

The Influence of Lower Extremity Lean Mass on Landing Biomechanics During Prolonged Exercise

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Context: The extent to which lower extremity lean mass (LELM) relative to total body mass influences one's ability to maintain safe landing biomechanics during prolonged exercise when injury incidence increases is unknown.

Objectives: To examine the influence of LELM on (1) pre-exercise lower extremity biomechanics and (2) changes in biomechanics during an intermittent exercise protocol (IEP) and (3) determine whether these relationships differ by sex. We hypothesized that less LELM would predict higher-risk baseline biomechanics and greater changes toward higher-risk biomechanics during the IEP.

Design: Cohort study.

Setting: Controlled laboratory.

Patients or Other Participants: A total of 59 athletes (30 men: age = 20.3 ± 2.0 years, height = 1.79 ± 0.05 m, mass = 75.2 ± 7.2 kg; 29 women: age = 20.6 ± 2.3 years, height = 1.67 ± 0.08 m, mass = 61.8 ± 9.0 kg) participated.

Intervention(s): Before completing an individualized 90-minute IEP designed to mimic a soccer match, participants underwent dual-energy x-ray absorptiometry testing for LELM.

Main Outcome Measure(s): Three-dimensional lower extremity biomechanics were measured during drop-jump landings

before the IEP and every 15 minutes thereafter. A previously reported principal components analysis reduced 40 biomechanical variables to 11 factors. Hierarchical linear modeling analysis then determined the extent to which sex and LELM predicted the baseline score and the change in each factor over time.

Results: Lower extremity lean mass did not influence baseline biomechanics or the changes over time. Sex influenced the biomechanical factor representing knee loading at baseline ($P = .04$) and the changes in the anterior cruciate ligament-loading factor over time ($P = .03$). The LELM had an additional influence only on women who possessed less LELM ($P = .03$ and $.02$, respectively).

Conclusions: Lower extremity lean mass influenced knee loading during landing in women but not in men. The effect appeared to be stronger in women with less LELM. Continually decreasing knee loading over time may reflect a strategy chosen to avoid injury. A minimal threshold of LELM may be needed to safely perform landing maneuvers, especially during prolonged exercise when the injury risk increases.

Key Words: body composition, anterior cruciate ligament, soccer

Key Points

- Body composition influenced changes in knee loading during prolonged intermittent exercise only in women.
- Women with below-average lower extremity lean mass appeared to be especially susceptible to fatigue-related changes in biomechanics.

The ability of the lower extremity musculature to stabilize the knee joint is likely a crucial factor in reducing injury risk and maintaining performance during exercise. However, factors underlying the ability to safely perform repetitive, dynamic movements during prolonged exercise are elusive. Body composition may be a plausible factor considering that women with above-average body mass index (BMI; an index of body composition) are 3.5 times more likely to sustain an anterior cruciate ligament (ACL) injury than those with lower BMIs.¹ Although BMI is not a true measure of body composition, previous research^{2,3} has shown that larger BMI in males is primarily due to greater lean mass as opposed to greater fat mass in females. This implies that the injury risk in women could be a consequence of possessing

more relative fat mass and, in turn, less lean mass when compared with their overall body mass.

To date, few investigators^{4,5} have examined the direct influence of body composition on high-risk biomechanical strategies (eg, knee valgus and rotation, upright landing postures) thought to place the ACL at risk for injury. If an individual has less relative lower extremity lean mass (LELM; ie, muscle) to control the body's total mass during dynamic activity, this may be a limiting factor in safely performing athletic maneuvers. To our knowledge, only 1 group⁶ has investigated the influence of LELM on sagittal-plane landing biomechanics; women with a greater amount of lean mass relative to total body mass were able to absorb a greater amount of energy about the hip, knee, and ankle, generally considered a "softer" and safer landing strategy.

Because lean muscle mass is highly correlated with muscle strength,⁷ this would suggest that the amount of LELM may in part determine the ability to produce adequate joint torques to control dynamic motion. Previous authors⁶ showed that the relationship between LELM and landing energetics was indeed mediated by maximal strength; however, strength alone could not explain the whole relationship between lean mass and landing biomechanics. As such, it appears that lean mass influences biomechanics by other mechanisms.

These prior studies have been limited to sagittal-plane biomechanics, so the effects of body composition on high-risk frontal- and transverse-plane biomechanics are relatively unknown. Loss of the sagittal-plane dynamic control provided by the thigh muscles may have multiplanar consequences, given that less peak sagittal-plane flexion during landing has been associated with greater frontal-plane knee motion and loads.⁸ Moreover, because the quantity of LELM is negatively associated with frontal- and transverse-plane knee laxity,⁹ which in turn influences frontal- and transverse-plane landing biomechanics,¹⁰ there remains a distinct possibility that LELM is related to those biomechanics as well. Thus, possessing less relative lean mass may contribute to decreased neuromuscular control and multiplanar high-risk landing strategies (eg, hip adduction, knee valgus and rotation, and less sagittal-plane flexion).

Lower extremity injuries have been consistently shown to increase with exercise duration in the sport of soccer, with more injuries reported during the later parts of each half of play compared with the beginning.^{11–13} Whereas lean body mass has been positively related to fitness level¹⁴ and therefore a greater maintenance of performance¹⁵ and the amount of LELM available to control total body mass dictates in part one's ability to maintain optimal lower extremity biomechanics during sport-related tasks, we are unaware of any prior researchers who have examined the influence of LELM relative to total body mass on maintenance of lower extremity biomechanics during prolonged exercise. This factor is particularly relevant for fatiguing sports such as soccer: its intermittent dynamic nature is frequently characterized by more than 1100 changes in direction and, hence, continued stretch-shortening demands on the lower extremity musculature^{16,17} as opposed to prolonged straight-ahead running. Possessing a greater LELM-to-body mass ratio could reduce the relative demand on the lower extremity musculature, which might delay muscular (peripheral) fatigue, leading to more appropriate biomechanical strategies during prolonged exercise. Understanding the factors that contribute to biomechanical strategies that place the knee at greater risk for ACL trauma during prolonged sport-related activity is critical if we are to refine effective prevention strategies to mitigate that risk.

Therefore, the purpose of our study was 3-fold: to examine the extent to which LELM influences (1) lower extremity biomechanics before exercise and (2) changes in biomechanics during a 90-minute individualized intermittent exercise protocol (IEP), designed to simulate the demands of a soccer match; and (3) to determine whether any relationships between LELM and the changes in biomechanics are moderated by sex. We hypothesized that less LELM would be related to (1) biomechanical factors

comprising correlated variables that describe the dissipation of landing forces, knee loading, and dynamic knee valgus during a drop-jump landing before exercise, and (2) greater relative changes toward higher-risk biomechanics with fatiguing exercise, and finally (3) higher-risk biomechanical strategies and greater changes in biomechanics in women due to having less relative LELM than men.

METHODS

The experimental protocol has been previously described in detail.^{18,19} Each participant attended a practice session in which he or she was familiarized with all study procedures. Participants first completed fitness testing via the Yo-Yo Intermittent Recovery Test–level 1 so that we could prescribe each participant's individual running load and intensity during the IEP. This prescription method ensured an equal relative physiological load across all participants.²⁰ Individuals then participated in 2 counterbalanced test sessions performed approximately 3 to 5 days apart. During the experimental session, they were measured serially before, during, and after the IEP, whereas during the control condition, they were measured at equivalently spaced time points while quietly resting between measurements. For the current study, only the drop-jump landing biomechanics during the experimental condition are reported. We have previously reported no changes in biomechanics during the control condition.¹⁸

Participants

As part of a larger study, 30 men and 30 women participated in this study.^{18,19} Participants were primarily recruited from the university's National Collegiate Athletic Association Division I and club sports teams. They were eligible to participate if they were regularly involved in competitive-level athletic activities that included running, sprinting, cutting, and jumping for the past 5 years and were currently active in their sport at least 6 hours per week. To reduce potentially confounding effects on movement mechanics, participants were excluded if they self-reported a previous injury to the knee ligaments, menisci, or osteochondral surface. Before participating, the athletes were informed of the study risks and provided their written consent per the university's institutional review board protocol. Participants then performed the Yo-Yo Intermittent Recovery Test–level 1 to determine their individual fitness level, which we then used to prescribe the load and intensity of the IEP.²⁰ This effectively controlled for differences in fitness levels among participants. The sports backgrounds and average fitness for all participants have been previously reported.¹⁸

Procedures

Body composition testing was performed via dual-energy x-ray absorptiometry (DXA; model Lunar Prodigy Advance; GE Healthcare, Milwaukee, WI). Because DXA is contraindicated during pregnancy, all women were scanned during the 7 days after the onset of menses. On arrival at the laboratory, they were asked to confirm that they were not pregnant before being scanned. All participants were measured for height and body mass using a standard stadiometer and scale and then were placed in a

standardized supine position on the DXA table. Participants were asked to remain still for the duration of the total-body scan so that the DXA machine could assess lean and fat mass.

On the day of biomechanical testing, we outfitted participants in custom compression shorts and a shank sleeve. They were then instrumented with clusters of 3 active optical LED markers (Phase Space, San Leandro, CA) on each segment of the *dominant limb* (defined as the stance limb when kicking a ball): pelvis, thigh, shank, and foot. The markers were attached to each segment with hook-and-loop material and secured with prewrap to minimize movement artifact. Hip-joint centers were estimated using the rotation method, whereas knee- and ankle-joint centers were estimated as the centroid of the medial and lateral epicondyles (knee) and malleoli (ankle) using MotionMonitor software (version 8.77; InnSport Training, Chicago, IL). Participants were then asked to complete a battery of biomechanical and laxity tests (described previously).^{19,21} For the purposes of this study, the data from the drop-jump protocol are reported. Drop jumps were performed from a 0.45-m box, placed 0.1 m from the front edge of the force platforms (model 4060-NC; Bertec Corp, Columbus, OH). Participants were asked to stand atop the box, hold their hands at the level of their ears, drop straight down (without stepping or jumping) off the box, land evenly on both feet, recoil, and perform a maximal vertical jump. During each trial, the participant was visually assessed by the investigators for performance of correct procedures and maximal effort. Kinematics were measured at 240 Hz using an 8-camera Impulse active optical motion-capture system (Phase Space) while kinetic data were obtained at 1000 Hz. Once instrumented and digitized for biomechanical modeling in the software, participants performed a standardized dynamic flexibility warm-up protocol designed to actively warm and stretch the lower extremity musculature. This protocol consisted of 4 minutes of active tissue warming achieved by jogging, shuffling, or similar activities, followed by a series of standardized exercises performed over a distance of 8 m, immediately followed by an accelerative run over 10 m, and finally an 18-m return jog. On completion of the dynamic warm-up, participants were immediately assessed for lower extremity biomechanics during a drop-jump landing according to the procedures described herein to represent each participant's baseline (T_0) biomechanics.

After the baseline biomechanical testing, the participants began the IEP, which consisted of intermittent running bouts interspersed with periods of maximal sprinting, cutting, and vertical jumping (as described by Cone et al²⁰ and Schmitz et al¹⁸). Participants performed 2 identical 45-minute bouts of exercise separated by a 20-minute, half-time intermission. Each 45-minute bout consisted of three 12-minute blocks of intermittent running, followed immediately by 2 maximal 20-m shuttle sprints, 2 maximal countermovement jumps, 3 maximal drop jumps, and knee-laxity testing. Three-dimensional (3D) lower extremity biomechanics were assessed during the maximal drop jumps at the end of each bout. Thus, data were acquired at 15-minute intervals during the 90-minute IEP, resulting in 8 measurement points (T_0 to T_7). Rating of perceived exertion (RPE) and sprint speed were measured at each time point as subjective and objective analogs, respectively,

for fatigue.^{18–20} We¹⁸ and others²⁰ have previously reported increases in RPE similar to those found during exhaustive running, as well as decreases in sprint¹⁹ and cutting²⁰ speeds during this protocol. It should be noted that whereas men had faster sprint speeds overall, the change in sprint speed over time was similar for men and women.¹⁹ Despite this, fatigue had a greater global effect on biomechanics in women versus men. This is in part what led us to examine differences in body composition as a possible underlying factor for these sex differences in response to fatiguing exercise. We²² previously reported the effect of LELM on changes in performance (RPE, sprint speed, and countermovement jump height). These data indicate that those with above-average and below-average LELM did not differ in their changes in RPE and sprint speed over time. Thus, it appears that the fatigue response to the protocol is similar regardless of sex or body composition profile, and therefore, we did not believe we needed to control for individual variability in fatigue.

Data Reduction

Lower extremity lean mass (kg) was quantified from the total body composition data acquired during a total body scan with the DXA, as previously described,⁶ to functionally include the musculature about the ankle, knee, and hip. The LELM was then normalized to total body mass to determine relative LELM (expressed as % total body mass) for each participant. Kinematic and kinetic data were processed (MotionMonitor) using a fourth-order, zero-lag, low-pass Butterworth filter at 12 Hz, and all biomechanical variables were measured during the deceleration phase of the drop-jump landing (initial contact to peak knee flexion). The reference system used for kinematic data was established for each segment, with the *positive z-axis* defined as the left-to-right axis, the *positive y-axis* defined as the distal-to-proximal vertical axis, and the *positive x-axis* defined as the posterior-anterior axis. Initial and peak 3D hip, knee, and ankle angles were calculated using Euler angle definitions with a rotational sequence of $zy'x''$. Intersegmental kinetic data were calculated via inverse dynamics to acquire 3D hip, knee, and ankle peak internal joint moments normalized to body weight and height ($\text{Nm} \times \text{N}^{-1} \times \text{m}^{-1}$). By convention, flexion, abduction, valgus, and external rotation are presented as positive values. Joint energy absorption was calculated as the integral of the negative joint power curves and normalized to body weight and height ($\text{J} \times \text{N}^{-1} \times \text{m}^{-1}$).

Statistical Analysis

Given the high potential for correlation among the 40 drop-jump biomechanical variables (3D hip, knee, and ankle kinematics, kinetics, and sagittal-plane energetics), authors of a previously reported^{18,19} principal components analysis (PCA) reduced the 40 variables to a more manageable number of interpretable factors. The same factors extracted from the master data set^{18,19} were used again for the current investigation. In brief, each factor was composed of the most highly correlated biomechanical variables so that we could better describe the changes in biomechanics in each person over time. This process resulted in 11 factors that explained 75.2% of the total variance in biomechanical changes in landing.¹⁸ Due to the

Table 1. Biomechanical Factors Obtained From Principal Components Analysis^a

Factor	Factor Loadings ^b	Biomechanical Changes on Jump Landing as Factor Score Increases ^c	Functional Result
1	↑ Peak hip flexion (0.180), hip-flexion excursion (0.270), hip work absorption (0.431)	↑ Hip flexion, energy absorption	↑ Dissipation of landing forces at hip
2	↑ Initial hip flexion (0.188), hip-flexion moment (0.219), stiffness (0.347)	Ground contact in ↑ hip flexion; ↑ hip-flexion moments, stiffness	↑ Loads on hip
3	↑ Peak ankle flexion (0.332), peak knee flexion (0.235), knee-flexion excursion (0.288), knee work absorption (0.220)	↑ Knee, ankle flexion at peak landing; ↑ knee energy absorption	↑ Dissipation of landing forces at knee
4	↑ Ground reaction force (0.256), anterior knee shear forces (0.343), knee-extensor moment (0.432), stiffness (0.386), work absorption (0.232)	↑ Stiff knee on landing → ↑ knee extensor loads, shear forces, ground reaction forces	↑ Loads on knee
5	↑ Initial ankle flexion (0.433), ↓ ankle-flexion excursion (−0.393)	Ground contact in ↑ ankle dorsiflexion, ↓ dorsiflexion motion on landing	↓ Reliance on ankle motion to dissipate landing forces
6	↑ Anterior knee shear forces (0.222), ankle-extensor moment (0.323), stiffness (0.289), work absorption (0.253)	↑ Stiff ankle on landing → ↑ ankle plantar-flexor loads, ↑ anterior knee shear forces	↑ Loads on ankle plantar-flexor loads, structures that restrain anterior tibial translation
7	↑ Initial hip external rotation (0.264), initial knee valgus (0.216), peak knee valgus (0.213), initial knee internal rotation (−0.346); ↓ peak knee external rotation (−0.330) and knee internal-rotation excursion (0.282)	Ground contact in ↑ relative hip external rotation, knee valgus, internal rotation; remain in ↑ knee valgus, internal rotation	Knee posture associated with ↑ anterior cruciate ligament loading, injury risk during landing
8	↑ Hip-adduction excursion (−0.183), knee-valgus excursion (0.208); ↓ peak hip internal rotation (0.260), internal-rotation excursion (0.264), peak knee varus (0.236), knee-varus excursion (0.324)	↑ Frontal-plane hip adduction, knee valgus motion; ↑ hip internal-rotation motion	More functional valgus posture during landing
9	↑ Peak knee internal rotation (−0.299), internal-rotation excursion (−0.229)	↑ Knee internal-rotation motion during landing	
10	↑ Knee external-rotation excursion (0.694)	↑ Knee external-rotation motion during landing	
11	↓ Hip-adduction moment (0.315), hip external-rotation moment (−0.225), knee-varus moment (0.411), knee internal-rotation moment (0.251)	↓ Hip adduction and external rotation, knee-varus and internal-rotation moments during landing	↓ Peak loading of structures associated with transverse, frontal control of hip, knee

^a Reprinted with permission from Shultz et al.¹⁹

^b Anterior-posterior flexion angles, extensor moments, stiffness, and work-absorption values are positive.

^c If factor score decreases, the opposite biomechanical changes are observed.

potential relationships between biomechanics in multiple planes (eg, the influence of sagittal-plane knee flexion on frontal- and transverse-plane mechanics),^{8,23} we included all 11 factors previously calculated,^{18,19} thus representing sagittal-plane (factors 1–6), frontal-plane (factor 8), transverse-plane (factors 9, 10), and combined multiplanar (eg, dynamic valgus; factors 7, 9, 11) biomechanics. The components and an interpretation of each factor are listed in Table 1. All 11 factors were used as the dependent variables for the current analysis.

We conducted a hierarchical linear model (HLM) analysis to determine the extent to which sex and LELM moderate changes in each factor over time. Specifically, HLM describes 2 levels of variables whereby level 1 represents individual differences in the repeated measures over time. Level 2 then models the extent to which individual characteristics (eg, sex and LELM) influence or predict the individual differences in the level 1 model. Thus, level 2 models the differences between individuals. In this case, the level 1 model indicates the growth or change for any given biomechanical factor as a function of

time, whereas level 2 models the effect of sex and LELM on the growth or change in any given biomechanical factor as a function of time.

Because level 1 models the factor score for each person as a function of time (ie, the growth curve), the individual's intercept, π_{0i} , represents his or her factor score at baseline (time = 0), and the slope, π_{1i} , represents the rate of change in factor score per unit of time (15-minute increments). In addition, the error term at level 1, e_{ij} , indicates the extent to which any observed score is different from what would be predicted. As in regression, this error term is assumed to be random and have a normal distribution; its variance describes the within-subject variability (often referred to as level 1 variance, σ^2). Note that the level 2 model then predicts the baseline score (π_{0i}) and the growth rate (π_{1i}) as a function of sex and LELM. Thus, the parameters in level 2 indicate the extent to which sex and LELM can predict an individual's baseline score and growth rate. As in a regression analysis, the β indicates the regression coefficients for each level 2 predictor. In addition, both error terms for the level 2 model are similar to regression, and

Table 2. Significant Hierarchical Linear Model Results With Level 2 Model Coefficients (SE) for the Baseline Scores (Intercept: π_{0i}) and Slope (π_{1i}) of Each Factor^{a,b}

Biomechanical Factor	Baseline Score						Slope					
	Sex		LELM		Sex × LELM		Sex		LELM		Sex × LELM	
	Coefficient (SE)	P Value	Coefficient (SE)	P Value	Coefficient (SE)	P Value	Coefficient (SE)	P Value	Coefficient (SE)	P Value	Coefficient (SE)	P Value
4: ↑ Loads on knee	-16.4 (7.7)	.04 ^c			120.3 (55.1)	.03 ^c						
7: Knee posture associated with ↑ anterior cruciate ligament loading, injury risk during landing							-1.1 (0.5)	.03 ^c			8.6 (3.5)	.02 ^c

Abbreviations: LELM, lower extremity lean mass; SE, standard error.

^a For full results, see Supplemental Tables 2 and 3.

^b Coefficients for sex (β_{01}), LELM (β_{02}), and sex × LELM (β_{03}).

^c Significant effect ($P < .05$).

therefore, they are assumed to be normally distributed and have estimated variances τ_0 and τ_1 for the baseline and growth rate, respectively. Finally, because both error terms describe between-subjects variability (in level 2), they are allowed to covary.

Sex was added to the level 2 model due to the known differences in LELM and lower extremity biomechanics between men and women, and hence, the potential to find a relationship between LELM and the change in an individual's biomechanics over time simply due to global sex differences. By controlling for sex, we also effectively controlled for other sex-dependent factors that could influence biomechanics over time and enabled better parsing of the independent contributions of LELM. To aid in interpretation, sex was entered into the model as a dummy-coded variable (men = 0, women = 1). Thus, the significance of sex in any model can be interpreted as the difference between baseline factor score and the change in factor score between men and women after controlling for LELM. The significance of LELM can then be interpreted as the effect above and beyond that predicted by sex. Finally, to determine whether any relationship between LELM and an individual's change in biomechanics is moderated by sex, we added a sex × LELM interaction term in the level 2 model. The following is a summary of the models created:

Level 1 model:

$$\text{Factor score} = \pi_{0i} + \pi_{1i} *(\text{time}) + e_{ij}$$

Level 2 model:

$$\text{Baseline } (\pi_{0i}) = \beta_{00} + \beta_{01} *(\text{sex}) + \beta_{02} *(\text{LELM}) + \beta_{03} *(\text{sex} \times \text{LELM}) + \mu_{0i}$$

$$\text{Slope } (\pi_{1i}) = \beta_{10} + \beta_{11} *(\text{sex}) + \beta_{12} *(\text{LELM}) + \beta_{13} *(\text{sex} \times \text{LELM}) + \mu_{1i}$$

RESULTS

A total of 30 men (age = 20.3 ± 2.0 years, height = 1.79 ± 0.05 m, mass = 75.2 ± 7.2 kg) and 29 women (age = 20.6 ± 2.3 years, height = 1.67 ± 0.08 m, mass = 61.8 ± 9.0 kg) successfully completed all aspects of the IEP. Due to excessive noise in the pelvic marker set during the baseline condition, 1 participant's hip data were eliminated from the analysis. Men possessed 14.4% ± 1.1% LELM

relative to total body mass, whereas women possessed 12.4% ± 1.2%. Descriptive data for the biomechanical factors have been reported previously by Schmitz et al.¹⁸ Analysis of the level 1 model results (effect of time on each factor) revealed a significant amount of variance in each factor (see Supplemental Table 1, available online at <http://dx.doi.org/10.4085/1062-6050-52.5.03.S1>), which indicated the appropriateness of modeling the person-level factors (effect of sex and LELM on each factor over time) at level 2.

Effect of Sex and LELM on Baseline Factor Scores

The significant results for the level 2 intercept (ie, baseline score for each biomechanical factor) are shown in Table 2. There was a significant effect of sex on the baseline factor score for increased knee loading (factor 4; $P = .04$). On average, women had baseline scores that were 16.4 points lower than men, indicating that before exercise, women's knee-loading scores were 36.8% less. This sex difference is depicted in Figure 1, which displays the sex difference in the raw mean baseline factor 4 scores.

Although LELM had no effect on this baseline score ($P = .48$), there was a significant sex × LELM interaction ($P = .03$), demonstrating that the effect of LELM on baseline score was moderated by sex. To illustrate this interaction, we separated men and women into above-average and below-average LELM groups. Figure 2 illustrates the effect of below-average LELM on the baseline score in women but not in men. Therefore, women with less LELM landed with less loading on the knee than women with above-average LELM or any man, regardless of his LELM.

There was no effect of sex (P value range, .11 to .90) or LELM (P value range, .17 to .92) or sex × LELM interaction for any of the other baseline factor scores (P value range, .14 to .94). Full model results for the level 2 baseline factor scores are available (see Supplemental Table 2).

Effect of Sex and LELM on the Rate of Change (Slope) in Factor Scores

The significant full model results for the level 2 slope (ie, growth curve or change in each biomechanical factor over time) are displayed in Table 2. Sex had a significant effect on the rate of change in a knee posture associated with ACL

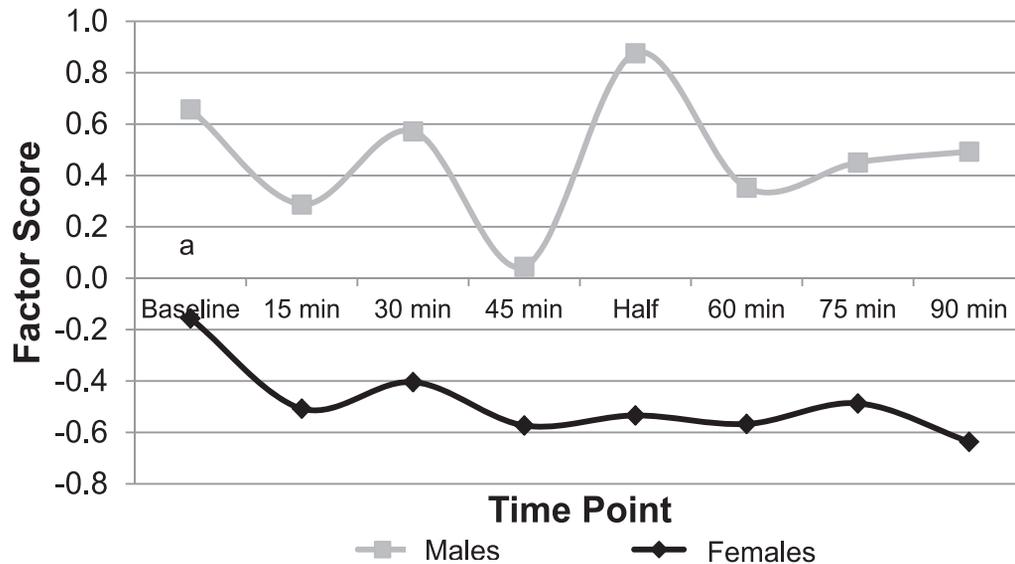


Figure 1. Effect of sex on baseline knee loading (factor 4). ^a Before beginning the exercise protocol, women, on average, had lower factor scores than men ($P = .04$).

loading (factor 7) over time ($P = .03$). The model coefficient for women decreased an average of 1.1 points at each time point, indicating that as exercise progressed, women landed with less initial hip external rotation, knee valgus, and internal rotation and remained in a less valgus and internally rotated position. There was no effect of LELM on the rate of change in factor 7 ($P = .39$), reflecting similar slopes between men and women, but there was a sex \times LELM interaction ($P = .02$), indicating that the effect of LELM on the rate of change in this factor depended on sex. This is illustrated in Figure 3, which shows the difference in

slope in factor 7 when once again looking at men and women with above-average or below-average LELM. The women with above-average LELM essentially had no change in the factor score over time, whereas those with below-average LELM consistently decreased in score, suggesting that they actually landed with a posture displaying less ACL loading.

No effect of sex (P value range, .14 to .96) or LELM (P value range, .12 to .91) or sex \times LELM interaction (P value range, .18 to .98) on the rate of change in any of the other biomechanical factors over time was noted. Full model

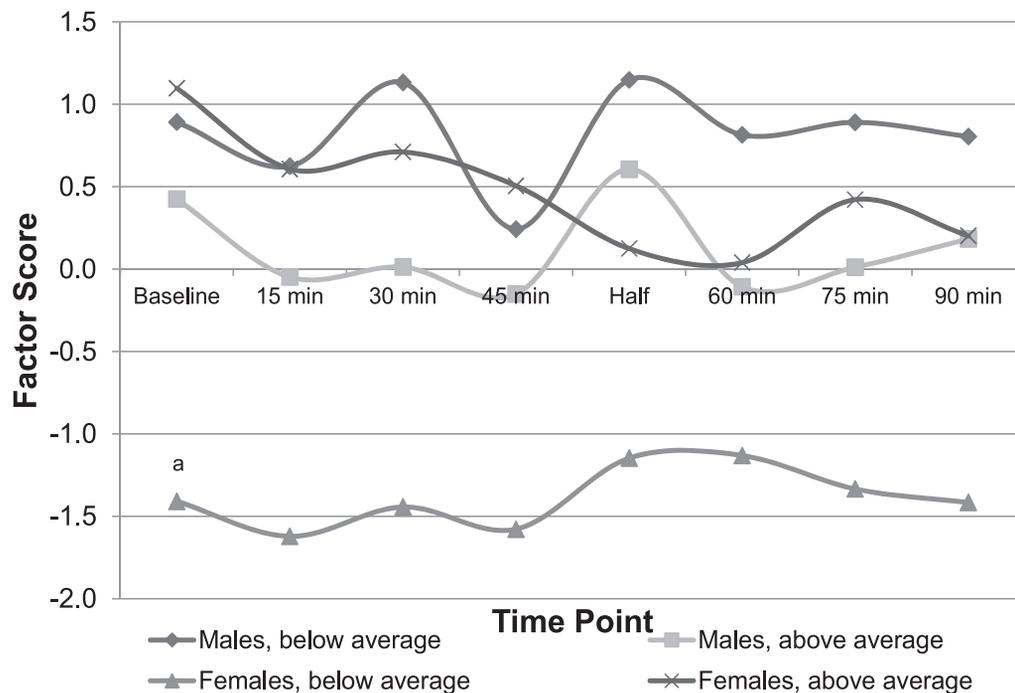


Figure 2. Sex \times lower extremity lean mass (LELM) interaction effect on baseline knee loading (factor 4). Men and women were each split into above-average and below-average groups on the basis of their normalized LELM group mean. ^a Before beginning the exercise protocol, women with below-average LELM ($n = 14$, $11.5\% \pm 0.7\%$) had lower factor scores ($P = .03$) compared with women with above-average LELM ($n = 15$, $13.4\% \pm 0.5\%$) and all men (below average: $n = 15$, $13.6\% \pm 0.6\%$; above average: $n = 15$, $15.2\% \pm 0.7\%$).

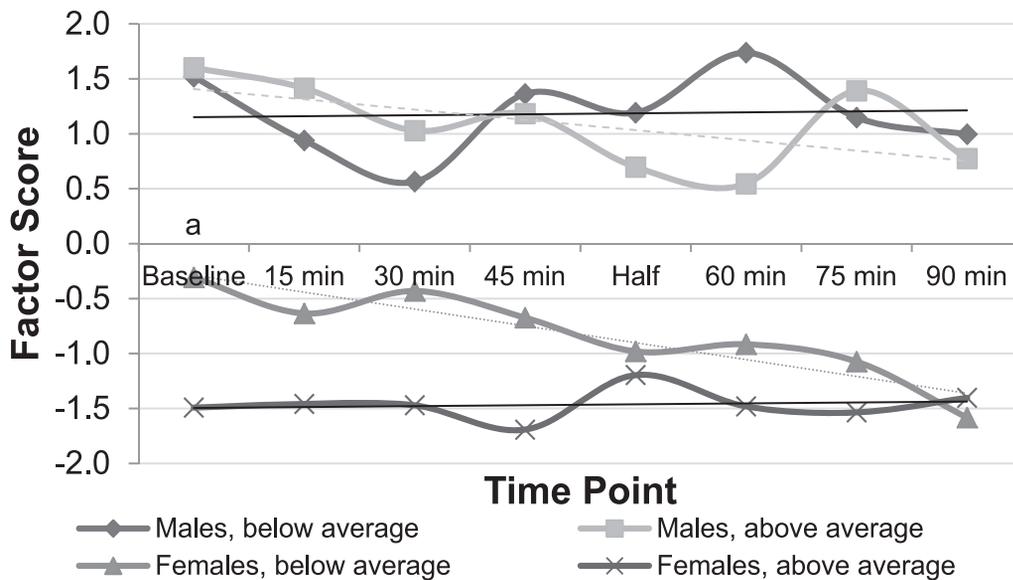


Figure 3. Sex \times lower extremity lean mass (LELM) interaction effect on rate of change (slope) in ACL loading (factor 7). Men and women were each split into above-average and below-average groups on the basis of their normalized LELM group mean. ^a Women with below-average LELM ($n = 14$, $11.5\% \pm 0.7\%$) had a greater decline (negative slope) in factor score over time ($P = .02$) compared with women with above-average LELM ($n = 14$, $13.4\% \pm 0.5\%$) and all men (below average: $n = 15$, $13.6\% \pm 0.6\%$; above average: $n = 15$, $15.2\% \pm 0.7\%$).

results for the level 2 slope (ie, growth curve or change in each biomechanical factor over time) are provided (see Supplemental Table 3).

DISCUSSION

To our knowledge, this is the first study to investigate relationships between LELM and multiplanar lower extremity biomechanics in men and women during prolonged exercise. We observed some sex differences in landing biomechanics; however, the unique finding was the significant effect of LELM on certain landing biomechanics in women but not in men.

Before beginning exercise, women landed with a biomechanical profile characterized by less knee stiffness and smaller knee-extensor loads, shear forces, and vertical ground reaction forces (factor 4). Whereas no sex difference was present in the rate of change in this factor over time, the influence of LELM on baseline factor 4 scores was sex specific. Women, but not men, with less LELM had lower factor 4 scores at baseline. This finding is consistent with previous work from our laboratory⁶ showing that more LELM was a predictor of greater sagittal-plane knee energy absorption (a composite measurement of joint moment and angular velocity) in women but not in men. For illustrative purposes, we performed a median split to create equal groups of men (below average: $n = 15$, $13.6\% \pm 0.6\%$; above average: $n = 15$, $15.2\% \pm 0.7\%$) and women (below average: $n = 14$, $11.5\% \pm 0.7\%$; above average: $n = 15$, $13.4\% \pm 0.5\%$) on the basis of their normalized LELM (Figure 2), and it became evident that the women with below-average LELM actually drove the sex difference in the baseline factor score, given that the women's above-average baseline scores were similar to the men's. Together with the sex \times LELM interaction, this implies that our findings are primarily specific to women with below-average LELM.

The lower baseline factor 4 scores indicate that women landed with less sagittal-plane knee loading, which is counterintuitive on the basis of the majority of earlier research^{24–26} that characterized women as landing with greater knee loading, which is thought to contribute to the risk of ACL injury. We hypothesize that this unique finding may reflect our current paradigm in which the participants were prepared to complete a 90-minute IEP. In that case, the landing pattern may have been consciously or unconsciously chosen to protect the knee in anticipation of the upcoming bouts of repeated sprinting, running, cutting, and jumping. In support of this theory is our report¹⁸ that men and women did not differ in factor 4 scores during the control session, when the participants rested quietly instead of completing the running bouts. Thus, the softer landing pattern may indicate a cautious attempt to avoid knee loading given the lack of sufficient strength to control the loading. Although the current HLM analysis did not enable us to compare men's and women's factor scores at each discrete time point (as in a repeated-measures analysis of variance), a look at the factor 4 scores (Figure 1) shows that the women's noticeably declined over time and actually demonstrated a larger difference than the men's at the 90-minute mark. It is unlikely that the women's landing performance improved (as we might interpret when looking at drop-landing biomechanics during a typical paradigm without exercise) but rather that the women became more cautious over time, compared with the men, who ended the exercise protocol with factor scores similar to those at the start. However, whereas the women's strategy could potentially protect the knee, it can also have negative implications for performance¹⁸ because greater knee loading is associated with greater jump performance,²⁷ which was not analyzed in the current study.

Less LELM has been associated with greater magnitudes of both frontal- and transverse-plane knee laxity,⁹ and greater frontal- and transverse-plane laxity has, in turn,

been associated with greater frontal and transverse hip and knee motions and loads during landing.¹⁰ Hence, the apparent indirect relationship between lean mass and these motions drove our expectation that LELM would predict baseline frontal- and transverse-plane biomechanics. Given that this hypothesis was not supported, it is unlikely that the amount of LELM is a sole factor in controlling frontal- and transverse-plane biomechanics. This conclusion may be supported by previous work⁶ showing that the relationships between LELM and energy absorption were mediated by maximal eccentric strength. Furthermore, because biomechanical modeling studies have shown that primary control of frontal-plane knee motion and loads is through activation of the quadriceps and hamstrings,²⁸ it may also be important to understand how lean mass combined with particular activation patterns influences the multiplanar knee stabilization required to protect the ACL during dynamic activity. This is particularly relevant with respect to the development of peripheral fatigue during prolonged intermittent exercise, when the force-producing capability of the lower extremity musculature decreases with time.²⁹ Measurements of strength and muscle activation along with available muscle mass (ie, how that muscle mass is used) would likely add to our understanding of these seemingly complex relationships.

We hypothesized that individuals with more relative LELM would be more resistant to changes toward high-risk landing strategies as exercise progressed. These hypotheses were not supported by our analysis; however, we observed an effect of LELM in women with below-average LELM only. Before starting exercise, a sex difference was displayed in the knee-loading factor only. As the exercise progressed, a sex difference was shown in the rate of change in ACL loading (factor 7) whereby women landed with less frontal- and transverse-plane hip and knee loading than men. However, similar to the factor 4 baseline scores, the sex \times LELM interaction revealed that the decline (negative slope) in the ACL loading factor was likely driven by the women with lower amounts of LELM (Figure 3), because the factor scores of the women with above-average LELM and of all the men remained fairly stable over time. The decrease in ACL loading over time may again point to a compensatory strategy in women with less LELM, who are weaker and thus choose a neuromuscular solution that may minimize biomechanics commonly associated with ACL loading and subsequent injury. However, because we cannot directly measure ACL loading and injury was not an outcome in our study, this possibility remains theoretical.

In earlier work,¹⁸ we reported subtle changes in sagittal-plane but not frontal- or transverse-plane hip and knee biomechanics during the IEP. Although there was no overall mean change (or a significant slope) in the rate of change in biomechanical factors over time that could be consistently explained by LELM, our level 1 analysis indicated significant interindividual differences in the rate of change in each of the 11 biomechanical factors over time. Because the factors included multiple variables that made the factor score difficult to interpret as a whole, we inspected the range of individual changes in the hip- and knee-joint biomechanical variables over the 90-minute IEP. These data showed that some individuals experienced marked changes in multiplanar biomechanics over time.

For example, regarding the minimum and maximum values for changes in peak hip external-rotation angle after 90 minutes of exercise, one individual's peak internal rotation was 11.5° greater than at baseline, whereas another individual rotated 7.1° less compared with baseline, resulting in an overall average group change of only 2°. This illustrates the possibility that the between-subjects variability (eg, the effect of LELM in some women) in the biomechanical responses to the prolonged exercise "washed out" any apparent overall (average) change in biomechanics. The inability to demonstrate our hypothesized changes may also have been partly due to our use of the PCA approach. Because we analyzed factor scores, we were unable to analyze individual biomechanical variables, some of which could have changed over time. However, given the complexity of the interrelationships between biomechanical variables during dynamic activity, using the PCA is a sensible way to assess global changes in biomechanics during prolonged exercise.

It is also possible that other factors in addition to LELM are contributing to this variability in fatigue-related responses. Future authors should examine other potential factors that may contribute to larger alterations in biomechanics in some individuals and their higher risk for injury as exercise progresses. Recognizing these individuals would enable clinicians to apply focused interventions (eg, body composition modifications, strength, fitness).

Standardizing the IEP to each individual's fitness level may also have limited our ability to identify a relationship between LELM and exercise-induced biomechanical changes. We based our second hypothesis on the assumption that greater LELM was related to greater fitness¹⁴ and, therefore, would better resist the deterioration in biomechanics that accompanies the neuromuscular fatigue that is thought to be responsible for the increase in injury incidence with exercise duration. However, because we used each individual's fitness level to prescribe the demands of the protocol in order to maximize our external validity and control the relative physiological load (ie, relative difficulty) across all participants, we may have limited our ability to examine the relationship between LELM and fatigue-related changes in biomechanics over time. The current approach has greater external validity, as individual performance is ultimately limited to that person's fitness and his or her ability to repeatedly perform athletic maneuvers such as sprinting and jumping.

In summary, LELM explained some sagittal-plane landing biomechanics at baseline as well as changes in some transverse- and frontal-plane mechanics indicative of knee loading and the ACL injury mechanism during a prolonged IEP designed to mimic a soccer match. However, the influence of LELM was limited to women in the current study, and the decrease in knee loading over time seemed to reflect a strategy chosen to avoid injury. Because men have a greater proportion of lean mass to total body mass, there may be a minimal threshold of strength at which LELM is not an influential factor in neuromuscular control during landing. It also appears that factors in addition to relative LELM contribute to individual variations in the degradation of lower extremity biomechanics during fatiguing exercise. Future investigators should focus on a comprehensive examination of multiple aspects of body composition,

physical fitness, and other personal characteristics (eg, injury history, pain) that may affect fatigability over time and, hence, the ability to maintain landing biomechanics that protect the ACL and also promote optimal performance.

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SUPPLEMENTAL MATERIAL

Supplemental Tables.

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