Influence of Lean Body Mass and Strength on Landing Energetics

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Abstract:

Purpose: Less lean body mass may limit one's ability to produce adequate muscle forces to safely control landing from a jump, thus increasing the risk for injury. The primary objective of this study was to determine the effect of lower extremity lean mass (LELM) and eccentric muscle strength on lower extremity energy absorption (EA) during a drop jump landing.
Methods: Seventy athletic subjects (35 men and 35 women) were measured for LELM with dual-energy x-ray absorptiometry, maximal eccentric strength of the quadriceps ($Quad_{ECC}$) and hamstrings (Ham_{ECC}), and lower extremity joint energetics during the initial landing of a drop jump. A mediation analysis examined the extent to which LELM predicted EA at each lower extremity joint (EA_{HIP}, EA_{KNEE}, and EA_{ANK}) and subsequently whether these relationships were mediated by each subject's maximal eccentric strength capabilities.
Results: LELM was a significant predictor of EA_{KNEE} ($R^2 = 0.22$, $P < 0.01$) in females but not in males ($R^2 = 0.03$, $P = 0.16$). In females, $Quad_{ECC}$ was a significant mediator of the effect of LELM on EA at the knee (ab = 179.72, 95% confidence interval [CI] = 10.43–423.42) and ankle (ab = 1.71, 95% CI = [0.16, 3.94]), whereas Ham_{ECC} was a significant mediator of the relationship between LELM and EA_{HIP} (ab = 4.89, 95% CI = 2.05–8.40). No significant relationships were observed in males.
Conclusions: LELM was a significant factor in energetic capabilities for females but not males. For females, this relationship was evident secondary to the stronger underlying relationship between maximal strength and EA. Thus, the maximal eccentric strength capabilities may be a more important determinant of energetic behaviors compared with the available quantity of lean mass alone. More work is needed to investigate these relationships and to reveal the underlying sex-specific mechanisms that determine EA capabilities.

Keywords: body composition | DXA | strength | ACL | energy absorption

Article:

Despite extensive prevention efforts during the past decade, females remain three to four times more likely to sustain a noncontact anterior cruciate ligament (ACL) injury than their male counterparts ([1,10]), a phenomenon often attributed to sex differences in neuromechanical strategies ([34]). ACL injury often occurs when trying to change the body's momentum ([13,23]). During these types of decelerating maneuvers, females have often been described as using a characteristically "stiffer" ([4,5,18]) landing strategy, which is associated with a reduced ability of the lower extremity muscles to absorb ground reaction forces ([5,37]) and a shift to greater relative demands on the knee and ankle joints (vs the hip) to absorb these forces ([4,30,37]). These factors may theoretically expose the passive anatomical structures of the knee to higher forces, thus injury. Although these sex-specific neuromechanical strategies have been well described, we still have an incomplete understanding of the underlying factors influencing these sex-specific strategies. Among previously proposed intrinsic anatomical and hormonal risk factors, one that remains relatively unexplored is the clear sex difference in body composition. This is despite the fact that sex differences in body size and body composition ([28,36]) emerge about the same time as sex differences in neuromechanical strategies ([6,9,26,31]) during maturation and that females with an above-average body mass index (BMI; likely attributable to greater fat mass in females) have been reported to have a 3.5 times greater risk of sustaining an ACL injury compared with those with an average BMI ([35]).

To date, limited work has examined the relationship between body composition (specifically the amount of lean mass relative to total body mass) and the ability to dissipate impact forces. Because muscle mass is highly correlated with muscle strength ([7]), decreased relative muscle strength (strength to body mass) may be the functional mechanism by which body composition may influence landing strategies in females. Consistent with having less relative total lean mass, and more specifically less lower extremity lean mass (LELM) than males, females also produce lower maximum quadriceps and hamstring torques ([18,29,33]). Although these reduced force-producing capabilities have been associated with stiffer single-leg ([18]) and double-leg ([29]) landings characterized by less knee flexion excursion ([18]) and larger peak knee extensor moments and vertical ground reaction forces compared with males ([29]), the role of body composition has yet to be directly explored. However, recent studies have shown that artificially increasing BMI (thus effectively reducing strength relative to body mass) induces dangerous landing strategies in males and females alike. Specifically, loading the trunk with 10% of body mass results in 1) a more erect landing position and larger normalized peak knee extensor moments during a stop-jump task ([3]), 2) larger quadriceps and gastrocnemius forces ([14]), and 3) increased ground reaction impulses and energy absorption (EA) about the knee ([15]) during a double-leg drop landing. Although these findings were a result of the acute placement of additional mass and were not analyzed by sex, they do provide initial insight into the consequence of possessing a larger BMI (produced by the addition of non-lean mass) and its potential influence on landing strategies. Hence, sex differences in joint stiffening and EA strategies may be reflective of a female's lower lean mass–total body mass ratio and subsequently result in lessened ability to produce eccentric muscle torques and control decelerations during the types of activity associated with ACL injury ([13]). This is supported by previous work that has shown stronger relationships between maximal isometric strength and landing energetics ([30]) and muscle activation amplitudes ([33]) in females compared with males. These findings suggest that strength may be a more important determinant in landing neuromechanics for females compared with males.

Because a body composed of a greater proportion of available lean muscle mass may likely possess a greater strength capacity to safely decelerate the body and maintain dynamic joint stability, body composition may be a crucial factor in our understanding of sex-specific neuromechanical strategies and injury risk. Hence, the primary objective of this study was to determine the effect of LELM on lower extremity EA strategies during a drop jump landing task and to determine whether the associated maximal eccentric thigh strength capability was the underlying factor driving these relationships. We hypothesized that 1) less LELM would predict less EA and 2) the relationship between LELM and EA would be mediated by maximal eccentric muscle strength. Finally, we hypothesized that the relationship between maximal eccentric muscle strength and EA would be stronger in females versus males.

METHODS

Subjects

On the basis of an *a priori* power analysis, 35 men and 35 women, ages 18–35 years, were recruited for this study, indicating that 31 subjects were needed per group to achieve 80% power to detect an $r = 0.35$ (moderate effect size) at a significance level of $P \leq 0.05$. These subjects were eligible to participate if they were experienced in and regularly participated in athletic activities (at least three times a week), which include jumping, landing, and quick deceleration with change of direction. To minimize potentially confounding effects of testing subjects who use compensatory movement strategies due to pain or dysfunction, subjects were excluded if they had a history of lower extremity orthopedic surgery, injury to the knee ligaments, or currently had a lower extremity injury or pain. In addition, given the dynamic nature of the task and to facilitate our matching criteria that was necessary for other aspects of the larger research study, we chose to exclude those who were classified as obese (BMI ≥ 30 kg·m^{-2}). Because body composition testing by dual-energy x-ray absorptiometry (DXA) is contraindicated during pregnancy, women were excluded from participating if they were pregnant. To separate out the effects of body composition and strength from other sex confounding variables, males and females were enrolled in pairs matched by similar BMIs (± 1.0 kg·m^{-2}). The university's institutional review board approved this study, and all subjects provided their informed consent before participating.

Measurements

Body composition testing.

Subjects reported to the Nutrition Assessment Research Laboratory for body composition assessment with the Lunar Prodigy Advance DXA (GE Healthcare, Madison, WI). A urinary pregnancy test (CVS Early Result Pregnancy Test; CVS Caremark, Woonsocket, RI) was administered to females to confirm that they were not pregnant before being scanned. While wearing light athletic clothing, body height and mass were measured using a digital stadiometer and scale, respectively. These data were entered into the patient database in the EnCORE 2007 software (GE Healthcare) for use in the software's calculations of body composition. The participant was then placed on the DXA table in the standard supine position suggested by the manufacturer for a total body scan. Once positioned, the participant was instructed to lie still for the duration of the total body scan.

Biomechanical testing.

Upon arrival to the laboratory for biomechanical testing, subjects were outfitted with standardized athletic shoes (Uraha 2; Adidas North America, Portland, OR), compression shorts, and shirt. To prepare for dynamic muscle contractions and to reduce the risk of undue muscle soreness and injury, subjects performed a standardized dynamic flexibility routine to actively warm and stretch the lower extremity musculature. This routine consists of 3–4 min of active tissue warming (jogging forward and backward and side shuffling at a self-selected pace), followed by a standardized sequence of dynamic flexibility exercises, specifically targeting the knee flexors and extensors, performed for a distance of 8 m, followed by a 10-m accelerative run, and an 18-m return jog. Subjects were then instrumented with clusters of three optical LED markers (Phase Space, San Leandro, CA) placed on the sacrum and thigh, shank, and foot of the dominant leg, defined as the stance leg when kicking a ball for maximum distance. The markers were affixed to the segments with standard hook and loop material and additionally secured with prewrap to minimize movement artifact.

The pelvis and the lower extremity were modeled with the Motion Monitor Software (Innovative Sports Training, Chicago, IL). Hip joint centers were estimated using the rotation method ([16]), whereas the knee and ankle joint centers were calculated as the middle of the medial and lateral femoral epicondyles and malleoli, respectively ([20]). 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. Three-dimensional hip, knee, and ankle flexion angles were calculated using Euler angle definitions with a rotational sequence of $ZY'X''$ ([12]). Kinematics and kinetics were measured with an eight-camera IMPULSE motion tracking system (Phase Space) at 240 Hz and two nonconducting force platforms (Type 4060-130; Bertec Corporation, Columbus, OH) at 1000 Hz, respectively, which were interfaced with Motion Monitor software (Innovative Sports Training) while subjects performed the drop jump landings.

To perform the drop jump landing, subjects were instructed to assume their initial position, drop straight down off the 0.45-m box (placed 0.1 m from the force platforms), land evenly on both feet, perform a maximal vertical jump, and land once again on both feet. They were asked to perform the drop landing and subsequent jump in one fluid motion (i.e., land, load, and jump) rather than two separate motions (i.e., land, pause, load, and jump). These instructions ensured that the subjects would perform the task in a natural and functional manner. Each participant was thoroughly familiarized to the landing task approximately 7 d before testing and on the day of testing, performed three to five practice trials before recording five successful trials during which kinematic and kinetic data were collected. During each trial, the investigator also subjectively assessed the participant's performance for proper execution of the task (as described previously), consistency of execution, and perception of maximal effort.

Strength testing.

After the drop jump landing protocol, subjects were positioned in the Biodex System 3 isokinetic dynamometer (Biodex Medical Systems, Inc., Shirley, NY) using standard procedures: seated in 90° of hip flexion, with the distal portion of the femur lined up with the edge of the seat and the lateral femoral epicondyle aligned with the axis of rotation on the dynamometer. Straps secured the chest, hips, thigh, and distal shank to ensure a constant body position. All strength testing was performed throughout a range of motion from 20° to 90° of flexion at a speed of $180°\cdot s^{-1}$, with all subjects performing the quadriceps protocol first. The quadriceps protocol consisted of a continuous concentric–eccentric knee extension-flexion protocol. To perform the alternating concentric and eccentric contractions of the quadriceps during knee extension and flexion actions, respectively, the participant was instructed to engage the quadriceps by kicking out against the distal tibia pad as hard as they could and to maintain the maximal contraction for the entire test, while disregarding the direction of dynamometer arm motion. Before testing, subjects were thoroughly familiarized to the isokinetic testing protocol approximately 7 d before testing to minimize any learning effect and to allow sufficient time for any residual muscle soreness to subside. On the day of testing, subjects performed a submaximal refamiliarization set of three to four repetitions at self-perceived intensity of 50%–75% maximal effort, followed by a short rest period, and finally the five maximal repetition trials during which the torque data were collected. After the quadriceps testing, subjects completed an identical protocol for the hamstrings, which consisted of a continuous eccentric–concentric knee extension-flexion protocol at $180°\cdot s^{-1}$ using the same 20°–90° range of motion. The participant was instructed to engage the hamstrings by pulling back against the distal tibia pad maximally for the entire test while disregarding the direction of dynamometer arm motion.

Data Reduction and Analysis

EnCORE 2007 software (GE Healthcare) was used to partition total body composition data into regional bone, lean, and fat mass so that relative amounts and locations of lean mass could be determined. The standard regions of interest (ROIs) provided within the software were manually adjusted using defined anatomical landmarks and boundaries. Specifically, the lower extremity ROI was formed by a diagonal line that extended inferomedially from the iliac crest through the femoral neck and then continued inferiorly to the tip of the longest toe and laterally to include all soft tissue of the leg (see Fig. 1). The investigator was able to consistently identify this ROI on repeat testing ($ICC_{2,1} \pm SEM = 0.99 \pm 0.21$ kg). From these data, LELM was extracted (kg) and used for analysis.

For the strength data, gravity-corrected torque data from the Biodex System 3 software were exported. Data were then low-pass filtered (10 Hz), and then to account for acceleration torque artifacts at the beginning and ending of the isokinetic repetition, torque data points associated with dynamometer velocities occurring at <70% of the target isokinetic speed were eliminated. The average peak eccentric torques across the three highest contractions (coefficient of variation <8%) for both the quadriceps and the hamstrings were then used for analysis.

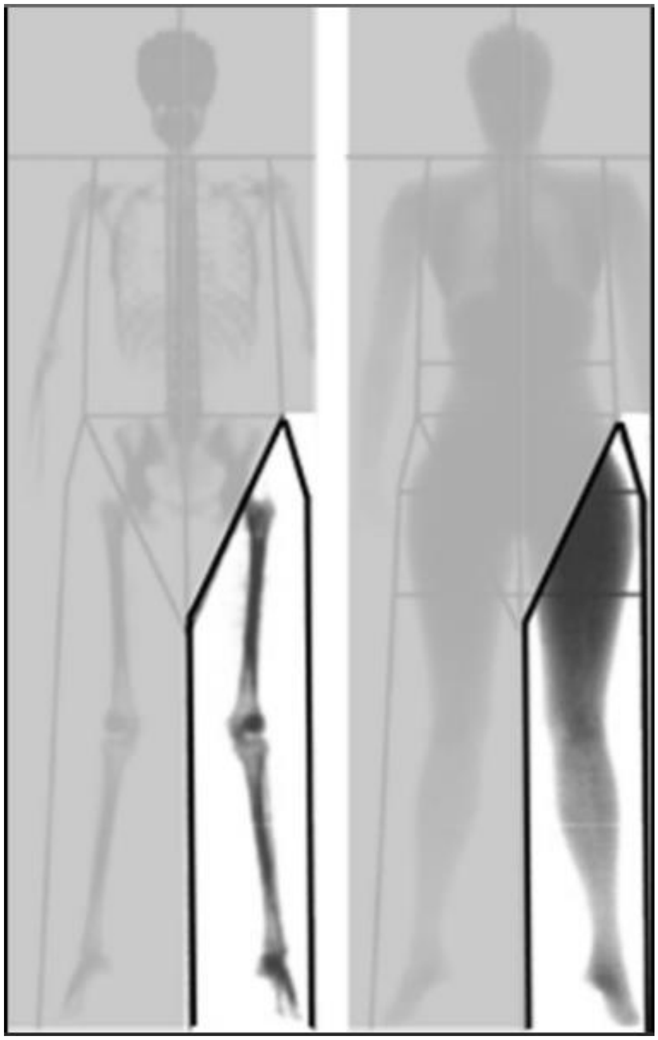

FIGURE 1. Standard ROIs are manually adjusted to defined the lower extremity.

Kinematic and kinetic data were processed (Motion Monitor; InnSports Training, Chicago, IL) using a fourth-order, zero-lag low-pass Butterworth filter at 12 Hz. Hip, knee, and ankle joint sagittal excursions from initial contact (vGRF > 10N) to peak vertical center of mass displacement were extracted and calculated as the average value obtained across the five trials. Hip, knee, and ankle moments were calculated using inverse dynamics solutions. EA (eccentric work of hip extensors, knee extensors, and ankle extensors) was calculated as the area under the negative power curve ([4,30,37]) for each joint (EA_{HIP}, EA_{KNEE}, and EA_{ANK}).

Statistical Analysis

Because of the assumed interrelatedness of the independent variables (LELM and strength), we chose to use a mediation analysis to test the first two hypotheses. This analysis was performed in two steps: First, to determine whether less LELM predicted less EA (hypothesis 1), separate linear regression analyses were used to determine whether less LELM predicted less EA at the hip (EA_{HIP}), knee (EA_{KNEE}), and ankle (EA_{ANK}). These linear regression models determine the “total effect” of LELM on EA ([25]) (Fig. 2). Because LELM is likely highly correlated with maximal force-producing capabilities of the thigh musculature, the second step of the analysis tested whether the relationship between LELM and each EA variable was still significant after accounting for maximal eccentric thigh strength; hence, a mediating effect (hypothesis 2). This was achieved by using a nonparametric bootstrapping procedure to perform tests for significance of the indirect path between LELM and EA, through the hypothesized mediators: maximal eccentric quadriceps and hamstrings strength ($Quad_{ECC}$ and Ham_{ECC}) (Path A × Path B [ab]; Fig. 2). This procedure resampled the data 5000 times, with replacement, to eliminate the assumption of the normality of data, which is present using parametric tests and is suggested to be the preferred methodology in current mediation analysis theory ([25]). These analyses were ultimately used to test whether the relationship between LELM and EA was significantly diminished when $Quad_{ECC}$ or Ham_{ECC} were added to the regression model, with the null hypothesis being that there is no difference between the two models (as evidenced by the 95% confidence interval [CI] including zero). Practically speaking, this indicates that significant relationships between LELM and EA exist only because of the underlying relationship between eccentric strength and EA. Conversely, if a significant relationship between LELM and EA is not diminished by adding strength to the model, it would imply that there is a unique amount of variance associated with both variables (i.e., LELM and strength are related to EA in unique ways). Because previous literature indicates that the relationships between strength and landing biomechanics may differ by sex ([30,33]), all analyses were stratified by sex. This allowed us to test whether the strength of these relationships would be stronger in females than males (hypothesis 3). In addition, although lean mass and strength data are typically normalized to body mass and kinetic data to body weight × height to reduce the variance due to body size, we chose to perform our analyses with non-normalized values to help avoid the potential of overcorrecting for body size (i.e., body weight and height, which are presumably related to thigh strength and LELM). We felt this was an acceptable approach because we analyzed our data within sex and therefore were not concerned with large differences in body size typically observed between males and females ([22]).

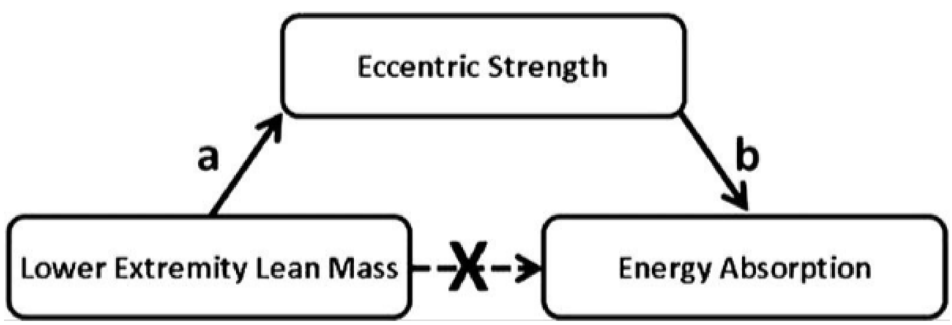

FIGURE 2. Total effect of LELM on EA: the extent to which LELM predicts EA (dashed line) and direct relationship between LELM and EA, mediated by strength (solid lines, A and B).

RESULTS

Thirty-five males (1.78 ± 0.1 m, 74.7 ± 8.9 kg, 20.9 ± 2.9 yr) and 35 females (1.67 ± 0.1 m, 65.3 ± 6.6 kg, 21.6 ± 3.6 yr) successfully completed data collection. These subjects were primarily recruited from the university’s National Collegiate Athletic Association division I athletics and club teams. For descriptive purposes, independent *t*-tests revealed that as expected, males were taller ($P < 0.001$) and heavier ($P < 0.001$) than their female counterparts, but because of the matching scheme used during participant recruitment, there were no differences in BMI (23.6 ± 2.2 vs 23.3 ± 2.2 kg·m^{-2}, $P = 0.596$). Despite the similar BMIs, males possessed more total body lean mass (61.6 ± 6.5 vs 43.8 ± 5.8 kg, $P < 0.001$) and specifically LELM in both absolute quantity (21.6 ± 2.8 vs 15.2 ± 1.9 kg, $P < 0.001$) and as a proportion of total body mass (29.1 ± 2.3 vs 23.6 ± 2.9%, $P < 0.001$) compared with females.

Table 1 (upper panel) presents the eccentric peak torques produced by males and females during the maximal strength testing as well as their EA data from the biomechanical testing. For descriptive purposes, independent *t*-tests revealed that in accordance with males being larger and having more LELM than females, males produced 41.2% and 48.0% larger peak $Quad_{ECC}$ and Ham_{ECC} torques (N·m), respectively, compared with females (both $P < 0.001$).

TABLE 1. Strength testing and EA results for males and females.

	Females (n = 35)	Males (n = 35)
Non-normalized		
$Quad_{ECC}$ (N·m)	205.9 ± 41.2	290.7 ± 65.9*
Ham_{ECC} (N·m)	125.1 ± 22.7	185.0 ± 30.9*
EA_{HIP} (J)	30.2 ± 15.5	50.8 ± 22.2*
EA_{KNEE} (J)	100.8 ± 29.5	128.9 ± 35.6*
EA_{ANK} (J)	34.8 ± 16.3	49.2 ± 17.7*
Normalized		
$Quad_{ECC}$ [a]	3.2 ± 0.5	3.9 ± 0.7*
Ham_{ECC} [a]	2.0 ± 0.3	2.5 ± 0.3*
EA_{HIP} [b]	2.7 ± 1.3	3.9 ± 1.7*
EA_{KNEE} [b]	9.1 ± 2.6	9.8 ± 2.6
EA_{ANK} [b]	3.1 ± 1.4	3.7 ± 1.2

Mean ± SD and between-sex effect size are provided for all data.
[a] Normalized to total body mass (N·m·kg^{-1}).
[b] Normalized to body weight × height (J·N^{-1}·m^{-1}); expressed ×10^2.
* Males > females ($P < 0.05$).

Table 2 presents the linear regression results from the first step of the mediation analysis, indicating the extent to which LELM predicted EA for males and for females. A moderate relationship between LELM and EA_{KNEE} was observed for females ($R^2 = 0.216$, $P < 0.01$), indicating that for every kilogram increase in LELM, there was a 7.7-J increase in EA on the knee (Table 2). However, this relationship was not evident in the males ($R^2 = 0.029$, $P = 0.16$). LELM was not a significant predictor of EA_{HIP} (females: $R^2 = 0.026$, $P = 0.18$; males:$R^2 = 0.022$, $P = 0.20$) or EA_{ANK} (females: $R^2 = -0.03$, $P = 0.99$; males: R^2= 0.015, $P = 0.23$).

TABLE 2. Regression coefficients and model R2 when predicting EA (EAHIP, EAKNEE, and EAANK; J) with LELM (kg) for females (n = 35) and males (n = 35).

Variable	Unstandardized β	SE	Standardized β	t	Adjusted R^2	P
Females						
Hip energy absorption (J)						
Intercept	0.717					
LELM	1.939	1.397	0.235	1.388	0.026	0.175
Knee energy absorption (J)*						
Intercept	−15.736					
LELM	7.669	2384	0.489	3.217	0.216	0.003
Ankle energy absorption (J)						
Intercept	34.803					
LELM	−0.002	1.516	0.000	−0.001	−0.030	0.999
Males						
Hip energy absorption (J)						
Intercept	12.269					
LELM	1.783	1.348	0.224	1.323	0.022	0.195
Knee energy absorption (J)						
Intercept	62.661					
LELM	3.059	2.150	0.240	1.423	0.029	0.164
Ankle energy absorption (J)						
Intercept	20.647					
LELM	1.321	1.075	0.209	1.229	0.015	0.228

* Significant model ($P < 0.05$).

Results from the nonparametric bootstrapping procedure used in the second step of the mediation analysis indicated that for females, $Quad_{ECC}$ was a significant predictor of EA_{KNEE} (ab = 179.72, 95% CI = 10.43–423.42) and EA_{ANK} (ab = 1.71, 95% CI = 0.16–3.94), whereas Ham_{ECC} was a significant mediator of the relationship between LELM and EA_{HIP} (ab = 4.89, 95% CI = 2.05, 8.40) (Table 3). No mediation effects were observed for the males. To compare our results with other work, the analysis of our data after normalizing each variable is also provided, which yielded similar results (see SDC Table 1, http://links.lww.com/MSS/A179, regression results when predicting normalized EA with normalized LELM, and SDC Table 2,http://links.lww.com/MSS/A180, for results of separate tests of normalized $Quad_{ECC}$ and Ham_{ECC} strength as mediators of the relationship between normalized LELM and EA).

TABLE 3. Results for separate tests of QuadECC and HamECC as a mediator of the relationship between LELM and EA in females and males.

	$QUAD_{ECC}$				HAM_{ECC}			
	ab	SE	95% CI		ab	SE	95% CI	
Females								
Hip EA	0.51	1.08	−1.78	2.66	4.89	1.59	2.05	8.40*
Knee EA	179.72	105.04	10.43	423.42*	0.02	2.74	−6.00	5.07
Ankle EA	1.71	0.97	0.16	3.94*	−0.71	1.23	−3.58	1.51
Males								
Hip EA	0.37	1.25	−2.16	2.83	0.80	1.18	−1.31	3.50
Knee EA	2.30	1.94	−1.49	6.38	1.85	2.54	−2.70	7.07
Ankle EA	−0.33	0.96	−2.24	1.53	1.58	1.09	−0.60	3.71

* Significance of the indirect path (ab) between LELM and EA.

DISCUSSION

Our primary findings were that the relationships between LELM, eccentric strength, and EA were observed in females only, indicating that strength was more important in determining EA strategies for females versus males. However, our hypotheses were only partially supported as

LELM was only related to EA at the knee, despite significant mediation effects of eccentric strength at all joints.

Sex Differences in Body Composition and Strength

This study confirmed previous findings regarding sex differences in body composition and strength, which was fundamentally important for the rationale for this study. Males had, on average, 40% more lean body mass relative to total body mass compared with females and 42% more LELM. The greater amount of total body lean mass in males versus females in this study is less than the 50%–70% difference previously reported in the literature ([19,21]). This may be attributed to the more highly trained population included in the current study (i.e., females having greater lean mass vs an untrained female population). Our findings of similar relative lean mass distribution in the lower extremity in both males and females are in agreement with another investigation of sex differences in regional body composition in former U.S. Army cadets ([24]), which reported that females possessed 70% of the absolute LELM of the males. Consistent with possessing greater amounts of lean mass, males also produced greater absolute eccentric quadriceps and hamstrings peak torques, which persisted once normalized to body mass.

Relationships between Lean Mass, Strength, and EA

Previous literature indicates that a larger BMI and/or a lower strength–body mass ratio may be related to dangerous landing strategies. The lower strength-producing capabilities in females compared with males may in part explain landings performed with less hip and knee flexion ([18]), greater demands on the knee extensors ([14,15,29,30,33]), and therefore larger landing forces ([29]). Specifically, greater maximal voluntary isometric contraction strength has been shown to predict greater EA about the knee, suggesting that those females with greater strength possessed a greater ability to control the body's deceleration about the knee joint ([30]).

Because females possess less lean body mass and leg strength than their male counterparts and absorb less energy during landing, it was hypothesized that the magnitude of LELM would positively predict the amount of EA but that this relationship would be mediated by the magnitude of eccentric thigh strength functionally produced by the available lean mass. Our findings indicated that greater lean mass predicted more EA at the knee joint and that this relationship was in turn a result of the underlying mediating relationship of eccentric quadriceps strength, but only in females. This indicates that greater eccentric strength of the knee extensors and secondarily, the amount of lean mass present in the leg, positively predicts EA about the knee. This may be clinically significant as females in this study absorbed approximately 0.7 $J \cdot N^{-1} \cdot m^{-1}$ less normalized EA_{KNEE} than males. Theoretically then, a 2% increase in a female's LELM relative to body mass could increase her EA capabilities about the knee to the same magnitude as the average male in this study. This could have important implications for intervention efforts as one's lean body mass–total body mass ratio can be increased through appropriate training interventions via a loss of fat mass and/or gain in lean body mass.

We also observed significant mediation effects of Ham_{ECC} and $Quad_{ECC}$ on the relationships between LELM and EA at the hip and ankle joints, respectively, despite no primary relationship between LELM and EA at those joints. Significant mediation effects in the absence of an initial total effect of LELM on EA suggest that there may have been intervening factors in the relationship between LELM and these EA variables (besides strength), which reduced the initial direct effect ([32]). As such, eccentric strength cannot be called a mediator *per se*; the nomenclature is slightly modified to denote a significant "indirect effect" (instead of mediating effect) of eccentric strength on the relationship between LELM and EA ([8,32]), although the functional interpretation is still that eccentric strength of the quadriceps and hamstrings is an intermediary factor between LELM and EA at the ankle and hip, respectively. Plausible intervening factors that would have reduced the initial direct effect would be those most likely related to both LELM and EA, such as muscle activation or hip extensor and ankle plantar flexor strength (which were not measured).

Our results were in agreement with previous work, which showed an interactive effect of sex and maximal voluntary isometric contraction strength on joint-specific energetics ([30]), where there was a significant relationship between maximal voluntary isometric contraction strength and EA about the knee in females, but not in males. In addition, we observed significant relationships between strength and EA in females but not males at the hip and ankle as well. To further compare these results to the current results, the extent to which eccentric strength predicted EA (a third component of the mediation analysis) was more closely examined. Maximal eccentric hamstring torque predicted 20.6% of the variance in hip EA in females, whereas the aforementioned study ([30]) did not find a relationship between maximal isometric hamstring torque and EA about the hip. The disparity between these studies may be explained by potential specificity of the hamstring strength measurements in the current study to the action at the hip during drop jump landing. The previous study used an isometric strength protocol, whereas the current study used an eccentric strength protocol. If the hamstrings did indeed undergo an eccentric muscle action to control hip and trunk flexion ([5]) in preparation for the subsequent vertical jump ([17]) during our drop jump task, it may help to explain the current findings. However, it is understood that the action of the hamstrings during landing is still disputed ([11,27]).

In the current study, maximal eccentric quadriceps strength explained 12.6% of the variance in knee EA in females, which is similar to the 11% explained by maximal isometric strength ([30]). The close similarity in predictive ability of these findings is somewhat surprising considering the preceding discussion regarding specificity of muscle contraction. The rationale for choosing to measure eccentric strength at $180°\cdot s^{-1}$ was that it was likely more reflective of the action of the muscles during the deceleration phase of the drop jump compared with strength measures used in previous studies ([2,18,30]).

The weak relationships between eccentric strength and EA found in this study may also be due to the methods used, specifically the attempt to relate a peak torque measurement captured at a specific knee flexion angle with data integrated over a wide range of motion. This notion was previously suggested in a study unable to relate peak strength measures to peak anterior knee shear force ([2]). A more comprehensive measurement of strength such as average torque (throughout range of motion) or work (the area under the joint power curve) may relate better to EA during landing because of its closer task demands to the EA performed during landing.

Another relevant methodological limitation acknowledged in this study is that only knee flexor and extensor strength were measured. Because the purpose of this study was to examine the effect of eccentric strength on lower extremity EA as it relates to knee injury risk, it was fundamentally important to measure the muscles that directly control knee function. However, as EA of the hip and ankle was also of interest, it is likely that measuring the strength of the primary musculature at those joints, specifically the primary hip extensors (gluteals) and plantar flexors (gastrocnemius–soleus complex), would have improved the relationships between strength and joint-specific EA. This may be particularly relevant in light of the significant mediation effects observed at the hip and ankle in the current study. Further, because the muscles do not act in isolation (as tested in this study), in the future, capturing an "index" of lower extremity strength would likely provide a more comprehensive assessment of the global force-producing capabilities and may further improve the ability to relate strength and EA.

We acknowledge the commonly accepted practice of normalizing biomechanical variables to reduce intersubject differences due to body size ([22]). However, as our analyses included other "predictor" variables that are highly influenced by body size (i.e., LELM and maximal strength), we chose to use non-normalized variables in our analyses to minimize the possibility of overaccounting for body size. Although the effect of using raw data can be seen in simple sex comparisons in energetics (Table 1, lower panel), our analyses were conducted within each sex, and we found that it made little difference if we normalized the data when predicting EA with lean mass within each subject. The essential difference between methods was that after normalizing the data, the mediation effects of Quad strength on knee and ankle EA for females become nonsignificant, although the effects remained nearly significant (see SDC Table 2,http://links.lww.com/MSS/A180, for results of separate tests of normalized $Quad_{ECC}$ and Ham_{ECC} strength as mediators of the relationship between normalized LELM and EA). We speculate that the differences between these two methods may be attributed to overaccounting for body size by predicting a normalized dependent variable with independent variables, which were also reduced by the same factors (i.e., body weight and height). The two methods yielded similar results, providing further support for the notion that there are sex-related influences on landing energetics that are not simply related to sex differences in body size.

CONCLUSIONS

In summary, the current findings concur with previous literature, which has demonstrated significant relationships between strength and EA only in females. Although the source of these sex differences is unclear at this time, it seems that the underlying mechanisms that determine EA capabilities are different between males and females. As eccentric strength seemed to be an intermediary factor in the relationship between lean mass and lower extremity EA, the current results indicate that increasing the amount of eccentric strength (with or without an increase in lean mass) that a female possesses may be accompanied by an increase in EA capabilities, which may theoretically decrease her risk of ACL injury. As such, clinicians should consider evaluating LELM and strength as relevant factors in prevention and intervention strategies.

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SDC Table 1. Regression coefficients and model R^2 when predicting energy absorption (EA_{HIP}, EA_{KNEE}, and EA_{ANK}) with lower extremity lean mass (LELM; % body mass) for females and males.

FEMALES						
Variable	**Unstandardized Beta**	**Standard Error**	**Standardized Beta**	**t-value**	**Adjusted R^2**	**p-value**
Hip Energy Absorption ($J*N^{-1}*m^{-1}$)						
Intercept	0.033	0.019		1.750		
LELM	-0.023	0.078	-0.052	-0.298	-0.028	0.768
Knee Energy Absorption ($J*N^{-1}*m^{-1}$)						
Intercept	0.005	0.034		0.157		
LELM	0.364	0.144	0.402*	2.520	0.136*	0.017
Ankle Energy Absorption ($J*N^{-1}*m^{-1}$)						
Intercept	0.042	0.021		2.022	-0.023	0.621
LELM	-0.043	0.087	-0.087	-0.500		
MALES						
Variable	**Unstandardized Beta**	**Standard Error**	**Standardized Beta**	**t-value**	**Adjusted R^2**	**p-value**
Hip Energy Absorption ($J*N^{-1}*m^{-1}$)						
Intercept	-0.013	0.036		-0.369		
LELM	0.179	0.124	0.244	1.444	0.031	0.158
Knee Energy Absorption ($J*N^{-1}*m^{-1}$)						
Intercept	0.084	0.058		1.454		
LELM	0.048	0.197	0.042	0.242	-0.028	0.810
Ankle Energy Absorption ($J*N^{-1}*m^{-1}$)						
Intercept	0.088	0.025		3.468		
LELM	-0.177	0.087	-0.332	-2.025	0.068	0.051

* Significant coefficient or model ($p<.05$)

SDC Table 2. Results for separate tests of $Quad_{ECC}$ ($Nm*kg^{-1}$) and Ham_{ECC} ($Nm*kg^{-1}$) as a mediator of the relationship between LELM (% body mass) and energy absorption ($J*N^{-1}*m^{-1}$) in females and males.

	$QUAD_{ECC}$				HAM_{ECC}			
FEMALES	**ab**	**SE**	**95% CI**		**ab**	**SE**	**95% CI**	
Hip Energy Absorption	0.007	0.052	-0.107	0.109	0.208	0.085	0.076	0.405*
Knee Energy Absorption	0.118	0.091	-0.036	0.330	-0.047	0.127	-0.326	0.177
Ankle Energy Absorption	0.051	0.055	-0.029	0.187	-0.052	0.054	-0.169	0.047
MALES	**ab**	**SE**	**95% CI**		**ab**	**SE**	**95% CI**	
Hip Energy Absorption	0.018	0.058	-0.086	0.153	0.012	0.037	-0.052	0.103
Knee Energy Absorption	0.084	0.097	-0.065	0.323	0.003	0.051	-0.104	0.120
Ankle Energy Absorption	-0.023	0.040	-0.118	0.044	-0.003	0.021	-0.052	0.036

* Indicates significance of the indirect path (ab) between LELM and EA.