immediate effects on joint kinematics and kinetics, patterns of joint motion and moments, and the variability of joint couplings. The acute

kinematic and kinetic changes at the hip and ankle were consistent with compensatory strategies, whereas changes at the knee were consistent with an increased risk of injury. The same appeared to be true for the patterns of joint motions and moments. Acute changes in the variability of inter- and intra-limb joint couplings were also consistent with compensatory modifications of lower limb biomechanics. Delayed effects were limited to patterns of joint motion and moments, and reflected joint-dependent combinations of compensatory strategies or mechanical changes that could increase knee injury risk. Although intense exercise had acute and prolonged effects on several biomechanical variables, none of the effects depended on the sex of participants.

These results indicate that intense exercise has immediate and prolonged effects on landing biomechanics, independent of sex. While the majority of changes point to a compensatory strategy, a few were consistent with increased risk of knee injury.

Acute and Delayed Effects of an Exhaustive Bout of Exercise on Landing Biomechanics in Women and Men

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Kristof Kipp, Author

CONTRIBUTIONS OF AUTHORS

Dr. Pavol contributed to the study design and assisted with data collection, development of data analysis programs, statistical analysis, interpretation, and writing. Dr. Hoffman contributed to the interpretation and writing.

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Acute and Delayed Effects of an Exhaustive Bout of Exercise on Landing Biomechanics in Women and Men

1. Introduction

Female participation in both college and recreational sports has steadily grown year after year. Coincident with the growth in participation is the occurrence of certain injuries. Most notably, female athletes are two to eight times more likely to sustain a non-contact ACL injury than their male counterparts (Griffin et al. 2006). It is reported that 40,000 – 175,000 non-contact ACL injuries occur each year (Hootman et al. 2007). Although the scientific community has paid a tremendous amount of attention to this type of injury, the rates of occurrence have steadily increased over the last 15 years (Hootman et al. 2007). While an injury to the ACL is not the most frequent type of lower extremity injury, it is among the most debilitating (Hootman et al. 2007). Each year approximately 100,000 ACL reconstructions are performed and a conservative estimate of the costs of a surgical reconstruction is upwards of $25,000 (Griffin et al. 2006; Hewett et al. 2006). Further, long-term, consequences of ACL injury include degenerative joint disease due to osteoarthritis (Griffin et al. 2006). The financial impact of the associated long-term treatments has yet to be determined, but only compound the associated health care costs of surgery and rehabilitation.

The factors that place women at greater risk of ACL injury than men are not completely understood. While it has been hypothesized that the observed sex bias is due to a combination of factors, including anatomical and hormonal, it appears that biomechanical and neuromuscular factors are the most important reason for the differing ACL injury rates in women and men (Griffin et al. 2006; Hewett et al. 2006).

More specifically, differences in muscular recruitment patterns, stiffness, and movement patterns have been implicated to play a role. Together, these biomechanical and neuromuscular factors are responsible for the dynamic control of joint loading and joint stability during athletic tasks.

Women perform dynamic tasks with different movement patterns than men (Decker et al. 2003b; Ford et al. 2005; Huston et al. 2001). During the execution of dynamic tasks such as landing and cutting, women typically exhibit a more erect hip and knee posture in the sagittal plane, but display greater knee frontal-plane motions than men (Decker et al. 2003a; Ford et al. 2005; Kernozek et al. 2007). Women also experience different joint loadings than men (Kernozek et al. 2005). Most notably, women exhibit significantly greater anterior shear forces at the knee, greater internal knee extension moments and greater external abduction moments at the knee than men (Chappell et al. 2005; Hewett et al. 1996). Since prospective evidence shows that the peak external knee abduction moment is a significant predictor of risk of ACL injury (Hewett et al. 2005), these sex-differences in movement patterns appear to predispose women to a greater risk of injury. While training programs have attempted to alter landing mechanics in women such as to ameliorate the presence of these risk factors, the disparity in ACL injury rates between women and men remains (Hootman et al. 2007). This suggests that factors other than biomechanical and neuromuscular control may also be involved. One additional factor that likely influences joint control and, hence, risk of injury, is acute, fatiguing exercise.

Epidemiological reports show that during athletic events, a large percentage of injuries occur either towards the end of the first half or towards the end of game-play

(Hawkins and Fuller 1999; Hawkins et al. 2001). Neuromuscular fatigue, reflected in a loss of force- or power-generating capacity, negatively influences dynamic muscle control of the knee and compromises dynamic joint stability (Wojtys et al. 1996). Exhaustive exercise may precipitate greater risk of knee injury through exposure to harmful joint positions and loadings, such as increased frontal-plane knee excursions and increased external knee valgus and rotation loadings (Chappell et al. 2005; Kernozek et al. 2007; McLean et al. 2007). Further, these changes appear to be more pronounced in women (McLean et al. 2007). Collectively, these acute fatigue-related changes result in less safe positions and loading of the lower extremity during movement, hence potentially greater risk of ACL injury, particularly in women.

An intense, fatiguing bout of exercise can also have prolonged neuromuscular effects, as recovery from this bout is a delayed process. The mechanical consequences of a fatiguing bout of exercise, such as decreased joint stiffness and compromised muscular recruitment patterns, can last for several days (Clarkson 1997; Komi 2000). If the residual effects of a single bout of exercise remain visible, it may be that the elevated risks of injury remain as well. While other studies (Avela and Komi 1998; Kuitunen et al. 2002) have investigated the acute and prolonged effects of intense exercise on jumping and landing mechanics, no study has deliberately examined these changes with regard to risk of injury. Since athletes in certain sports, such as intercollegiate basketball, soccer, and volleyball, often play multiple games within a short period of time, the establishment of a time course of recovery for risk factors for knee injury would be of great significance. Additionally, these athletes may benefit

from carefully planned programs that aim to minimize long-lasting changes caused by intense exercise.

As a step towards understanding the factors that contribute to ACL injury, the objective of this dissertation was to examine the acute and prolonged effects of a fatiguing bout of exercise on risk factors associated with non-contact knee injury during landing in women and men. The central hypothesis was that adverse changes in landing mechanics would continue to be exhibited two days after an initial fatiguing bout of exercise, and that women would exhibit these persistent changes to greater extent than men. The rationale was that understanding the role of fatiguing exercise in precipitating knee injuries represents an important step in the development of effective injury prevention strategies.

The specific aim of this dissertation was to: Determine the extent to which an intense bout of exercise has immediate and prolonged effects on landing biomechanics in women and men. The hypotheses were that: 1) an intense bout of exercise would acutely influence landing mechanics, patterns of motion, and joint coordination in a manner consistent with increased risk of knee injury; 2) the effects would still be observable two days later; and 3) the effects would differ between women and men. While each of the manuscripts presented in this dissertation addresses the specific aim, they differ in the way they address the first hypothesis. Each manuscript makes a unique contribution in that each addresses the immediate and prolonged changes of an intense bout of exercise from a different perspective. The first manuscript focuses on analyzing traditional biomechanical variables that include peak joint angles and moments during landing, as well as joint angles at touchdown. The second manuscript

analyzes differences in patterns of joint motion and joint moments during landing through the use of principal component analysis. Finally, the third manuscript focuses on examining the variability of intra- and inter-joint coordination through the use of a vector-coding method. Together, these manuscripts form a comprehensive examination of the acute and prolonged effects of a bout of fatiguing exercise on landing biomechanics in women and men.

2. Acute and prolonged effects of fatiguing exercise on landing mechanics in women and men

2.1 Introduction

Between 80,000 – 250,000 anterior cruciate ligament (ACL) injuries occur each year and approximately 50-70% of these injuries occur without contact from another player (Hootman et al. 2007). Although non-contact ACL injuries are not among the most frequent types of lower extremity injuries, they are among the most debilitating and thus carry significant consequences (Hootman et al. 2007). Each year, approximately 100,000 ACL's are surgically reconstructed at an annual estimated cost of $ 2.5 billion (Griffin et al. 2006; Hewett et al. 2006). Further, ACL injury early in adulthood may lead to premature degenerative joint disease due to osteoarthritis, which, in the long-term, would only compound the aforementioned cost (Griffin et al. 2006). While it has been hypothesized that ACL injuries occur due to a combination of factors, the associated risk factors are not completely understood. One factor that could potentially contribute to the risk of ACL injuries is exercise-induced neuromuscular fatigue.

Epidemiological reports show that, during athletic events, a large percentage of all injuries occur either towards the end of the first half or towards the end of game-play (Hawkins and Fuller 1999; Hawkins et al. 2001). Fatiguing exercise appears to have acute deleterious effects on landing biomechanics in that it precipitates exposure to joint positions and loadings that may place the ACL at greater risk of injury (Chappell et al. 2005; Kernozek et al. 2007; McLean et al. 2007). Exercise-induced changes in joint positions during landing can include increased frontal- and

transverse-plane angles, greater external abduction loading at the knee, and a decreased knee flexion angle at the time of peak anterior tibial shear (Chappell et al. 2005; McLean et al. 2007). Since increased knee joint abduction angles and frontal-plane loadings are associated with risk of knee injury (Hewett et al. 2005), exercise-induced changes in movement patterns and joint loading may collectively affect risk factors associated with ACL injury.

In addition to immediate biomechanical and neuromuscular changes, very intense exercise is associated with a delayed recovery process and may lead to prolonged changes in muscle and joint function (Clarkson 1997; Komi 2000). These prolonged effects are particularly prominent when the exercise involves repeated lengthening actions or repeated stretch-shortening cycles that are common during jumping and various other athletic tasks (Avela and Komi 1998; Kuitunen et al. 2002). If the residual effects of a single bout of exercise persist for several days, landing biomechanics may remain affected as well. While studies show that exercise can have acute effects on risk factors associated with ACL injury, no such studies to date have attempted to identify potential negative consequences of the prolonged effects that are known to follow a single bout of intense exercise. Since many collegiate and international sports play multiple games within a short period of time, such as in conference or tournament play, the establishment of a time course of recovery for risk factors associated with non-contact knee injury would be of great significance. Additionally, athletes in these sports may benefit from carefully planned programs that aim to minimize prolonged changes caused by intense exercise.

Of particular concern is whether fatiguing exercise might have a greater effect on risk factors for ACL injury in women than in men. Women appear two to eight times more likely to sustain a non-contact ACL injury than men when matched for sport and activity levels (Griffin et al. 2006). While it is hypothesized that the sex bias in these injury rates is due to a combination of factors, biomechanical and neuromuscular factors are generally thought to be the greatest contributors to this disparity (Griffin et al. 2006; Hewett et al. 2006). During the execution of dynamic tasks such as landing and cutting, females typically exhibit less hip and knee flexion, but greater knee joint excursions in the frontal plane, along with greater anterior tibial shear forces and greater internal knee extension moments and external abduction moments (Chappell et al. 2002; Decker et al. 2003; Ford et al. 2005; Huston et al. 2001; Kernozek et al. 2005; Malinzak et al. 2001). Collectively, these sex-differences in movement patterns and joint loadings may increase ACL loading and place females at a higher risk of injury. Effects of neuromuscular fatigue could potentially add to these risks (Chappell et al. 2005; Kernozek et al. 2007; McLean et al. 2007).

While prior research indicates that intense exercise has immediate deleterious effects on landing mechanics that are consistent with increased ACL loading (Chappell et al. 2005; Kernozek et al. 2007; McLean et al. 2007), to date, no study has examined whether a bout of fatiguing exercise affects landing mechanics over subsequent days. Since women are more likely to incur ACL injuries, possible sex-differences in the effects of fatiguing exercise are of particular interest. Thus, the purposes of this study were to determine if a bout of fatiguing exercise would acutely influence landing mechanics in a way that is consistent with increased ACL loading,

whether any effects would remain observable two days after the initial bout of exercise, and whether these effects would differ between sexes.

2.2 Materials and Methods

In order to detect moderate within-group and between-group differences with a statistical power of at least .80 at $\alpha < .05$, a minimum of 10 subjects per group were required (Kirk 1972). Fifteen healthy women (mean ±SD age 25.5±4.2 yrs; height: 1.67±0.06 m; mass: 61.5±6.0 kg) and 15 healthy men (age: 21.9±3.4 yrs; height: 1.83±0.09 m; mass: 81.1±6.1 kg) participated in this study. Participants were required to have participated in activities that required repeated jumping efforts or leg resistance/power training for the prior month on a twice-weekly or greater basis. Exclusion criteria included a self-reported history of serious lower extremity injury, chronic musculoskeletal disease, or neurological illness that would have limited their full participation. Participants read and signed an informed consent form that was approved by the University Institutional Review Board. Participants were asked to refrain from moderate-to-intense exercise for 48 hours prior to and during their participation in this study.

In order to determine the acute and prolonged effects of exercise on landing biomechanics, participants reported to our lab for two testing sessions 44-52 hours apart. Biomechanical data were collected during the landing phase of a participant's execution of drop vertical jumps (DVJ). We compared data from three sets of 10 DVJ of interest: an initial set of jumps on the first day ("pre" condition), a set performed at the end of a fatiguing exercise protocol on the first day ("post" condition), and a set performed on the second day of testing ("48hr" condition). Pre- to post and pre- to 48hr comparisons were made to assess the immediate and prolonged effects of exercise on landing mechanics, respectively.

Thirty-three reflective markers were attached to anatomical landmarks on the participants' skin and clothing. Participants then performed a set of exercises that served as practice and warm-up for the exercise protocol. The warm-up exercises included 10 squats, 10 lunges (five per leg, in an alternating manner), five vertical jumps, and five DVJ. These exercises were performed with no added weight. Following the exercises, the participants were guided through a sequence of six stretching exercises that encompassed the major muscle groups of the lower limbs (i.e., calves, hamstrings, quadriceps, hip flexors, hip adductors, and hip abductors). Each stretch was performed bilaterally and held for 30 seconds.

After the warm-up and stretching exercises, participants performed a test of lower extremity muscle power on a Bassey power rig (University of Nottingham, Nottingham, U.K.). Participants performed three unilateral warm-up trials with each leg at increasing levels of effort. They then performed seven maximal trials with each leg in which they were instructed to push as hard and as fast as possible. Trials alternated between legs. Peak power for each maximal trial was recorded, the highest and lowest values for each leg were excluded, and the remaining values were averaged across the left and right legs and normalized to body mass for analysis.

After the power testing, each participant performed a set of 10 DVJ off a 30.5 cm-high box, this set representing the "pre" condition. For the execution of the DVJ, participants were asked to step off of the box, land with both legs simultaneously, and rebound immediately into a maximal vertical jump. The step-off leg alternated between trials. During each trial, motion capture data were collected with a nine-camera motion capture system (Vicon, Lake Forest, CA) at a rate of 120 Hz. Bilateral

ground reaction forces during landing were sampled at 1080 Hz with two force plates (model 6040, Bertec, Columbus, OH). Jump height during each DVJ was determined as the maximum height of the pelvis relative to its previously-determined average height during standing, where pelvis height was found by averaging the heights of four markers attached to the anterior and posterior iliac spines.

After the initial DVJ testing, participants moved on to the exercise protocol, which consisted of repeated sets of the same exercises that were done in the warm-up but with twice the repetitions and greater intensity. Each set consisted of 20 squats, 20 lunges (10 per leg, in an alternating manner), 10 vertical jumps, and 10 DVJ from a 30.5 cm-high box, in that order. Participants were asked to execute the first two exercises as fast as safely possible and, in the case of the jumps, to jump as high as possible. Motion capture and force plate data were collected during the DVJ. Upon completing each set of exercises, participants received 45 seconds of rest before continuing. All participants performed at least two sets of the exercise protocol, after which they continued until any of the following occurred: a) the average jump height during the DVJ trials at the end of a set was less than 90% of the average jump height during the "pre" condition, b) a participant indicated that he or she was unwilling or unable to safely continue, or c) an investigator deemed that the participant was unable to safely continue. The 10 DVJ performed at the end of the last set of exercises represented the "post" condition. Immediately following the execution of the last 10 DVJ, participants repeated the leg power testing on the Bassey power rig. During the "48hr" condition, participants completed the same warm-up, leg power testing, and initial set of 10 DVJ as on the first day. At the beginning of each of the testing

sessions, participants were also asked to rate their perceived level of leg muscle soreness on a 10 cm analog scale, where 0 represented no pain and 10 represented the worst pain ever experienced.

For analysis, the lower extremity was modeled as a 3-dimensional system of rigid links. Three-dimensional body segment orientations and joint center locations during each DVJ were reconstructed from the trajectories of the reflective markers that were attached to participants. Marker trajectories and force plate data were low-pass filtered with a 4th-order, zero-lag Butterworth filter at 15 Hz. Joint angles of the hip, knee, and ankle were then computed in three dimensions based on a Cardan rotation sequence of flexion/extension, abduction/adduction, and internal/external rotation of the distal segment. Body segment masses, center of mass locations, and mass moments of inertia were calculated from measured anthropometrics and published sex-dependent relationships (de Leva 1996). Resultant internal joint moments acting at the hip, knee, and ankle were then calculated with a three-dimensional inverse dynamics approach (BodyBuilder, Vicon, Lake Forest, CA), expressed about the Cardan rotation axes, and normalized to participant mass and height. Variables extracted for each joint and each direction of joint rotation were the angles at touchdown and the peak values of the angles and moments during the landing period. Touchdown was defined as the instant when the vertical component of the ground reaction force exceeded 10 N, while the landing period was from touchdown to either maximum knee or hip flexion, whichever occurred later. The extracted variables were averaged between limbs and across trials within a set of DVJ for the statistical analyses.

Kinematic and kinetic variables from three sets of DVJ trials were analyzed: the first and last sets from the first testing session and the set from the second session, which represented the pre, post, and 48hr conditions, respectively. Average DVJ height, leg power, and muscle soreness were also analyzed. A general linear model analysis of variance was used to test for differences in joint angles at touchdown, peak joint angles, peak joint moments, DVJ height, and leg power. The model consisted of a 3 x 2 (condition x sex) analysis to test for within-subject differences (condition) and for between-subject (sex) differences. Within-subject differences (i.e. across conditions) were treated as repeated measures. Assumptions of the test statistic were verified and adjusted with the Greenhouse-Geisser method where appropriate. Comparisons between muscle soreness from pre to 48hr in women and men were made with a 2x2 (condition x sex) general linear model analysis of variance with repeated measures. The standard of proof to show statistical significance was set at a level of $\alpha < .05$. Paired t-tests with appropriate Bonferroni adjustments were used in the case of multiple comparisons between conditions during post hoc testing. In the absence of a significant interaction effect, data were pooled across sexes for post hoc testing. All statistical analyses were performed using SPSS version 17.0 (SPSS, Chicago, IL).

2.3 Results

Women and men completed 4.9±3.6 (range 2-17) and 2.3±0.6 (range 2-4) rounds of the fatiguing exercise, respectively. The exercise protocol significantly affected DVJ height ($p<.004$) and lower extremity power ($p<.005$) (Table 2.1). As a result, jump height during the DVJ decreased significantly in both women and men from pre- to post-exercise ($p<.001$ for each sex), but remained decreased at 48hr only in men ($p<.001$). Jump height during the DVJ was significantly lower in women than in men for all comparisons ($p<.001$). Peak normalized lower extremity power also decreased significantly pre- to post-exercise ($p=.005$) in both women and men, but returned to pre-exercise levels by the 48hr testing session. Normalized lower extremity power was significantly lower in women than in men ($p<.001$), independent of condition. Muscle soreness increased significantly ($p<.001$) between the pre and 48hr testing session, independent of sex.

The joint angles at the instant of touchdown were influenced by condition and sex (Table 2.2). The acute effects of exercise led both women and men to land with reduced knee flexion ($p<.001$) and increased ankle plantarflexion ($p=.002$) post-exercise. However, by the 48hr condition, neither these nor any other angles at touchdown differed from pre-exercise ($p>0.05$). Independent of condition, women exhibited smaller hip abduction ($p=.011$) and knee flexion angles ($p=.045$) than men at touchdown. A significant condition-by-sex interaction was observed for knee adduction ($p=.047$) but post-hoc analysis was unable to confirm significant differences.

Peak landing phase kinematics were influenced by condition and sex (Table 2.3); however, there was no interaction between the effects of condition and sex ($p>.05$). Specifically, immediately post-exercise, both women and men showed greater hip abduction during landing ($p=.005$). No prolonged effects of exercise were found on peak joint angles during the 48hr testing session. Women displayed greater peak hip flexion ($p=.007$) and peak knee abduction angles ($p=.032$), but smaller hip abduction angles ($p=.015$) than men, independent of condition.

Peak landing phase kinetics were influenced by condition and sex (Table 2.4). However, there was no interaction between the effects of condition and sex ($p>0.05$). Exercise affected peak landing kinetics only immediately after exercise. Post-exercise, women and men landed with smaller hip extension ($p=.005$), hip external rotation ($p=.004$), and knee extension moments ($p<.001$), but with greater hip abduction ($p=.008$), hip internal rotation ($p<.001$), knee abduction ($p<.005$), and knee external rotation moments ($p<.009$). No prolonged effects of exercise were found on peak joint kinetics during the 48hr follow-up session. Women displayed smaller peak hip extension ($p=.032$) and knee adduction moments ($p=.016$) than men, independent of condition.

2.4 Discussion

Previous research indicates that intense exercise has immediate deleterious effects on landing mechanics that are consistent with greater ACL loading (Chappell et al. 2005; Kernozek et al. 2007; McLean et al. 2007). However, to date, no such study has examined whether a bout of fatiguing exercise affects landing mechanics over subsequent days. The purpose of this study was to determine if a single bout of fatiguing exercise would lead to acute and prolonged changes in landing mechanics in women and men. We measured landing mechanics before, immediately after, and 48 hours after participants performed a bout of exercise. Participants experienced an acute decrease in drop leg power and in vertical jump height. Together, these measures respectively indicate that isolated and functional lower extremity performance was compromised post-exercise. Muscle power recovered by the second day of testing in both women and men. However, vertical jump height recovered only in women, while muscle soreness increased significantly in both sexes in the 48 hours between the first and second day of testing, suggesting that some compromise was still present at 48 hours.

Similar to other studies, we found that women and men display differences in landing mechanics (Decker et al. 2003; Ford et al. 2005; Huston et al. 2001; Kernozek et al. 2005). The observed sex differences in landing kinematics and kinetics were limited to the hip and knee joint in the sagittal and frontal planes. More specifically, at touchdown, women landed with less knee flexion and hip abduction than men. After touchdown, women proceeded to go into greater hip flexion and greater knee abduction than men. An increase in hip flexion, as experienced by the women in our

study, has recently been implicated in knee injury (Boden et al. 2009). In addition, the smaller hip abduction and greater knee abduction angles displayed by the women suggest a more dynamically abducted knee position during landing, which is consistent with increased risk of non-contact ACL injury (Hewett et al. 2005). Women also displayed smaller peak internal hip extension and knee adduction moments than men. The smaller hip extension moment is likely associated with the greater hip flexion observed during landing, in that a weaker musculature would take a larger range of motion to slow rotation during landing. The finding of smaller knee adduction moments in women conflicts with some literature reports (Chappell et al. 2005; McLean et al. 2007), but agrees with others (Kernozek et al. 2005). Typically, a large internal knee adduction moment is considered to be particularly deleterious to ACL loading, especially when combined with a knee that is in an abducted position (Hewett et al. 2005; Markolf et al. 1995). However, a smaller internal knee adduction moment during the landing phase may also be less able to keep the knee from going into abduction, which may have led to the increased peak knee abduction angle in women. Collectively, the observed sex-differences are consistent with those reported in the literature and suggest that women display landing mechanics that are consistent with an increased risk of non-contact ACL injury.

The exercise protocol had an acute effect on landing mechanics in women and men. These changes, however, did not depend on sex. Immediately after exercise, both women and men displayed greater ankle plantarflexion and lesser knee flexion at touchdown. The greater plantarflexion angle at touchdown, along with an unchanged plantarflexion moment, may act to increase shock absorption and reduce ground

reaction forces upon impact and may thus be a protective strategy (Self and Paine 2001). The kinematic changes were also accompanied by decreased internal hip and knee extension moments. A decrease in these joint moments may indicate a reduction in the functional capacity of the hip and knee extensor musculature, which would likely explain the shift to a protective energy absorption strategy at the ankle. The smaller knee flexion angle at touchdown may also be related to the decrease in knee extension moment, since muscles that cannot generate as much force to reduce the momentum of the body and absorb the shock of landing may need to apply the force over a greater range of motion.

A shift in the distribution of moments among lower extremity joints may be an adaptive strategy in response to acute exercise (Madigan and Pidcoe 2003). The decreases in sagittal-plane hip and knee joint moments may impair energy dissipation by the major muscle groups active during landing and cause participants to rely on secondary stabilizers and support structures to absorb the forces experienced upon impact. Whether this shift would affect risk of non-contact ACL injury may depend on the specific joint in question. While some of the sagittal-plane joint moments were decreased immediately after exercise, a few of the frontal and transverse plane joint moments actually increased. More specifically, participants experienced increased hip abduction and internal rotation moments, along with increased internal knee abduction and external rotation moments. An increased hip abduction moment in the face of a decreased hip extension moment may point to a shift from the large hip extensor musculature, such as the gluteus maximus, to the smaller hip abductor musculature, such as the gluteus medius. This shift may represent a protective compensatory

response, since the gluteus medius acts to provide joint stability at the hip during dynamic tasks. Given that the gluteus maximus also acts as an external rotator, the observed decrease in hip external rotation moment and increase in hip internal rotation moment would also appear logical. While the shift in joint moments at the hip may act as a protective mechanism, the same may not be entirely true at the knee. A decreased internal knee extension moment would point to decreased activity in the quadriceps musculature or increased hamstring activation. Both of these scenarios are considered beneficial in terms of protecting the ACL during the impact phase of dynamic tasks (Chappell et al. 2005; Griffin et al. 2006; Hewett et al. 2005). However, the observed increases in internal knee abduction and external rotation moments may be deleterious to ACL loading since joint rotations in these planes may not be actively controlled by muscles crossing the knee and rely more on passive support from soft tissue structures, such as the ACL. The increases in these frontal- and transverse-plane moments may be especially harmful in a more extended knee position (Markolf et al.1995), as was observed at the moment of touchdown post-exercise. The acute exercise-induced changes observed at the knee may thus precipitate a potentially deleterious joint loading environment in women and men.

While the exercise protocol in our study led to acute changes immediately after exercise, there were no changes that persisted to the testing session 48 hours later. The lack of persistent effects on landing mechanics 48 hours after the initial testing session is a novel finding and suggests that lower extremity biomechanics during landing are not affected by having performed a moderately fatiguing exercise 48 hours earlier. Several studies have examined changes in jumping performance following

exhaustive stretch-shortening cycle exercise (Avela and Komi 1998; Kuitunen et al. 2002). Although these studies did not examine the effects of exercise in the context of risk factors for ACL injury, their findings consistently show that stretch-shortening cycle performance may remain compromised for several days after the initial bout of exercise. It may be that the exercise protocol used in our study was not intense enough to elicit long-lasting changes in muscular performance. Since all our participants regularly performed activities that involved repeated jumping or power training, it may be possible that their training status negated any lasting deleterious effects. However, participants did report a significant increase in muscle soreness between the first and second days of testing, suggesting that muscle damage was indeed present at 48 hours. While we did not observe any prolonged changes in landing mechanics after a single bout of exercise, it may be possible that repeated bouts could compound and eventually lead to persistent mechanical changes that increase the risk of non-contact ACL injury during landing activities. Since tournament play for certain sports, such as handball, may involve 7-10 games over a span of 10-14 days (Ronglan et al. 2006), an inquiry into the cumulative effects of intense exercise on risk factors associated with ACL injury may be warranted.

This study expands on the understanding of how exercise affects landing mechanics in women and men. Fatiguing exercise acutely affected a number of biomechanical variables, but the effects did not depend on sex. Some of these changes appear to be consistent with a compensatory strategy, while others may precipitate potentially harmful joint positions and loadings. Although the trade-off between these changes remains to be investigated, the fact that knee loading became more

deleterious immediately after exercise would suggest an overall greater risk of ACL injury. While the absence of a sex-dependent interaction suggests that exercise does not affect women differently than men, women still displayed knee and hip kinematics and kinetics that were consistent with a greater risk of ACL injury. An important finding was that no negative prolonged effects on factors associated with ACL injury were observed 48 hours after the initial bout of exercise. The present findings therefore provide evidence to suggest that with respect to ACL loading and the relative risk of ACL injury, it would be safe to engage in successive bouts of exercise or compete two days apart, although further investigation may be warranted.

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Table 2.1

Mean ± SD performance variables and soreness as a function of condition and sex

	Pre		**Post**		**48Hr**	
	Women	Men	Women	Men	Women	Men
Leg Power (W/kg)*	2.9±0.6	3.5±0.7	2.7±0.5†	3.3±0.6†	2.9±0.6	3.5±0.8
DVJ Height (cm)*§	36.7±4.0	51.6±8.2	34.7±4.2†	43.8±7.1†	35.6±4.3	49.4±8.8†
Soreness (0-10)	0.2±0.3	0.3±0.6	--------	-------	4.6±2.2†	3.7±2.8†

* $p<.05$ for Women vs. Men, † $p<.05$ vs. Pre-exercise, § $p<.05$ for Condition x Sex interaction
DVJ = drop vertical jump

Table 2.2

Mean ± SD lower extremity joint angles (degrees) at instant of touchdown

		Pre		**Post**		**48Hr**	
Joint	Rotation	Women	Men	Women	Men	Women	Men
Hip	Flexion	26.6±5.9	22.2±13.0	25.8±12.6	19.2±13.0	27.7±7.9	21.5±8.0
	Abduction*	6.7±2.2	8.9±2.7	6.6±2.0	8.8±3.1	6.4±2.2	9.1±2.6
	External Rotation	0.8±5.1	3.7±8.5	1.6±5.5	2.7±8.5	2.1±2.2	4.5±3.1
Knee	Flexion*	28.7±5.2	33.2±8.4	22.2±7.1†	27.5±7.5†	26.5±5.9	30.1±5.8
	Adduction§	1.8±3.1	3.5±4.5	0.9±3.3	3.9±4.4	1.2±2.3	3.3±4.2
	Internal Rotation	5.3±3.8	4.3±7.6	4.1±4.5	2.6±7.3	5.1±4.0	2.0±5.6
Ankle	Plantar-flexion	17.4±8.0	17.0±6.5	26.7±14.6†	21.1±5.3†	20.7±5.6	18.9±6.2
	Inversion	11.0±3.6	11.0±7.4	11.9±11.7	12.7±3.8	10.8±3.4	13.5±5.1

* $p<.05$ for Women vs. Men, † $p<.05$ vs. Pre-exercise, § $p<.05$ for Condition x Sex interaction

Table 2.3

Mean ± SD maximal joint angles during landing (degrees)

Joint	Rotation	Pre		Post		48Hr	
		Women	Men	Women	Men	Women	Men
Hip	Flexion*	71.2±14.1	59.1±11.5	76.5±12.6	60.0±15.9	72.3±12.1	62.1±12.5
	Abduction*	9.1±3.7	13.6±5.4	10.4±3.7†	14.2±6.3†	9.6±3.8	14.3±4.6
	Adduction	-2.9±2.8	-6.2±4.0	-3.4±2.5	-6.0±4.1	-3.5±3.2	-6.9±3.7
	Ext. Rotation	4.4±4.8	4.9±8.4	5.0±5.6	5.1±8.6	4.5±4.6	5.0±4.3
	Int. Rotation	7.5±4.1	8.6±8.6	7.2±5.5	9.0±8.1	6.8±5.0	8.2±7.2
Knee	Flexion	95.9±11.5	101.1±20.1	92.5±17.9	99.7±22.2	96.4±14.4	100.6±20.1
	Abduction*	5.8±4.6	1.3±6.7	6.6±6.6	2.4±7.0	4.9±4.0	-0.2±6.7
	Adduction	6.3±3.4	9.4±7.9	5.8±5.2	10.2±7.2	6.4±3.5	10.1±7.8
	Ext. Rotation	-3.8±4.0	-3.2±7.3	-2.7±4.7	-2.0±7.1	-4.2±4.1	-1.6±5.7
	Int. Rotation	18.1±6.2	20.5±8.7	19.2±6.3	21.9±9.8	18.8±6.1	20.0±8.6
Ankle	Dorsi-flexion	30.6±2.8	30.5±3.5	24.6±18.0	28.5±3.6	30.2±3.6	29.7±3.5
	Eversion	7.6±2.6	10.0±5.0	6.8±13.8	7.9±4.2	7.5±2.9	7.4±5.5
	Inversion	10.9±3.5	11.5±7.3	12.3±12.2	13.3±3.8	11.0±3.2	15.0±4.4

Note: A negative value indicates rotation in the opposite direction (e.g. -2.9 degrees of hip adduction = 2.9 degrees of hip abduction)
* $p<.05$ for Women vs. Men, † $p<.05$ vs. Pre-exercise

Table 2.4

Mean ± SD maximal internal joint moments during landing [Nm/(kg·m)]

		Pre		**Post**		**48Hr**	
Joint	Rotation	Women	Men	Women	Men	Women	Men
Hip	Extension*	1.05±0.13	1.23±0.36	0.96±0.11†	1.17±0.28†	1.00±0.16	1.11±0.22
	Abduction	0.19±0.06	0.18±0.10	0.21±0.08†	0.22±0.13†	0.17±0.07	0.19±0.10
	Adduction	0.13±0.05	0.17±0.10	0.12±0.06	0.19±0.12	0.13±0.07	0.16±0.11
	Ext. Rotation	0.13±0.05	0.16±0.06	0.11±0.04†	0.15±0.06†	0.12±0.04	0.15±0.06
	Int. Rotation	0.08±0.04	0.06±0.05	0.09±0.05†	0.08±0.06†	0.07±0.05	0.07±0.05
Knee	Extension	0.99±0.14	1.01±0.21	0.85±0.18†	0.88±0.21†	0.92±0.11	0.97±0.24
	Abduction	0.11±0.04	0.10±0.05	0.12±0.06†	0.13±0.07†	0.11±0.05	0.12±0.07
	Adduction*	0.12±0.05	0.18±0.10	0.10±0.04	0.17±0.08	0.11±0.04	0.17±0.09
	Ext. Rotation	0.05±0.02	0.05±0.02	0.06±0.02†	0.06±0.02†	0.06±0.02	0.06±0.02
	Int. Rotation	0.02±0.02	0.03±0.02	0.03±0.02	0.03±0.02	0.02±0.01	0.03±0.02
Ankle	Plantar-flexion	0.61±0.15	0.69±0.14	0.56±0.11	0.65±0.19	0.58±0.09	0.65±0.10
	Eversion	0.03±0.03	0.01±0.01	0.02±0.02	0.01±0.02	0.02±0.03	0.02±0.02
	Inversion	0.04±0.02	0.07±0.04	0.07±0.10	0.07±0.04	0.05±0.02	0.08±0.03

* $p<.05$ for Women vs. Men, † $p<.05$ vs. Pre-exercise

3. Acute and prolonged effects of fatiguing exercise on lower extremity landing patterns in women and men

3.1 Introduction

Approximately 80,000 – 250,000 anterior cruciate ligament (ACL) injuries occur each year (Hootman et al. 2007). Roughly 50-70% of ACL injuries that occur are due to a non-contact episode (Hootman et al. 2007). Women are two to eight times more likely to sustain a non-contact ACL injuries than men when matched for sport (Griffin et al. 2006). While this sex bias in injury rates appears to result from a combination of factors, biomechanical and neuromuscular factors are thought to be the greatest contributors to this discrepancy (Griffin et al. 2006; Hewett et al. 2006). In terms of biomechanical and neuromuscular risk factors, it is known that during dynamic tasks, such as landing and cutting, females typically exhibit different postures, positions, and movement patterns than males (Chappell et al. 2002; Decker et al. 2003; Ford et al. 2005; Huston et al. 2001; Kernozek et al. 2005; Malinzak et al. 2001). Collectively, these sex-differences in movement patterns, especially during the landing phase, are implicated to result in greater joint loadings in females and to predispose them to a higher risk of ACL injury.

Epidemiological research shows that a larger percentage of injuries occur either towards the end of the first half or towards the latter stages of game-play (Hawkins and Fuller 1999; Hawkins et al. 2001). Intense exercise may adversely affect risk factors associated with ACL injury and contribute to knee injuries through increased exposure to joint positions that result in harmful loading environments (Chappell et al. 2005; Kernozek et al. 2007; McLean et al. 2007). In addition to acute

changes in biomechanical and neuromuscular performance, very intense exercise may also lead to prolonged changes in muscle and joint function and a delayed recovery process (Clarkson 1997; Komi 2000). These prolonged effects become particularly evident when the exercise involves repeated muscle lengthening or stretch-shortening cycles (SSC) that are common to various athletic tasks, such as running and jumping (Avela and Komi 1998; Kuitunen et al. 2002). If a single bout of exercise negatively affects neuromuscular performance for several days, it may be possible that risk of injury is affected as well. Because conference or tournament play in sport often requires that teams play multiple games within a short period of time, the establishment of a time course of recovery for risk factors associated with ACL injuries would be of great significance.

To date, the prolonged effects known to follow a single fatiguing bout of intense SSC exercise have been examined in the context of risk factors for ACL injury by only one study (Kipp and Pavol 2009). While the authors did observe acute effects of intense exercise on peak landing kinematics and kinetics in women and men, they did not observe any prolonged effects. However, while peak values can provide important information related to injury risk, they provide no information regarding the timing or patterns of joint motion and moments. The loss of this underlying information with respect to movement patterns may well be one of the most important limitations of traditional analyses of discrete measures (Landry et al. 2007a, b). The use of principal components (PC) analysis may effectively remedy these problems. For example, Wrigley and colleagues (Wrigley et al. 2005) demonstrated that principal components analysis identified important biomechanical differences in

coordinated movements among clinical populations where traditional empirical analyses did not. Other authors have recently used principal components analysis to examine sex differences across a variety of movement tasks (Landry et al. 2007a, b). A natural extension of using principal components analysis to compare movement patterns across tasks would be to use said analysis to compare movement patterns before and after exercise. The purpose of this study was to use principal components analysis to determine if a bout of fatiguing exercise would have acute and prolonged influences on landing patterns, consistent with increased loading of the ACL, and whether these effects would differ between women and men.

3.2 Materials and Methods

In order to detect moderate within-group and between-group differences with a statistical power of at least .80 at $\alpha < .05$, a minimum of 10 subjects per group were required (Kirk 1972). Fifteen healthy women (mean ±SD age: 25.5±4.2 yrs; height: 1.67±0.06 m; mass: 61.5±6.0 kg) and 15 healthy men (age: 21.9±3.4 yrs; height: 1.83±0.09 m; mass: 81.1±6.1 kg) participated in this study. Participants were required to have participated in activities that required repeated jumping efforts or leg resistance/power training for the prior month on a twice weekly or greater basis. Exclusion criteria included a self-reported history of serious lower extremity injury, chronic musculoskeletal disease, or neurological illness that would have limited their full participation. Participants read and signed an informed consent form that was approved by the University Institutional Review Board. Participants were asked to refrain from moderate-to-intense exercise for 48 hours prior to and during their participation in this study.

In order to determine the acute and prolonged effects of exercise on landing mechanics, participants reported to our lab for two testing sessions 44-52 hours apart. Biomechanical data were collected during the landing phase of a participant's execution of drop vertical jumps (DVJ). We compared data from three sets of 10 DVJ of interest: an initial set of jumps on the first day ("pre" condition), a set performed at the end of a fatiguing exercise protocol on the first day ("post" condition), and a set performed on the second day of testing ("48hr" condition). Pre- to post and pre- to 48hr comparisons were made to assess the immediate and prolonged effects of exercise on landing mechanics, respectively.

Thirty-three reflective markers were attached to anatomical landmarks on the participants' skin and clothing. Participants then performed a set of exercises that served as practice and warm-up for the exercise protocol. The warm-up exercises included 10 squats, 10 lunges (five per leg, in an alternating manner), five vertical jumps, and five DVJ. These exercises were performed with no added weight. Following the exercises, the participants were guided through a sequence of six stretching exercises that encompassed the major muscle groups of the lower limbs (i.e., calves, hamstrings, quadriceps, hip flexors, hip adductors, and hip abductors). Each stretch was performed bilaterally and held for 30 seconds.

After the warm-up and stretching exercises, participants performed a test of lower extremity muscle power on a Bassey power rig (University of Nottingham, Nottingham, U.K.). Participants performed three unilateral warm-up trials with each leg at increasing levels of effort. They then performed seven maximal trials with each leg, alternating legs between trials, in which they were instructed to push as hard and as fast as possible. Peak power was recorded for each maximal trial, the highest and lowest values for each leg were excluded, and the remaining values were averaged across legs and used for analysis.

After the power testing, each participant performed a set of 10 DVJ off a 30.5 cm-high box, this set representing the "pre" condition. For the execution of the DVJ, participants were asked step off of the box, land with both legs simultaneously, and rebound immediately into a maximal vertical jump. The step-off leg alternated between trials. During each trial, motion capture data were collected with a nine-camera motion capture system (Vicon, Lake Forest, CA) at a rate of 120 Hz. Bilateral

ground reaction forces were sampled at 1080 Hz with two force plates (model 6040, Bertec, Columbus, OH). Jump height during each DVJ was determined as the maximum height of the pelvis relative to its previously-determined average height during standing, where pelvis height was found by averaging the heights of four markers attached to the anterior and posterior iliac spines.

After the initial DVJ testing, participants moved on to the exercise protocol, which consisted of repeated sets of the same exercises that were done in the warm-up but with twice the repetitions and greater intensity. Each set consisted of 20 squats, 20 lunges (10 per leg, in an alternating manner), 10 vertical jumps, and 10 DVJ from a 30.5 cm-high box. Participants were asked to execute the first two exercises as fast as safely possible and, in the case of the jumps, to jump as high as possible. Upon completing each set of exercises, participants received 45 seconds of rest before continuing. All participants performed at least two sets of the exercise protocol, after which they continued until any of the following occurred: a) the average jump height during the DVJ trials at the end of a set was less than 90% of the average jump height during the "pre" condition, b) a participant indicated that he or she was unwilling or unable to safely continue, or c) an investigator deemed that the participant was unable to safely continue. The 10 DVJ performed at the end of the last set of exercises represented the "post" condition. Immediately following the execution of the last 10 DVJ, participants once again underwent the leg power testing on the Bassey power rig. During the "48hr" condition, participants completed the same warm-up, leg power testing, and initial set of 10 DVJ as on the first day. Participants were asked to

rate their perceived level of muscle soreness on a 10 cm analog scale at the beginning of each of the testing sessions.

The lower extremity was modeled as a 3-dimensional system of rigid links. Three-dimensional body segment orientations and joint center locations during each DVJ were reconstructed from the trajectories of the reflective markers that were attached to participants. Marker trajectories and force plate data were low-pass filtered with a 4th-order zero-lag Butterworth filter at 15 Hz. Joint angles of the hip, knee, and ankle were then computed in three dimensions based on a Cardan rotation sequence of flexion/extension, abduction/adduction, and internal/external rotation of the distal segment. Body segment masses, center of mass locations, and mass moments of inertia were calculated from measured anthropometrics and published relationships (de Leva 1996). Resultant internal joint moments acting at the hip, knee, and ankle were then calculated with a three-dimensional inverse dynamics approach (BodyBuilder, Vicon, Lake Forest, CA), expressed about the Cardan rotation axes, and normalized to participant mass and height.

Data from three sets of DVJ trials were analyzed: the first and last sets from the first testing session and the set from the second session, which represented the pre, post, and 48hr conditions, respectively. For each subject and condition, ensemble-average waveforms were constructed for each joint rotation and moment at the hip, knee, and ankle during the landing period, defined as the time from touchdown to either maximum knee or hip flexion, whichever occurred later. Touchdown was identified as the instant when the vertical component of the ground reaction force exceeded 10 N. For the ensemble-averaging, cubic spline interpolation was used to

determine the value of the dependent variable at each 5% of landing, and the values at each of these percentages of landing were averaged across trials and limbs. The ensemble average of the entire sample of participants over the three testing conditions was then subtracted from each participant's individual ensemble average.

For each of the nine joint rotations and nine joint moments of interest, the mean-removed ensemble waveforms from the three selected sets of DVJ trials were subjected to a PC analysis. The input to the PC analysis for a given joint rotation or moment comprised the mean-removed ensemble average waveforms for all participants and all conditions (i.e. 30 participants x 3 conditions = 90 waveforms), with the values at each 5% of landing considered the "variables" in the PC analysis. This yielded a 90 waveforms x 21 "variables" matrix for each joint rotation and moment. From these waveforms, principal components were extracted for each joint rotation and moment using a covariance matrix decomposition method. A scree plot was used to identify the principal components that explained nontrivial proportions of the waveform variance and these were retained for analysis. The retained principal components were each normalized to a unit vector and projected onto the individual waveforms of each participant for each condition. This operation gave a set of PC scores that expressed the extent to which each principal component was present in the individual waveforms for each participant and condition. The PC scores for each of the retained principal components were then subjected to statistical analysis.

A general linear model ANOVA was used to test for differences in PC scores as a function of condition and sex. The model consisted of a 3 x 2 (condition x sex) analysis to test for within-subject differences (condition) and for between-subject

(sex) differences. Within-subject differences (i.e. across conditions) were treated as repeated measures. Assumptions of the test statistic were verified and adjusted with the Greenhouse-Geisser method where appropriate. The standard of proof to show statistical significance was set at a level of $\alpha < 0.05$. Paired t-tests with appropriate Bonferroni adjustments were used to compare the "pre" to the "post" and the "48hr" conditions during post hoc testing. In the absence of a significant interaction effect, data were pooled across sexes for post hoc testing. All statistical analyses were performed with SPSS version 17 (SPSS, Chicago, IL).

3.3 Results

As reported previously (Kipp & Pavol, 2009), the exercise protocol acutely affected lower extremity muscle performance. DVJ height was lower in women than in men pre-exercise (37±4 cm vs. 52±8 cm). Post-exercise, DVJ height had decreased by 5.5±4.6 % and 15.1±13.5 % in women and men, respectively, while lower extremity power decreased by 6.1±1.7 %, independent of sex. At 48hr, muscle power had returned to pre-exercise levels, as did jump height in women, but muscle soreness had increased by 3.9±2.4 out of 10 and men exhibited a 4.1±7.6 % lower jump height than pre-exercise.

Between one and three principal components from the PC analysis were retained for each kinematic and kinetic variable at each of the three joints of the lower extremity. Ankle inversion moment was the only variable with one principal component, whereas ankle flexion angle, knee external rotation moment, and hip extension moment were the only variables with three principal components. All other waveforms had two principal components. These sets of components explained a minimum of 90.3% and a maximum 97.7% of the total variance in the angle or moment in question. For the joint angles, it generally appeared that the first principal component represented an offset from the ensemble average (i.e. a change in magnitude), whereas the second principal component typically represented a difference in range of motion. For the joint moments, the first principal component also represented an offset from the ensemble average (i.e. a change in magnitude), whereas the second principal component typically represented a difference in

operating range. In addition, larger PC scores indicated a greater magnitude or larger ranges of motion or operation in the directions indicated.

The extent and manner in which the principal components of the kinematic waveforms were present were influenced by condition and sex (Table 3.1). The exercise protocol had both acute and prolonged effects on several kinematic PC scores, and these effects were independent of sex. Acute effects only were observed for ankle flexion PC1 ($p<.001$; Figure 3.1) and knee flexion PC2 ($p=.001$; Figure 3.2), whereas prolonged effects only were found for hip external rotation PC2 ($p=.001$). Both acute and prolonged effects were observed for ankle flexion PC3 ($p<.001$; Figure 3.1), hip abduction PC1 ($p=.014$; Figure 3.3), and hip external rotation PC1 ($p=.015$). Across all conditions, women and men differed in the extent/manner in which six principal components were present. Women displayed greater PC scores for hip flexion PC1 ($p=.005$) and hip external rotation PC1 ($p=.013$), but smaller scores for hip abduction PC1 ($p=.015$) than men. Women also displayed significantly smaller scores for knee external rotation PC2 ($p=.033$), ankle toe out position PC2 ($p=.002$), and ankle inversion PC2 ($p=.021$).

The extent and manner in which the principal components of the kinetic waveforms were present were influenced by condition and sex (Table 3.2). The exercise protocol had significant acute and prolonged affects on several kinetic PC scores and these effects were independent of sex. Acute effects at the hip were observed as decreased scores for extension moment PC1 ($p<.011$) and external rotation moment PC2 ($p=.001$) and increased scores for abduction moment PC2 ($p=.006$; Figure 3.4) post-exercise. Additional acute effects were observed at the knee

in decreased scores for extension moment PC2 ($p<.005$; Figure 3.5) and increased scores for abduction moment PC2 ($p=.001$; Figure 3.6). Prolonged-only effects were found as scores for hip abduction moment PC1 ($p=.015$; Figure 3.4) were decreased at 48hr. Combined acute and prolonged effects were also observed as scores for ankle plantarflexion moment PC1 ($p<.008$; Figure 3.7), ankle plantarflexion moment PC2 ($p=.015$; Figure 3.7), and knee extension moment PC1 ($p=.007$; Figure 3.5) decreased post-exercise and at 48hr compared to pre-exercise. Women and men differed in the extent/manner in which two principal components were present. Women exhibited smaller PC scores for ankle plantarflexion moment PC2 ($p=.008$) and greater scores for knee external rotation moment PC3 ($p=.017$) than men.

3.4 Discussion

Previous research indicates that intense exercise has acute deleterious affects on landing mechanics that are consistent with an increase in ACL loading, particularly in women (Chappell et al. 2005; Kernozek et al. 2007; McLean et al. 2007). Since very intense exercise is also associated with prolonged changes in muscle and joint function and typically involves a delayed recovery process (Clarkson 1997; Komi 2000), it would be of great significance to establish whether risk factors associated with increased ACL loading follow a similar pattern. Only one study (Kipp and Pavol 2009) has attempted to investigate whether the prolonged effects of intense exercise persist for several days, but the study found no delayed effects in peak landing kinematics or kinetics. While these results provided important information related to potential risk of ACL injury, peak values do not provide any information regarding the timing or patterns of joint motion and moments and may not be sensitive enough to detect differences. So, it remains to be elucidated if the effects of exercise on risk factors for ACL injury persist for several days. The purpose of this study was to use methods more sensitive to waveform variability to determine if a single bout of fatiguing exercise would lead to acute and prolonged changes in landing patterns in women and men. We used principal components analysis to quantify patterns of joint kinematics and kinetics during landing before, immediately after, and 48 hours after participants performed an intense bout of exercise. The analysis used in this study was able to identify acute and prolonged changes in kinematic and kinetic patterns in response to the fatiguing exercise protocol, as well as differences in landing mechanics between women and men.

Participants experienced an acute decrease in leg power and in drop vertical jump height after completion of the exercise circuit. Together, these measures indicate that isolated and functional lower extremity performance was compromised, respectively. Leg muscle power recovered to pre-testing levels within 48 hours in both women and men. However, vertical jump height recovered only in women, while muscle soreness increased significantly in both sexes in the 48 hours between the first and second day of testing, suggesting that some compromise was still present at 48 hours.

The exercise protocol had an acute effect on landing mechanics in women and men. These effects, however, did not depend on sex. Immediately after exercise, both sexes displayed smaller magnitudes of ankle dorsiflexion (ankle flexion angle PC1) and smaller ranges of knee flexion (knee flexion angle PC2) during the entire landing phase. Without any changes in sagittal-plane hip angles, these changes would indicate a more erect posture. The decreased ankle flexion magnitude and knee flexion range of motion were paralleled by decreased extension moment magnitudes at these joints (ankle plantarflexion moment PC1 and knee extension moment PC1). During landing, the extensor muscles of the lower extremity actively lengthen in order to absorb energy and function to control joint movement. Lower extensor moments of force during the landing phase may indicate fatigued extensor muscles and a compromised ability to effectively dissipate energy. We also observed a shift from a knee adduction moment to a knee abduction moment during early landing phase (knee abduction moment PC2), which may increase deleterious knee abduction. The combination of a more erect posture, reduced energy absorption by the extensors, and compromised

control of knee abduction may prove potentially harmful in that it could lead to a 'ligament-dominant' landing strategy and unduly stress soft tissues at the knee while it is in an especially high-risk position (Hewett et al. 2006).

At the hip, the magnitudes of abduction (hip abduction PC1) increased while hip external rotation (hip external rotation PC1) decreased immediately after exercise. These kinematic changes were accompanied by smaller magnitudes of hip extension moments (hip extension moment PC1) and external rotation moments (hip external rotation PC1) during almost the entire landing, but greater hip abduction moments (hip abduction moment PC2) during early landing. Madigan and Pidcoe (Madigan and Pidcoe 2003) showed that an initial response to fatiguing exercise is a distal-to-proximal re-distribution of joint function during landing and suggest that this may help resist a collapse of the lower extremity during landing. The changes observed in our study may indicate a similar shift, but from hip extensors and external rotators to the hip abductors, and may act as a compensatory strategy that increases stability of the hip or prevents an increase in knee abduction during the impact phase of landing (Jacobs et al. 2007). Hip abductor function is thought to play an important role in neuromuscular control of the knee, particularly in women (Jacobs et al. 2007). Greater levels of hip abduction strength appear to be related to decreased knee abduction when landing from a jump, potentially decreasing the risk of ACL injury (Jacobs et al. 2007). The observed acute change in hip abduction moments with exercise may well be a compensatory strategy that aims to reduce deleterious knee loading through changes in proximal joint function.

While the exercise protocol in our study led to acute changes immediately after exercise, a few of the changes persisted until the testing session 48 hours later. Similar to the acute changes observed immediately after exercise, none of the prolonged changes differed between women and men. Landing-phase magnitudes of hip abduction (hip abduction angle PC1) motion remained generally larger during the 48hr testing condition compared to pre-exercise. Surprisingly, this occurred in the presence of decreased hip abduction moment magnitudes throughout landing (hip abduction moment PC1). Magnitudes of knee extension moments (knee extension moment PC1) and ankle plantarflexion moments (ankle plantarflexion moment PC1) also remained depressed through the 48 hour testing session. Interestingly, not just the magnitude but also the effective operating range of the plantarflexion moment (ankle plantarflexion moment PC2) remained diminished. Combined, the changes in plantarflexor function suggest an altered activation strategy. The finding that multiple aspects of plantarflexor biomechanics (i.e. movement and moment magnitudes, and range of movement and moments) change and remain changed 48 hours after exercise warrants further investigation with regards to ACL injury risk. Nevertheless, despite all the prolonged changes in lower extremity mechanics, none were consistent with increased ACL loading.

Similar to other studies, we showed that women and men display differences in landing mechanics (Decker et al. 2003; Ford et al. 2005; Huston et al. 2001; Kernozek et al. 2005). Women displayed greater hip flexion (hip flexion PC1) magnitudes than men during landing, but lesser hip abduction (hip abduction PC1). Larger hip flexion at initial contact has been linked to deleterious knee loading (McLean et al. 2005),

while greater peak hip flexion during landing is thought to be a associated with knee injury (Boden et al. 2009). Women also exhibited smaller ranges of motion in knee external rotation (knee external rotation PC2), ankle toe out position (ankle toe out PC2), and inversion (ankle inversion PC2). Smaller ankle and knee rotation may signify less active pronation during landing, indicating a more rigid joint. Although this finding conflicts with that of Kernozek and colleagues (Kernozek et al. 2005), they do suggest that greater ankle pronation may be a strategy to absorb ground reaction forces, minimize the impact transferred to the knee, and thus decrease ACL load. In addition to these kinematical sex-differences, women also displayed a smaller operating range of ankle plantarflexion moments (ankle plantarflexion moment PC2), but greater knee rotation moment (knee external rotation moment PC3) operating ranges during landing. Another study (McLean et al. 2007) also found smaller magnitudes of ankle plantarflexion moments and greater knee rotation moments in women. Our results corroborate this finding and may indicate distinct sex-differences in landing strategy. A lower plantarflexor moment may indicate less impact absorption (Madigan and Pidcoe 2003). Ineffective energy absorption at the ankle may transfer more energy to the knee and result in a larger knee rotation moment, as observed in the women of this study, and could be considered harmful to the knee, especially in a position of knee abduction (Markolf et al. 1995). Collectively, the observed sex-differences in the joint motion and moment patterns are consistent with those reported in the literature for peak kinematics and kinetics and suggest that women display landing mechanics that are consistent with an increased risk of ACL injury.

This study expands the body of knowledge on landing patterns in women and men with special regards to the acute and prolonged effects of exercise. Fatiguing exercise acutely affected a number of biomechanical variables, but the effects did not depend on sex. A novel finding was that persistent effects of exercise were observed in landing patterns 48 hours after the initial bout of exercise, although none of these changes were consistent with increased ACL loading. Immediate and prolonged changes in hip mechanics appear to be consistent with a compensatory strategy, while those observed at the knee and ankle may precipitate potentially harmful joint positions and loadings. While the net effect of this trade-off remains to be investigated, knee loading did become more deleterious immediately after exercise and would suggest an overall greater risk of ACL injury. Although we also observed sex differences in landing patterns that were consistent with the literature, the immediate and prolonged effects of fatigue did not differ between women and men, which suggest that exercise-induced changes in landing patterns do not explain a portion of the observed sex-bias in ACL injury rates.

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Table 3.1

Mean (SD) principal component (PC) scores for lower extremity kinematics during landing

			Pre		**Post**		**48Hr**	
Measure	PC	Meaning	Women	Men	Women	Men	Women	Men
Ankle flexion	PC1†	Magnitude throughout landing	3.70 (11.72)	3.54 (21.38)	-3.60 (17.97)	-9.32 (20.25)	3.83 (10.60)	1.85 (19.01)
Ankle flexion	PC3†‡	Magnitude during early landing	3.11 (5.42)	1.43 (4.89)	-1.49 (4.96)	-1.60 (6.30)	0.54 (4.65)	-2.00 (5.18)
Ankle toe out	PC2*	Range of motion	-3.18 (3.91)	2.45 (4.50)	-1.03 (6.73)	3.30 (5.35)	-2.97 (3.49)	1.14 (3.11)
Ankle inversion	PC2*	Range of motion	-1.96 (4.94)	3.42 (8.29)	-4.02 (7.78)	1.55 (6.51)	-2.90 (4.57)	2.60 (9.49)
Knee flexion	PC2†	Range of motion	3.80 (14.36)	5.05 (12.55)	-8.24 (17.34)	-2.44 (18.24)	-0.72 (17.14)	2.55 (16.31)
Knee external rotation	PC2*	Range of motion	-5.05 (8.09)	1.86 (10.97)	-2.21 (9.74)	3.87 (10.33)	-3.15 (7.68)	4.69 (11.32)
Hip flexion	PC1*	Magnitude throughout landing	20.72 (50.02)	-28.19 (47.80)	31.52 (47.81)	-28.98 (63.02)	22.99 (40.22)	-18.06 (50.01)
Hip abduction	PC1*†‡	Magnitude during mid-to-late landing	-12.33 (17.20)	7.26 (21.54)	-6.95 (16.33)	7.90 (24.86)	-8.34 (17.88)	12.46 (20.12)
Hip external rotation	PC1*†‡	Magnitude throughout landing	12.27 (17.12)	-7.32 (21.32)	7.05 (16.21)	-7.99 (24.68)	8.45 (17.82)	-12.47 (20.05)
Hip external rotation	PC2‡	Range of motion	1.18 (5.40)	0.50 (5.17)	-0.84 (5.22)	0.59 (7.33)	-0.84 (4.88)	-0.59 (5.85)

Note: Larger PC values indicate a greater magnitude or larger range of motion in the direction indicated

* $p<0.05$ for Women vs. Men, † $p<0.025$ for Pre vs. Post, ‡ $p<0.025$ for Pre vs. 48Hr

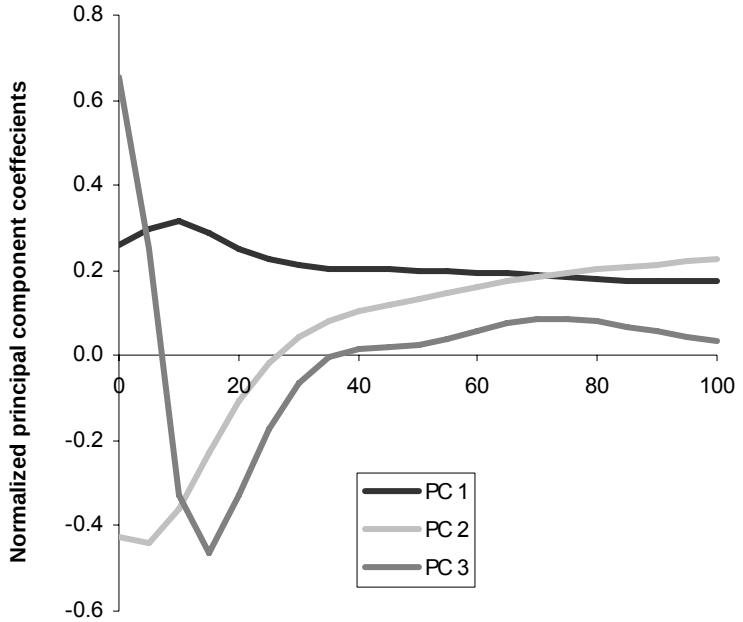
Table 3.2

Mean (SD) principal component (PC) scores for lower extremity kinetics during landing

			Pre		**Post**		**48Hr**	
Measure	PC	Meaning	Women	Men	Women	Men	Women	Men
Ankle plantar-flexion	PC1[†‡]	Magnitude throughout landing	0.058 (0.846)	0.327 (0.734)	-0.205 (0.660)	0.065 (0.931)	-0.220 (0.665)	-0.025 (0.580)
Ankle plantar-flexion	PC2[*†‡]	Magnitude during mid-to-late landing	-0.043 (0.138)	0.179 (0.198)	-0.096 (0.134)	-0.006 (0.227)	-0.099 (0.138)	0.058 (0.205)
Knee extension	PC1[†‡]	Magnitude throughout landing	0.432 (0.622)	0.365 (0.926)	-0.335 (0.912)	-0.288 (0.912)	0.021 (0.527)	-0.194 (0.912)
Knee extension	PC2[†]	Magnitude during early landing	0.163 (0.243)	-0.073 (0.241)	0.022 (0.378)	-0.174 (0.300)	0.077 (0.289)	-0.015 (0.316)
Knee abduction	PC2[†]	Magnitude during early landing	-0.042 (0.122)	-0.033 (0.138)	-0.017 (0.149)	0.060 (0.129)	-0.002 (0.133)	0.034 (0.111)
Knee external rotation	PC3[*]	Magnitude change during landing	0.009 (0.021)	-0.009 (0.036)	0.016 (0.028)	-0.004 (0.029)	0.007 (0.026)	-0.019 (0.024)
Hip extension	PC1[†]	Magnitude throughout landing	0.049 (0.352)	0.199 (0.830)	-0.178 (0.561)	-0.008 (0.762)	-0.126 (0.451)	0.064 (0.820)
Hip abduction	PC1[‡]	Magnitude throughout landing	0.134 (0.306)	-0.052 (0.546)	0.057 (0.338)	0.003 (0.621)	-0.006 (0.407)	-0.136 (0.519)
Hip abduction	PC2[†]	Magnitude during early landing	-0.023 (0.132)	-0.051 (0.161)	0.049 (0.178)	0.029 (0.204)	0.008 (0.135)	-0.012 (0.133)
Hip external rotation	PC2[†]	Magnitude during mid-to-late landing	0.032 (0.106)	0.022 (0.126)	-0.004 (0.102)	-0.033 (0.118)	-0.001 (0.096)	-0.016 (0.075)

Note: Larger PC values indicate a greater magnitude or larger range of motion in the direction indicated

[*] $p<0.05$ for Women vs. Men, [†] $p<0.025$ for Pre vs. Post, [‡] $p<0.025$ for Pre vs. 48Hr



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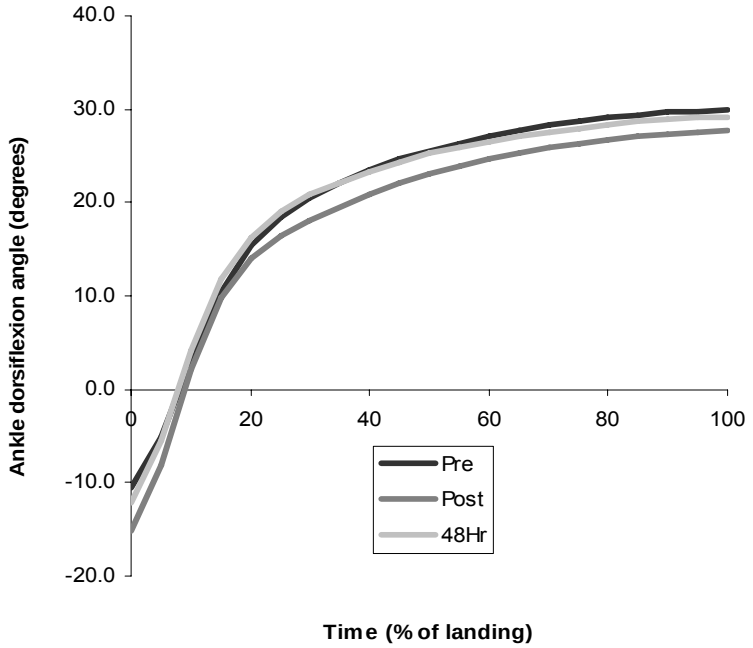

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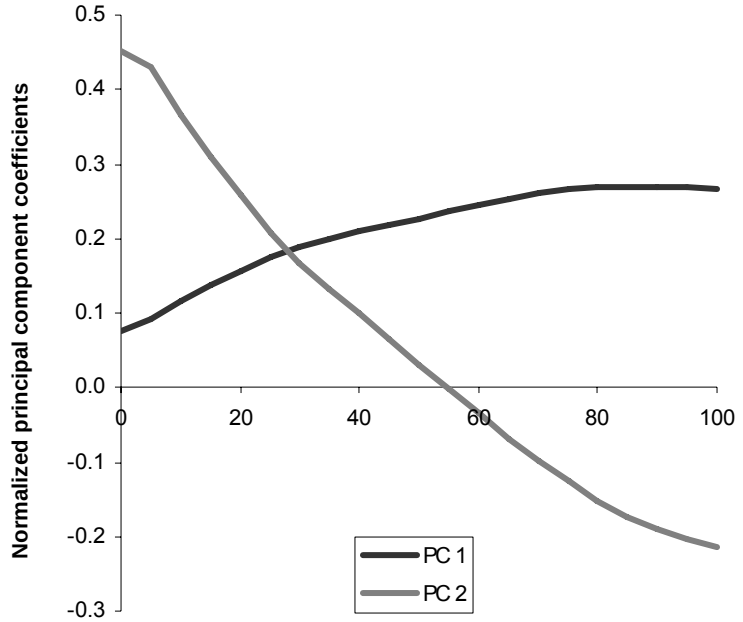
Figure 3.1: a) Normalized principal component coefficients for ankle flexion angle; b) Ensemble average for ankle dorsiflexion angle (degrees), as a function of condition, for all participants from the point of touchdown to the end of landing



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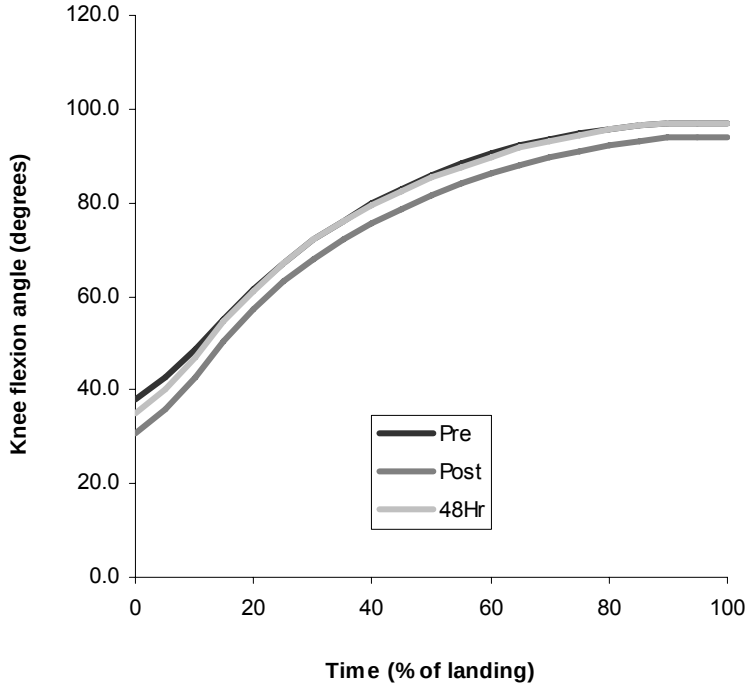

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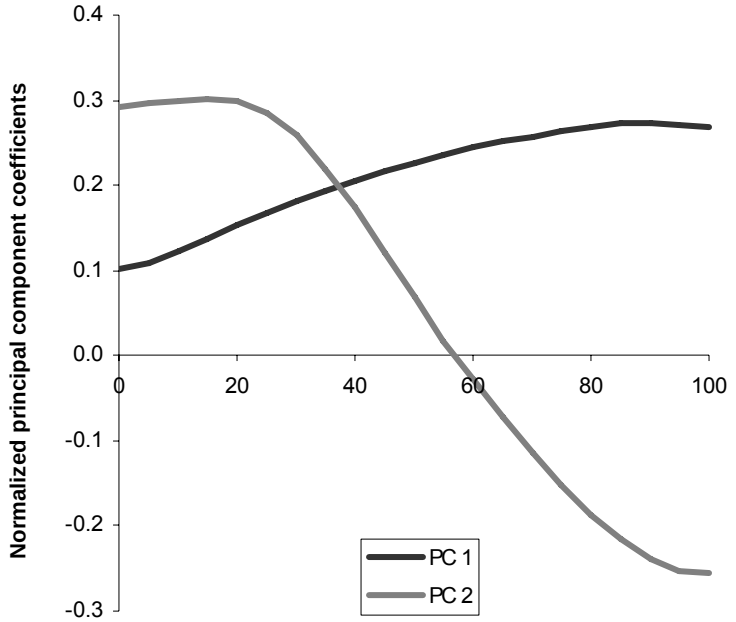
Figure 3.2: a) Normalized principal components coefficients for knee flexion angle; b) Ensemble average for knee flexion angle (degrees) for all participants from point of touchdown to end of landing



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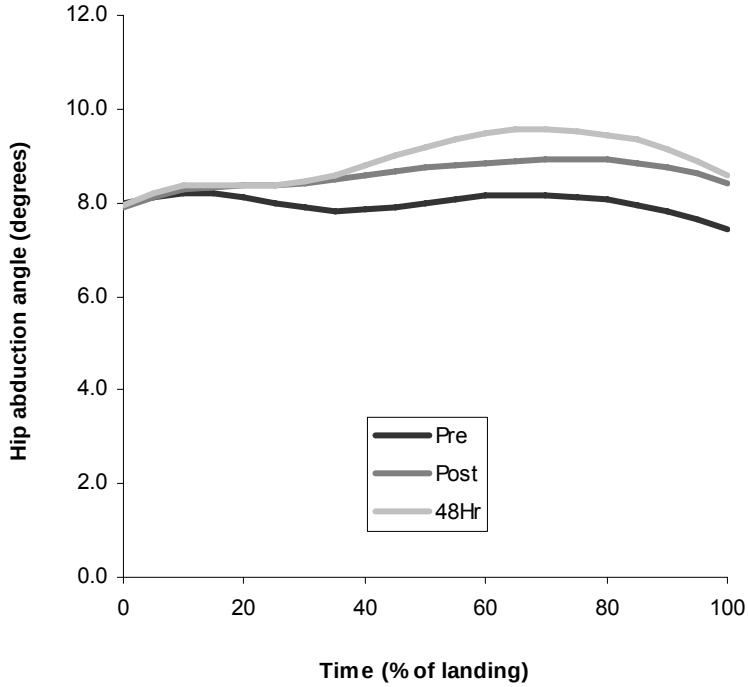

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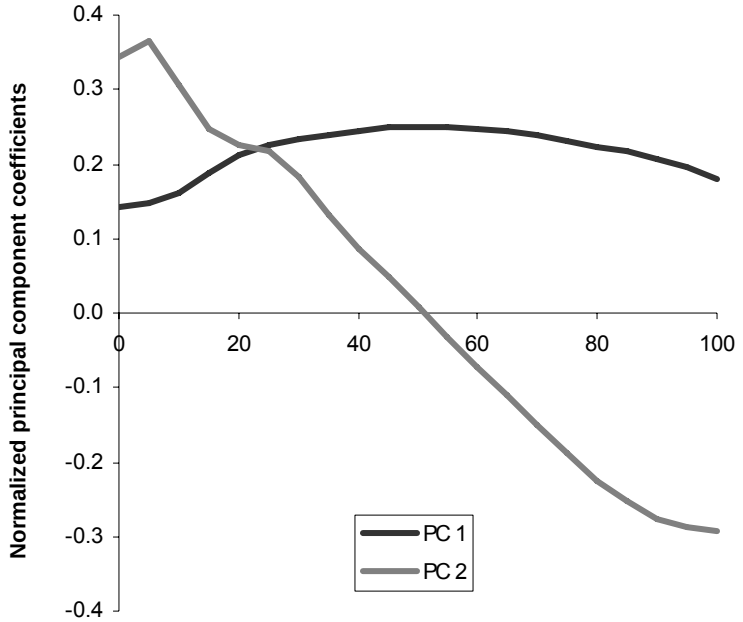
Figure 3.3: a) Normalized principal components coefficients for hip abduction angle; b) Ensemble average for hip abduction angle (degrees) for all participants from point of touchdown to end of landing



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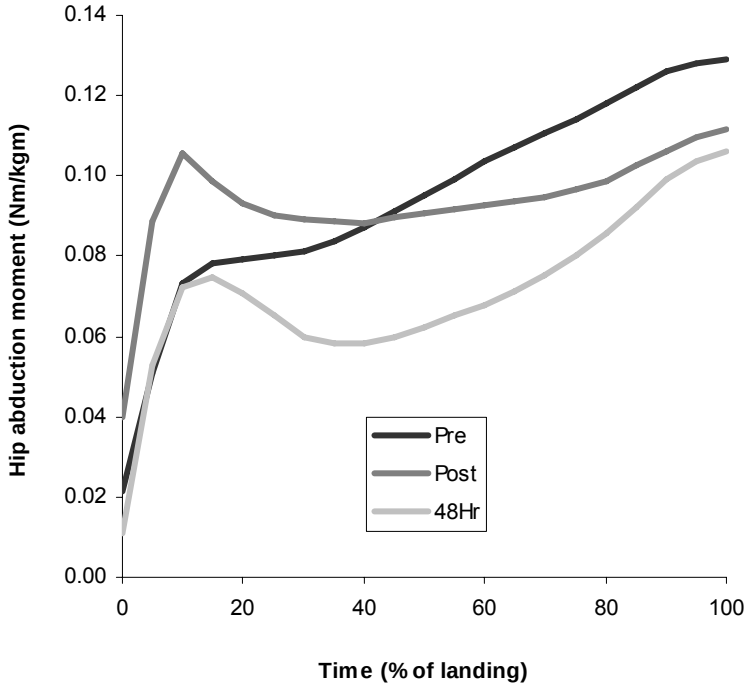

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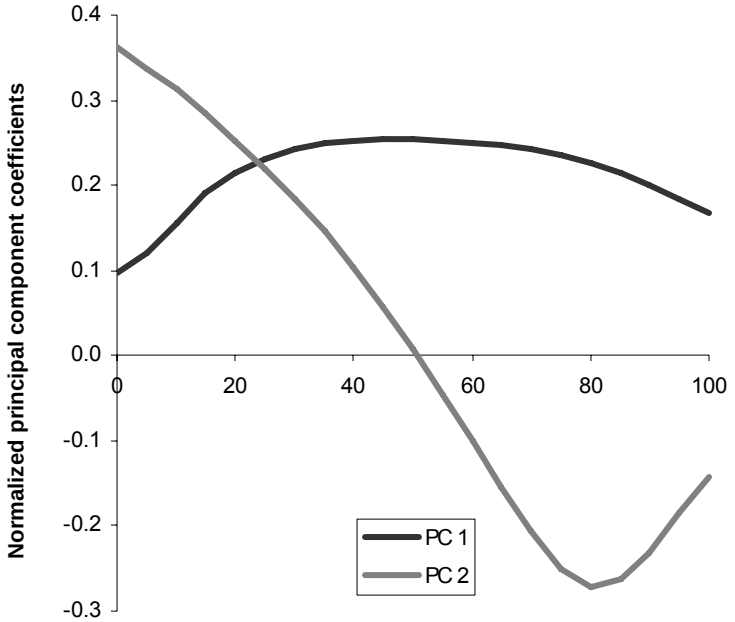
Figure 3.4: a) Normalized principal component coefficients for hip abduction moment; b) Ensemble average for hip abduction moment [N·m/(kg·m)] for all participants from point of touchdown to end of landing



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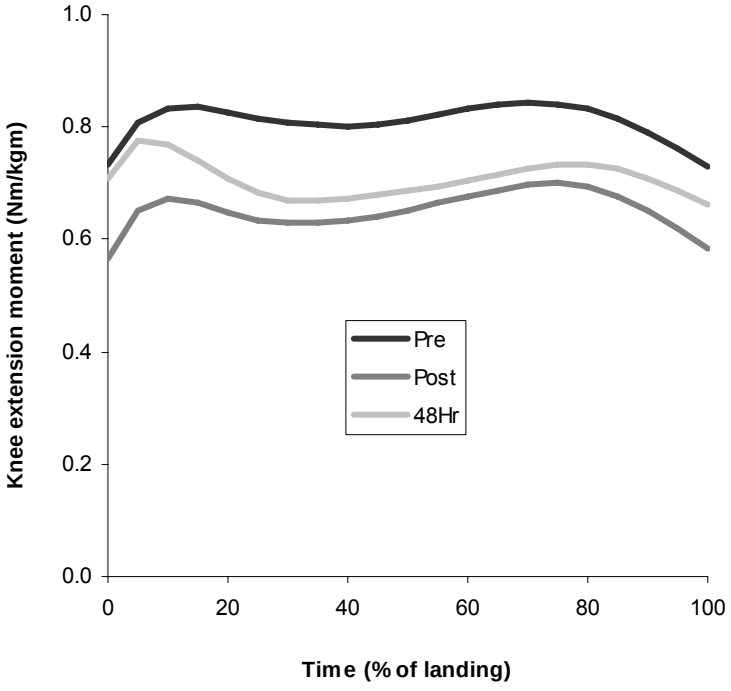

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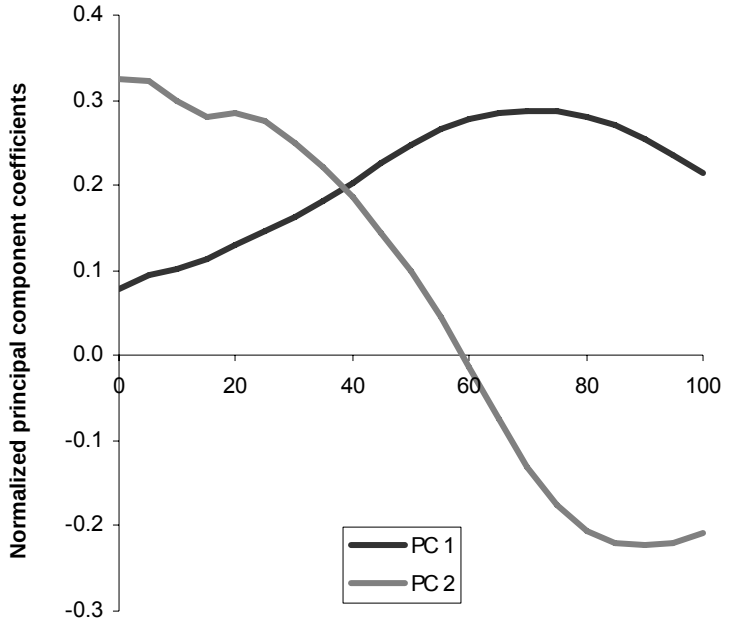
Figure 3.5: a) Normalized principal components coefficients for knee extension moment; b) Ensemble average for knee extension moment [N·m/(kg·m)] for all participants from point of touchdown to end of landing



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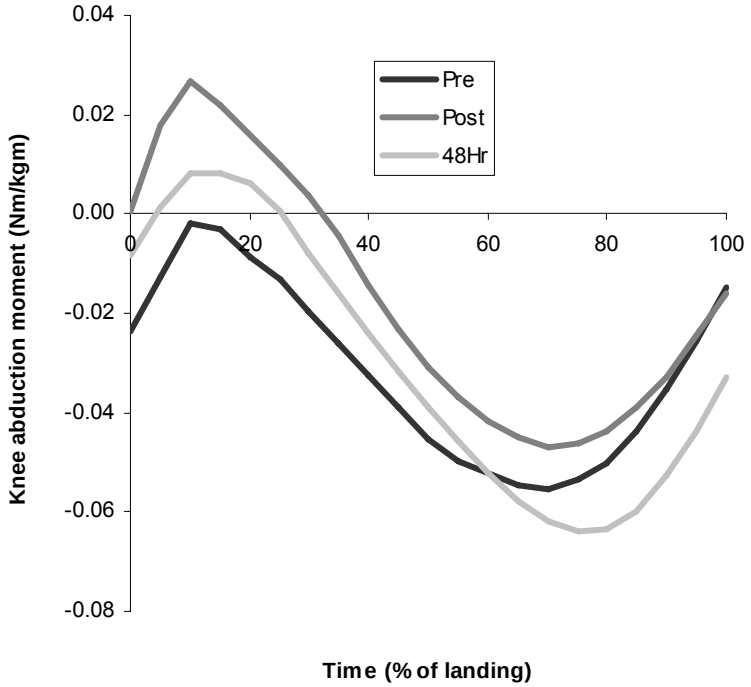
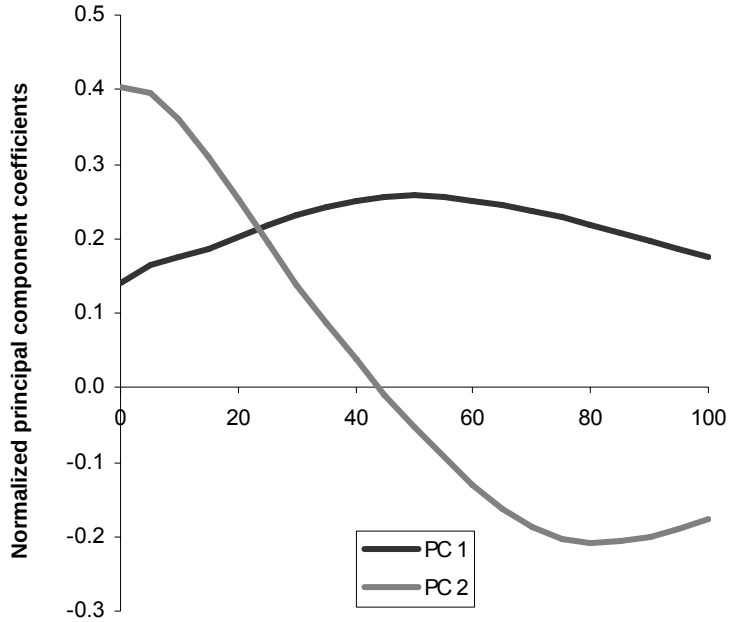
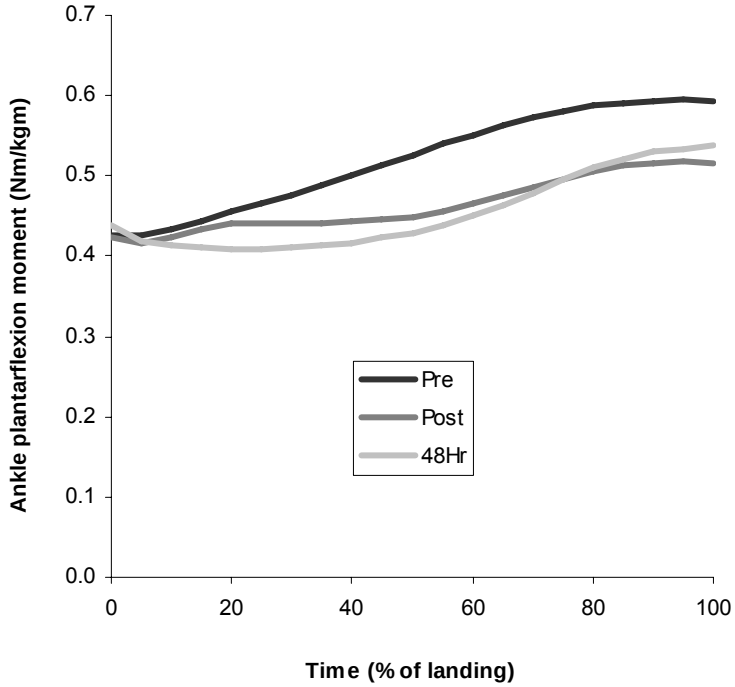


b)

Figure 3.6: a) Normalized principal components coefficients for knee abduction moment; b) Ensemble average for knee abduction moment [N·m/(kg·m)] for all participants from point of touchdown to end of landing



a)



b)

Figure 3.7: a) Normalized principal component coefficients for plantarflexion moment; b) Ensemble average for ankle plantarflexion moment [N·m/(kg·m)] as a function of condition for all participants from point of touchdown to end of landing

4. Exercise-induced changes in lower extremity joint coupling variability during landing in women and men persists less than two days

4.1 Introduction

Approximately 80,000 – 250,000 anterior cruciate ligament (ACL) injuries occur each year (Hootman et al. 2007). Roughly 50-70% of ACL injuries that occur are due to a non-contact episode (Hootman et al. 2007). Furthermore, women are two to eight times more likely to sustain an ACL injury through a non-contact mechanism than men (Griffin et al. 2006). While this sex bias in injury rates appear to be the result of a combination of factors, these factors and the ways that they contribute to ACL injuries are still not fully understood (Griffin et al. 2006; Hewett et al. 2006). Intense exercise leading to fatigue may be a factor that contributes to ACL injury, not just immediately but also over the subsequent days.

Intense exercise may precipitate knee injuries through exposure to joint positions that result in harmful loadings environments associated with ACL injury (Chappell et al. 2005; Kernozek et al. 2007; McLean et al. 2007). While intense exercise has immediate effects on peak landing mechanics and landing patterns in women and men that are consistent with increased risk of ACL injury, studies to date are unclear as to the prolonged effects a single bout of exercise may have with regard to the same risk of injury (Kipp and Pavol 2009). Movement patterns during deceleration or change-in-direction maneuvers particularly may result in greater joint loadings and lead to a higher risk of injury. However, normally extracted peak kinematic and kinetic biomechanical parameters typically do not consider the complex multi-joint nature of the lower extremity chain.

In addition to differences in movement kinematics and kinetics, women also display less variability of limb coupling during dynamic maneuvers than men (Pollard et al. 2005). Less variability in movement patterns and joint couplings may indicate coordination patterns less able to adapt to possible perturbations encountered in a sports environment and result in ligament injury (Pollard et al. 2005). The lower coupling variability observed in women may thus be a contributing factor that places them at higher risk of non-contact knee injury. In the face of the multi-faceted physiological response to exercise, it may be prudent to consider an analysis method that incorporates how multiple joints and/or multiple directions of joint motion couple together during coordinated movement. Special consideration to the variability in joint coupling may also elucidate the dynamic response of the body with regards to exercise and risk of injury, particularly in women. The purposes of this study were to determine if a bout of exercise would acutely influence joint coupling variability in a way that is consistent with increased risk of ACL injury, whether these effects would remain observable for 48 hours after the initial bout of exercise, and whether these effects would differ between women and men.

4.2 Materials and Methods

In order to detect moderate within-group and between-group differences with a statistical power of at least .80 at $\alpha < .05$, a minimum of 10 subjects per group were required (Kirk 1972). Fifteen healthy women (mean ±SD age: 25.5±4.2 yrs; height: 1.67±0.06 m; mass: 61.5±6.0 kg) and 15 healthy men (age: 21.9±3.4 yrs; height: 1.83±0.09 m; mass: 81.1±6.1 kg) participated in this study. Participants were required to have participated in activities that required repeated jumping efforts or leg resistance/power training for the prior month on a twice weekly or greater basis. Exclusion criteria included a self-reported history of serious lower extremity injury, chronic musculoskeletal disease, or neurological illness that would have limited their full participation. Participants read and signed an informed consent form that was approved by the University Institutional Review Board. Participants were asked to refrain from moderate-to-intense exercise for 48 hours prior to and during their participation in this study.

In order to determine the acute and prolonged effects of exercise on landing mechanics associated with non-contact ACL injury, participants reported to our lab for two testing sessions 44-52 hours apart. Biomechanical data were collected during the landing phase of a participant's execution of drop vertical jumps (DVJ). We compared data from three sets of 10 DVJ of interest: an initial set of jumps on the first day ("pre" condition), a set performed at the end of a fatiguing exercise protocol on the first day ("post" condition), and a set performed on the second day of testing ("48hr" condition). Pre- to post and pre- to 48hr comparisons were made to assess the immediate and prolonged effects of exercise on landing mechanics, respectively.

Thirty-three reflective markers were attached to anatomical landmarks on the participants' skin and clothing. Participants then performed a set of exercises that served as practice and warm-up for the exercise protocol. The warm-up exercises included 10 squats, 10 lunges (five per leg, in an alternating manner), five vertical jumps, and five DVJ. These exercises were performed with no added weight. Following the exercises, the participants were guided through a sequence of six stretching exercises that encompassed the major muscle groups of the lower limbs (i.e., calves, hamstrings, quadriceps, hip flexors, hip adductors, and hip abductors). Each stretch was performed bilaterally and held for 30 seconds.

After the warm-up and stretching exercises, participants performed a test of lower extremity muscle power on a Bassey power rig (University of Nottingham, Nottingham, U.K.). Participants performed three unilateral warm-up trials with each leg at increasing levels of effort. They then performed seven maximal trials with each leg, alternating legs between trials, in which they were instructed to push as hard and as fast as possible. Peak power was recorded for each maximal trial, the highest and lowest values for each leg were excluded, and the remaining values were averaged across legs and used for analysis.

After the power testing, each participant performed a set of 10 DVJ off a 30.5 cm-high box, this set representing the "pre" condition. For the execution of the DVJ, participants were asked step off of the box, land with both legs simultaneously, and rebound immediately into a maximal vertical jump. The step-off leg alternated between trials. During each trial, motion capture data were collected with a nine-camera motion capture system (Vicon, Lake Forest, CA) at a rate of 120 Hz. Bilateral

ground reaction forces were sampled at 1080 Hz with two force plates (6040 model, Bertec, Columbus, OH). Jump height during each DVJ was determined as the maximum height of the pelvis relative to its previously-determined average height during standing, where pelvis height was found by averaging the heights of four markers attached to the anterior and posterior iliac spines.

After the initial DVJ testing, participants moved onto the exercise protocol, which consisted of repeated sets of the same exercises that were done in the warm-up but with twice the repetitions and greater intensity. Each set consisted of 20 squats, 20 lunges (10 per leg, in an alternating manner), 10 vertical jumps, and 10 DVJ from a 30.5 cm-high box. Participants were asked to execute the first two exercises as fast as safely possible and, in the case of the jumps, to jump as high as possible. Upon completing each set of exercises, participants received 45 seconds of rest before continuing. All participants performed at least two sets of the exercise protocol, after which they continued until any of the following occurred: a) the average jump height during the DVJ trials at the end of a set was less than 90% of the average jump height during the "pre" condition, b) a participant indicated that he or she was unwilling or unable to safely continue, or c) an investigator deemed that the participant was unable to safely continue. The 10 DVJ performed at the end of the last set of exercises represented the "post" condition. Immediately following the execution of the last 10 DVJ, participants once again underwent the leg power testing on the Bassey power rig. During the "48hr" condition, participants completed the same warm-up, leg power testing, and initial set of 10 DVJ as on the first day. Participants were asked to

rate their perceived level of muscle soreness on a 10 cm analog scale at the beginning of each of the testing sessions.

The lower extremity was modeled as a 3-dimensional system of rigid links. Three-dimensional body segment orientations and joint center locations during each DVJ were reconstructed from the trajectories of the reflective markers that were attached to participants. Marker trajectories and force plate data were low-pass filtered with a 4th-order zero-lag Butterworth filter at 15 Hz. Joint angles of the hip, knee, and ankle were then computed in three dimensions based on a Cardan rotation sequence of flexion/extension, abduction/adduction, and internal/external rotation of the distal segment. Body segment masses, center of mass locations, and mass moments of inertia were calculated from measured anthropometrics and published relationships (de Leva 1996). Resultant internal joint moments acting at the hip, knee, and ankle were then calculated with a three-dimensional inverse dynamics approach (BodyBuilder, Vicon, Lake Forest, CA), expressed about the Cardan rotation axes, and normalized to participant mass and height. The landing phase was defined as the time from touchdown to maximum knee flexion. Touchdown was defined as the point where the vertical component of the ground reaction force exceeded 10 Newtons.

Lower limb couplings were calculated during the landing period using a modified vector coding technique (Pollard et al. 2005). Briefly, a coupling angle was calculated as the direction of the resultant vector between two adjacent points on an angle-angle plot. Three intra-joint and eight inter-joint combinations were plotted and used to calculate 8 distinct couplings. The couplings were chosen for analysis if they involved one of the degrees of freedom of the knee joint. Couplings as a function of

time were interpolated to 50 frames with a cubic spline. An ensemble-average was computed for each participant, coupling, and condition. Thereafter, if any individual trial fell outside of a 180 degree range from the ensemble average, the waveform data for the trial was adjusted by 360 degrees so that it would remain within the 180 degree range. Ensemble averages were then recomputed and standard deviation bands were calculated from the adjusted ensemble averages for all trials. The root mean square of the standard deviation was then calculated across an entire trial for each coupling. Values for the left and right leg were averaged. The landing period was then further divided into two phases; the first 25% and last 75%. The initial period was taken to represent the impact phase, while the latter period was taken to represent the weight acceptance phase during landing. The mean coupling variability for each of the two phases was then determined and used for statistical analysis.

Variability in joint couplings from three sets of DVJ trials was analyzed: the first and last sets from the first testing session and the set from the second session. These sets represent the pre, post, and 48hr conditions, respectively. Eleven separate general linear model ANOVAs were used to test for differences in coupling variability. Each model consisted of a 2 x 3 x 2 (sex x session x phase) analysis to test for within-subject differences (session & phase) and for between-subject (sex) differences. Within-subject differences (i.e. across session) were treated as repeated measures. Assumptions of the test statistic were verified and adjusted with the Greenhouse-Geisser method where appropriate. Statistical significance was set at an alpha-level of 0.05. Paired t-tests with appropriate Bonferroni adjustments were used during post hoc testing. The comparison between the pre and post condition was used

to assess immediate effects, whereas the comparison between the pre and 48hr condition was made to assess prolonged effects. All statistical analyses were performed with SPSS version 17 (SPSS, Chicago, IL).

4.3 Results

As reported previously (Kipp & Pavol, 2009), the exercise protocol acutely affected lower extremity muscle performance. DVJ height was lower in women than in men pre-exercise (37±4 cm vs. 52±8 cm). Post-exercise, DVJ height had decreased by 5.5±4.6 % and 15.1±13.5 % in women and men, respectively, while lower extremity power decreased by 6.1±1.7 %, independent of sex. At 48hr, muscle power had returned to pre-exercise levels, as did jump height in women, but muscle soreness had increased by 3.9±2.4 out of 10 and men exhibited a 4.1±7.6 % lower jump height than pre-exercise.

The exercise protocol resulted in an acute increase from pre- to post-exercise in the variability of the coupling between knee flexion and knee internal/external rotation ($p<.011$), regardless of phase or sex (Table 4.1). However, at 48hr, this difference relative to the pre-exercise condition was no longer evident. Neither of the other intra-knee couplings exhibited an acute or a delayed change in coupling variability following the exercise bout.

Variability in hip/knee joint couplings was significantly influenced by condition and phase, but remained independent of sex (Table 4.2). A significant condition-by-phase interaction was observed for hip internal/external rotation-knee internal/external rotation ($p<.05$). The coupling variability in hip internal/external rotation-knee internal/external rotation was increased post-exercise during the first 25% of landing only ($p<.001$), while the variability during the remaining 75% of landing did not change. Further, a significant immediate increase was observed in hip internal/external rotation-knee abduction/adduction coupling variability ($p<.011$)

regardless of phase. The changes relative to the pre-exercise condition were no longer significant during the 48hr testing session for both hip/knee couplings.

Testing condition significantly influenced the variability in knee/ankle joint couplings (Table 4.3). Knee internal/external rotation-ankle inversion/eversion coupling variability increased significantly ($p<.001$) immediately after exercise, regardless of phase or sex. Once again at 48hr, this difference was no longer evident.

The variability of each of the intra- and inter-joint couplings investigated did not differ between women and men, regardless of condition or phase. However, in all cases, coupling variability was smaller during the initial 25% than during the last 75% of landing.

4.4 Discussion

Previous research indicates that intense exercise has deleterious effects on landing mechanics that are consistent with an increased risk of non-contact knee injury (Chappell et al. 2005; Kernozek et al. 2007; McLean et al. 2007). A recent study (Kipp and Pavol 2009) also found that prolonged effects of intense exercise persist for at least two days following a bout of intense exercise. Of note, however, all of these previous studies have analyzed landing mechanics by extracting data that focus on a single degree of freedom at a single joint (e.g. knee flexion angle or external knee abduction moment). Yet, a general consensus exists that non-contact knee injuries result from a combination of lower extremity loading and motion patterns. Examining the coupling and coupling variability between degrees of freedom within and across the joints of the lower extremity may be more effective in addressing this consensus. The purpose of this study was to determine if a single bout of fatiguing exercise would lead to acute and prolonged changes in inter- and intra-limb coupling variability. In addition, given the greater incidence of ACL injury in women, it was of interest to determine whether changes in coupling variability would differ between women and men.

Participants experienced an acute decrease in leg power and in drop vertical jump height after completion of the exercise circuit. Together, these measures indicate that isolated and functional lower extremity performance was compromised, respectively. Leg muscle power recovered to pre-testing levels within 48 hours in both women and men. Vertical jump height however returned to pre-testing levels only in men. Lower extremity muscle soreness experienced by participants

significantly increased from the first day to the 48 hour testing session and was similar between women and men. Although we did not make any histological or biochemical measures of muscle damage, the increased muscle soreness experienced by participants on the second day of testing likely indicates the presence of some structural damage.

The exercise protocol had an acute effect on coupling variability in women and men. These changes, however, did not depend on sex. Immediately after exercise, the variability of knee flexion-knee internal/external rotation, hip internal/external rotation-knee abduction/adduction, hip internal/external rotation-knee internal/external rotation, and knee internal/external rotation-ankle inversion/eversion couplings increased. An increase in the variability of joint coupling is generally considered to be associated with more flexible coordination patterns that are more adaptable to environmental perturbations (Hamill et al. 1999). This increased adaptability is thought to effectively mitigate external perturbations and subsequently decrease the risk of non-contact knee injury (Pollard et al. 2005). The increase in coupling variability in response to acute exercise may thus represent a compensatory strategy.

The dynamic coupling of knee internal/external rotation and ankle inversion/eversion essentially describes foot pronation. Kernozek et al. (Kernozek et al. 2005) have suggested that effective foot pronation may characterize a strategy used to absorb ground reaction forces, minimize impact energy transferred to the knee, and thus decrease ACL load. The increased variability and subsequent adaptability may more effectively deal with sudden deleterious changes in external forces and decrease the risk of non-contact knee injury. The observed increases in knee flexion-knee

internal/external rotation variability may corroborate this suggestion and dynamically link the couplings at the ankle joint to those at the knee joint as one of the rotations in both couplings involves knee transverse motion.

We also observed an acute increase in hip internal/external rotation-knee abduction/adduction coupling variability. Prospective evidence suggests that high amounts of knee valgus motion are associated with increased risk of knee injury (Hewett et al. 2005). While greater variability does not necessarily imply greater knee valgus motions, the coupling variability of hip internal/external rotation and knee abduction/adduction may be particularly important as they may combine to synergistically increase the amount of potentially deleterious dynamic valgus motions. Others (McLean et al. 2007) have reported that acute exercise deleteriously increases the amount of knee valgus during landing, consistent with an increased risk of injury. The observed changes in knee abduction/adduction couplings in the present study, however, do not appear deleterious. As discussed earlier, an increase in joint coupling variability is generally considered to be positive in that it allows for more flexible coordination patterns in response to potentially dangerous perturbations (Hamill et al. 1999; Pollard et al. 2005). Increased adaptability in coordination patterns that involve frontal plane knee motions may act to counter potentially dangerous knee excursions.

The variability in hip internal/external rotation-knee internal/external rotation coupling also increased immediately after the exercise protocol, albeit only during the first 25% of landing. Again, the increased variability in joint coupling is likely a protective strategy, especially since it occurs during the initial part of the landing. The first 25% of the landing phase is characterized by high impact forces that may result in

a potentially dangerous knee joint loading, since the magnitude of the ground reaction force during landing determines a large portion of the load experienced by the ACL (Pflum et al. 2004). A positive change in landing strategy during the early part of the landing phase would thus be particularly beneficial in ameliorating risk of knee injury. We also observed that the coupling variability for all couplings was greater during the last 75% than during the initial 25% portion. This phase-dependent difference is likely due to the characteristics associated with each phase. Increased variability is typically observed around transition points where movement patterns tend to change. Since the latter part of the landing phase during the drop vertical jump consists of a transitioning from joint flexion to joint, we may expect to see increased variability during this phase. Similarly, these results indicate that the initial part of landing, where the coupling variability was observed to be low, may be associated with less likelihood of responding to changes in movement patters and external perturbations and thus precipitate a greater risk of ACL injury.

While the exercise protocol in our study led to acute changes immediately after exercise, there were no changes that persisted to the testing session 48 hours following. While several studies (Avela and Komi 1998; Kuitunen et al. 2002) demonstrate changes in jumping and landing mechanics performance following exhaustive stretch-shortening cycle exercise that last for several days, none of these studies have examined effects on joint coupling variability. Typically measures of joint coupling variability appear to be more sensitive than peak kinematic and kinetic values in revealing differences in joint coordination or interaction (Pollard et al. 2005). It is possible that the exercise protocol used in our study was not intense

enough to elicit long-lasting changes in muscular performance. Since individuals had to regularly participate in activities that involve repeated jumping or power training to be included in the study, it may be that their training status negated any lasting deleterious effects. However, participants did report a significant increase in muscle soreness on the second day of testing. While we did not observe any prolonged changes in landing mechanics after a single bout of exercise, it may be possible that repeated bouts could compound and eventually lead to mechanical changes during jumping or landing activities consistent with risk factors associated with non-contact knee injury. Since tournament play for certain sports, such as handball, may involve 7-10 games over a span of 10-14 days (Ronglan et al. 2006), an inquiry into the cumulative affects on risk factors associated with ACL injury may be warranted.

Coupling variability in the lower extremity did not differ between women and men during the drop vertical jumps in our study. Only one other study has examined lower extremity joint coupling variability between men and women (Pollard et al. 2005). The authors of that study found that during an unanticipated cutting-maneuver, women displayed lower levels of variability for several lower extremity joint couplings than men. The discrepancy between the aforementioned study and our study may lie in the maneuvers that were chosen to be analyzed or in the experience level of the participants. The unanticipated nature of the cutting task used by Pollard (Pollard et al. 2005) would serve to increase the task complexity, while the drop vertical jump in our study limits the role of central processing. Additionally, in the cutting study, the approach speeds were controlled to remain sub-maximal, whereas

each of the present drop vertical jumps required maximal effort. It is possible that the maximal nature of the drop vertical jump requires a distinct set of motor commands that remain impervious to exercise and would not differ between women and men (Rodacki et al. 2002). Differences in skill level (recreationally trained in our study vs. college soccer players) may also explain the lack of sex-differences in our study, as the nature of variability in multi-joint systems changes with the skill of the performer (Davids et al. 2003). It thus appears that women and men of equal skill levels perform drop vertical jumps with similar amounts of variability in lower extremity coupling. Comparing coupling variability between women and men across a variety of tasks and skill levels or before and after skill acquisition may offer additional insight into sex-differences with regard to non-contact knee injury risk.

This study expands the body of knowledge on coordination patterns during a drop vertical jump in women and men and how these patterns change with exercise. Although, we did not observe any sex differences in joint coupling variability, acute exercise did significantly affected several coupling parameters. The increases in joint coupling variability appear consistent with a compensatory strategy aimed to maximize the dynamic stability of the lower extremity chain in response to the effects of acute exercise. The absence of any changes in joint couplings variability, observed in both women and men, during the 48hr condition suggest that coordination patterns remain unaffected by prolonged effects of exercise.

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Table 4.1

Mean±SD intra-joint coupling variability (degrees) of the knee joint during landing

		Pre		**Post**		**48Hr**	
Coupling	Phase	Women	Men	Women	Men	Women	Men
KneeFlx-KneeAb/Add	25%	7.9±2.7	8.0±3.4	17.1±22.1	11.1±5.1	7.0±1.9	9.7±6.3
	75%†	29.0±8.4	28.7±5.7	36.3±15.1	31.4±9.8	27.8±6.1	31.0±15.9
KneeFlx-KneeI/ERot	25%	10.1±3.0	10.9±2.9	1.3±25.8*	8.4±17.2*	9.8±2.7	12.7±5.5
	75%†	23.9±5.3	22.8±5.8	4.3±20.4*	30.7±16.0*	22.6±4.4	27.9±17.6
KneeAb/Add-KneeI/ERot	25%	55.9±30.9	59.4±30.0	59.2±28.1	54.4±19.0	44.8±16.8	50.6±15.7
	75%†	79.3±21.2	73.9±13.8	74.0±15.9	81.8±16.3	67.0±16.7	70.6±20.7

* $p<0.05$ for pre vs. post condition; † $p<0.05$ for first 25% vs. last 75% of landing
Flx = flexion, Ab/Add = abduction/adduction, I/ERot = internal/external rotation

Table 4.2

Mean±SD of hip/knee inter-joint coupling variability (degrees) during landing

		Pre		**Post**		**48Hr**	
Coupling	Phase	Women	Men	Women	Men	Women	Men
HipFlx-KneeFlx	25%	4.3±1.0	6.1±3.1	14.1±25.5	9.1±5.0	4.1±0.9	7.5±6.9
	75%†	19.2±4.3	18.5±5.7	32.0±29.7	22.6±10.5	18.3±4.7	21.9±13.6
HipAb/Add-KneeAb/Add	25%	61.7±24.4	59.9±22.7	59.5±19.3	54.7±16.7	55.2±22.0	55.0±19.6
	75%†	81.1±12.5	78.3±16.9	75.3±15.5	79.0±15.8	67.1±15.4	70.1±17.5
HipAb/Add-KneeI/ERot	25%	53.9±22.8	51.4±21.9	65.9±32.8	57.5±23.0	54.4±24.9	46.4±13.8
	75%†	77.6±20.3	70.0±16.9	82.3±14.5	73.5±21.4	71.9±20.6	62.7±22.4
HipI/ERot-KneI/ERot§	25%	43.4±12.4	52.3±25.3	63.3±26.2*	59.7±20.0*	47.0±28.8	54.0±24.7
	75%†	75.5±16.5	74.1±14.3	78.9±17.3	73.9±17.5	70.4±16.8	70.3±18.8
HipI/ERot-KneeAb/Add	25%	51.5±20.8	51.0±24.7	63.6±15.3*	64.7±24.2*	50.0±22.0	51.9±18.4
	75%†	72.9±15.9	75.9±14.5	80.0±16.1*	76.8±14.9*	72.2±20.5	79.5±13.5

* $p<0.05$ for pre vs. post condition; † $p<0.05$ for first 25% vs. last 75% of landing, § $p<.05$ for Condition x Phase interaction
Flx = flexion, Ab/Add = abduction/adduction, I/ERot = internal/external rotation

Table 4.3

Mean±SD of knee/ankle inter-joint coupling variability (degrees) during landing

		Pre		**Post**		**48Hr**	
Coupling	Phase	Women	Men	Women	Men	Women	Men
KneeFlx-AnkleFlx/Ext	25%	6.8±6.2	7.8±3.7	16.0±26.5	9.2±3.2	5.3±1.1	8.5±4.6
	75%†	17.3±5.2	19.5±5.3	27.2±21.7	23.5±7.2	17.0±4.9	22.0±16.5
KneeI/ERot-AnkleInv/Ev	25%	27.1±9.2	25.8±12.8	39.5±19.7*	32.7±15.6*	26.2±6.6	29.9±16.3
	75%†	61.1±11.8	57.4±22.3	75.5±15.7*	68.7±20.2*	61.5±13.2	65.2±19.7
KneeAb/Add-AnkleInv/Ev	25%	25.8±12.8	24.6±12.7	33.2±16.8	29.6±11.6	24.7±9.2	29.2±23.1
	75%†	67.6±17.7	66.1±11.5	69.6±15.1	72.1±12.6	61.5±13.7	71.2±18.7

* $p<0.05$ for pre vs. post condition; † $p<0.05$ for first 25% vs. last 75% of landing
Flx = flexion, Ab/Add = abduction/adduction, I/ERot = internal/external rotation, Inv/Ev = inversion/eversion

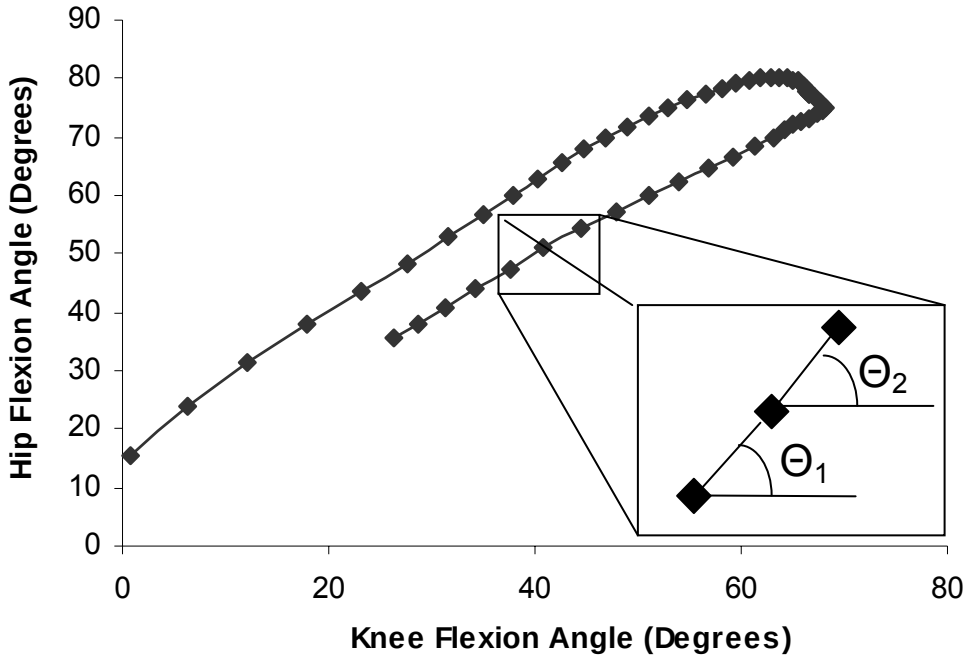

Figure 4.1: Angle-angle graph illustrating the calculation of a single coupling angle over time between successive intervals

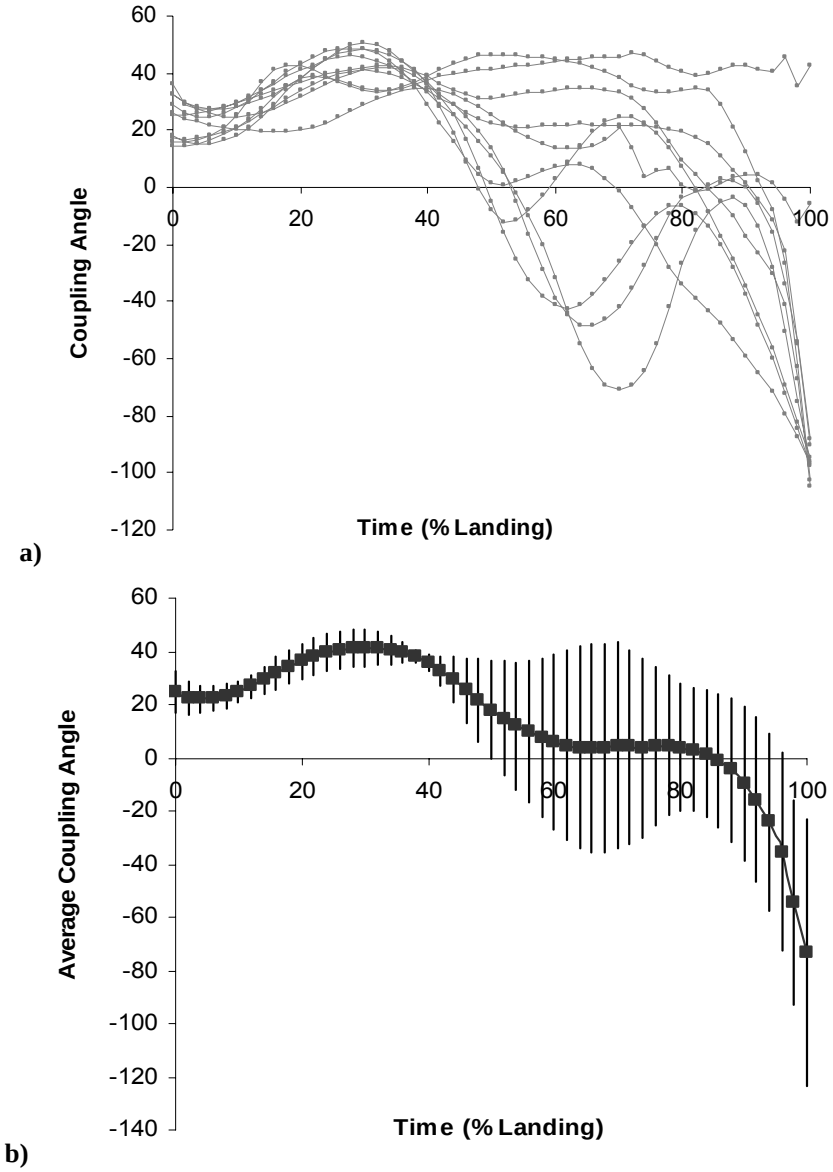

Figure 4.2: a) Time-normalized coupling angles for a representative participant; b) Ensemble average of mean coupling angle with standard deviation bars indicating the coupling variability over time

5. Conclusions

The purpose of this study was to determine if a single bout of exercise would lead to acute and prolonged changes in landing biomechanics and whether these changes would differ between women and men. Previous research indicated that intense exercise has acute deleterious effects on landing mechanics that are consistent with an increased risk of non-contact knee injury, specifically to the anterior cruciate ligament (ACL) (Chappell et al. 2005; Kernozek et al. 2007; McLean et al. 2007). No study had attempted to investigate whether any prolonged effects of intense exercise on potential biomechanical risk factors for ACL injury remain over the days following. Furthermore, most studies had analyzed standard kinematics and kinetics measures, such as peak joint angles and moments. Relatively few had attempted to use more innovative methods to identify sex-differences or exercise-related changes in coordination or movement patterns that might be associated with ACL injury risk. As differences in joint coordination and movement patterns are thought to be very important in regards to the sex-bias in ACL injury rates, it was believed that such analyses might provide new insight into the potential underlying mechanisms of this bias. In addition, the application of these methods would potentially expand our understanding of how the negative effects of fatigue interact to precipitate risk of injury.

In order to determine the acute and prolonged effects of fatigue on potential risk factors for ACL injury during landing, we identified the extent to which the effects of a fatiguing activity were apparent both at the end of and two days after the activity. In two sessions, approximately 48 hours apart, biomechanical data were

collected during a participant's execution of the landing and subsequent take-off phases of a drop vertical jump. Participants completed a fatigue protocol during the first testing session until they were either volitionally fatigued, their drop jump height decreased by more than 10% from its initial value, or they were judged to be unable to safely continue. We then compared the un-fatigued drop vertical jumps to the fatigued drop vertical jumps on the first day and to the drop vertical jumps on the second day to determine the acute and prolonged effects of fatigue, respectively. Participants also performed a muscle power test on a flywheel leg-press machine pre- and post-fatigue on the first day of testing, as well as on the second day of testing, in order to objectively quantify the acute and prolonged changes in lower extremity power.

Participants experienced an acute decrease in leg power and in drop vertical jump height at completion of the exercise circuit. Together, these measures indicate that isolated and functional lower extremity performance was compromised, respectively. Leg muscle power recovered to pre-testing levels within 48 hours in both women and men. Vertical jump height however returned to pre-testing levels only in women. Lower extremity muscle soreness experienced by participants significantly increased from the first day to the 48 hour testing session and was similar between women and men. Although we did not make any histological or biochemical measures of muscle damage, the increased muscle soreness experienced by participants on the second day of testing likely indicates the presence of some structural damage.

The first part of this dissertation focused on analyzing the data set with respect to traditional biomechanical measures that included joint angles at touchdown and

peak joint angles and peak joint moments during landing. The analysis revealed that the fatiguing exercise acutely resulted in smaller knee flexion angles, but greater plantarflexion angles at touchdown. Peak hip abduction angle was also greater immediately after exercise. Peak internal hip abduction, hip internal rotation, knee external rotation, and knee abduction moments were greater immediately after exercise, while peak hip and knee extension moments decreased. It appears that potentially deleterious changes in landing kinetics immediately after exercise were countered by protective changes in landing kinematics at the hip but not the knee. While none of the observed exercise-induced changes depended on sex, women and men did exhibit numerous differences in these traditional biomechanical variables. Most notably, women exhibited smaller hip abduction and less knee flexion at touchdown, but greater peak hip flexion and knee abduction angles. Women also displayed smaller peak hip extension and knee adduction moments during landing. The observed sex-differences were generally consistent with those previously reported across a variety of tasks and generally suggest a higher risk of ACL injury in women. A novel finding of the first analysis was that, in both sexes, no prolonged deleterious effects of exercise with regards to potential ACL injury risk were observed in the joint angles at touchdown or in the peak joint angles and peak joint moments during landing 48 hours after the initial bout of exercise.

The second part of this dissertation used principal components analysis to extract joint movement patterns and patterns of joint moments from the data set. This analysis method has the ability to give information beyond traditional biomechanical analyses that focus on discrete quantitative parameters from kinematic and kinetic

waveforms, such as the first analysis of this dissertation. Since principal components analysis extracts common, underlying patterns from waveform data based on patterns of variability, it has a distinct advantage over traditional data analysis techniques in that it has a higher sensitivity, reduces the dimensionality of a data set, and detects differences across entire waveforms, including differences in timing and patterning of motion. Similar to the first analysis, the results from the principal components analysis revealed that the fatiguing exercise had significant immediate effects on landing biomechanics. The principal components analysis, however, not only showed that these changes occurred across the entire landing, but also that a few of the changes in magnitude and timing were restricted to specific parts of the landing phase. Most notably, though, the principal components analysis was able to detect prolonged changes in kinematic and kinetic waveforms. Sagittal-plane knee and ankle joint motion and moments showed marked acute and, except for knee motion, prolonged decreases in magnitude throughout the entire landing. Ankle plantarflexion moments also showed selective reductions during the mid-to-late portion of the landing phase. Frontal- and transverse-plane patterns of hip motion also changed and appeared to be consistent with a compensatory strategy, likely compensating for changes that were observed in sagittal-plane hip motion and moments. The principal components analysis also detected sex-differences in landing patterns consistent with results from the first analysis and with literature reports that suggest a higher risk of ACL injury in women. However, similar to the first analysis, none of the exercise-induced changes depended on sex.

The third and last part of this dissertation used a modified vector-coding technique to analyze the variability of joint coupling during landing. Most analytic methods in biomechanics focus on extracting values from a single joint and a single plane of motion, such as in the first and second parts of this dissertation. Yet, it is generally agreed upon that knee injuries result from a combination of lower extremity loading and motion patterns. It was believed that examining the coupling variability between and within the degrees of freedom of the joints of the lower extremity could effectively address this issue. The vector-coding method demonstrated that acute exercise significantly affected several coupling parameters. Most notably the variability in knee internal/external rotation-ankle inversion/eversion, and hip internal/external rotation-knee abduction/adduction coupling increased immediately after exercise. The immediate increases in variability appear to be consistent with a compensatory strategy aimed to maximize dynamic stability and exploit a greater range of coordination patterns of the lower extremity chain in response to the adverse effects of acute exercise. None of the couplings investigated exhibited a prolonged or delayed change in coupling variability following the exercise bout. No effect of sex was inherent in joint coupling variability or in the effect that exercise had on this measure.

As a whole, this study provided important new findings regarding the acute and prolonged effects of fatiguing exercise on landing mechanics in women and men. There were some limitations to the study, however. A general limitation common to all analyses was the lack of a true control group. Although all statistical analyses used a repeated-measures design to test for differences, without a separate control group it

may not be entirely clear whether any of the prolonged effects resulted from the exercise protocol or due to participants' learning. This limitation should be especially considered in the interpretation of the results from the principal components analysis, as that analysis was the only one to show significant prolonged effects. However, participants also experienced a significant increase in soreness on the second day of testing, which again would indicate that the exercise protocol led to noticeable changes during the 48hr testing session. Although muscle soreness was significantly elevated on the second day of testing, lower extremity muscle power was not compromised, which may suggest that the exercise protocol was not intense enough to elicit prolonged changes in muscle function. Further, on the second day of testing the drop vertical jump height remained depressed only in men and may be due to sex-differences in fatigability as women did perform more rounds of the exercise protocol than men. In addition, the drop vertical jump represents a relative simple movement and may not be sensitive enough to expose complex interactions between sex and exercise-induced changes in landing mechanics. Finally, we only examined prolonged changes in landing mechanics in an initial state on the second day of testing and it remains to be seen if a subsequent bout of exercise would exacerbate deleterious changes in knee joint loading even further.

It may be prudent for future research to focus on the cumulative effects of exercise conducted in multiple bouts over short or longer time periods, such as extended tournament play or the course of an entire sport season, respectively. Different exercise protocols should also be useful in addressing the difference in fatigue resistance between sexes. An exercise protocol of set duration aimed to mimic

game-play (e.g. 10 minute quarter), combined with more intense or game-like exercises may thus prove useful. Considering individual responses to exercise may also elucidate exercise-induced changes that are otherwise masked by pooling women and men into groups. In addition, future training studies may find it beneficial to use methods such as principal components analysis or vector-coding in evaluating the effects of interventions aimed to reduce non-contact knee injuries in women and men.

Our original hypotheses were that: 1) an intense bout of exercise would acutely influence movement biomechanics, patterns, and coordination in a manner consistent with increased risk of ACL injury; 2) the effects would still be observable two days later; and 3) the effects would differ between women and men. Each of the three parts of this dissertation attempted to address these hypotheses, albeit through slightly different means. In addition to a traditional biomechanical analysis, we used principal components analysis and vector-coding methods in attempts to capture more subtle variations between sexes and testing conditions. Each of these analyses added unique perspectives in testing the hypotheses. While all analyses showed an acute effect of exercise, only the principal component analysis showed prolonged effects. Further, the vector-coding method was the only method to definitively show immediate protective changes in lower limb mechanics in response to exercise. Surprisingly, none of the observed effects of the fatiguing exercise depended on the sex of participants. Thus, an intense bout of exercise 1) acutely changes landing mechanics, patterns of motion, and joint coordination; 2) causes long-lasting changes in patterns of motion; and 3) affects men and women equally.

These results translate into three primary findings. First, although the observed sex-differences in landing patterns were consistent with literature reports, the immediate and prolonged effects of fatigue did not differ between women and men. This suggests that exercise-induced changes in landing patterns do not explain a portion of the observed sex-bias in ACL injury rates. Second, although the majority of acute effects of fatigue appeared to indicate a shift to protective and compensatory strategies that would serve to decrease risk of injury, a few of the effects were consistent with an increased risk of ACL injury in women and men. This suggests that ACL injury prevention programs should aim to ameliorate exercise-induced changes in knee mechanics so as to prevent exercise-related increases in ACL loading and potential injury risk. Third, only motion patterns, not peak joint angles and moment magnitudes remained changed into the second day of testing. Thus, the absence of negative prolonged effects on deleterious knee positions and loading after the initial bout of exercise suggests that, with respect to ACL loading and the relative risk of ACL injury, it would be safe to engage in successive bouts of exercise or to compete two days apart. These findings expand the body of knowledge concerning the effects of intense exercise on risk of ACL injury in women and men, and should provide justifications in designing preventative exercise interventions and rationales for scheduling practices and competition matches.

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APPENDIX

LITERATURE REVIEW

LITERATURE REVIEW

ACL Injury. The anterior cruciate ligament functions as a restraint to anterior translation of the tibia with respect to the femur. It also functions as a secondary stabilizer in the frontal plane and controls rotation of the tibia on the femur. Excessive motion at the tibiofemoral joint in any of the anatomical planes may thus stress the ACL. Moreover, cadaver studies show that in-vivo loading of the ACL increases when movements from different planes are combined (Markolf et al. 1995). Combinations of any of the following external loadings that are known to place the ACL at increased risk of injury are simultaneous anterior tibial shear, varus, valgus, and internal rotation or external rotation (Markolf et al. 1995). However, the knee is part of a kinetic chain and motion at joints other than the knee, such as the ankle and hip, may also contribute to ACL injury (Griffin et al. 2006).

The most common high-risk situation for non-contact ACL injury appears to involve rapid deceleration during athletic maneuvers such as cutting and landing. At the time of injury, positions of the lower extremity during these maneuvers may display decreased hip flexion, extension at the knee, knee valgus, tibial rotation, and ankle eversion (Griffin et al. 2006). Together, these positions may lead to an excessive three-dimensional valgus motion at the knee. This 3-D valgus collapse, sometimes referred to as dynamic valgus, may collectively be represented as a combination of femoral adduction, knee abduction, and foot pronation (Hewett et al. 2005). Excessive dynamic valgus during landing is proposed to be potentially injurious to the ACL. Prospective evidence shows that dynamic valgus is a significant predictor of risk of ACL injury in adolescent female athletes (Hewett et al. 2005).

Biomechanical Risk Factors. Biomechanical and neuromuscular risk factors are thought to be most the important reasons for the difference in ACL injury rates between women and men (Griffin et al. 2006). Specifically, three factors are proposed to be most deleterious: altered muscular activation patterns, stiffness, and differing movement patterns (Griffin et al. 2006). Studying the biomechanical components of these risk factors is important, as it may lead to a greater understanding of the mechanisms of injury and help delineate the sex-bias (Griffin et al. 2006).

To prevent an injury during the performance of dynamic athletic tasks, a sufficient level of joint stability is needed. In order to satisfy the functional demand for joint stability, a balanced level of coactivation between agonist and antagonist muscles is required (Markolf et al. 1976). Conversely, an unbalanced level of coactivation may prove detrimental in regard to risk of injury. At the knee joint, excessive quadriceps activation without sufficient hamstring activation may increase the risk of ACL injury (Myer et al. 2004). It is thought that an imbalanced activation of the quadriceps actively loads the ACL, because the line of action of the quadriceps may increase anterior translation of the tibia with respect to the femur. As women display greater quadriceps activation than men in preparation for and during landing, a quadriceps-dominant muscle activation pattern during landing is thus implicated as a contributor to the greater risk of ACL injury in women (Chappell et al. 2007; Malinzak et al. 2001; Myer et al. 2004).

Joint stability is modulated through coactivation strategies that in turn are influenced by various types of joint, muscle, and leg stiffness as well as the associated stiffness recruitment strategies (Padua et al. 2005). Padua et al. (Padua et al. 2005)

showed that, although men and women display similar levels of leg stiffness during hopping, women achieved this stiffness through greater activation of the quadriceps and soleus muscles. The muscular recruitment strategies chosen by women to achieve sufficient stiffness may be potentially harmful to the ACL, as a quadriceps-dominant recruitment strategy would increase the net internal knee extension moment, which again would increase anterior translation of the tibia with respect to the femur.

Women perform dynamic tasks with different movement patterns than men (Decker et al. 2003b; Ford et al. 2005; Huston et al. 2001). During the execution of dynamic tasks such as landing and cutting, women typically exhibit a more erect posture in the sagittal plane (e.g. less hip and knee flexion) and display greater knee joint excursions in the frontal plane than men (Decker et al. 2003a; Ford et al. 2005; Kernozek et al. 2007). Women also experience different joint loadings than men (Kernozek et al. 2005). On average, women exhibit significantly greater anterior shear forces at the knee during the landing phase of stop-jump tasks than men (Chappell et al. 2005; Kernozek et al. 2005). Women also demonstrate greater internal knee extension moments during a variety of landing tasks (Chappell et al. 2002). Furthermore, women display greater external abduction moments at the knee during a drop-jump task than men (Chappell et al. 2005; Hewett et al. 1996). The latter finding is significant, because prospective evidence shows that the peak external knee abduction moment is a significant predictor of risk of ACL injury (Hewett et al. 2005). Collectively, these sex-differences in movement patterns appear to predispose women to a greater risk of injury.

Altered muscular activation patters and sex differences in stiffness appear to be significant neuromuscular contributors to the sex bias in ACL injuries. Together these two factors can be expected to result in biomechanical changes that would in turn lead to changes in movement patterns. The between-sex differences in neuromuscular and biomechanical factors thus appear to be highly interrelated.

Quantifying Movement Patterns and Coordination. As stated earlier, differences in movement patterns and coordination are thought to be among the greatest contributors to the sex-bias in ACL injury rates. Traditionally, the associated biomechanical aspects have been analyzed by subjectively extracting parameters from kinematic and kinetic waveforms. Limitations to these techniques include the subjective nature and the limited information on the variability of the chosen parameters, as well as the loss of temporal information with respect to sequencing and coordination of movements. However, two techniques exist that may effectively remedy these problems: principal components analysis and a dynamical systems technique. The multivariate analysis technique of principal components analysis (PCA) extracts common, underlying patterns from waveform data based on variability. It has a distinct advantage over traditional data analysis techniques in that it 1) has a higher sensitivity, 2) reduces the amount of variables in a data set, and 3) detects group differences across entire waveforms (Landry et al. 2007a, b). The second type of analysis uses a vector-coding technique to express the extent of between-joint interaction and intra-limb coupling in terms of a relative phase angle (Pollard et al. 2005). This technique is often used in the analysis of dynamical systems. A significant advantage of this method is that it combines the position and velocity

measures of two joints into a single variable. Since studies have found that women and men exhibit differences in discrete lower extremity posture at multiple joints, there exists a need to capture the between-joint coordination (Decker et al. 2003a; Huston et al. 2001; Kernozek et al. 2005).

Both approaches have been used successfully in the analysis of biomechanical differences between women and men during athletic maneuvers (Landry et al. 2007a, b; Pollard et al. 2005). Landry et al. (Landry et al. 2007a, b) used PCA to show that women and men use different biomechanical patterns to execute a side-cut or a run-crosscut maneuver. While these studies showed similar differences in lower extremity biomechanics to those previously reported in the literature, they were the first to show that these differences existed across the entire time-course of the executed tasks. Pollard et al. (Pollard et al. 2005) used the dynamical systems approach that incorpoated a modified vector-coding technique to examine sex differences in the variability of lower extremity joint couplings during an unanticipated cutting maneuver. They found that women exhibited less coordination variability than men. The authors suggested that less flexible coordination patterns in women during dynamic tasks may be related to risk of ACL injury, as women may prove to be less adaptable to the environmental perturbations experienced during competition. Interestingly, traditional kinematic and kinetic analysis of the same data set had previously failed to identify sex differences (Pollard et al. 2004).

Principal components analysis and vector-coding methods thus appear to be ideal to investigate movement patterns and coordination, respectively. The

application of these methods to study fatigue-induced differences may also prove beneficial.

Acute Fatigue. Fatigue is commonly described as exercise-induced reductions in the force- or power-generating capacity of the neuromuscular system (Enoka and Duchateau 2008; Komi 2000). While these impairments are readily described, their etiology is not clear. The mechanisms that underlie these impairments may stem from changes in any of the physiological processes that generate muscle force, such as generation of motor commands, action potential transmission, excitation-contraction coupling, or actin-myosin interaction (Enoka and Duchateau 2008). These processes are typically divided into two categories: central and peripheral, which are defined as processes that occur proximally and distally to the neuromuscular junction, respectively. While athletes certainly encounter both types of fatigue over the course of a match or practice, it has been suggested that peripheral muscle fatigue is inevitable (McLean et al. 2007). Peripheral fatigue may in part be related to the level of endurance conditioning. Not considering an effect of conditioning, central or neural fatigue may therefore play a more prominent role in terms of precipitating risk of injury.

Studies have shown that neural mechanisms attempt to compensate for the fatigue-induced loss in muscle force-generating capability. Zhang and Rymer (Zhang and Rymer 2001) showed that compensatory changes following a fatigue protocol are modulated through alterations in neural reflex activity. Specifically, gains in the dynamic stretch reflex may offset a reduction in muscle stiffness. The stiffness at a joint is regulated through a combination of neural feedback gain and muscle activation

level (Osu and Gomi 1999). The latter plays an integral role, as it provides coactivation of the musculature that surrounds the joint and thus contributes to dynamic joint stability.

During fast single-joint movements, fatigue increases the duration of the agonist burst while it delays the timing of the antagonist burst (Corcos et al. 2002). Taken together, this would increase the movement time, adversely affect movement coordination among muscles, and possibly influence the ability of the motor system to reach equilibrium positions (Corcos et al. 2002). Wojtys and Huston (Wojtys et al. 1996) showed that fatigue slows the muscle reflex activation during a postural perturbation. Delays in cortical-level activity were associated with increases in anterior tibial displacement after fatigue. These authors suggested that fatigue affects the dynamic stability of the knee such that it alters the neuromuscular responses to anterior tibial translation, a potential risk factor for ACL injury.

Acute Fatigue & Risk of Knee Injury. Isolated neuromuscular fatigue has a negative influence on lower-limb joint control and may precipitate the risk of injury (Wojtys et al. 1996). In game situations such as soccer, for example, it is reported that a large percentage of non-contact knee injuries occur either towards the end of the first half or the end of the game (Hawkins and Fuller 1999; Hawkins et al. 2001). More recently, whole-body functional fatigue has been implicated to affect neuromuscular factors that are thought to be associated with ACL injury risk during various jumping and hopping tasks (Chappell et al. 2005; Madigan and Pidcoe 2003; McLean et al. 2007; Padua et al. 2006).

Muscular recruitment strategies and stiffness are among the neuromuscular factors associated with risk of knee injury that are influenced by fatigue (Padua et al. 2006). Padua et al. (Padua et al. 2006) investigated the effects of fatigue on muscle activation and leg stiffness recruitment strategies during hopping and showed that, with the onset of fatigue, both women and men exhibited a quadriceps-dominant strategy. Both men and women showed an increase in EMG activity of the quadriceps with fatigue while maintaining a similar level of vertical leg stiffness. However, women failed to increased the activation of the hamstrings which effectively decreased the coactivation ratio of quadriceps to hamstrings (Padua et al. 2006; Padua et al. 2005). This may predispose women to greater risk of injury than men, as a lack of coactivation may have a negative influence on risk of knee injury. Furthermore, an increase in quadriceps muscle activity could lead to an increase in anterior tibial shear force, particularly in the absence of hamstring muscle contribution to co-activation at the knee. Theoretically, these changes would tend to increase loading of the ACL (Chappell et al. 2005; Hewett et al. 2005; Markolf et al. 1995). The changes in muscular recruitment patterns and stiffness control would also change the associated movement strategies. Since these changes are thought to be associated with risk of ACL injury, fatigue may be a negative influence on this risk.

Fatigue may precipitate greater risk of knee injury through exposure to harmful joint loadings and positions (Chappell et al. 2005; Kernozek et al. 2007; Madigan and Pidcoe 2003; McLean et al. 2007). Fatigue-induced changes in joint positions during landing occur in all anatomical planes (McLean et al. 2007). McLean et al. (McLean et al. 2007) showed that fatigue increased frontal and transverse plane angles, while

Pidcoe and Madigan (Madigan and Pidcoe 2003) showed that fatigue increased knee joint flexion during a fatiguing landing activity. The increased range of motion at the knee joints is consistent with the aforementioned dynamic valgus that is thought to be associated with risk of knee injury. Additionally, Chappell et al. (Chappell et al. 2005) showed that fatigue significantly decreased the knee flexion angle at the time of peak anterior tibial shear. Decreased knee flexion angles during landing are suggested to increase stress on the ACL, because the protective effects of coactivation at these positions may become compromised due to changes in insertion angles between muscles and bones (Yu and Garrett 2007). Another study also showed that anterior shear forces at the knee increased to a significantly greater extent in women than in men after fatigue (Kernozek et al. 2007). No sex- or fatigue-related differences have been found in internal extension moments at the knee. However, external valgus loading at the knee during jumping tasks was found to be acutely greater after an exhausting bout of exercise in two studies (Chappell et al. 2005; McLean et al. 2007). McLean et al. (McLean et al. 2007) also noted a temporal shift in peak knee external valgus loading in fatigued women. The loading peak moved much closer to the initial contact where non-contact ACL injury is thought to occur. The women in the study by McLean et al. (McLean et al. 2007) further showed an increase in rotational moments about the knee. Combined with increased external valgus loading, the increase in rotational moment may present a manifestation of the mechanism of injury in women. The combined changes in joint loading and movement patterns that occur with acute fatigue may thus collectively increase the risk of knee injury.

Long-lasting Fatigue. A single bout of fatiguing exercise has negative consequences on neuromuscular performance that may last for several days. This is particularly true when the exercise involves lengthening actions or repeated stretch-shortening cycles (SSC). Repeated active muscle lengthening or SSC may lead to muscle damage and, ultimately, to similar changes in joint control strategies as observed with acute fatigue (Clarkson 1997; Komi 2000). The difference between acute fatigue and muscle damage, though, lies in the fact that the recovery of neuromuscular function from muscle damage remains compromised for several days (McHugh et al. 1999). Muscle damage may therefore precipitate the risk of injury as long as the negative effects are still present.

The inflammation process that follows an activity that causes muscle damage may, in part, help explain the delayed recovery of neuromuscular function (Kuitunen et al. 2002). Muscle inflammation is attributed to biochemical substances, such as creatine-kinase (CK) and lactic acid. Avela et al. (Avela et al. 2006) observed that increases in CK-activity after intensive SSC exercise occurred in parallel with decreases in neural reflex activity. Additionally, the rate of recovery of stretch reflex function after SSC exercise is related to the metabolic clearance rate of CK (Komi 2000). These results indicate that substances related to muscle damage may lead to an inhibition of reflex and muscle function. Kuitunen et al. (Kuitunen et al. 2002) showed that exhausting SSC exercise also led to decreased ankle and knee joint stiffness during a drop jump maneuver. The recovery of joint stiffness took between 2 to 4 days. This long-lasting decrease in joint stiffness may result in compromised joint control and coactivation strategies (Avela and Komi 1998). Furthermore, the

decrease in joint stiffness was related to greater joint range of motion and lower joint moments. With regards to risk of injury, this may effectively mean that participants completed the task with riskier movement patterns, while also lacking proper muscle control. While these studies repeatedly demonstrated the dramatic long-lasting effects of a single bout of exercise on movement patterns and muscle activation, none have examined these effects with regards to risk of injury or sex differences (Avela and Komi 1998; Kuitunen et al. 2002).

Following intense stretch-shortening cycle exercises that induce muscle damage, muscles may take up to 2 weeks to repair (Clarkson 1997). After the period of repair, however, muscles appear to be able to tolerate the same exercise task not only with less damage but also with faster recovery (Clarkson 1997). This is known as the repeated bout effect (McHugh et al. 1999). This effect may protect against future muscle damage. It is thus possible that an increased tolerance to damage would ameliorate the negative long-lasting effects of a fatiguing bout of exercise (McHugh et al. 1999). Preparing muscles for the trauma and damage invoked by repeated high force generation thus might ameliorate fatigue-induced risks of injury (Komi 2000).

Summary. While studies have shown deleterious effects of acute fatigue on risk factors for ACL injury, none of these studies attempted to identify the potential negative consequences of the long-lasting effects that are also known to follow a single bout of fatiguing exercise. Furthermore, most studies have analyzed standard kinematics and kinetics measures. Relatively few have attempted to use more innovative methods to identify sex differences in coordination or movement patterns that might be associated with ACL injury risk. As differences in coordination and

movement pattern are thought to be very important in regards to the sex-bias in ACL injury rates, the use of non-linear or statistical methods would provide novel insight into the potential underlying mechanisms of this bias. Furthermore, the application of said methods would potentially expand our understanding of how the negative effects of fatigue interact to precipitate risk of injury.