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Research article

Effects of fatigue on frontal plane knee motion, muscle activity, and ground reaction forces in men and women during landing

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Abstract

Women tear their Anterior Cruciate Ligament (ACL) 2-8 times more frequently than men. Frontal plane knee motion can produce a pathological load in the ACL. During a state of fatigue the muscles surrounding the knee joint may lose the ability to protect the joint during sudden deceleration while landing. The purpose of this study was to investigate the effects of fatigue and gender on frontal plane knee motion, EMG amplitudes, and GRF magnitudes during drop-jump landing. Pretest-posttest comparison group design was used. Twenty-six volunteers (14 women; 12 Men; Mean ± standard deviation age = 24.5 ± 2.7 yrs; height = 1.73 ± 0.09 m; mass = 74.3 ± 11.8 kg) participated in the study. Knee frontal plane ranges of motion and positions, ground reaction force peak magnitudes, and surface EMG RMS amplitudes from five lower extremity muscles (vastus medialis, vastus lateralis, medial hamstring, lateral hamstring, and lateral gastrocnemius) were obtained during the landing phase of a drop-jump. MANOVA and ANOVA indicated that peak GRF significantly ($p < 0.05$; 2.50 ± 0.75 BW vs. 2.06 ± 0.93 BW) decreased during fatigued landings. No other variables exhibited a fatigue main effect, although there was a significant ($p < 0.05$) fatigue by gender interaction for the frontal plane range of motion from initial contact to max knee flexion variable. Follow-up analyses failed to reveal significant gender differences at the different levels of fatigue for this variable. Additionally, no variables exhibited a significant gender main effect. Single subject analysis indicated that fatigue significantly altered frontal plane knee motion, peak GRF, and EMG in some subjects and the direction of differences varied by individual. Fatigue altered some aspects of landing performance in both men and women, but there were no gender differences. Additionally, both group and single subject analyses provided valuable but different information about factors representing neuromuscular control during drop-jump landing.

Key words: ACL, injury, gender differences, drop-jump landing.

Introduction

Injury to the anterior cruciate ligament (ACL) is a devastating event. Women tear their ACL 2-8 times more frequently than men (Rozzi et al., 1999). Numerous studies have investigated the possible reasons why there is such a discrepancy between the sexes. The cause of ACL injuries, has been described as multi-factorial and involves anatomical (Hertel et al., 2004; James et al., 2004; Moul 1998; Trimble et al., 2002), biomechanical (Decker et al., 2003; Hewett et al., 1996; Markolf et al., 1995; McLean et al., 1999), and physiological characteristics (Slauterbeck et al., 2002; Wojtys et al., 2002;). Colby et al. (2000) reported that 70% of all ACL tears occur as a result of a non-contact mechanism. The mechanism of a non-contact ACL injury almost always involves a sudden deceleration or change in direction that occurs during a cutting or a landing maneuver (Hewett et al., 1996; Markolf et al., 1995). Boden et al. (2000) in a retrospective study evaluated videotapes of ACL injuries as they occurred during a sport activity. They reported that 65% of the videotaped injuries were non-contact, all were at foot strike with the knee close to extension, and most demonstrated excessive dynamic valgus collapse.

In a state of fatigue the muscles surrounding the knee joint may lose the ability to protect the joint. Altered neuromuscular control due to fatigue may be reflected by changes in electromyographic (EMG) activity, joint kinematics, and vertical ground reaction force magnitudes, and these changes also may be observed as an altered lower extremity stiffness during landing (James et al., 2006). Altered stiffness during landing has been linked to a decrease in stored elastic energy and possibly a change in the sensitivity and activation of the stretch reflex (Gollhofer et al., 1987; Horita et al., 1996). Alteration of the stiffness during drop landing due to fatigue may negatively affect neuromuscular control of the knee joint, thereby, making it more susceptible to injury (Gollhofer et al., 1987; Horita et al., 1996).

Though it is well known that women tear their ACL more frequently than men, few studies have investigated the role of fatigue in altering knee joint neuromuscular control in both women and men. Therefore, the purpose of this study was to investigate the effects of fatigue and gender on frontal plane knee motion, EMG amplitudes, and GRF magnitudes during drop-jump landing. We hypothesized that women would exhibit: 1) greater dynamic frontal plane motion, 2) less EMG amplitudes, and 3) less GRF magnitudes than men. We also hypothesized that fatigue would result in 4) greater dynamic valgus, 5) greater EMG amplitudes, and 6) less GRF magnitudes in both men and women.

Methods

Experimental design

A pretest-posttest comparison group design was used to evaluate the effects of fatigue and differences between men and women. We tested subjects prior to (pre-) and following (post-) a fatiguing exercise. The independent variables were state of fatigue and gender.

Subjects

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Twenty-six healthy, active volunteers (14 women and 12 men) of average height and weight, between the ages of 18 and 35 years old, participated in the study. None of the subjects reported any prior ACL injury. Activity level was determined by the subject rating his or her activity level based on the Physical Activity Level Scale described by Wojtys et al. (1996; see Table 1). Only the subjects who reported a score of 6 or 8 on the scale were included in the study in order to ensure that subjects were physically capable of completing the required activities, but were not currently engaged in plyometrics. Each subject completed a questionnaire to determine his or her eligibility. Prior to participation in the study each subject read and signed an informed consent that had been approved by the Institutional Review Board (IRB) at the affiliated university.

Table 1. Physical activity level (adapted from Wojtys et al., 1996).

Score	Activities
10	Competitive jumping, turning, twisting sports
8	Recreational jumping, turning, twisting sports
6	Jog, bike, swim, occasional pivoting sports
4	No jumping, turning, twisting sports; swim, bike, jog regularly
2	No jumping, turning, twisting; occasional jog, swim, bike
0	Inactive

Instrumentation

Kinematic assessment: We assessed frontal plane motion of the right knee using a biaxial electrogoniometer with a four channel amplifier (Penny & Giles K100 & XM180, Santa Monica, CA). The rigid arms of the goniometer were affixed to the lateral aspect of the knee with double sided adhesive tape. The proximal arm of the goniometer was affixed to the lateral distal thigh just above the knee joint, while the distal arm was secured to the lateral proximal leg just below the joint. Knee flexion/extension and varus/valgus data were recorded and stored via the analog module of an Ariel Performance Analysis System (APAS) at a sampling rate of 1000 Hz (APAS; Coto De Caza, CA.). The electrogoniometer was zeroed when the subject was standing motionless in the anatomic position.

Ground reaction force assessment: We collected vertical GRF data using a force plate (AMTI OR6-5-2000, SGA-6 amplifier, Watertown MA) via the APAS system (1000 Hz). The GRF data were exported to a laptop computer for analysis with custom laboratory software (Matlab® Version 6.5.1 Mathworks Inc, Natick, MA). From the GRF-time curve, we extracted peak vertical ground reaction force (Pkf) using the analysis program by identifying the greatest value present during the first 600 ms of sampling. The Pkf variable occurred in less than 100 ms and during the landing phase, but an additional 500 ms of data were sampled to ensure acquisition of the relevant kinematic and EMG variables.

Electromyographic assessment: We collected EMG data from five muscles: vastus medialis, vastus lateralis, medial hamstrings, lateral hamstring, and lateral gastrocnemius. The skin was cleaned with isopropyl alcohol, shaved when necessary, and an electrolyte electrode gel was applied to maximize conductivity. Pre-amplified, double differential electrodes with stainless steel contact surfaces (Motion Control, Iomed, Salt Lake City, UT) were placed by palpation on the belly of the muscle while the subject performed an isometric contraction. The electrodes were affixed to the skin using double sided adhesive electrode discs. Electromyographic (EMG) data were sampled (1000 Hz) using the APAS. Specifications of the EMG electrode pre-amplifiers included a common mode rejection ratio of 103 dB, bandwidth of 9 Hz-31 kHz, and an impedance of 100,000 MegaOhms, as reported by the manufacturer. Raw scaled EMG signals in mV from each muscle were normalized to a functional maximum value observed during the non-fatigued condition and reported as a percentage.

Testing procedure

Immediately following the set-up, subjects warmed up on a cycle ergometer for five minutes at a self-selected pace. Following the warm up each subject assumed a testing position on a 50 cm raised platform. Each subject was given verbal instructions, a demonstration by one of the investigators (MPS), and allowed three practice bilateral landings onto the force plate inset into the laboratory floor. Subjects were barefooted during all landing activities. A synthetic turf with two inch padding covered the landing surface, including the force plate, to reduce the risk of injury. The subjects then performed 10 pre-fatigued bilateral landings from the 50 cm raised platform on to the force plate. Ten pre-fatigued landing trials were obtained to ensure a stable baseline performance with which to compare the fatigued landings. The subjects were instructed to step off the raised platform, leading with their right leg, without jumping up. Subjects were instructed to jump for an object suspended from the ceiling as soon as they landed on the ground. The right foot landed on the force plate while the left foot landed on the adjacent floor. After the pre-fatigued data were collected and saved, the subjects began the fatigue protocol, as described by James et al. (2005), which is described briefly here. The subjects stood with their feet on pre-marked areas of the force plate with their knees flexed to 60°. This angle has been reported to generate the greatest torque of the knee extensor mechanism (Ruiter, 2004). They were asked to perform a maximum voluntary isometric contraction (MVC) of the lower extremities by pushing up against an exercise bar that was chained to the floor. The chains were adjusted for each subject so they were in a squat position with 60 degrees of knee flexion during the MVC. The subjects then performed repeated bouts of 15 seconds of maximum isometric contraction and five seconds relaxation until they reached fatigue (less than 50% of their MVC). Force output was monitored by the researcher watching a computer monitor that displayed in real-time the force-time tracing from the force plate. During the contraction phase the subjects were given verbal encouragement to perform with maximize effort. Immediately following the final isometric contraction, when the subject was determined to be fatigued, five fatigue landings from the 50 cm platform onto the force plate were recorded and saved. Five fatigued landings were deemed appropriate for obtaining a stable (reliable) performance, without permitting time for physiological recovery fromthe fatiguing exercise.

Data reduction and analysis

Using the custom laboratory software program, the dependent variables were extracted from the recorded data sets. The dependent variables were frontal plane knee angle at the instant of maximum knee flexion (FPmax), frontal plane knee range of motion during the initial landing phase (ground contact to maximum knee flexion; FPrommax), frontal plane knee angle at 30 degrees of knee flexion (FP30), frontal plane knee range of motion from contact to 30 degrees knee flexion (FProm30), EMG amplitude (root mean square, RMS, during the first 600 ms of landing) and Pkf. We defined dynamic frontal plane motion as the amount of knee motion that occurred in the frontal plane during the dynamic landing phase of the drop-jump landing sequence. Negative values obtained from the electrogoniometer represented valgus motion and positive values represented varus motion. The electrogoniometer data were smoothed (6 Hz; 2-pass, 4th-order, no phase-shift Butterworth digital filter) and the Pkf data were normalized to body weight. Electromyographic signals were digitally filtered with a Butterworth polynomial using a low pass cutoff of 400 Hz, high pass cutoff of 20 Hz, and a notch filter (configured to remove 60 Hz hum) (Winter, 2005). Once the EMG data were filtered, the RMS values were calculated. Root mean square data were then exported into a spread sheet for normalization. We normalized the RMS data by dividing the individual RMS values by the greatest RMS value for each respective muscle during the pre-fatigued condition. Normalized values were converted to a percentage by multiplying the number by 100.

Statistical analysis

We calculated group mean descriptive values for age, height, mass, all experimental variables, and two additional descriptive variables (knee flexion angle at ground contact, KFlexCon, and knee flexion range of motion from contact to max knee flexion, KFlexROM). The hypotheses were tested using a 2 x 2 mixed design repeated measures multivariate analysis of variance (MANOVA), with gender as the between-subjects factor and fatigue state as the within-subjects factor. The experimental dependent variables were FPmax, FPrommax, FP30, FProm30, Pkf, and RMS for vastus lateralis (VL), vastus medialis (VM), medial hamstrings (MH), lateral hamstring (LH), and gastrocnemius (GA). Fatigue, gender, and fatigue by gender interaction were tested at $\alpha = 0.05$ (SPSS 12.0, Chicago, IL). Univariate ANOVAs were used follow-up significant MANOVA main and interaction effects.

In addition to the group analysis, we performed single-subject analyses using the two standard deviation band method (Portney and Watkins, 2009). The baseline measures (pre-fatigued condition) were plotted along with a two standard deviation (above and below the baseline mean) band. The intervention measures (fatigued condition) also were plotted on the same graph. A difference between the baseline and fatigued conditions was considered significant if two consecutive data points in the fatigued condition fell outside of the two standard deviation band (Portney and Watkins, 2009).

Table 2 Means (±SD) of all variables.

Variable	Group	Pre-Fatigue	Fatigue
Pkf	♀	2.31 (.50)	1.81 (.75)
(multiple of BW)	♂	2.71 (.94)	2.36 (1.06)
	♀+♂	2.50 (.80)	2.06 (.93)
KFlexCon	♀	14.4 (7.3)	17.0 (15.0)
(Degrees)	♂	17.7 (5.7)	16.9 (11.3)
	♀+♂	15.9 (6.7)	16.9 (13.2)
KFlexROM	♀	60.5 (8.7)	57.3 (6.6)
(Degrees)	♂	57.5 (7.6)	62.5 (8.3)
	♀+♂	59.1 (8.2)	59.7 (7.7)
FPmax	♀	5.6 (10.5)	4.3 (10.3)
(Degrees)	♂	-2.6 (15.0)[a]	-1.1 (16.5)[a]
	♀+♂	1.8 (13.2)	1.8 (13.5)
FP30	♀	5.4 (5.0)	4.8 (4.9)
(Degrees)	♂	1.9 (5.8)	1.3 (5.3)
	♀+♂	3.8 (5.6)	3.2 (5.3)
FProm30	♀	3.6 (2.5)	3.5 (4.0)
(Degrees)	♂	.4 (3.2)	1.5 (3..0)
	♀+♂	2.1 (3.2)	2.6 (3.6)
FPrommax	♀	3.7 (7.5)	2.96 (8.46)
(Degrees)	♂	-4.2 (12.8)[a]	-.8 (14.2)[a]
	♀+♂	.1 (10.9)	1.2 (11.4)
VL	♀	73.5 (7.7)	73.1 (18.7)
(RMS) (%*)	♂	77.1 (7.4)	87.1 (33.2)
	♀+♂	75.2 (7.6)	79.6 (26.8)
VM	♀	77.5 (6.8)	73.8 (16.3)
(RMS) (%*)	♂	74.1 (9.4)	71.9 (20.3)
	♀+♂	75.9 (8.1)	72.9 (17.9)
MH	♀	71.6 (12.4)	72.8 (30.8)
(RMS) (%*)	♂	70.6 (9.8)	69.1 (28.3)
	♀+♂	71.2 (11.1)	71.1 (29.1)
LH	♀	70.4 (14.0)	78.9 (43.1)
(RMS) (%*)	♂	77.3 (36.2)	89.9 (36.2)
	♀+♂	73.6 (12.1)	84.0 (39.7)
GA	♀	70.8 (7.2)	73.1 (15.1)
(RMS) (%*)	♂	70.2 (7.2)	78.1 (31.3)
	♀+♂	70.6 (7.1)	75.4 (23.6)

[a] negative value indicates valgus; positive value indicates varus. Pkf = Peak vertical ground reaction force, BW = body weight, KFlexCon = Knee flexion angle at initial contact, FPmax = Frontal plane knee angle at maximum knee flexion, FP30 = Maximum frontal plane angle at 30 degrees of knee flexion, FProm30 = Knee range of motion in the frontal plane from 0 degrees of knee flexion to 30 degrees of knee flexion, FPrommax = Knee range of motion in the frontal plane from 0 degrees of knee flexion to maximum knee flexion, VL = vastus lateralis muscle, VM = vastus medialis muscle, MH = medial hamstring muscles, LH = lateral hamstring muscle, GA = gastrocnemius muscle (Lateral head), * = RMS was normalized to a percent of the greatest RMS value, for that muscle, during the pre-fatigue condition.

Results

The data from twenty six subjects (14 women; 12 Men; Mean ± standard deviation age = 24.5 ± 2.7 yrs; height = 1.73 ± 0.09 m; mass = 74.3 ± 11.8 kg) were included in the analysis. The group results revealed that fatigue, but not gender influenced neuromuscular control during the landing performance (see Tables 2 and 3). The results of the MANOVA demonstrated a significant ($p \leq 0.05$) difference between the pre-fatigued and the fatigued conditions but there were no significant ($p > 0.05$) differences observed for gender or the fatigue by gender interaction (see Table 3). Follow-up ANOVA indicated that the Pkf variable significantly differed between conditions (pre-fatigued > fatigued; F = 15.89; p = 0.001; Partial Eta-squared Effect Size = 0.40; Observed Power = 0.97; see Table 2). Additionally, follow-up ANOVA indicated a significant fatigue by gender interaction for FPrommax (F=7.35; p=0.012; Partial Eta-squared Effect Size=0.24; Observed Power = 0.74; see Table 2). Examination of the mean values (see Table 2) suggests that the interaction occurred because female subjects decreased FPrommax by 0.77 degrees during the fatigued condition, while male subjects increased by 3.34 degrees.

Table 3. Summary of 2x2 MANOVA.

Source	Combined Variables		
	Wilks' Lambda	F	p
Fatigue	.29	4.42	.005
Gender	.49	1.89	.13
Fatigue X Gender	.61	1.15	.39

The single subject results revealed additional but differential fatigue effects among individuals (see Table 4 and Figure 1). Only three female and three male subjects exhibited no significant differences between conditions for any of the dependent variables (see Table 4). Three female (21%) and two male (17%) subjects showed a significant increase in FPmax during fatigue. Changes in FPmax were observed in both varus and valgus directions. One female subject exhibited increased varus and the other two exhibited increased valgus with fatigue. Conversely, one male subject exhibited increased varus and the other subject exhibited increased valgus with fatigue (see Table 4). Four female (29%) and six male (50%) subjects showed a significant increase in FP30, which also varied bi-directionally, during the fatigued condition. Two of the four female subjects exhibited increased varus and two displayed increased valgus with fatigue. In comparison, two male subjects showed increased varus, while four displayed increased valgus with fatigue (see Table 4). Three female (21%) and three male (25%) subjects showed a significant increase in FProm30 during the fatigued condition. Two of the three female subjects exhibited an increased amount of varus motion from contact to 30 degrees of knee flexion, while the third subject exhibited increased valgus motion with fatigue. The male subjects exhibited the same patterns of change as the female subjects in the FProm30 variable during the fatigued landing condition (see Table 4). One female (7%) and two male (17%) subjects showed a significant increase in FPrommax during the fatigued condition. The female subject and one of the male subjects exhibited an increase in valgus range of motion, while the other male subject exhibited an increase in varus range of motion with fatigue (see Table 4). The Pkf GRF variable decreased for six female (43%) subjects and four male

Table 4. Results of single-subject analysis (each cell that is occupied indicates that it was significant for that particular variable).

Subject	Pkf	FPmax	FP30	FProm30	FPrommax	VL	VM	MH	LH	GA
3 F		sig var						↑ RMS		
4 F	↓ pkf			sig valg				↑ RMS		
6 F	↓ pkf							↑ RMS		
7 F			sig var	sig var						
9 F	↓ pkf		sig var	sig var		↑ RMS		↑ RMS		
10 F										
12 F	↓ pkf		sig valg							
13 F	↓ pkf								↑ RMS	
15 F		sig valg			sig valg					
19 F										
20 F		sig valg	sig valg							
21 F	↓ pkf								↑ RMS	
22 F								↓ RMS		
23 F										
5 M			sig valg		sig valg			↑ RMS	↑ RMS	
8 M	↓ pkf		sig var							
16 M										
17 M	↓ pkf	sig var	sig var		sig var					↑ RMS
24 M				sig var			↓ RMS			
26 M	↓ pkf					↑ RMS				↑ RMS
28 M			sig valg	sig var		↑ RMS				
29 M										
33 M										
35 M	↓ pkf	sig valg	sig valg	sig valg				↓ RMS		
36 M									↑ RMS	
37 M			sig valg						↑ RMS	

↓ indicates a significant decrease in that variable, ↑ indicates a significant increase in that variable, sig var = significant in the varus direction, sig valg = significant in the valgus direction.

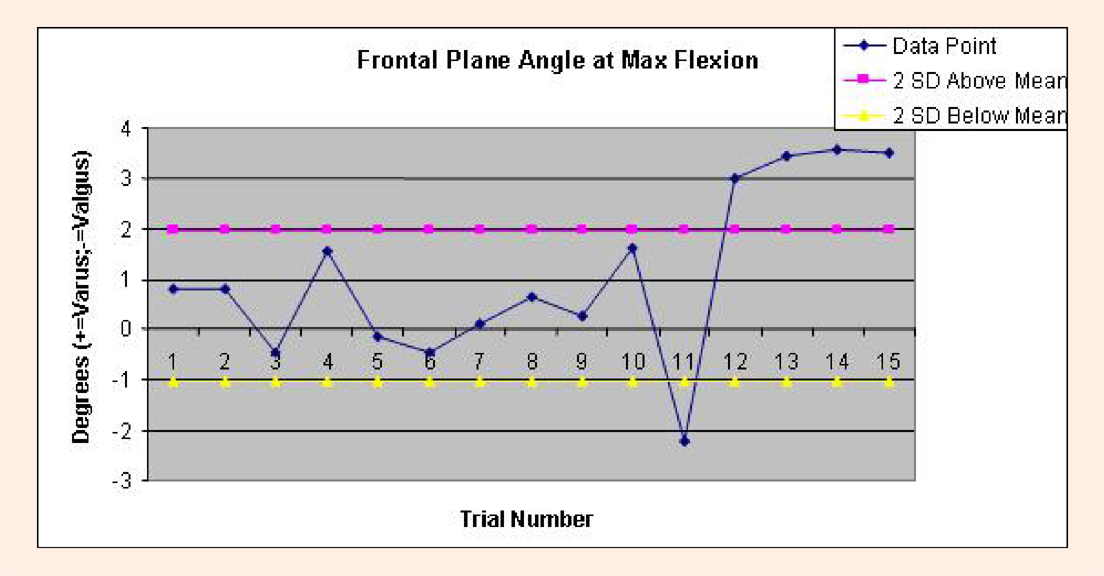

Figure 1. Example of single-subject analysis (2 or more consecutive data points above or below the 2 SD line indicates significance).

(33%) subjects (see Table 4). Finally, 18 of 130 EMG variables (14%) across all subjects exhibited a change in normalized RMS amplitude values during fatigued landings. Fifteen of the EMG variables (12%) increased in amplitude, while three (2%) decreased. The medial and lateral hamstring muscles produced the most frequent increases in RMS amplitude during the fatigued condition (see Table 4).

Discussion

The purpose of this study was to investigate the effects of fatigue and gender on frontal plane knee motion, EMG amplitudes, and GRF magnitudes during drop-jump landing. We hypothesized that women would exhibit: 1) greater dynamic frontal plane motion, 2) less EMG amplitudes, and 3) less GRF magnitudes than men. We also hypothesized that fatigue would result in 4) greater dynamic valgus, 5) greater EMG amplitudes, and 6) less GRF magnitudes in both men and women.

There was a significant fatigue main effect for the Pkf variable and a fatigue by gender interaction effect for the FPrommax variable, but there were no differences between men and women (gender main effect) for any variable. Therefore, the first hypothesis that women would exhibit greater dynamic frontal plane knee motion was not supported. Our results do not support many reports from the literature that men and women differ in frontal plane knee motion (Boden et al., 2000; Derrick, 2004; Hewett et al., 1996; James et al., 2001; Madigan and Pidcoe, 2003; Marson and Goncalves, 2003; McLean et al., 1999; Nyland et al., 1994; Rozzi et al, 2000). The discrepancy between our results and other reports in the literature may be due to differences in the technology used to obtain frontal plane knee motion measurements, differences in subjects, or differences in the activity. First, we elected to use a direct measure of frontal plane knee motion via an electrogoniometer. The goniometer provides a measurement of the frontal plane angle between the thigh and leg and did not account for lower extremity or knee positioning involving thigh or leg rotation. Second, our subjects were college-age recreational athletes and this group of subjects may not exhibit extreme characteristics often observed in trained athletes. Finally, many of the previous studies have investigated the gender differences with activities other than drop-jump landings (Boden et al., 2000; James et al., 2001; McLean et al., 1999; Nyland et al., 1994) and it could be that our 50 cm bilateral landing activity did not elucidate actual differences. Hewett et al. (1996) however, found that high school female athletes, regardless of their physical training level, exhibited excessive frontal plane motion (into the direction of valgus) at the knee when dropping from a 60 cm platform, which was not exhibited by age-matched males. Ford et al. (2003) reported that high school female athletes displayed significantly higher maximum valgus angles than their male counterparts during drop-jump landings. Hewett et al. (2004) reported that mature (high school age) females lost neuromuscular control that lead to increased valgus motion at the knee when compared to immature (pre-pubescent) female subjects. Thus, subject age may have influenced the differences observed in our present study, where we enlisted college-age subjects versus the younger (primary and secondary aged) subjects used in other studies. McLean et al. (2007) reported that fatigue induced greater valgus moments earlier in women than in men during jump landing a jump landing activity, but we did not evaluate joint moments.

The second hypothesis that women would exhibit less EMG amplitudes than men also was not supported. While many women may exhibit less strength than men, the amplitude of neural input to the muscle appears to be similar during drop-jump landing. However, it has been reported that women can generate a greater RMS for quadriceps activation during knee flexion movements (White et al, 2003). Other EMG variables used to assess muscle function include recruitment sequence and timing. These variables have been used to compare genders with conflicting results (Huston and Wojtys, 1996). Therefore, the role of these variables in ACL injury is still unclear and warrants further investigation. The similarities of the EMG amplitudes between men and women in the current study provide further support for the similarities observed in frontal plane knee motion. The men and women in our study may not have differed on these dependent measures, suggesting that individual subject characteristics may have been more important than gender for determining landing performance.

The third hypothesis that women would have less GRF magnitudes than men was not supported. Ground reaction forces are influenced by muscle contraction, body motion, body geometry, and other factors (James, et al, 2006). In the current study, as previously indicated, there were no differences between men and women in frontal plane kinematics or EMG amplitude. Additionally, there appeared descriptively to be no difference between genders in knee flexion angle at contact or knee flexion ROM. These results likely explain the similarities between genders in Pkf, further suggesting that any differences between men and women were superseded by the variations in individual subject characteristics.

The fourth hypothesis that both men and women would have greater frontal plane knee motion during the fatigued landings was not supported by the group analysis. Single subject analyses indicated that some subjects increased valgus during fatigued landings, while other subjects increased varus. Markolf et al. (1995) indicated that both varus and valgus positions of the knee can load the ACL particularly when accompanied by sagittal and transverse plane motions. Therefore, the single subject results observed in our study are important because they might indicate which subjects are at a greater risk of loading the knee ligament systems in either varus or valgus during fatigued landings. The richness of the single subject descriptions suggests that individuals are variable in their behaviors and that different behaviors reflecting altered neuromuscular control of the knee may occur during fatigued drop-jump landing, possibly exposing the ACL to potentially injurious forces. Based on Markolf et al. (1995), we speculate that subjects who demonstrated excessive varus or valgus positional behaviors during landing may have increased risk of ACL injury. Moreover, the variability among subjects may explain why we did not observe the consistent valgus differences between men and women that other investigators have previously reported. Had we limited our analysis to only the aggregate group data and explored only valgus behaviors, we likely would have missed identifying potentially risky knee kinematic behaviors in some subjects.

Similarly, the single subject results revealed several significant increases (varus and valgus) in frontal plane angle at 30 degrees of flexion as a result of fatigue. This may help to explain why the majority of non-contact ACL injuries occur with the knee in less than 30 degrees of flexion (Boden et al., 2000; Colby et al. 2000). In this position the quadriceps muscles are at an optimal angle to provide anterior shear force and the hamstrings are at a mechanical disadvantage to co-contract and protect the ligament systems. Renström et al. (1986) reported that the quadriceps muscles could significantly increase the strain on the ACL at flexion angles less than 45 degrees during simulated isometric and isotonic contractions when compared with passive normal strain. Although there may be an increased strain on the ACL in response to these muscle-generated anterior shear forces, these findings are controversial in terms of their contribution to knee ligament injury. McLean et al. (2004) demonstrated that anterior shear forces cannot reach great enough magnitudes to cause the ACL to fail in subject-specific forward dynamic musculoskeletal models. However, the inability of the hamstrings to co-contract will allow anterior shear force in the sagittal plane, thus limiting the hamstrings' ability to protect the knee joint from frontal plane motions (Colby et al. 2000; Osternig et al., 1995). This combination of motions may be sufficient for producing a pathomechanical load of the ACL.

Single-subject results also revealed that several male and female subjects had significant increases in FProm30 and FPrommax motions during fatigued landings, yet differential responses among subjects precluded definitive group results. Moreover, these increases in ROM were not strictly limited to one direction of movement. The majority of subjects oscillated between varus and valgus throughout knee motion in the sagittal plane. This may help provide insight about neuromuscular control patterns observed during the drop-jump landing activity in our study.

The effect of fatigue on frontal plane motion at the knee joint has not been studied by many researchers. Huston and Wojtys (1996) reported that women rely more on their quadriceps than their hamstrings in response to anterior tibial translation during a fatigued state, which increases strain on the ACL. They also reported that females took significantly longer than males to generate peak hamstring torque during isokinetic testing. However, the Huston and Wojtys (1996) study did not include functional activities and only focused on a single lower extremity. Wojtys and Huston et al. (1996) showed that isotonic and isokinetic strength training of the lower extremity musculature does not appear to improve reaction time to anterior tibial translation, whereas agility exercises do. This result is similar to what has been reported, which indicates agility and plyometric exercise can increase functional stability of the knee by reducing anterior tibial translation and dynamic valgus (Madigan and Pidcoe, 2003; McLean et al., 1999). Wojtys, Wylie, and Huston (1996) reported the effects of muscle fatigue on neuromuscular function and anterior tibial translation in healthy knees. They reported that fatigue does alter the neuromuscular response to anterior tibial translation. Therefore, fatigue may play a role in the pathomechanics of knee injuries.

Osternig et al. (1995) investigated the co-activation patterns of the biceps femoris muscle between healthy knees and ACL injured knees. They reported that during knee extension the hamstrings produced approximately 15 – 40% of the activity in which they produced during knee flexion. This indicates that the hamstrings co-contract during extension trying to help stabilize the knee joint. During fatigue conditions, the ability of the hamstrings to co-contract may be jeopardized thus placing the knee at risk for injury. Rozzi et al. (1999) investigated knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. They reported that women had significantly greater knee joint laxity in the sagittal plane. They also reported that women reached peak hamstring torque quicker than the men. The authors explained this by speculating that due to the increased sagittal plane laxity the hamstrings had reacted quicker in order to protect the knee. They went on to speculate that during a fatigued condition this neuromuscular adaptation may be compromised and contribute to the increased ACL injury rate seen in women (Rozzi et al., 1999).

The fifth hypothesis that fatigue would result in greater EMG amplitudes in both men and women during fatigued landings was not supported by the group analysis. However, several individual subjects (single subject analysis) exhibited significant EMG amplitude changes and the direction of these changes tended to be increases rather than decreases. Additionally, both female and male subjects showed similar amplitude alterations during the fatigued condition. The changes in EMG amplitude likely were not revealed by the group analysis due to the variable response patterns observed among subjects (see Table 2). The medial and lateral hamstring muscles were the most often and consistently affected by the fatiguing exercise. Ten of the twelve significant amplitude changes observed for the medial and lateral hamstring variables during fatigued landings were increases, with six of those occurring in female subjects. Therefore, it seems that an increase in EMG amplitude may indicate fatigue in the hamstring muscles, which could signify an alteration of the neuromuscular protection mechanism of the knee joint (Wojtys, Huston et al., 1996).

Chan et al. (2001) reported a significant increase of the electromechanical delay of the quadriceps muscles, at varying degrees of knee extension, following a fatigue protocol. The most significant delays were when the knee was extended 90 degrees and 150 degrees (Chan et al., 2001) This may explain why the majority of non-contact ACL injuries occur when the knee is at 150 degrees of extension (i.e., 30 degrees of flexion). A consequence of altered joint proprioception due to fatigue is a decrease in neuromuscular control (Huston and Wojtys, 1996). Because of the increased latency periods during the fatigued state, muscles are not able to respond quickly enough to protect a joint from injury. Our results do not appear to support a functional difference between men and women during the fatigued landing activity used in the current study.

The sixth hypothesis that both women and men would have less GRF magnitudes during the fatigued condition was supported. Both men and women showed a significant reduction in Pkf during fatigued landings which is consistent with many studies (Coventry et al., 2006; Horita et al., 1996; Horita et al., 1999; Madigan and Picoe, 2003). Although sagittal plane knee motion was not an experimental variable in our study, descriptively we observed that when men were fatigued they landed with about 5 degrees more knee flexion ROM, while women landed with about 3 degrees less knee flexion ROM. Additionally, we observed that knee flexion angle at contact in women was almost 3 degrees greater during the fatigued landings, whereas the values for men were essentially unchanged. These descriptive kinematic results are important because sagittal plane knee angle and ROM during landing provide insight about implied lower extremity stiffness, which is an important factor in determining GRF magnitudes (James et al., 2006). However, while both men and women had a significant decrease in Pkf as a result of the fatiguing exercise, it appears that their strategies differed. Men appeared to use greater total knee ROM as a landing strategy, which is similar to observations reported by Orishimo and Kremenic (2006), whereas women landed with greater initial knee flexion at contact. Women may have relied more on ankle or hip strategies, possibly landing with greater ankle plantar flexion or hip flexion (or a combination of both) in order to reduce Pkf (Decker et al., 2003; Madigan and Pidcoe, 2003), although ankle and knee kinematics were not measured in our study.

Future research should continue to explore fatigue effects, gender differences, and the role of individual subject characteristics during landing. It also may be beneficial to examine the influence of different types and sites of fatigue. Additionally, investigating neuromuscular training as well as endurance training of the hamstring muscles may be beneficial for providing insight about the protective benefit of the hamstring muscles during activity. Improving neuromuscular control of all muscles crossing the knee joint may help prevent pathological motions believed to be related to ACL injury risk. Finally, further evaluation of varus motion at the knee, its relationship to injury risk, and its interaction with valgus motion may yield further insight into the pathological kinematics that can occur at the knee during fatigued landings.

Conclusion

In conclusion, fatigue altered some aspects of landing performance in both men and women, but there were no gender differences. Additionally, both group and single subject analyses provided valuable but different information about factors representing neuromuscular control during drop-jump landing. Based on the current results, fatigue appears to result in increased frontal plane knee motion in both varus and valgus directions, increased EMG amplitudes of the lower extremity muscles, particularly the hamstrings, and decreased peak ground reaction force magnitudes during landing.

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Key points

- Fatigue reduces ground reaction forces in both men and women during drop-jump landings.
- There was no significant difference in frontal plane knee kinematics between men and women when they were fatigued.
- Men and women did show differences in frontal plane knee kinematics in the fatigued state compared to the pre-fatigued state and the increased motion was in the valgus direction and varus direction.
- Single subject analysis shows that both women and men exhibit characteristics that may predispose them to ACL injury.

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