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Research article

The effect of gender and fatigue on the biomechanics of bilateral landings from a jump: Peak values

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Abstract
Female athletes are substantially more susceptible than males to suffer acute non-contact anterior cruciate ligament injury. A limited number of studies have identified possible biomechanical risk factors that differ between genders. The effect of fatigue on the biomechanics of landing has also been inadequately investigated. The objective of the study was to examine the effect of gender and fatigue on peak values of biomechanical variables during landing from a jump. Thirty-two recreational athletes performed bilateral drop jump landings from a 40 cm platform. Kinetic, kinematic and electromyographic data were collected before and after a functional fatigue protocol. Females landed with 9° greater peak knee valgus ($p = 0.001$) and 140% greater maximum vertical ground reaction forces ($p = 0.003$) normalized to body weight compared to males. Fatigue increased peak foot abduction by 1.7° ($p = 0.042$), peak rectus femoris activity by 27% ($p = 0.018$), and peak vertical ground reaction force ($p = 0.038$) by 20%. The results of the study suggest that landing with increased peak knee valgus and vertical ground reaction force may contribute to increased risk for knee injury in females. Fatigue caused significant but small changes on some biomechanical variables. Anterior cruciate ligament injury prevention programs should focus on implementing strategies to effectively teach females to control knee valgus and ground reaction force.

Key words: Anterior cruciate ligament injury, injury prevention, knee injury, sports biomechanics.

Introduction

Anterior cruciate ligament (ACL) tear is a debilitating sports injury with an estimated 80,000 ACL occurrences in the United States annually (Griffin et al., 2000; Miyasaka et al., 1991; Pedowitz et al., 2003). The literature almost unanimously suggests that females are substantially more susceptible than males in suffering acute non-contact injury of the ACL (Arendt and Dick, 1995; Delfico and Garrett, 1998; Gray et al., 1985; Griffin, 2001; Hutchinson and Ireland, 1995; Messina et al., 1999; Powell and Barber-Foss, 2000; Stevenson et al., 1998; Tillman et al., 2002). The ACL injury rate in females is higher in a variety of exercise activities such as soccer (2-6 times higher), basketball (4-10 times higher) and military training (10 times higher) (Arendt and Dick, 1995; Gray et al., 1985; Griffin, 2001; Hutchinson and Ireland, 1995; Messina et al., 1999; Powell and Barber-Foss, 2000).

A conference on the prevention of ACL injuries sponsored by the American Orthopaedic Society for Sports Medicine in 1999 issued a consensus statement suggesting that biomechanical and neuromuscular factors appear to be the most important factors associated with ACL injury and the higher incidence of injury in female athletes (Griffin, 2001). A primary recommendation of the conference was that research efforts should focus on the investigation of biomechanical risk factors (Griffin, 2001; Harmon and Ireland, 2000) during activities that can cause knee injury, such as landing from a jump. Two-thirds of ACL injuries occur via a non-contact mechanism, and the majority of these injuries occur at landing from a jump (Arendt and Dick, 1995; Boden et al., 2000; Gray et al., 1985; Griffin et al., 2000; 2001; Hewett et al., 1999; Kirialanis et al. 2003; Kirkendall and Garrett, 2000).

Although the ACL gender bias is likely multifactorial, three main theories have been proposed to explain the higher incidence of female ACL injury: the ligament dominance theory (Hewett et al., 2001), the quadriceps dominance theory (Hewett et al., 2001), and the straight knee landing theory (Huston et al., 2001). The ligament dominance theory suggests that the lower extremity muscles do not adequately absorb the impact of landing, resulting in knee valgus which causes increased loading of the ACL (Ford et al., 2003). The quadriceps dominance theory suggests that females tend to rely on their quadriceps more than their hamstrings creating excessive anterior translation of the tibia (Ford et al., 2003; Hewett et al., 1996; Huston and Wojtys, 1996). The straight knee landing theory suggests that females exhibit less knee flexion at the time of impact that may lead to ACL injury either by hyperextension or by anterior tibial translation (Decker et al., 2003; Huston et al., 2001). The present study investigated whether there is support for these three theories in a controlled laboratory environment by collecting biomechanical data for males and females as they are landing from a drop jump.

Fatigue is another factor that has been linked to athletic injuries. Several epidemiological studies support the notion that fatigue is a predisposing factor responsible for increased number of injuries (Bottini et al., 2000; Gabbett, 2000; 2002; Hawkins et al., 2001; Kersey and Rowan, 1983; Rahnama et al., 2002). Despite this, a very limited number of studies have examined the effect of fatigue on biomechanical variables during drop landing (Fagenbaum and Darling, 2003; Madigan and Pidcoe, 2003; Rozzi et al., 1999a) and only one of them (Madigan and Pidcoe, 2003) has used a functional fatigue protocol consisting of tasks that mimic sports activities such as squat and jumping.

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In a study (Rozzi et al., 1999a) of male and female athletes who were fatigued to 25% of their original torque with the use of an isokinetic dynamometer, the researchers found decreased knee proprioception and increased onset of contraction time for the hamstrings and the gastrocnemius as subjects performed a landing task. They found no significant effect of gender or fatigue on balance or anterior tibial translation. However, males exhibited significantly increased mean vastus lateralis normalized EMG (NEMG) after fatigue compared to females (Rozzi et al., 1999a). The authors acknowledged that a significant limitation of their study was the non-functional fatigue protocol (isokinetic) (Rozzi et al., 1999a). Madigan and Pidcoe (2003) looked at the effects of a functional fatigue protocol on the biomechanics of landing but all subjects were male and the authors did not collect frontal plane knee kinematic data.

Fagenbaum and Darling (2003) concluded that fatigue had a similar effect on males and females but they used an isokinetic fatigue protocol which may not have replicated the fatigue that athletes experience during sports. Chappell et al. (2005) suggested that a fatigue protocol of vertical jumps and sprints caused subjects to land with increased proximal tibia peak anterior shear forces and decreased knee flexion at the time that peak anterior shear forces occur. Moreover, females landed with an external knee valgus moment that was increased in the post-fatigue condition while males exhibited an external varus moment. Females also exhibited a greater external knee flexion moment that the authors suggested may be due to increased quadriceps contraction, decreased hamstrings contraction or a combination of both conditions. However, NEMG data was not collected to further clarify the mechanism that leads to an increased external knee flexion moment.

The primary aim of the present study was to determine the effect of gender and fatigue on peak NEMG, kinetic, and kinematic variables during bilateral drop landings from a 40 cm platform. We hypothesized that females will exhibit landing biomechanics that predispose them to knee injury [greater knee valgus, greater vertical ground reaction force (VGRF)] and that males and females will land with increased knee valgus, VGRF, and NEMG activity of the rectus femoris and hamstrings after the fatigue protocol.

Methods

The study was conducted at the Harkness Dance Center Motion Analysis Laboratory, NYU - Hospital for Joint Diseases. It was a repeated measures pre-fatigue and post-fatigue experimental study using measures of EMG, kinetic, and kinematic data.

Based on a power analysis of the findings of a pilot study (3 males and 3 females) this study required 32 subjects to answer the hypotheses with a power of 0.8 and α level of 0.05. Power analysis was performed with the use of G Power for knee valgus, VGRF, and rectus femoris NEMG (Buchner et al., 1997).

Thirty-two subjects were recruited from universities and colleges in the New York City area via announcements during classes. Only healthy volunteers between the ages of 20-40 years were recruited because this age group is more susceptible to ACL injury (Griffin, 2001). The inclusion criteria included participation in recreational sports at least twice/week for a minimum of 45 min. per practice session.

Exclusion criteria were: obesity (body mass index greater than 30 $kg \cdot m^{-2}$); a history of injuries and/or diseases that would render unsafe the execution of the protocol; and a history of injuries and/or diseases that could affect the biomechanics of landing such as lower extremity fractures. Subjects were excluded if they had received specialized training in jumping and landing techniques such as through participation in gymnastics or dance.

All 32 subjects completed the entire protocol (pre-fatigue data collection, fatigue protocol, and post-fatigue data collection) in a single session. Subjects performed bilateral landings on a force plate from a 40 cm platform. The height was chosen to allow comparisons with the findings of other investigators who used similar protocols (Decker et al., 2003; Fagenbaum and Darling, 2003; Ford et al., 2003; Madigan and Pidcoe, 2003; Rozzi et al., 1999a; 1999b) and as in these studies all subjects landed from the same height in an effort to minimize variability.

All NEMG and kinematic measurements were in reference to the right lower extremity. The literature supports that athletes injure the dominant and non-dominant extremity with equal frequency (Matava et al., 2002), and therefore comparisons between the dominant and non-dominant limb were not performed.

EMG data were collected with the Noraxon Myosystem 1400 (Noraxon USA, Inc., Scottsdale, AZ). The electrodes were disposable, surface, passive electrodes (Blue Sensor, Ambu, Inc., Linthicum, MD). The force plate was an OR6-5 AMTI biomechanical platform (AMTI, Watertown, MA). Kinematic data were collected with the use of eight Eagle cameras (Motion Analysis Corp. Santa Rosa, CA) and reflective markers were placed as per the “Helen Hayes system” (Richards, 2002). The software for data collection was the EvaRT 4.0 (Motion Analysis Corp. Santa Rosa, CA). Video data were smoothed using a Butterworth fourth order low pass filter with a cut-off frequency of 6 Hz. EMG data were filtered through a low pass 2^{nd} order Butterworth filter with a 6Hz cut-off frequency.

The force platform was time synchronized to the EMG and the motion analysis system. The kinetic and EMG data were sampled at 1200 Hz and the kinematic data were sampled at 240 Hz as appropriate for fast athletic maneuvers. Before each data collection session the system was calibrated to the manufacturer’s recommendations.

Subjects were verbally informed of the study protocol and all risks and possible harms as described in the consent form. All subjects completed a sports activity and medical history questionnaire, signed a consent form approved by the NYU School of Medicine IRB, and were measured for height, weight, knee width, foot width, and foot length.

The skin was prepared and the surface electrodes were placed on the medial gastrocnemius, rectus femoris, biceps femoris, and medial hamstrings as described elsewhere (Fagenbaum and Darling, 2003). These sites of electrode placement are consistent with recent guidelines (Hermens et al., 2000) and are located between the motor point and the distal tendon in order to improve intra and inter-subject comparison reliability (Basmajian and DeLuca, 1985). Two electrodes were placed on each muscle at a 20 mm distance and parallel to fiber orientation (Hermens et al., 2000). Athletic tape was used to fixate the electrodes and decrease movement artifact (Hermens et al., 2000). The reflective markers were placed bilaterally on the second metatarsal, calcaneus, lateral malleolus, fibula, lateral knee joint line, thigh, anterior superior iliac spine, acromion, lateral humeral epicondyle, and distal radioulnar joint. Reflective markers were also placed on the sacrum and the left posterior superior iliac spine (offset) as per the "Helen Hayes" system (Richards, 2002). An initial "neutral" standing position of each subject was used to account for skeletal alignment differences as in similar studies (Hewett et al., 2005; Kernozek et al., 2005). With this technique, zero degree angles were defined as the angles between adjacent segments during the neutral standing trial.

The subjects were allowed two practice jumps and then performed three bilateral drop jumps from the 40 cm platform. They were instructed to drop directly down off the box and land with both legs on the force plate. Subjects did not receive any instructions on the landing technique to avoid a coaching effect. The effect of the arms was minimized by asking the subjects to keep their arms crossed against their chest (Rodacki et al., 2002; Decker et al., 2003). Trials were repeated when they were judged as non-acceptable (such as when subjects lost their balance or did not land with both feet on the force plate). Upon completion of three successful jumps, the wires were disconnected from the electrodes (but the electrodes were not removed). The subjects followed the fatigue protocol that consisted of 100 consecutive jumps over short (5-7 cm) obstacles and 50 maximal vertical jumps. This combination of activities was chosen to simulate activities commonly performed in sports and because an eccentric-concentric fatigue protocol is more effective in producing fatigue than a concentric fatigue protocol (Svantesson et al., 1998). The fatigue protocol was designed in a way that the fatigue-induced pattern is applicable to functional activities outside the laboratory setting. The protocol used in the present study is similar to fatigue protocols used in recent research (Chappell et al., 2005; Madigan and Pidcoe, 2003). Similar protocols were sufficient in inducing fatigue as measured by quadriceps force output and jump height (Skurvydas et al., 2000; 2002) and mean EMG frequency (Madigan and Pidcoe, 2003). Moreover, the demands of games such as soccer are very similar for males and females in terms of distance covered, sprint duration, and exercise intensity (Davis and Brewer, 1993) suggesting that laboratory fatigue protocols have greater applicability if they fatigue male and female athletes in a similar way as occurs on the athletic field. After the fatigue protocol was completed, the wires were re-connected to the EMG electrodes and the same procedure of landings was repeated for the post-fatigue part of data collection. All subjects completed all post-fatigue trials within six minutes after the completion of the fatigue protocol. The landing cycle was defined as the time between initial contact and peak knee flexion.

The Orthotrak 5.0 (Motion Analysis Corp. Santa Rosa, CA) software was used to derive kinetic, kinematic, and EMG variables. The peak value for all variables during the landing cycle were identified and averaged across the three trials. The VGRF was normalized to body weight as in previous studies (Hewett et al., 1996; 1999). EMG amplitude was normalized to the maximum linear-enveloped EMG of each muscle (Arampatzis et al., 2003; Horita et al., 1999; Rodacki et al., 2002; Viitasalo et al., 1998) exhibited during the landing phase of bilateral landings from a 20 cm platform (mean of three trials).

Statistical analysis

Gender differences for anthropometric and sports participation variables were tested with independent sample t-tests. A repeated measures MANOVA was performed with the use of a statistical software package (SPSS 12.0, SPSS Inc., Chicago, IL, 60606) with gender and fatigue as independent variables., The dependent variables were peak values for knee flexion, knee valgus, foot abduction, VGRF, quadriceps NEMG, lateral hamstrings NEMG, medial hamstrings NEMG, and gastrocnemius NEMG as well as knee flexion angle at impact. The data were inspected and tested to insure that the assumptions for data normality of the univariate and multivariate repeated measures analysis of variance (ANOVA and MANOVA) were not violated, Separate univariate repeated measures ANOVA were performed for each dependent variable when the MANOVA reached statistical significance ($p < 0.05$) (Bray and Maxwell, 1985; Stevens, 2002). Cohen's d statistic of effect size was calculated in order to give a more complete picture of the effect of the independent variables on the dependent variables. The effect size is defined as trivial if it is <0.2, small 0.2-0.5, medium 0.5-0.8, and large>0.8 (Portney and Watkins, 2000).

Results

Table 1 shows the descriptive statistics of demographic, anthropometric, and sports participation data. There were no gender differences in regards to age and sports activity. As expected, there were differences in the anthropometric variables between genders.

Table 1. Demographic, anthropometric and sports activity data for males and females, p-values of t-test. Data are means (±SD).

	Male (n = 16)	Female (n = 16)
Height (m)	1.82 (.07)	167 (.05) *
Weight (kg)	81 (10)	59 (6) *
Age (yrs)	28.8 (3.9)	28.2 (5.4)
Sports activity (hr/wk)	6.5 (2.9)	6.5 (5.9)

* Significant differences p < 0.001.

The results of the MANOVA showed that the effects of gender ($F_{9,22} = 5.763$, $p < 0.001$) and fatigue ($F_{9,22} = 2.934$, $p = 0.019$) were statistically significant but not the interaction of gender and fatigue ($F_{9,22} = 1.050$, $p = 0.434$).

Table 2. Means, (95% confidence internals) and p-values for gender differences (LSD test) of biomechanical variables measured during landing.

Variables	Males	Females	P-value (Cohen's d)
Peak Knee valgus (°)	6.0 (2.3-9.7)	14.9 (11.2-18.6)	.001 * (1.18)
Peak foot abduction (°)	6.2 (3.2-9.3)	8.7 (5.6-11.7)	.262 (.39)
Peak VGRF (BW)	3.9 (3.3-4.5)	5.3 (4.7-6.0)	.003 * (1.08)
Peak Rectus NEMG (%)	137 (116-157)	159 (138-180)	.132 (.45)
Peak Medial Hamstrings NEMG (%)	127 (94-160)	122 (89-155)	.832 (.07)
Peak Lateral Hamstrings NEMG (%)	113 (87-139)	123 (97-149)	.589 (.16)
Peak Gastrocnemius NEMG (%)	134 (112-157)	122 (99-145)	.438 (.22)
Knee Flexion at contact (°)	20.2 (15.8-24.6)	20.0 (15.6-24.4)	.957 (.02)

* Statistically significant at α=0.05
Abbreviations: LSD = least significant difference, VGRF = vertical ground reaction force, BW = body weight, NEMG = normalized electromyography.

Univariate repeated measures ANOVA revealed that females landed with greater peak knee valgus ($F_{1,30}$ = 12.242, p = 0.001) and peak VGRF ($F_{1,30}$ = 10.548, p = 0.003) but knee flexion at contact was not different between males and females ($F_{1,30}$ = 0.003, p = 0.957). After the fatigue protocol subjects landed with increased peak foot abduction ($F_{1,30}$ = 4.534, p = 0.042), peak VGRF ($F_{1,30}$ =4.7, p = 0.038), and peak rectus NEMG ($F_{1,30}$ = 6.252, p = 0.018). Tables 2 and 3 show the means (95% confidence intervals) and p-values (Cohen's d effect size statistic) for all dependent variables grouped by gender and fatigue condition respectively.

Discussion

The objective of this study was to investigate the effects of gender and fatigue on the kinetics, kinematics, and NEMG of the lower extremity during landing from a drop jump. Gender had a significant effect on one kinematic variable (knee valgus) and the sole kinetic variable studied (VGRF). The findings regarding knee valgus agree with previous studies (Ford et al., 2003; Hewett et al., 2004; Kernozek et al., 2005) demonstrating that females exhibit greater knee valgus than males during landing from a jump. Increased knee valgus may produce excessive stress on the inert structures and lead to traumatic injury, consistent with the ligament dominance theory (Ford et al., 2003; Hewett et al., 2004).

Studies have shown that the knee is in a position of valgus at the time of ACL injury (Boden et al., 2000; Delfico and Garrett, 1998; Griffin, 2001; Griffin et al., 2000; Olsen et al., 2004) and that females exhibit greater peak knee valgus than males in a variety of athletic activities (Ferber et al., 2003; Horita et al., 1999; Kirkendall and Garrett, 2000; Zeller et al., 2003). Moreover, in a prospective study (Hewett et al., 2005), female athletes who subsequently suffered ACL injury were found to have increased peak knee valgus compared to female athletes who did not injure their ACL. The findings of this study provide further evidence that knee valgus is one of the key gender differences that may explain the increased incidence of ACL injuries in females.

The effect of gender on VGRF was also significant with females landing with higher normalized VGRF than males (5.3 BW vs. 3.9 BW). The VGRF reveals the ability of the athlete to efficiently attenuate the impact of landing. The lower the VGRF the more optimal the landing strategy, while high VGRF can lead to knee injuries (Dufec and Bates, 1991; Hewett et al., 1996; 2005). The VGRF findings of the present study show that females experience greater peak impact forces that may predispose them to non-contact injuries as they transfer to more proximal joints of the kinetic chain, such as the knee joint.

To the authors' knowledge, only one more study (Kernozek et al., 2005) has suggested that females landing from a drop jump have increased normalized VGRF compared to males. A study by Hewett et al. (1996) showed that a plyometric training program is effective in reducing peak VGRF in female athletes. VGRF has been shown to be modifiable with training (Hewett et al., 1996), linked to injury risk (Dufec and Bates, 1991; Hewett et al., 1996; 2005) and a significant gender difference as per the findings of the current study. Injury prevention programs should consider training females to land with a decreased VGRF in order to decrease risk of ACL injury.

Gender did not have a statistically significant effect on the peak NEMG of any of the muscles measured. However, females landed with 22% higher rectus femoris

Table 3. Means, (95% confidence internals) and p-values for the effect of fatigue (LSD test) of biomechanical variables measured during landing.

Variables	Pre-fatigue	Post-fatigue	P-value (Cohen's d)
Peak Knee valgus (°)	10.6 (7.9-13.3)	10.3 (7.5-13.1)	.719 (.03)
Peak foot abduction (°)	6.6 (4.2-9.0)	8.3 (6.1-10.5)	.042 * (.26)
Peak VGRF (BW)	4.5 (4.1-5.0)	4.7 (4.3-5.2)	.038 * (.14)
Peak Rectus NEMG (%)	134 (102-148)	161 (140-183)	.018 * (.53)
Peak Medial Hamstrings NEMG (%)	115 (98-131)	134 (97-171)	.245 (.36)
Peak Lateral Hamstrings NEMG (%)	106 (88-123)	131 (104-157)	.056 (.40)
Peak Gastrocnemius NEMG (%)	125 (113-137)	132 (105-158)	.595 (.12)
Knee Flexion at contact (°)	20.8 (17.9-23.7)	19.4 (15.9-22.8)	.077 (.16)

* Statistically significant at α=0.05
Abbreviations: LSD = least significant difference, VGRF = vertical ground reaction force, BW = body weight, NEMG = normalized electromyography.

NEMG activity compared to males. It is important to recognize that comparison of NEMG muscle activity depends on the normalization method. In the present study, we normalized to peak EMG activity that was exhibited when each subject performed a similar task (landing from a 20 cm platform). Task specific EMG normalization has been reported to be superior to maximum voluntary contraction (MVC) for cyclical activities (Arendt-Nielsen and Sinkjaer, 1991; Kamen and Caldwell 1996) and to exhibit less variability between and within subjects (Burden et al., 2003; Yang and Winter, 1984). However, the lack of statistical significance in regards to the effect of gender on rectus femoris NEMG in the present study may be explained by the similarity of the task that was used for normalization to the 40 cm landings. That is, females may have landed with higher rectus femoris activity from the 20 cm platform compared to males; therefore, the normalization method would have minimized the NEMG gender differences during the 40 cm landings. A different normalization method may have resulted in significant gender differences relative to rectus femoris NEMG. Fagenbaum and Darling (2003) normalized to MVC and reported that females landed with higher quadriceps NEMG activity but did not provide details on the magnitude of the difference which precludes comparisons with the findings of the present study. Zeller et al. (2003) investigated gender differences during a single leg squat task and also normalized to MVC and reported that females exhibited 47% higher mean rectus femoris NEMG than males.

The effect of fatigue on male and female athletes who participated in the present study was significant relative to three variables: peak VGRF, peak foot abduction, and peak rectus femoris NEMG. Although the changes in VGRF were statistically significant, the clinical significance is questionable; males and females landed with increased forces after the fatigue protocol by 0.13 BW (3.4% increase) and 0.34 BW (6.5% increase) respectively. It is unclear to what degree an increase of this magnitude can be said to contribute to injury. These findings, however, are opposite those of Madigan and Pidcoe (2003) who reported that fatigue caused a 12% decrease in peak VGRF in a group of men. The difference in results may be due to the methodology used by Madigan and Pidcoe (2003); they did not test female subjects that contributed most of the peak VGRF increase in the present study and they fatigued subjects to exhaustion. Another difference between the two studies is that the level of fatigue was not measured in the present study; therefore some subjects may have been fatigued by the protocol more than other subjects. The VGRF increase in the current study suggests that athletes' ability to attenuate the impact of landing decreases after fatigue.

In the present study, subjects in the post-fatigue condition exhibited a significant increase in foot abduction from 6.6° to 8.3° The role of foot abduction in the occurrence of ACL injury is unclear, however some have suggested that it leads to increased knee valgus (Lin et al., 2001) and subsequent knee injury, although in the present study fatigue did not cause a significant increase in knee valgus. Further research is needed to clarify the role of foot abduction on the mechanism of ACL injury.

Subjects in the post-fatigue condition exhibited a statistically significant increase of rectus femoris NEMG ($F_{1,30} = 6.252$, $p = 0.018$). This finding, however, does not mean that quadriceps forces were higher after fatigue. Although the NEMG activity was higher, the ability of the muscle fibers to develop tension decreases with fatigue. Dimitrova and Dimitrov (2003) critically reviewed the literature and reported that fatigue can cause an increase, decrease, or insignificant change on the NEMG amplitude during dynamic activities, however, most studies have shown that fatigue increases the amplitude of quadriceps EMG activity (Bonnard et al., 1994; Nummela et al., 1994; Psek and Cafarelli, 1993; Rodacki et al., 2001; Viitasalo et al., 1993). The findings of the present study also suggest that fatigue causes an increase in muscle activity when measured by dynamic EMG.

Previous studies (Decker et al., 2003; Huston et al., 2001) have provided support to the straight knee landing theory by reporting that females land with their knees closer to extension than males. However, the findings of the present study are in agreement with recent studies (Fagenbaum and Darling, 2003; McLean et al., 2004) that do not support the straight knee landing theory. Males and females landed with very similar knee flexion angles at the time of impact (20.2° vs. 20.0°, $F_{1,30} = 0.003$, $p = 0.957$).

The effectiveness of sports injury prevention programs has been well documented both in epidemiological studies that showed a decrease of athletic injuries (Cerulli et al., 2001; Hewett et al., 1999; Myklebust et al., 2002) and in laboratory studies that showed a decrease in peak VGRF (Hewett et al., 1996). However, the outcomes of these programs may improve if they focus on variables that have been identified by biomechanical studies as reflecting genuine differences due to gender or fatigue and have been proven to be modifiable. In the present study, females landed with greater peak knee valgus and peak VGRF than males. Fatigued subjects exhibited increased peak VGRF and peak rectus femoris NEMG. The findings of the present study may be used to guide injury prevention programs designed to improve the landing technique of female athletes involved in sports. Control of these variables will likely reduce landing patterns that result in high VGRF, increased stress on the passive structures, and subsequently, ligamentous injuries.

Limitations

The present study was performed in a controlled laboratory environment where subjects knew exactly what to expect. Although this allows accurate comparison between groups, it does not closely simulate the athletic environment. Most ACL injuries are non-contact in nature but there are additional unexpected factors during a game such as decreased friction of the floor surface, motion of the opponent, or miscalculation of ball motion that make landing from a jump more unpredictable and dangerous than in a laboratory setting. Moreover, the landing task itself was not identical to the landing technique observed in the athletic field since we instructed subjects to keep their arms crossed across their chest and jump down from a platform. These modifications decrease the generalizability of the findings to the athletic field.

All subjects were recreational athletes who participated at least twice per week in a variety of sports that involved jumping. There were no differences between males and females in regards to hours of sports participation per week. However, this does not insure equal proficiency in drop landings; some subjects might have been more proficient than others in landing from a jump. We also did not objectively measure the effect of the fatigue protocol on the volunteers' musculoskeletal system. A more homogenous group of subjects such as recreational basketball or volleyball players would make the findings of this study less generalizable but would increase the internal validity of the study.

Finally, a limitation inherent of this study as well as of most sports biomechanics studies is that the values used for statistical analysis were the peak values of the biomechanical variables. Peak values of kinetic, kinematic and NEMG variables would possess greater clinical significance if they were shown to occur at the first part of the landing cycle that coincides with the phase the ACL is loaded (Pflum et al., 2004) and injuries are known to occur (Boden et al., 2000; Griffin, 2001; Olsen et al., 2004).

Conclusion

The present study investigated the effect of gender and fatigue on the biomechanical variables of landing from a jump. The findings show that females land with increased peak knee valgus and VGRF suggesting that the stress on the inert structures can become excessive and lead to traumatic injury. Fatigue elicited a similar response in males and females, resulting in significantly increased peak VGRF, peak foot abduction, and peak rectus femoris NEMG activity.

Future research should identify where within the landing cycle peak values occur and more fully examine variables within the early phase of the cycle where injuries are thought to occur. Consideration should be given in injury prevention programs to include activities that train female athletes to control excessive knee valgus and VGRF during landings from a jump.

References

Arampatzis, A., Morey-Klasping, G. and Bruggemann, G. (2003) The effect of falling height on muscle activity and foot motion during landings. *Journal of Electromyography & Kinesiology* **13,** 533-544.

Arendt, E. and Dick, R. (1995) Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. *American Journal of Sports Medicine* **23,** 694-701.

Arendt-Nielsen, L. and Sinkjaer, T. (1991) Quantification of human dynamic muscle fatigue by electromyography and kinematic profiles. *Journal of Electromyography & Kinesiology* **1,** 1-8.

Basmajian, J. and DeLuca, C. (1985). *Muscles alive*. Baltimore, MD, Williams and Wilkins.

Boden, B.P., Dean, G.S., Feagin, J.A.,Jr. and Garrett, W.E.,Jr. (2000) Mechanisms of anterior cruciate ligament injury. *Orthopedics* **23**, 573-578.

Bonnard, M., Sirin, A., Oddsson, L. and Thorstensson, A. (1994) Different strategies to compensate for the effects of fatigue revealed by neuromuscular adaptation processes in humans. *Neuroscience Letters* **166,** 101-105.

Bottini, E., Poggi, E., Luzuriaga, F. and Secin, F. (2000) Incidence and nature of the most common rugby injuries sustained in Argentina (1991-1997). *British Journal of Sports Medicine* **34,** 94-97.

Bray, J. and Maxwell, S. (1985). *Multivariate Analysis of Variance*. Newbury Park, Sage Publications.

Burden, A., Trew, M. and Baltzopoulos, V. (2003). Normalization of gait EMGs: a re-examination. *Journal of Electromyography & Kinesiology* **13,** 519-532.

Buchner, A., Erdfelder, E. and Faul, F. (1997) How to use G*Power. Available from URL: http://www.psycho.uniduessedorf.de/aap/projects/gpower/how_to_use_gpower.html

Cerulli, G., Benoit, D., Caraffa, A. and Ponteggia, F. (2001) Proprioceptive training and prevention of anterior cruciate ligament injuries in soccer. *Journal of Orthopaedic and Sports Physical Therapy* **31,** 655-660.

Chappell, J., Herman, D., Knight, B., Kirkendall, D., Garrett, W. and Yu, B. (2005) Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. *American Journal of Sports Medicine* **33,** 1022-1029.

Davis, J. and Brewer, J. (1993) Applied physiology of female soccer players. *Sports Medicine* **16,** 180-189.

Decker, M., Torry, M., Wyland, D., Sterett, W. and Steadman, J. (2003) Gender differences in lower extremity kinematics, kinetics, and energy absorption during landing. *Clinical Biomechanics* **18,** 662-669.

Delfico, A. and Garrett, W. (1998) Mechanisms of injury of the anterior cruciate ligament in soccer players. *Clinics in Sports Medicine* **17,** 779-785.

Dimitrova, N. and Dimitrov, G. (2003) Interpretation of EMG changes with fatigue: facts, pitfalls, and fallacies. *Journal of Electromyography & Kinesiology* **13,** 13-36.

Dufec, J. and Bates, B. (1991) Biomechanical factors associated with injury during landing in jump sports. *Sports Medicine* **12,** 326-337.

Fagenbaum, R. and Darling, W. (2003) Jump landing strategies in male and female college athletes and the implications of such strategies for anterior cruciate ligament injury. *American Journal of Sports Medicine* **31,** 233-240.

Ferber, R., McClay Davis, I. and Williams III, D. (2003) Gender differences in lower extremity mechanics during running. *Clinical Biomechanics* **18,** 350-7.

Ford, K., Myer, G. and Hewett, T. (2003) Valgus knee motion during landing in high school female and male basketball players. *Medicine & Science in Sports &Exercise* **35,** 1745-1750.

Gabbett, T. (2000) Incidence, site, and nature of injuries in amateur rugby league over three consecutive seasons. *British Journal of Sports Medicine* **34,** 98-103.

Gabbett, T. (2002), Incidence of injury in amateur rugby league sevens. *British Journal of Sports Medicine* **36,** 23-26.

Gray, J., Taunton, J., McKenzie, D., Clement, D., McKonkey, J. and Davidson, R. (1985) A survey of injuries to the anterior cruciate ligament of the knee in female basketball players. *International Journal of Sports Medicine* **6,** 314-316.

Griffin, L. (2001) *Prevention of noncontact ACL injuries*. Rosemont, IL, American Academy of Orthopaedic Surgeons.

Griffin, L., Agel, J., Albohm, M., Arendt, E., Dick, R., Garrett, W., Garrick, J., Hewett, T., Huston, L., Ireland, M., Johnson, R., Kibler, B., Lephart, S., Lewis, J., Lindenfeld, T., Mandelbaum, B., Marchak, P., Teitz, C. and Wojtys, E. (2000) Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *Journal of the American Academy of Orthopaedic Surgeons* **8,** 141-150.

Harmon, K. and Ireland, M. (2000) Gender differences in noncontact anterior cruciate ligament injuries. *Clinics in Sports Medicine* **19,** 287-302.

Hawkins, R., Hulse, M., Wilkinson, C., Hodson, A. and Gibson, M. (2001) The association football medical research programme: an audit of injuries in professional football. *British Journal of Sports Medicine* **35,** 43-47.

Hermens, H., Freriks, B., Disselhorst-Klug, C. and Rau, G. (2000) Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography & Kinesiology* **10,** 361-374.

Hewett, T., Lindenfeld, T., Riccobene, J. and Noyes, F. (1999) The effect of neuromuscular training on the incidence of knee injury in female athletes. *American Journal of Sports Medicine* **27,** 699-705.

Hewett, T., Myer, G. and Ford, K. (2001) Prevention of anterior cruciate ligament injuries. *Current Womens Health Report* **1,** 218-224.

Hewett, T., Myer, G. and Ford, K. (2004) Decrease in neuromuscular control about the knee with maturation in female athletes. *Joual of Bone & Joint Surg* **86-A,** 1601-1608.

Hewett, T., Myer, G., Ford, K., Heidt, R., Colosimo, A., McLean, S., Van Den Bogert, A., Patterno, M. and Succop, P. (2005) Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes. *American Journal of Sports Medicine* **33,** 492-501.

Hewett, T., Stroupe, A., Nance, T. and Noyes, F. (1996) Plyometric training in female athletes: decreased impact forces and increased hamstring torques. *American Journal of Sports Medicine* **24,** 765-773.

Horita, T., Komi, P., Nicol, C. and Kyrolainen, H. (1999) Effect of exhausting stretch-shortening cycle exercise on the time courseof mechanical behaviour in the drop jump: possible role of muscle damage. *European Journal of Applied Physiology* **79,** 160-167.

Huston, L. and Wojtys, E. (1996) Neuromuscular performance characteristics in elite female athletes. *American Journal of Sports Medicine* **24,** 427-436.

Huston, L.J., Vibert, B., Ashton-Miller, J.A. and Wojtys, E.M. (2001) Gender differences in knee angle when landing from a drop-jump. *American Journal of Knee Surgery* **14,** 215-219.

Hutchinson, M.R. and Ireland, M.L. (1995) Knee injuries in female athletes. *Sports Medicine* **19,** 288-302.

Kamen, G. and Caldwell, G. (1996) Physiology and interpretation of the electromyogram. *Journal of Clinical Neurophysiology* **13,** 366-384.

Kernozek, T., Torry, M., Van Hoof, H. and Cowley, H. (2005) Gender differences in frontal and sagittal plane biomechanics during drop landings. *Medicine & Science in Sports & Exercise* **37,** 1003-1012.

Kersey, R. and Rowan, L. (1983) Injury account during the 1980 NCAA wrestling championships. *American Journal of Sports Medicine* **11,** 147-151.

Kirialanis, P., Malliou, P., Beneka, A. and Giannakopoulos, K. (2003) Occurence of acute lower limb injuries in artistic gymnasts in relation to event and exercise phase. *British Journal of Sports Medicine* **37,** 137-139.

Kirkendall, D. and Garrett, W. (2000) The anterior cruciate ligament enigma: injury mechanisms and prevention. *Clinical Orthopaedics & Related Research* **372,** 64-68.

Lin, C.J., Lai, K.A., Chou, Y.L. and Ho, C.S. (2001) The effect of changing the foot progression angle on the knee adduction moment in normal teenagers. *Gait & Posture* **14,** 85-91.

Madigan, M. and Pidcoe, P. (2003) Changes in landing biomechanics during a fatiguing landing activity. *Journal of Electromyography & Kinesiology* **13,** 491-498.

Matava, M.J., Freehill, A.K., Grutzner, S. and Shannon, W. (2002) Limb dominance as a potential etiologic factor in noncontact anterior cruciate ligament tears. *American Journal of Knee Surgery* **15,** 11-16.

McLean, S., Huang, X., Su, A. and Van Den Bogert, A. (2004) Sagittal plane biomechanics cannot injure the ACL during sidestep cutting. *Clinical Biomechanics* **19,** 828-838.

Messina, D., Farney, W. and DeLee, J. (1999) The incidence of injury in Texas high school basketball. *American Journal of Sports Medicine* **27,** 294-299.

Miyasaka, K., Daniel, D. and Stone, M. (1991) The incidence of knee ligament injuries in the general population. *American Journal of Knee Surgery* **4**, 3-8.

Motion Analysis (2003) *EvaRT 4.0*. Santa Rosa, CA, Motion Analysis.

Myklebust, G., Engebretsen, L., Braekken, I., Skjolberg, A., Olsen, O. and Bahr, R. (2002) Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. *Clinical Journal of Sport Medicine* **13,** 71-78.

Nummela, A., Rusko, H. and Mero, A. (1994) EMG activities and ground reaction forces during fatigued and nonfatigued sprinting. *Medicine and Science in Sports and Exercise* **26,** 605-609.

Olsen, O., Myklebust, G., Engebretsen, L. and Bahr, R. (2004) Injury mechanisms for anterior cruciate ligament injuries in team handball. *American Journal of Sports Medicine* **32,** 1002-1012.

Pedowitz, R.A., O'Connor, J. and Akeson, W. (2003) *Daniel's knee injuries: Ligament and cartilage structure, function, injury and repair*. Philadelphia, Lippincott, Williams & Wilkins.

Pflum, M., Shelburne, K., Torry, M., Decker, M. J. and Pandy, M. (2004) Model prediction of anterior cruciate ligament force during drop-landings. *Medicine & Science in Sports & Exercise* **36,** 1949-1958.

Portney, L. and Watkins, M. (2000) *Foundations of clinical research: applications to practice*. Upper Saddle River, Prentice-Hall.

Powell, J. and Barber-Foss, K. (2000) Sex-related injury patterns among selected high school sports. *American Journal of Sports Medicine* **28,** 385-391.

Psek, J. and Cafarelli, E. (1993). Behavior of coactive muscles during fatigue. *Journal of Applied Physiology* **74**: 170-175.

Rahnama, N., Reilly, T. and Lees, A. (2002) Injury risk associated with playing actions during competitive soccer. *British Journal of Sports Medicine* **36,** 354-359.

Richards, J. (2002) *Orthotrak 5.0*. Santa Rosa, CA, Motion Analysis.

Rodacki, Fowler AL and Ne, B. (2001) Multi-segment coordination: fatigue effects. *Medicine & Science in Sports & Exercise* **33,** 1157-1167.

Rodacki, A., Fowler, N. and Bennett, S. (2002) Vertical jump coordination: fatigue effects. *Medicine & Science in Sports & Exercise* **34,** 105-116.

Rozzi, S., Lephart, S. and Fu, F. (1999a) Effects of muscular fatigue on knee joint laxity and neuromuscular characteristics of male and female athletes. *Journal of Athletic Training* **34,** 106-114.

Rozzi, S., Lephart, S., Gear, W. and Fu, F. (1999b) Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. *American Journal of Sports Medicine* **27,** 312-319.

Skurvydas, A., Dudodiene, V., Kalvenas, A. and Zuoza, A. (2002) Skeletal muscle fatigue in long distance runners, sprinters and untrained men after repeated drop jumps performed at maximal intensity. *Scandinavian Journal of Medicine & Science in Sports* **12,** 34-39.

Skurvydas, A., Jaskaninas, J. and Zachovajevas, P. (2000). Changes in height of jump, maximal voluntary contraction force and low frequency fatigue after 100 intermittent or continuous jumps with maximal intensity. *Acta Physiologica Scandinavia* **169,** 55-62.

Stevens, J. (2002). *Applied multivariate statistics for the social sciences*. Mahwan, Lawrence Erlbaum Associates.

Stevenson, H., Webster, J., Johnson, R. and Beynnon, B. (1998) Gender differences in knee injury epidemiology among competitive alpine ski racers. The *Iowa Orthopaedic Journal* **18,** 64-66.

Svantesson, U., Osterberg, U., Thomee, R., Peeters, M. and Grimby, G. (1998) Fatigue during repeated eccentric-concentric and pure concentric muscle actions of the plantar flexors. *Clinical Biomechanics* **13,** 336-343.

Tillman, M.D., Smith, K.R., Bauer, J.A., Cauraugh, J.H., Falsetti, A.B. and Pattishall, J.L. (2002). Differences in three intercondylar notch geometry indices between males and females: a cadaver study. *Knee* **9,** 41-46.

Viitasalo, J., Salo, A. and Lahtinen, J. (1998) Neuromuscular functioning of athletes and non-athletes in the drop jump. *European Journal of Applied Physiology* **78,** 432-440.

Viitasalo, J.T., Hamalainen, K., Mononen, H.V., Salo, A. and Lahtinen, J. (1993) Biomechanical effects of fatigue during continuous hurdle jumping. *Journal of Sports Sciences* **11,** 503-509.

Yang, J. and Winter, D. (1984) Electromyographic amplitude normalization methods: improving their sensitivity as diagnostic tools in gait analysis. *Archives of Physical Medicine & Rehabilitation* **65,** 517-521.

Zeller, B., McCrory, J., Kibler, B. and Uhl, T. (2003) Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *American Journal of Sports Medicine* **31,** 449-456.

Key points

- Female athletes landed with increased knee valgus and VGRF which may predispose them to ACL injury.
- Fatigue elicited a similar response in male and female athletes.
- The effectiveness of sports injury prevention programs may improve by focusing on teaching females to land softer and with less knee valgus.

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