

Lower Extremity Fatigue, Sex, and Landing Performance in a Population With Recurrent Low Back Pain

Ram Haddas, PhD*; C. Roger James, PhD†; Troy L. Hooper, MPT, PT, ATC†

*Texas Back Institute Research Foundation, Plano; †Texas Tech University Health Sciences Center, Center for Rehabilitation Research, School of Allied Health Sciences, Lubbock

Context: Low back pain and lower extremity injuries affect athletes of all ages. Previous authors have linked a history of low back pain with lower extremity injuries. Fatigue is a risk factor for lower extremity injuries, some of which are known to affect female athletes more often than their male counterparts.

Objective: To determine the effects of lower extremity fatigue and sex on knee mechanics, neuromuscular control, and ground reaction force during landing in people with recurrent low back pain (LBP).

Design: Cross-sectional study.

Setting: A clinical biomechanics laboratory.

Patients or Other Participants: Thirty-three young adults with recurrent LBP but without current symptoms.

Intervention(s): Fatigue was induced using a submaximal free-weight squat protocol with 15% body weight until task failure was achieved.

Main Outcome Measure(s): Three-dimensional knee motion, knee and ankle moments, ground reaction force, and trunk and lower extremity muscle-activity measurements were collected during 0.30-m drop vertical-jump landings.

Results: Fatigue altered landing mechanics, with differences in landing performance between sexes. Women tended to have greater knee-flexion angle at initial contact, greater maximum knee internal-rotation angle, greater maximum knee-flexion moment, smaller knee-adduction moment, smaller ankle-inversion moment, smaller ground reaction force impact, and earlier multifidus activation. In men and women, fatigue produced a smaller knee-abduction angle at initial contact, greater maximum knee-flexion moment, and delays in semitendinosus, multifidus, gluteus maximus, and rectus femoris activation.

Conclusions: Our results provide evidence that during a fatigued 0.30-m landing sequence, women who suffered from recurrent LBP landed differently than did men with recurrent LBP, which may increase women's exposure to biomechanical factors that can contribute to lower extremity injury.

Key Words: clinical biomechanics, rehabilitation, female athletes, anterior cruciate ligament injuries

Key Points

- Sex differences in landing mechanics (fatigued and unfatigued) and neuromuscular control in men and women with recurrent low back pain are similar to the sex differences seen in individuals without a history of low back pain.
- Women experienced a greater knee-flexion angle at initial contact and maximum knee internal rotation, greater maximum knee-flexion moment, smaller maximum knee-adduction and ankle-inversion moments, smaller ground reaction forces at impact, and earlier multifidus activation.
- Reduced knee abduction at initial contact, increased maximum knee-flexion moment, and delayed activation of the semitendinosus, multifidus, gluteus maximus, and rectus femoris muscles were found in both men and women when landing after lower extremity fatigue.
- These changes are consistent with an increased risk of lower extremity injury for women, particularly when landing while fatigued.

Low back pain is a common occurrence in athletes. Estimates of the incidence vary, depending on the sport but range from 10% to 80%.¹ Despite apparent advances in the diagnosis and management of low back pain (LBP), this disorder continues to place a large burden on individuals and society.² Similarly, injuries to the lower extremity frequently affect athletes of all ages, accounting for approximately 53% of all injuries in collegiate athletes.³ Recognizing those at increased risk for back and lower extremity injury and discovering interventions that may reduce that risk are important research goals.

Recently, authors^{4–8} have proposed a neuromuscular model linking the function of the low back and the lower limbs. Alterations in the operation of this kinetic chain linkage proximally may increase injury risk at more distal regions. Because pelvic stability is influenced by activity of the trunk muscles through their attachments to the pelvis, an inability to properly activate those muscles may create an unstable pelvic base and contribute to altered lower extremity neuromuscular control. Previous studies have shown that activation of the trunk musculature affects lower extremity mechanics. For example, activation of the transversus abdominis significantly decreases activity of

the lumbar erector spinae muscles, increases activity of the gluteus maximus and medial hamstrings, and decreases anterior pelvic tilt during prone active hip extension.⁹

Trunk-muscle function is altered in LBP sufferers.¹⁰ Therefore, those individuals may not be able to produce sufficient pelvic stability to provide a stable base for lower extremity motion and control. The relationship between LBP and altered lower extremity movement control has been observed in several studies. Individuals with LBP have diminished lower extremity strength, flexibility, and range of motion,^{11–13} as well as altered lower extremity biomechanics and neuromuscular control.^{14,15} Those changes may increase the risk of lower extremity injury.

Authors of prospective clinical studies have linked LBP history with lower extremity injuries. Zazulak et al¹⁶ found that a history of LBP was a significant predictor of knee injury in females and knee-ligament injury in males. Nadler et al¹³ observed that athletes with a history of lower extremity overuse or ligamentous injury were more likely to be treated for LBP during the following year. Additionally, football players with 2 or more of 3 risk factors (trunk-flexion–hold times of less than the median for the team, Oswestry Disability Index scores of 6 or more, or wall–sit–hold times of less than the median for the team) related to low back dysfunction and trunk-muscle endurance were at twice the risk for back and lower extremity injuries than were those with fewer than 2 factors.¹⁷

Female athletes are up to 8 times more likely than male athletes to experience an anterior cruciate ligament (ACL) injury and are more prone to injuries from noncontact mechanisms.^{18,19} The higher risk for ACL rupture among female athletes has been explained by hormonal, mechanical, neuromuscular, skeletal, and genetic factors.²⁰ The increased incidence of knee-ligament injuries in female athletes is multifactorial; which factors are dominant is currently unknown.²¹ Although both intrinsic and extrinsic factors may contribute, the injury occurs during a loading event, which can be moderated by mechanical and neuromuscular factors.^{19,22} Landing technique and neuromuscular function can be improved with training and may potentially reduce the risk of ACL injury.²² Previous investigators have suggested that an increase in quadriceps activation²⁰ and a discrepancy between quadriceps and hamstrings strength may contribute to ACL injuries.²³

Female athletes are more likely to sustain certain lower extremity injuries, such as ACL tears. Additionally, females more often develop those injuries as a result of noncontact mechanisms,¹⁸ which may reflect a failure of neuromuscular control because the injury occurs during loading.^{19,22} It is unknown whether the occurrence of LBP affects lower extremity biomechanical and neuromuscular responses differently in males versus females.

The effects of fatigue on lower extremity control responses in people with recurrent LBP are unknown. Fatigue serves as a major risk factor for lower extremity injury by altering muscle shock-absorbing capacity and coordination of the locomotor system.²⁴ Fatigue can affect neuromuscular input and output pathways.²⁵ Neuromuscular alterations that occur during fatigue potentially increase the risk of injury,^{22,23} and muscle fatigue has been linked to a variety of lower extremity injuries.^{24–26} Previous researchers²³ have suggested that the order of muscle activation may not change during fatigue, but muscle premotor and reaction phases may be

noticeably greater, suggesting a possible compromise in their protective role. Muscle fatigue moderates lower extremity muscle-activation patterns during landing by altering muscle-burst activation, duration, and intensity, as well as the ability of the lower extremity muscles to absorb repetitive shock or stress.^{27–29}

The effects of sex and fatigue on performance and injury risk are well documented.^{19,22–24} Recurrent LBP has been established in the literature as a significant predictor of lower extremity injury.^{16,17} However, limited information is available on the effects of lower extremity fatigue and sex on lower extremity control during landing in people with recurrent LBP. The purpose of our study was to determine the effects of lower extremity fatigue and sex on knee mechanics, neuromuscular control, and ground reaction force (GRF) during landing in people with recurrent LBP.

METHODS

Design

We used a controlled laboratory study involving a mixed, 2-factor design to determine the effects of sex (male or female) and lower extremity fatigue (fatigued or not fatigued) in people with recurrent LBP. Thirty-three young adults with recurrent LBP participated. We estimated the sample size needed in this study to approach 80% statistical power from the data of previous authors who examined landing.^{23,24,30,31} A large effect-size index of $f = 0.50$ was estimated. With a desired power of 80% ($1 - \beta = .80$) and a desired $\alpha = .05$, this effect-size index required a minimum sample size of 16 per group.³²

Sample

Fifteen women (47%; age = 20.60 ± 1.85 years, height = 1.62 ± 0.14 m, mass = 65.47 ± 12.41 kg) and 17 men (53%; age = 21.65 ± 2.30 years, height = 1.75 ± 0.80 m, mass = 82.42 ± 10.48 kg) participated in the study. All participants were between ages 18 and 35 years, were moderately active based on their scores on a physical activity scale,³³ and had a history of recurrent LBP that was intermittent, involving unilateral or bilateral symptoms between T12 and the mid-thigh. At the time of testing, participants verbally confirmed that they were in a period of remission from their recurrent LBP symptoms.³⁰ Volunteers were excluded if they had a history of knee pain in the previous 2 years, a history of surgery to the knee or lumbar spine, or pregnancy, all documented by self-report. Additionally, participants were excluded if they had previously trained in a jump-landing program. All participants read and signed an informed consent form approved by the Texas Tech University Health Sciences Center Institutional Review Board for the Protection of Human Subjects, which also approved the study.

Preparatory Procedures

We applied 23 reflective markers using locations and procedures adapted from Vaughan et al³⁴ to collect 3-dimensional kinematics (Nexus 1.7.1, Vicon Motion Systems, Centennial, CO) of the lower extremity and lumbar spine at a sampling rate of 100 Hz. Raw 3-dimensional coordinates were smoothed using a fourth-

order, no-phase-shift, Butterworth low-pass digital filter with cutoff set to 6 Hz before being exported for further analysis. The GRF data were collected at 2000 Hz using 2 parallel force plates (Advanced Mechanical Technology, Inc, Watertown, MA) positioned side by side. Electromyographic data from the right internal oblique, external oblique, multifidus, gluteus maximus, rectus femoris, semitendinosus, and vastus medialis were measured using preamplified surface electrodes (Delsys Inc, Boston, MA) at 2000 Hz. The signal bandwidth for the electromyography bioamplifier was 20 to 450 Hz with 3- μ V peak-to-peak baseline noise. The overall channel noise was less than 0.75 μ V, with a common-mode rejection ratio of less than 80 dB. We cleaned the skin with alcohol, shaved as necessary, and then lightly abraded it to reduce impedance.

Data-Collection Procedures

Participants wore T-shirts, shorts, socks, and a pair of standard athletic shoes. Before data collection, participants received instructions about performing drop vertical-jump (DVJ) trials and were allowed to practice until they were comfortable with the task. Participants stood with their toes at the edge of a 0.30-m box. The DVJ trial was started when the participant stepped forward with the right foot and dropped down off the box, simultaneously landing on a separate force platform with each foot and then immediately performing a maximum vertical jump. The participant reached with both arms overhead.

Participants performed a series of 12 DVJ trials, although not all trials were included in the current analysis. Three trials each were performed with and without abdominal muscle contraction. After completion of 6 successful DVJ trials, the participants performed a fatigue protocol. The fatigue protocol included dynamic squatting in a squat machine with 15% of body weight until *task failure*,^{35,36} which was defined as altered squat performance (increased forward trunk lean or altered forward knee position relative to the ankle) or an inability or unwillingness to continue. Then, participants performed another series of 6 DVJ trials with and without abdominal muscle contraction in a fatigued condition. Six of the 12 trials (50%) included abdominal contraction. Analysis of those 6 trials was excluded from the current study but was reported elsewhere.²¹ The 6 trials that did not include abdominal contraction were retained and were averaged to represent each participant's performance. A standing, static trial was recorded, with participants positioned in a neutral, standing posture to create a reference position for defining neutral joint angles.

Data Reduction

All raw data were exported from the Vicon Nexus system and imported into a custom MATLAB program (MathWorks, Inc, Natick, MA) for processing. Peak GRF, GRF impact, and joint moment variables were normalized to body mass. The electromyography data were band-pass filtered between 20 and 450 Hz with a fourth-order, no-phase-shift, Butterworth digital filter. The filtered electromyography data were analyzed to manually determine the activation of each muscle with a visual-identification method developed in MATLAB. The intrarater reliability of the visual method for determining activation was

examined using a subset of data and was excellent (intraclass correlation coefficient > 0.974).

The current study included 3 statistical families of dependent variables. The first group included the following kinematic variables: sagittal-, frontal-, and horizontal-plane knee angles at initial contact and the maximum values during the eccentric-landing phase. The *eccentric-landing phase* was defined as the instant of initial contact of the foot with the force platform until maximum knee flexion. The convention for positive angles was flexion, abduction, and external rotation. The second statistical family included the following kinetic variables: peak vertical GRF, GRF impact peak, and internal moments in the sagittal and frontal planes at the ankle and knee. The third statistical family included variables representing electromyography activation values (in seconds) of external oblique, multifidus, gluteus maximus, rectus femoris, semitendinosus, and vastus medialis.

Statistical Analyses

We calculated a 2×2 mixed analysis of variance to determine differences between sexes and between fatigue conditions for each dependent variable. The α level was initially set to .05, but within each statistical family, we used the Holm-Sidak correction for the multiple dependent variables.³⁷ Follow-up tests were conducted as necessary, with α correction at each step. Statistical analyses were conducted using SPSS (version 21.0; IBM Corporation, Inc, Chicago, IL).

RESULTS

All participants performed the fatiguing activity until task failure. The number of repetitions to achieve task failure varied by group (women = 107 ± 50 repetitions [range, 30–230 repetitions], time = $4:15 \pm 2:06$ minutes; men = 100 ± 43 repetitions [range, 35–190 repetitions], time = $3:15 \pm 1:41$ minutes).

Landing performance differed between male and female participants, and fatigue did not alter that relationship. No dependent variables exhibited a significant 2-way interaction effect. We found several significant main effects for sex, indicating differences between male and female participants during the 0.30-m landing performance (Tables 1 through 3). In comparison with the men, women had 4.4° greater knee-flexion angle at initial contact ($P = .002$, $\eta_p^2 = 0.271$, power = 0.890), 7.6° greater maximum knee internal rotation ($P = .011$, $\eta_p^2 = 0.199$, power = 0.751), and 0.71 Nm/kg greater maximum knee-flexion moment ($P = .001$, $\eta_p^2 = 0.515$, power = 1.000). Additionally, the female participants exhibited a knee-flexion moment, whereas the men presented with an extension moment. Female participants also exhibited 0.53 Nm/kg smaller maximum knee-adduction moment ($P = .001$, $\eta_p^2 = 0.295$, power = 0.929), 0.36 Nm/kg smaller maximum ankle-inversion moment ($P = .007$, $\eta_p^2 = 0.220$, power = 0.804), and 0.07 Nm/kg smaller GRF impact ($P = .001$, $\eta_p^2 = 0.303$, power = 0.937) compared with male participants. Additionally, multifidus muscle activation was 0.003 seconds earlier in female participants ($P = .021$, $\eta_p^2 = 0.166$, power = 0.656).

Fatigue altered landing mechanics, as demonstrated by several significant main effects. Fatigue altered knee-joint kinematics, kinetics, and muscle activity during the 0.30-m landing performance (Tables 1 through 3). Compared with

Table 1. Knee Kinematic Results by Fatigue Condition and Sex

Variable, ° ^a	Fatigue Condition, Mean ± SD (95% Confidence Interval)			
	No Fatigue		Fatigue	
	Women	Men	Women	Men
Knee sagittal-plane angle at initial contact ^b	5.41 ± 4.6 (-0.4, 10.4)	1.7 ± 4.6 (-5.2, 8.1)	6.0 ± 2.6 (1.6, 10.2)	1.2 ± 3.9 (-4.7, 7.7)
Knee frontal-plane angle at initial contact ^c	39.6 ± 15.3 (9.8, 61.4)	42.0 ± 17.2 (11.4, 63.9)	43.8 ± 17.9 (14.5, 67.4)	47.5 ± 16.8 (18.2, 71.6)
Knee transverse-plane (rotation) angle at initial contact ^b	31.0 ± 13.4 (10.0, 54.5)	23.2 ± 13.4 (8.3, 62.6)	30.1 ± 13.6 (5.2, 60.8)	24.6 ± 18.5 (3.7, 73.9)
Maximum sagittal-plane knee angle	58.0 ± 14.3 (35.4, 86.9)	58.0 ± 10.7 (42.7, 77.3)	56.8 ± 13.8 (35.0, 86.8)	58.7 ± 10.1 (41.7, 77.9)
Maximum frontal-plane knee angle	12.2 ± 4.8 (2.5, 20.7)	16.7 ± 8.9 (0.1, 35.3)	11.0 ± 4.5 (3.2, 18.6)	16.5 ± 9.9 (-3.3, 42.6)
Maximum knee transverse-plane (rotation) angle	15.1 ± 6.6 (2.5, 27.6)	9.2 ± 4.5 (4.3, 16.7)	14.6 ± 6.1 (2.8, 25.9)	10.1 ± 5.1 (4.3, 19.5)

^a The convention for positive angles is flexion, abduction, and external rotation.

^b Significant difference by sex.

^c Significant difference by fatigue condition.

the no-fatigue condition, fatigue resulted in a 3.7° smaller knee-abduction angle at initial contact ($P = .002$, $\eta_p^2 = 0.272$, power = 0.900), and 0.77 Nm/kg greater maximum knee-flexion moment ($P = .008$, $\eta_p^2 = 0.215$, power = 0.797). Additionally, the no-fatigue condition resulted in a knee-extension moment, whereas the fatigue condition presented with a flexion moment. Fatigue delayed muscle activation of the semitendinosus by 0.081 seconds ($P = .001$, $\eta_p^2 = 0.456$, power = 0.998), multifidus by 0.065 seconds ($P = .001$, $\eta_p^2 = 0.414$, power = 0.994), gluteus maximus by 0.056 seconds ($P = .001$, $\eta_p^2 = 0.414$, power = 0.994), and rectus femoris by 0.052 seconds ($P = .014$, $\eta_p^2 = 0.185$, power = 0.713).

DISCUSSION

The purpose of our study was to determine the effects of lower extremity fatigue and sex on knee mechanics and neuromuscular control during landing in people with recurrent LBP. Their biomechanical responses were generally similar to those of populations without recurrent LBP in previous landing studies. When performing 0.30-m

landings, women with recurrent LBP landed differently than did men with recurrent LBP. Women tended to have greater knee-flexion angle at initial contact but no difference in maximum knee-flexion angle, which indicates decreased knee-flexion range of motion during the eccentric-landing phase. McLean et al²³ did not find a difference in knee angle at initial contact or maximum knee flexion between men and women without a history of recurrent LBP during a 0.50-m drop-jump-landing task. Although our maximum knee-flexion results support those in the McLean et al²³ study, the differences observed between sexes in knee angle at initial contact could reflect differences in the participant populations, suggesting differences in landing preparation for women with recurrent LBP. The decreased knee range of motion we observed may have resulted in a shorter landing time available for shock absorption.³ However, because GRF impact was less for women and maximum GRF was not different between sexes, it is unlikely that the reduced knee flexion in women resulted in an overall stiffening of the lower extremity. Instead, women may have used a landing strategy that relied on joints other than the knee to absorb landing

Table 2. Ground Reaction Force (GRF) and Knee and Ankle Kinetic Results by Fatigue Condition and Sex

Variable ^a	Fatigue Condition, Mean ± SD (95% Confidence Interval)			
	No Fatigue		Fatigue	
	Women	Men	Women	Men
Peak vertical GRF, N/kg	18.11 ± 5.60 (10.03, 29.58)	23.07 ± 8.78 (11.55, 44.37)	16.74 ± 5.53 (10.43, 31.74)	20.92 ± 7.31 (13.43, 36.72)
GRF impact, ^b N/kg × m	2.26 ± 0.49 (1.56, 3.32)	2.91 ± 0.56 (1.70, 4.24)	2.19 ± 0.53 (1.37, 3.05)	2.91 ± 0.63 (1.86, 4.06)
Knee sagittal-plane moment, ^{b,c} N/kg	-0.05 ± 1.57 (-3.96, 2.26)	-1.31 ± 2.06 (-6.97, 1.26)	0.41 ± 1.75 (-4.06, 2.05)	-0.09 ± 2.04 (-4.82, 2.17)
Knee frontal-plane moment, ^b N/kg	-3.84 ± 1.15 (-6.84, -2.37)	-5.55 ± 1.44 (-9.35, -3.58)	-3.67 ± 1.09 (-5.83, -2.16)	-5.21 ± 1.77 (-10.31, -1.70)
Ankle sagittal-plane moment, N/kg	1.30 ± 0.41 (0.81, 2.29)	1.92 ± 0.40 (0.68, 2.41)	1.31 ± 0.34 (0.86, 2.17)	-0.09 ± 2.04 (-4.82, 2.17)
Ankle frontal-plane moment, ^b N/kg	-4.19 ± 1.30 (-7.44, -2.50)	-5.80 ± 1.71 (-9.89, -3.34)	-4.09 ± 1.27 (-7.05, -2.54)	-5.21 ± 1.77 (-10.49, -2.37)

^a The convention for positive angles is flexion, abduction, and external rotation.

^b Significant difference by sex.

^c Significant difference by fatigue condition.

Table 3. Muscle-Activation Results by Fatigue Condition and Sex

Muscle Activation, s ^a	Fatigue Condition, Mean ± SD (95% Confidence Interval)			
	No Fatigue		Fatigue	
	Women	Men	Women	Men
External oblique	-0.023 ± 0.037 (-0.084, 0.78)	-0.023 ± 0.022 (-0.042, 0.066)	0.031 ± 0.031 (-0.059, 0.051)	0.034 ± 0.022 (-0.029, 0.052)
Multifidus ^{b,c}	-0.094 ± 0.036 (-0.121, -0.029)	-0.072 ± 0.035 (-0.098, 0.014)	-0.021 ± 0.047 (-0.031, 0.011)	-0.020 ± 0.041 (-0.031, 0.030)
Rectus femoris ^c	-0.040 ± 0.016 (-0.047, 0.065)	-0.060 ± 0.031 (-0.066, -0.048)	0.001 ± 0.015 (-0.017, 0.076)	-0.002 ± 0.024 (-0.023, 0.085)
Gluteus maximus ^c	-0.039 ± 0.034 (-0.049, 0.008)	-0.051 ± 0.021 (-0.054, 0.062)	0.018 ± 0.016 (0.021, 0.077)	0.009 ± 0.045 (-0.009, 0.036)
Semitendinosus ^c	-0.073 ± 0.021 (-0.079, -0.035)	-0.072 ± -0.069 (-0.074, 0.007)	0.010 ± 0.023 (-0.012, 0.161)	0.006 ± 0.045 (-0.021, 0.138)
Vastus medialis	-0.036 ± 0.11 (-0.058, 0.042)	-0.049 ± 0.026 (-0.065, 0.115)	0.013 ± 0.012 (0.009, 0.065)	0.052 ± 0.025 (0.012, 0.093)

^a Time zero is initial contact. Negative values indicate muscle activation before initial contact.

^b Significant difference by sex.

^c Significant difference by fatigue condition.

energy. Additionally, women with recurrent LBP tended to have greater maximum knee internal-rotation angles during the landing phase, which agrees with previous data on landing in women without recurrent LBP.^{4,19,23} An increase in knee internal rotation has been associated with an increase in ACL injury risk.⁴

Women with recurrent LBP exhibited a greater maximum knee-flexion moment than did men, who presented with an extension moment. The differences in the magnitude and sign of the knee-flexion moment are inconsistent with the McLean et al²³ results and might indicate different landing strategies in people with recurrent LBP. Individuals with recurrent LBP demonstrate impaired postural control, delayed muscle-reflex latencies, and abnormalities in trunk-muscle-recruitment patterns.^{16,38} Additionally, decreased neuromuscular control of the spine appears to influence dynamic stabilization of the knee joint and to increase the risk of lower extremity injury.^{17,21,38}

Women may have landed with a more-erect trunk posture,⁵ potentially increasing the knee-flexion moment, although this relationship is speculative because we did not examine trunk position. Women with recurrent LBP tended to have smaller knee-adduction and ankle-inversion moments than did men with recurrent LBP, which could indicate different hip-knee-ankle alignments and an increased risk for ACL injury.²² These results do not agree with those of McLean et al,²³ which may be due to the different populations examined and might indicate different landing strategies in people with recurrent LBP. Multifidus muscle activation occurred earlier in women with recurrent LBP, which may indicate a neuromuscular mechanism to alter trunk posture compared with the men,⁵ although the 0.003-second difference may not be clinically meaningful.

The observed differences between men and women demonstrate a relationship between sex and landing performance. However, no participants were injured in this study, nor was injury incidence quantified. Therefore, the associations between the observed sex differences and injury risk are speculative, but they are based on suggested relationships reported in the literature.^{39,40}

Our findings also demonstrated that fatigue altered landing performance in men and women with recurrent LBP. Fatigue

produced a smaller knee-abduction angle at initial contact, which supported the results of Benjaminse et al²² but disagreed with those of McLean et al.²³ Increased knee abduction has been associated with an increased risk of ACL injury under certain loading conditions.²⁰ Therefore, less knee abduction may reduce ACL stress under similar loading conditions but may increase stress on the medial collateral ligament if the internal knee-adduction moment also increases, which we did not observe. Furthermore, fatigue produced a greater maximum knee-flexion moment, which may reflect an alteration in the shock-absorbing mechanism at the knee joint. This result contradicts that of McLean et al²³ but supports other research.⁷ Nyland et al⁷ found an increase in knee-flexion moment in response to a quadriceps-fatigue protocol and a decrease in flexion moment with a hamstrings-fatigue protocol. An increase in knee-flexion moment can have at least 2 explanations. First, the quadriceps muscle group was more affected by the fatigue protocol than the hamstrings muscle group, possibly decreasing the gross extensor moment at the knee produced by the quadriceps, resulting in a shift of the net joint moment toward a flexion tendency. Second, the fatigue condition may have caused a more-erect trunk posture, thereby shifting the body's center of mass behind the knee axis, which would increase the knee-flexion moment.

The semitendinosus and rectus femoris muscle activations were delayed because of lower extremity fatigue. A delay in knee-muscle activity has been suggested to be a major risk factor for knee instability and ACL injury risk.²⁴ Moreover, the gluteus maximus and multifidus muscles acting at the hip and trunk also exhibited delays because of lower extremity fatigue. Delays in hip- and trunk-muscle activation have been linked to pelvic instability, which is a risk factor for lower extremity injuries, such as ACL tears.³¹

CONCLUSIONS

Our results provide evidence for sex and fatigue differences in landing mechanics and neuromuscular control in participants with recurrent LBP. Most of the differences between men and women and the differences between the unfatigued and fatigued conditions are consistent with results from similar studies of participants

without a recurrent LBP history. Fatigue alters landing mechanics and creates changes that are consistent with an increased risk for ACL injury.²¹ Women who suffer from recurrent LBP also exhibited biomechanical factors that may increase their risk for ACL injury during landing from a 0.30-m height when compared with men. Accurate identification of potentially risky movements is important for appropriate conditioning, treatment, and rehabilitation. Our findings may serve as a guide for modifications to equipment, training, or preparation practices for women with recurrent LBP and for both women and men during fatigued-landing events. Clinicians can use this information when designing neuromuscular-control training programs for women with recurrent LBP and potentially reduce the exposure of female athletes to biomechanical factors associated with lower extremity injury risk.

REFERENCES

- Bono CM. Low-back pain in athletes. *J Bone Joint Surg Am.* 2004; 86(2):382–396.
- Dagenais S, Caro J, Haldeman S. A systematic review of low back pain cost of illness studies in the United States and internationally. *Spine J.* 2008;8(1):8–20.
- Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J Athl Train.* 2007;42(2):311–319.
- Ireland ML. The female ACL: why is it more prone to injury? *Orthop Clin North Am.* 2002;33(4):637–651.
- McGregor AH, Hukins DW. Lower limb involvement in spinal function and low back pain. *J Back Musculoskelet Rehabil.* 2009; 22(4):219–222.
- Zazulak B, Cholewicki J, Reeves NP. Neuromuscular control of trunk stability: clinical implications for sports injury prevention. *J Am Acad Orthop Surg.* 2008;16(9):497–505.
- Borghuis J, Hof AL, Lemmink KA. The importance of sensory-motor control in providing core stability: implications for measurement and training. *Sports Med.* 2008;38(11):893–916.
- Kibler WB, Press J, Sciascia A. The role of core stability in athletic function. *Sports Med.* 2006;36(3):189–198.
- Oh JS, Cynn HS, Won JH, Kwon OY, Yi CH. Effects of performing an abdominal drawing-in maneuver during prone hip extension exercises on hip and back extensor muscle activity and amount of anterior pelvic tilt. *J Orthop Sports Phys Ther.* 2007;37(6):320–324.
- Hammill RR, Beazell JR, Hart JM. Neuromuscular consequences of low back pain and core dysfunction. *Clin Sports Med.* 2008;27(3): 449–462.
- Van-Dillen LR, Bloom NJ, Gombatto SP, Susco TM. Hip rotation range of motion in people with and without low back pain who participate in rotation-related sports. *Phys Ther Sport.* 2008;9(2):72–81.
- Fabian S, Hesse H, Grassme R, Bradl I, Bernsdorf A. Muscular activation patterns of healthy persons and low back pain patients performing a functional capacity evaluation test. *Pathophysiology.* 2005;12(4):281–287.
- Nadler SF, Wu KD, Galski T, Feinberg JH. Low back pain in college athletes: a prospective study correlating lower extremity overuse or acquired ligamentous laxity with low back pain. *Spine (Phila Pa 1976).* 1998;23(7):828–833.
- Shum GL, Crosbie J, Lee RY. Effect of low back pain on the kinematics and joint coordination of the lumbar spine and hip during sit-to-stand and stand-to-sit. *Spine (Phila Pa 1976).* 2005;30(17): 1998–2004.
- Hamill J, Moses M, Seay J. Lower extremity joint stiffness in runners with low back pain. *Res Sports Med.* 2009;17(4):260–273.
- Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J Sports Med.* 2007;35(7):1123–1130.
- Wilkerson GB, Giles JL, Seiber DK. Prediction of core and lower extremity strains and sprains in collegiate football players: a preliminary study. *J Athl Train.* 2012;47(3):264–272.
- Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer: NCAA data and review of literature. *Am J Sports Med.* 1995;23(6):694–701.
- Gilchrist J, Mandelbaum BR, Melancon H, et al. A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. *Am J Sports Med.* 2008; 36(8):1476–1483.
- Barber-Westin SD, Noyes FR, Smith ST, Campbell TM. Reducing the risk of noncontact anterior cruciate ligament injuries in the female athlete. *Phys Sportsmed.* 2009;37(3):49–61.
- Haddas R, Sizer PS, Sawyer SF, Brooks T, Chyu M-C, James CR. Effect of volitional spine stabilization and lower extremity fatigue on landing performance in a recurrent low back pain population. Poster presented at: the 37th Annual Meeting of the American Society of Biomechanics; September 5, 2013; Omaha, NE.
- Benjaminse A, Habu A, Sell TC, et al. Fatigue alters lower extremity kinematics during a single-leg stop-jump task. *Knee Surg Sports Traumatol Arthrosc.* 2008;16(4):400–407.
- McLean SG, Felin RE, Suedekum N, Calabrese G, Passerallo A, Joy S. Impact of fatigue on gender-based high-risk landing strategies. *Med Sci Sports Exerc.* 2007;39(3):502–514.
- James CR, Scheuermann BW, Smith MP. Effects of two neuromuscular fatigue protocols on landing performance. *J Electromyogr Kinesiol.* 2010;20(4):667–675.
- Miura K, Ishibashi Y, Tsuda E, Okamura Y, Otsuka H, Toh S. The effect of local and general fatigue on knee proprioception. *Arthroscopy.* 2004;20(4):414–418.
- Arndt A, Ekenman J, Westblad P, Lundberg A. Effects of fatigue and load variation on metatarsal deformation measured in vivo during barefoot walking. *J Biomech.* 2002;35(5):621–628.
- Arendt-Nielsen L, Sinkjaer T. Quantification of human dynamic muscle fatigue by electromyography and kinematic profiles. *J Electromyogr Kinesiol.* 1991;1(1):1–8.
- Edwards S, Steele JR, McGhee DE. Does a drop landing represent a whole skill landing and is this moderated by fatigue? *Scand J Med Sci Sports.* 2010;20(3):516–523.
- Hortobagyi T, Lambert NJ, Kroll WP. Voluntary and reflex responses to fatigue with stretch-shortening exercise. *Can J Sport Sci.* 1991; 16(2):142–150.
- MacDonald D, Moseley GL, Hodges PW. People with recurrent low back pain respond differently to trunk loading despite remission from symptoms. *Spine.* 2010;35(7):818–824.
- Haddas R, Hooper LT, James CR, Sizer PS. Effects of volitional preemptive abdominal contraction on trunk and lower extremity biomechanics and neuromuscular control during a drop vertical jump. Poster presented at: the 36th Annual Meeting of the American Society of Biomechanics; August 16, 2012; Gainesville, FL.
- Portney LG, Watkins MP. *Foundations of Clinical Research: Applications to Practice.* 3rd ed. Upper Saddle River, NJ: Pearson & Prentice Hall; 2009.
- Huston LJ, Wojtys EM. Neuromuscular performance characteristics in elite female athletes. *Am J Sports Med.* 1996;24(4):427–436.
- Vaughan CL, Davis BL, O’Conner JC. *Dynamics of Human Gait.* 2nd ed. Cape Town, South Africa: Kiboho; 1999.
- Hunter SK, Duchateau J, Enoka RM. Muscle fatigue and the mechanisms of task failure. *Exerc Sport Sci Rev.* 2004;32(2):44–49.
- Maluf KS, Enoka RM. Task failure during fatiguing contractions performed by humans. *J Appl Physiol (1985).* 2005;99(2):389–396.

37. Glantz S. *Primer of Biostatistics*. 7th ed. New York, NY: McGraw-Hill Professional; 2011.
38. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J Sports Med*. 2007;35(7):1123–1130.
39. Levine JW, Kiapour AM, Quatman CE, et al. Clinically relevant injury patterns after an anterior cruciate ligament injury provide insight into injury mechanisms. *Am J Sports Med*. 2013;41(2):385–395.
40. Hewett TE, Myer GD. The mechanistic connection between the trunk, knee, and anterior cruciate ligament injury. *Exerc Sport Sci Rev*. 2011;39(4):161–166.

Address correspondence to Ram Haddas, PhD, Texas Back Institute Research Foundation, 6020 W Parker Road, Suite 200, Plano, TX 75093. Address e-mail to rhaddas@texasback.com.