Thigh Strength and Activation as Predictors of Knee Biomechanics during a Drop Jump Task

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Abstract:
Purpose: To examine whether normalized quadriceps and hamstring strength would predict quadriceps and hamstring muscle activation amplitudes and whether these neuromuscular factors would predict knee kinematics and kinetics during a drop jump task. ***Methods:*** Thirty-nine females and 39 males were measured for isometric quadriceps and hamstring strength and were instrumented to obtain surface electromyography, kinematic, and kinetic measures during the initial landing of a drop jump. Multiple linear regressions first examined the relationship between thigh strength and activation then examined whether these neuromuscular variables were predictive of hip and knee flexion excursions, knee extensor moments (KEM), and anterior knee shear forces during the deceleration phase of the drop jump. ***Results:*** Females versus males produced lower normalized thigh strength and demonstrated greater quadriceps and hamstring activation amplitudes during the drop jump. Lower thigh muscle strength was a weak (males) to moderate (females) predictor of greater quadriceps activation amplitudes. However, thigh strength and activation were poor predictors of hip and knee joint excursions and KEM. Regardless of sex and thigh strength, anterior shear forces were greater in individuals who demonstrated less hip flexion and greater knee flexion excursions and greater peak quadriceps activation and internal KEM during the landing. ***Conclusions:*** Although thigh muscle strength explained some of the variance in quadriceps and hamstring activation levels as measured with surface electromyography, we failed to support the hypothesis that these neuromuscular factors are strong predictors of sagittal plane hip and knee flexion excursions or KEM. Although greater quadriceps activation amplitude was a significant predictor of greater anterior tibial shear forces, its contribution was relatively small compared with kinematic and kinetic variables.

Key Words:
QUADRICEPS DOMINANCE, ACL RISK FACTORS, LANDING BIOMECHANICS, PEAK TORQUE TO BODY WEIGHT

Article:

The greater risk of noncontact anterior cruciate ligament (ACL) injury in physically active females compared with males continues to be an important health concern. To understand the causes for the greater risk in females, extensive research over the past decade has examined sex differences in neuromuscular and biomechanical patterns during landing and cutting. On the basis of available literature, expert consensus in 2006 suggested that females have quadriceps dominant activation strategies (11) based on studies where females compared with males were reported to activate their quadriceps muscles earlier relative to the hamstrings muscles (13,30) and land and cut with greater quadriceps activation both preground (4,23) and postground (21,31) contact. This quadriceps dominant activation pattern is thought to be a major contributing factor to ACL injury because high levels of quadriceps activation and low levels of hamstring activation during a concentric contraction are thought to produce significant anterior displacement of the tibia relative to the femur (11). This is supported by cadaveric studies that demonstrate unopposed quadriceps forces result in greater loads on the ACL (1,9,20,22), which are sufficient to strain (in vivo and in vitro) (2,35) and to injure (in vitro) (8) the ACL. Because females have also been reported to land and cut with lower knee flexion angles (12,19,21), greater quadriceps activation at these smaller knee flexion angles is thought to contribute to the greater normalized anterior knee shear forces (5,39) and knee extensor moments (KEM) (5,28,31) observed in females compared with males.

Few studies have collectively examined surface electromyography (sEMG), kinematic, and kinetic data to directly make the connection between greater quadriceps activation, decreased knee flexion, and greater KEM and knee joint forces. Sigward and Powers (31) recently compared 15 male and 15 female soccer athletes on muscle activation and sagittal plane knee kinematic and kinetics during the early deceleration of a side-step cut and reported that females demonstrated greater quadriceps activation, smaller net knee flexor moments, but no difference in knee flexion angles. Although they suggested that greater quadriceps activation in females may explain their smaller net knee flexor moment, they did not directly examine this relationship. Sell et al. (28) lends some support to this theory, examining seven predictors of anterior tibial shear force in 36 subjects during a stop jump task. They reported that greater integrated EMG of the vastus lateralis along with greater peak posterior ground reaction force, external knee flexion moment, knee flexion angle, and sex (female) were significant predictors of greater anterior shear force (ASF).

An important consideration of this body of work (28,31) is that quadriceps activation has been based on sEMG recordings, which fails to incorporate a quantification of muscle force. It is well accepted that muscle activation amplitude as measured by EMG is not always linearly related with the force of the muscle contraction (38), and this becomes even more difficult to interpret during ballistic activities (25). Further, because males compared with females have a greater proportion of muscle mass to total body mass, lending to greater average strength to body mass (19,32), the forces exerted during a maximal voluntary isometric contraction (MVIC) by which these sEMG data are typically normalized are not the same for each sex. As a result, the greater quadriceps activation observed in females during dynamic tasks may reflect these sex differences in body composition and strength, with females having to use more of their available muscle force producing capabilities to control the same amount of absolute body weight during a given task. Because similar demands are not placed on the hamstring muscles during these tasks, greater quadriceps activation may not necessarily be accompanied by greater hamstring activation. Whether greater quadriceps activation observed in females during dynamic movements simply represents a relative quadriceps weakness (resulting in no appreciable effect on dynamic knee control) or is indicative of greater KEM and ASF is an important distinction in our approach to injury prevention strategies.

Therefore, our purpose was to examine the relationships between body weight normalized strength and neuromuscular and biomechanical variables during the initial landing of a drop jump. Our first goal was to determine whether sex differences in the level of quadriceps and hamstring muscle activation during the drop jump could be explained by sex differences in isometric strength normalized to body mass. Our hypothesis was that lower relative strength to body weight of the quadriceps and hamstring muscle groups would be strong predictors of greater quadriceps and hamstring muscle activation amplitudes. Once we understood these strength–muscle activation relationships, our second goal was to examine the extent to which muscle strength and activation contributed to sagittal plane knee joint kinematics and kinetics once accounting for other sex-dependent factors. Our expectation was that the combination of muscle strength and activation would be stronger predictors of knee and hip flexion motion, KEM, and anterior tibial shear forces during the drop jump than when muscle activation levels were considered alone.

MATERIALS AND METHODS

As part of a larger ongoing project, 39 females (22.2 ± 2.9 yr, 162.9 ± 6.8 cm, 58.8 ± 7.8 kg) and 39 males (22.6 ± 2.6 yr, 177.8 ± 10.1 cm, 81.7 ± 14.0 kg) were measured for body mass index (BMI) and isometric quadriceps and hamstring strength and were fully instrumented to obtain sEMG, kinematic, and kinetic measures during a double leg drop jump. Height and weight were obtained during the initial intake session, and participants were evaluated for strength and landing neuromechanics after first being familiarized to all testing procedures approximately 2 wk before actual testing. All females were tested during the first 6 d of menses to control for any potential hormone effects on strength (26) or resulting knee joint neuromechanics. The dominant stance limb (defined as the stance leg when kicking a soccer ball) was measured on all participants. Before participation, subjects were informed of all study procedures and signed a consent form approved by the Institution's Review Board for the Protection of Human Subjects.

A Biodex System 3 isokinetic dynamometer (Biodex Medical Systems Inc., Shirley, NY) was used to resist maximal voluntary isometric contractions (MVIC) and record peak knee extension and flexion torques (N-m). Subjects were seated and positioned at a fixed knee flexion angle of 25° (to best mimic the flexion angle at initial contact position [7]). The dynamometer axis was aligned with the lateral femoral epicondyle, and the resistance pad was placed at the distal tibia approximately two fingers breath proximal to the medial malleolus. Knee extension and flexion torque were recorded while asking subjects to kick out (extend the knee) or flex the knee, respectively, as hard as possible. Subjects were asked to keep their arms crossed over their chest while consistent verbal encouragement was provided. Three 3-s MVIC trials were obtained for both knee extension and knee flexion with a 30-s rest period separating each trial. A coefficient of variation of less than 10% across trials was confirmed.

For normalization of the sEMG data during the landing task, sEMG data were simultaneously collected during the MVIC trials using a 16-channel Myopac telemetric system (Run Technologies, Mission Viejo, CA) with an amplification of 1 mV-Vj 1, a frequency bandwidth of 10 to 1000 Hz, a common mode rejection ratio of 90 dB min at 60 Hz, an input resistance of 1 Mfl, and an internal sampling rate of 8 KHz. The sEMG signals were detected with 10 mm bipolar Ag–AgCl surface electrodes (Blue Sensor N-00-S; Ambu Products, Ølstykke, Denmark) with a center-to-center distance of 20 mm. Myoelectric data were acquired, stored, and analyzed using DataPac 2K2 lab application software (Version 3.13; Run Technologies). The skin was shaved and thoroughly cleaned with isopropyl alcohol, and the

TABLE 1. Means and SD for measures of BMI, thigh muscle strength, and biomechanical outcome variables during a double leg drop jump landing.

	Females (N = 39) Mean ± SD	Males (N = 39) Mean ± SD	P Value
BMI	22.2 ± 2.4	25.8 ± 3.3	<0.001*
Quadriceps torque (N·m·kg^{-1})	2.2 ± 0.4	2.5 ± 0.3	<0.001*
Hamstring torque (N·m·kg^{-1})	1.7 ± 0.2	2.0 ± 0.3	<0.001*
Initial knee flexion angle (°)	17.0 ± 5.9	17.3 ± 6.5	0.844
Knee flexion excursion (°)	71.6 ± 10.0	65.5 ± 12.1	0.018*
Initial hip flexion angle (°)	25.3 ± 6.4	22.9 ± 9.1	0.185
Hip flexion excursion (°)	48.0 ± 13.7	40.1 ± 17.2	0.029*
Peak KEM (N·m × BW^{-1} × Ht^{-1})	0.087 ± 0.029	0.072 ± 0.028	0.026*
Peak anterior tibial shear force (%BW)	68.6 ± 9.7	66.6 ± 15.6	0.492

* Significant difference between sex ($P \leq 0.05$).

electrodes were then placed midway between the motor point and the distal tendon of the lateral quadriceps (LQ), the medial quadriceps (MQ), the medial hamstrings (MH), and the lateral hamstrings (LH), oriented perpendicular to the length of the muscle fibers. The reference electrode was attached over the flat portion of the anteromedial aspect of the tibia. Absence of crosstalk between sampled muscles was visually confirmed during manual muscle testing using the scope mode of the data acquisition software.

With the sEMG electrodes still firmly attached, six degree-of-freedom position sensors (Ascension Technologies, Burlington, VT) were attached with double-sided tape and elastic wrap over the anterior midshaft of the third metatarsal, the midshaft of the medial tibia, and the lateral aspect of the midshaft of the femur of the dominant stance limb. Two additional sensors were placed on the sacrum and over the C7 spinous process. Hip joint centers were calculated using the Leardini et al. (18) method. Knee joint centers were calculated as the centroid of the medial and the lateral femoral epicondyles, and ankle joint centers were calculated as the centroid of the medial and the lateral malleoli. All kinematic data were collected at 100 Hz using the Motion Monitor software (Innovative Sports Training, Chicago, IL).

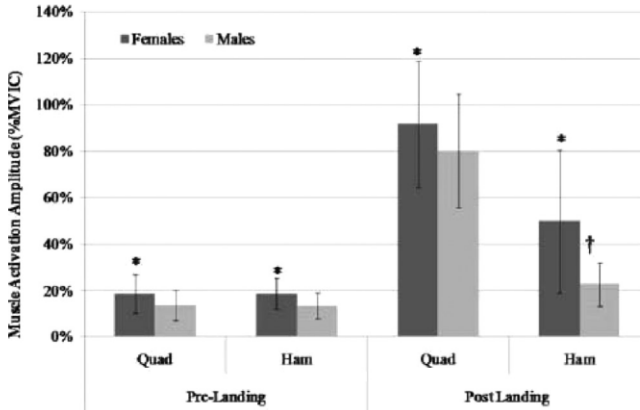

FIGURE 1—Comparison of males and females on quadriceps and hamstring pre- and postlanding muscle activation (%MVIC) during the initial landing of the drop jump. *Females > males. †The relative sex difference increased from pre- to postlanding activation for the hamstring muscles but decreased for the quadriceps muscles.

Once instrumented and digitized, five drop jumps were performed with the subject barefoot, dropping from a wooden platform measuring 0.45 m in height and placed 0.1 m behind the rear edge of the force plate (Type 4060- nonconducting; Bertec Corporation, Columbus, OH). For all trials, subjects began in a standardized takeoff position in which the toes were aligned along the leading edge of the wooden platform and the hands were placed at the level of the ears. Subjects were then instructed to drop off the platform with both feet and perform a maximal vertical jump upon landing. Subjects were not given any special instructions with regard to their drop jump mechanics to prevent experimenter bias. The hands remained at ear level throughout the task to eliminate variability in jumping mechanics due to arm swing. In addition to the familiarization session, practice repetitions (typically three) were allowed before test trials to insure the subject remained comfortable with the task (both visually and subjectively). Kinematic data sampled at 100 Hz and sEMG and kinetic data sampled at 1000 Hz were then collected during the initial landing phase of five successful drop jumps. All data were synchronized using the software's trigger sweep acquisition mode, using a foot contact threshold of 10 N to trigger data collection. A trial was discarded, and subjects were asked to repeat the trial if we observed them to step or jump off the box, if they lost their balance, if they did not land bilaterally, if their hands dropped below the level of the ears, or if they failed to land back onto the force plate after the maximal vertical jump.

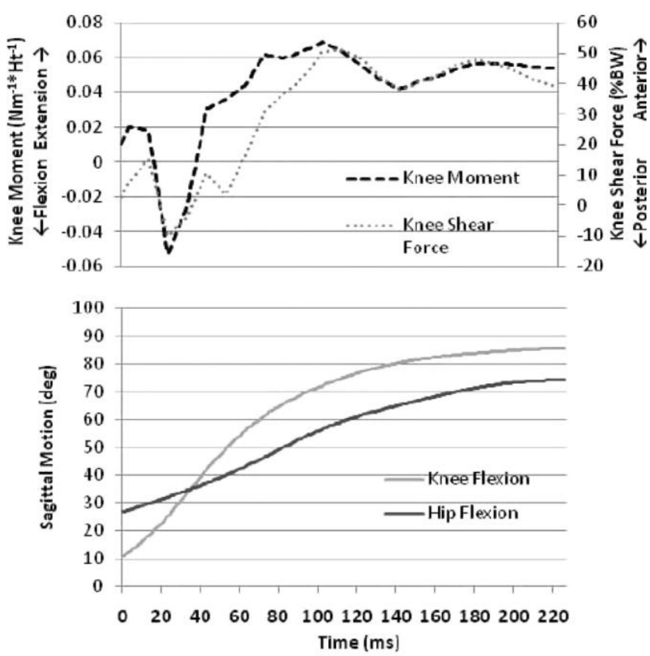

FIGURE 2—Representative trial demonstrating the time course of kinematic and kinetic data during the initial landing of the drop jump.

TABLE 2. Regression coefficients from the full regression model when predicting pre- and postlanding quadriceps activation based on quadriceps and hamstring peak torque ($N \cdot m \cdot kg^{-1}$) once accounting for BMI and reciprocal hamstring activation.

	Females (N = 39)				Males (N = 39)			
Variable	Parameter Estimate	SE	t Value	P Value	Parameter Estimate	SE	t Value	P Value
Prelanding activation								
Intercept	0.455	0.178	2.559	0.015	0.028	0.152	0.193	0.848
BMI	−0.005	0.005	−0.928	0.360	0.003	0.003	0.803	0.428
Hamstring preactivation	0.250	0.205	1.218	0.231	0.142	0.190	0.749	0.459
Quad peak torque	−0.071	0.033	−2.158	0.038*	−0.055	0.033	−1.681	0.102
Ham peak torque	−0.030	0.063	−0.480	0.634	0.077	0.040	1.904	0.065
Postlanding activation								
Intercept	2.229	0.515	4.328	0.000	1.240	0.501	2.478	0.018
BMI	−0.025	0.016	−1.562	0.127	−0.009	0.012	−0.739	0.4653
Hamstring postactivation	0.172	0.129	1.332	0.192	−0.058	0.420	−0.138	0.891
Quad peak torque	−0.252	0.095	−2.654	0.012*	−0.271	0.121	−2.238	0.032*
Ham peak torque	−0.172	0.173	−0.994	0.327	0.233	0.148	1.574	0.125

* Significant regression coefficient, $P < 0.05$.

Data reduction and analyses.

Quadriceps and hamstring torque data were recorded as the mean of the peak torques obtained over the three MVIC trials for each muscle group and normalized to the subject's body mass and reported in newton-meters per kilogram of body mass ($N \cdot m \cdot kg^{-1}$). To estimate body composition (34), we calculated body mass index (BMI) as the body weight in kilograms divided by the square height in meters. To analyze muscle activation amplitude, we band-pass filtered the sEMG signal of the LQ, MQ, LH, and MH from 10 to 350 Hz, using a fourth-order, zero-lag Butterworth filter (16) then processed using a centered root mean square algorithm using a 100-ms time constant for MVIC trials and a 25-ms time constant for the drop jump trials. sEMG data from the five landing trials were ensemble averaged, and the peak RMS amplitude obtained from each muscle during the 150-ms immediate before (preactivation) and after (postactivation) initial ground contact of the first landing phase was obtained. These amplitudes were then normalized using the average of the peak sEMG amplitudes obtained over the three MVIC trials (%MVIC). Normalized activation amplitudes obtained from the medial and the lateral aspects of each muscle were then averaged and used to represent activation of the quadriceps and hamstring muscles, respectively.

All biomechanical data were processed using MotionMonitor Software (InnSport, Chicago, IL). Kinematic signals from the position sensors were linearly interpolated to force plate data and were subsequently low-pass filtered at 12 Hz using a fourth-order, zero-lag Butterworth filter. A segmental reference system was defined for all body segments, with the positive Z-axis defined as the medial to lateral axis, the positive Y-axis defined as the distal to proximal longitudinal axis, and the positive X-axis defined as the posterior to anterior axis. Knee angles were calculated using Euler angle definitions with a rotational sequence of Z Y' X'' (14). Hip and knee flexion angles were each extracted at initial ground contact and at maximum knee flexion angle (coinciding with the maximum center of mass displacement) of the initial landing phase, and the excursion values were calculated (peak – initial) and averaged across the five drop jump trials. Kinetic data were low-pass filtered at 60 Hz using a fourth-order, zero-lag Butterworth filter, and peak KEM and anterior tibiofemoral shear force data were obtained between the point of initial ground contact and the maximum knee flexion angle. Intersegmental kinetic data were calculated via an inverse dynamics model (10) and were normalized to each participant's height and weight ($N \cdot m \times BW^{-1} \times Ht^{-1}$), and shear force data were normalized to weight (%BW).

TABLE 3. Regression coefficients from the full regression model when predicting pre- and postlanding hamstring activation based on quadriceps and hamstring peak torque (N·m·kg^{-1}) once accounting for BMI and reciprocal quadriceps activation levels.

	Females (*N* = 39)				Males (*N* = 39)			
Variable	Parameter Estimate	SE	*t* Value	*P* Value	Parameter Estimate	SE	*t* Value	*P* Value
Prelanding activation								
Intercept	0.313	0.149	2.100	0.043	0.216	0.122	1.774	0.085
BMI	−0.003	0.004	−0.652	0.519	−0.003	0.003	−1.115	0.273
Quad preactivation	0.167	0.137	1.218	0.231	0.114	0.152	0.749	0.459
Quad peak torque	0.042	0.028	1.508	0.141	−0.002	0.031	−0.060	0.952
Ham peak torque	−0.106	0.048	−2.207	0.034*	−0.004	0.038	−0.118	0.907
Postlanding activation								
Intercept	1.089	0.811	1.342	0.188	0.043	0.222	0.195	0.847
BMI	−0.020	0.021	−0.946	0.351	0.005	0.005	0.991	0.329
Quad postactivation	0.289	0.217	1.332	0.192	−0.010	0.070	−0.138	0.891
Quad peak torque	−0.032	0.135	−0.235	0.816	0.017	0.053	0.322	0.750
Ham peak torque	−0.200	0.225	−0.891	0.379	0.013	0.063	0.200	0.842

* Significant regression coefficient, $P < 0.05$.

TABLE 4. Regression coefficients from the full regression model when examining neuromuscular and kinematic contributions to peak KEM (*N* = 78).

Variable	Parameter Estimate	SE	*t* Value	*P* Value
Peak KEM				
Intercept	0.120	0.040	3.029	0.003
Sex	−0.024	0.008	−2.837	0.006*
Knee flexion excursion	0.000	0.000	0.491	0.625
Hip flexion excursion	−0.001	0.000	−2.831	0.006*
Quad peak torque	0.006	0.010	0.671	0.505
Ham peak torque	0.006	0.013	0.479	0.633
Quad preactivation	−0.026	0.056	−0.465	0.643
Ham preactivation	−0.014	0.055	−0.249	0.804
Quad postactivation	−0.004	0.017	−0.259	0.796
Ham postactivation	0.013	0.015	0.879	0.383

* Significant regression coefficient, $P < 0.05$.

Independent-samples t-tests compared males and females on BMI, initial hip ($HFLEX_{INIT}$) and knee ($KFLEX_{INIT}$) flexion angles, hip ($HFLEX_{EXC}$) and knee flexion ($KFLEX_{EXC}$) excursions, height and weight normalized peak knee extensor moments (KEM), and weight normalized peak anterior shear force (ASF) during the deceleration phase of the drop landing. A 2 x 2 repeated-measures ANOVA examined sex differences in quadriceps ($QUAD_{TRQ}$) and hamstring (HAM_{TRQ}) muscle peak torque relative to body mass. A 2 x 2 x 2 repeated-measures ANOVA compared males and females on quadriceps and hamstring prelanding ($QUAD_{PRE}$, HAM_{PRE}) and postlanding ($QUAD_{POST}$, HAM_{POST}) activation during the drop jump. Post hoc testing for significant interactions consisted of main effects testing. After confirming sex differences in strength and landing activation strategies, separate multiple linear regression analyses examined the extent to which quadriceps and hamstring peak torque normalized to body mass predicted the amount of normalized quadriceps and hamstring pre- and postlanding activation once accounting for BMI and reciprocal muscle activation (e.g., accounting for postlanding hamstring activation when predicting postlanding quadriceps activation). Because the means and the distributions of the muscle activation variables differed so widely by sex and because of the known sex differences in BMI, we ran separate regression models for males and females because we did not feel it would be sufficient to simply control or adjust for sex when examining these relationships. All analyses were evaluated at $P < 0.05$. Power calculations determined that with a sample of 39 subjects for each analyses and with a maximum of four independent variables, we had 80% power to detect a multiple R^2 of 0.25 (6). This criterion was considered acceptable because a large effect would be required to establish thigh strength as a meaningful and an accurate predictor of quadriceps activation.

To address our second goal, we constructed separate planned stepwise linear regression models to examine the extent to which muscle strength and activation contributed to sagittal plane kinematics ($HFLEX_{EXC}$, $KFLEX_{EXC}$) and kinetics (KEM, ASF) once accounting for other sex- dependent factors. To parse out the contributions of muscle strength and activation to $HFLEX_{EXC}$ and $KFLEX_{EXC}$ during the drop jump, we entered sex on the first step, strength variables ($QUAD_{TRQ}$ and HAM_{TRQ}) on the second step, and muscle activation amplitudes ($QUAD_{PRE}$, HAM_{PRE} $QUAD_{POST}$, and HAM_{POST}) on the third step. This allowed us to examine the contribution of quadriceps and hamstring activation to the dependent variables once the individual's sex and strength were accounted for. A similar approach was taken for KEM, with the exception that we also accounted for $HFLEX_{EXC}$ and $KFLEX_{EXC}$ in the model, and these variables were included in the first step along with sex. To examine the neuromuscular contributions to ASF, we first controlled for and entered the individual's sex, $HFLEX_{EXC}$, $KFLEX_{EXC}$, and KEM on the first step, followed by strength ($QUAD_{TRQ}$ and HAM_{TRQ}) on the second step, and muscle activation ($QUAD_{PRE}$, HAM_{PRE} $QUAD_{POST}$, and HAM_{POST}) on the third step. On the basis of a sample size of 78 and a maximum of 10 predictor variables (ASF analysis), we determined we had over 90% power to detect a multiple R^2 of 0.25 (6).

RESULTS

Means and SD for thigh muscle strength are provided in Table 1. When comparing males and females on quadriceps and hamstring muscle torque, a significant main effect for sex (P = 0.001) but no interaction between sex and muscle (P = 0.739) indicated that females produced 15.6% lower knee extensor and flexor torque (11.8% and 17.2% for the quadriceps and the hamstring, respectively) for the same relative body mass compared with males. When comparing males and females on quadriceps and hamstring muscle activation during the initial landing of the drop jump, significant effects for sex (P < 0.001), sex x muscle (P = 0.047), and sex x muscle x landing phase (P = 0.016) interactions were revealed. Post hoc analyses indicated that females had greater quadriceps and hamstring activation amplitude both pre- and postlanding compared with males. However, the three-way interaction revealed that whereas females had 27% and 29% more $QUAD_{PRE}$ and HAM_{PRE} during the preactivation phase, the relative sex difference

TABLE 5. Regression coefficients from the full regression model when examining neuromuscular, kinematic, and kinetic contributions to peak anterior tibial shear force (*N* = 78).

Variable	Parameter Estimate	SE	*t* Value	*P* Value
Peak anterior tibial shear force				
Intercept	0.426	0.145	2.930	0.005
Sex	−0.037	0.030	−1.223	0.226
Knee flexion excursion	0.003	0.002	2.110	0.039*
Hip flexion excursion	−0.005	0.001	−3.934	0.000*
KEM	1.805	0.417	4.325	0.000*
Quad peak torque	0.059	0.033	1.785	0.079
Ham peak torque	−0.032	0.044	−0.711	0.480
Quad preactivation	−0.199	0.195	−1.021	0.311
Ham preactivation	−0.119	0.188	−0.632	0.529
Quad postactivation	0.173	0.058	2.988	0.004*
Ham postactivation	−0.082	0.052	−1.593	0.116

* Significant regression coefficient, $P < 0.05$.

decreased for $QUAD_{POST}$ (females 13% > males) but increased for HAM_{POST} (females 54% > males) during the postlanding phase (Fig. 1). Table 1 also presents the means and SD and the results of the independent-samples t-tests comparing males and females on BMI and each of the biomechanical variables. In addition to the muscle strength and activation differences observed, females were also observed to have a lower BMI and land with greater hip and knee flexion angular excursions and greater peak KEM. However, despite these differences, no sex differences in peak ASF were observed. Figure 2 demonstrates the kinematic and the kinetic time course of a representative trial.

Tables 2 and 3 present the parameter estimates for the full regression model separated by sex when predicting quadriceps pre- and postlanding activation and hamstring pre- and postlanding activation, respectively. When examining the extent to which an individual's muscle strength was associated with their quadriceps pre- and postlanding activation amplitudes during the drop jump, $QUAD_{TRQ}$ and HAM_{TRQ} explained an additional 17.2% (sign R^2 change, P = 0.032; overall R^2 = 23.7%, P = 0.050) and 22.2% (sign R^2 change, P = 0.006; overall R^2 = 38.0%, P = 0.002) of the variance in females for pre- and postlanding, respectively, and 11.4% (R^2 change, P = 0.120; overall R^2 = 14.3%, P = 0.247) and 13.7% (R^2 change, P = 0.079; overall R^2 = 14.7%, P = 0.233) of the variance in males for pre- and postlanding, respectively, once controlling for individual differences in BMI and hamstring activation levels. However, only the parameter estimate for $QUAD_{TRQ}$ was significant for $QUAD_{PRE}$

(-0.370, P = 0.038) and $QUAD_{POST}$ (-0.406 P = 0.012) in females and $QUAD_{POST}$ (-0.405, P = 0.032) in males. In each case, these estimates indicate that lower quadriceps torque to body mass predicted greater quadriceps activation amplitude. When predicting pre- and postlanding hamstring activation amplitudes once controlling for individual differences in BMI and hamstring activation levels, $QUAD_{TRQ}$ and HAM_{TRQ} explained only 12.9% (R^2 change, P = 0.080; overall R^2 = 19.2%, P = 0.116) and 2.6% (R^2 change, P = 0.589; overall R^2 = 17.7%, P = 0.146) of the variance in females for pre- and postlanding, respectively, and essentially none of the variance in males (HAM_{PRE}: R^2 change = 0%, P = 0.984; overall R^2 = 4.7%, P = 0.790) (HAM_{POST}: R^2 change = 0.8%, P = 0.875; overall R^2 = 3.3%, P = 0.884). The parameter estimate for HAM_{TRQ} was only significant (-0.388, P = 0.034) when predicting HAM_{PRE} in females, indicating that lower hamstring torque to body mass was related to greater hamstring preactivation before the landing.

Results for the prediction of $HFLEX_{EXC}$ during the drop jump reveal that once accounting for sex (R^2 = 6.1%, P = 0.029) and quadriceps and hamstring strength (R^2 change = 2.5%, P = 0.370), pre- and postlanding activation explained an additional 7.8% of the variance (F change, P = 0.170; overall R^2 = 16.5, P = 0.071). Although the overall model was not significant, the parameter estimate for $QUAD_{PRE}$ was significant (0.347, P = 0.024) once controlling for these other variables, indicating that

TABLE 6. Summary of findings from each of the regression models examined, noting the dependent variable examined, the predictor variables entered, and the final R^2 value and regression equation obtained.

Dependent Variable	Predictor Variables	Sex	R^2 Value	Final Regression Equation
$QUAD_{PRE}$	BMI, HAM_{PRE}, $QUAD_{TRQ}$, and HAM_{TRQ}	Female	0.237*	$QUAD_{PRE} = 0.455 - 0.005_{BMI} + 0.250_{HAMPRE} - 0.071_{QUADTRQ*} - 0.030_{HAMTRQ}$
		Male	0.143	$QUAD_{PRE} = 0.028 + 0.003_{BMI} + 0.142_{HAMPRE} - 0.055_{QUADTRQ} + 0.077_{HAMTRQ}$
$QUAD_{POST}$	BMI, HAM_{POST}, $QUAD_{TRQ}$, and HAM_{TRQ}	Female	0.380*	$QUAD_{POST} = 2.229 - 0.025_{BMI} + 0.172_{HAMPOST} - 0.252_{QUADTRQ*} - 0.172_{HAMTRQ}$
		Male	0.147	$QUAD_{POST} = 1.240 - 0.009_{BMI} - 0.058_{HAMPOST} - 0.271_{QUADTRQ*} - 0.233_{HAMTRQ}$
HAM_{PRE}	BMI, $QUAD_{PRE}$, $QUAD_{TRQ}$, and HAM_{TRQ}	Female	0.192	$HAM_{PRE} = 0.313 - 0.003_{BMI} + 0.167_{QUADPRE} + 0.042_{QUADTRQ} - 0.106_{HAMTRQ*}$
		Male	0.047	$HAM_{PRE} = 0.216 - 0.003_{BMI} + 0.114_{QUADPRE} - 0.002_{QUADTRQ} - 0.004_{HAMTRQ}$
HAM_{POST}	BMI, $QUAD_{POST}$, $QUAD_{TRQ}$, and HAM_{TRQ}	Female	0.177	$HAM_{POST} = 1.089 - 0.020_{BMI} + 0.289_{QUADPOST} - 0.032_{QUADTRQ} - 0.200_{HAMTRQ}$
		Male	0.033	$HAM_{POST} = 0.043 + 0.005^{BMI} - 0.010_{QUADPOST} + .017_{QUADTRQ} + 0.013_{HAMTRQ}$
$HFLEX_{EXC}$	SEX, $QUAD_{TRQ}$, HAM_{TRQ}; $QUAD_{PRE}$, $QUAD_{POST}$, HAM_{PRE}, and HAM_{POST}		0.165	$HFLEX_{EXC} = 53.41 - 8.28^{SEX} + 7.88_{QUADTRQ} - 4.37_{HAMTRQ} + 70.02_{QUADPRE*} - 37.52_{HAMPRE} - 15.56_{QUADPOST} + 2.99_{HAMPOST}$
$KFLEX_{EXC}$	SEX, $QUAD_{TRQ}$, HAM_{TRQ}; $QUAD_{PRE}$, $QUAD_{POST}$, HAM_{PRE}, and HAM_{POST}		0.125	$KFLEX_{EXC} = 81.35 - 8.81_{SEX*} + 4.67_{QUADTRQ} - 2.54_{HAMTRQ} + 9.18_{QUADPRE} - 20.43_{HAMPRE} - 2.61_{QUADPOST} - 4.57_{HAMPOST}$
KEM	SEX, $KFLEX_{EXC}$, $HFLEX_{EXC}$, $QUAD_{TRQ}$, HAM_{TRQ}; $QUAD_{PRE}$, HAM_{PRE}, $QUAD_{POST}$, and HAM_{POST}		0.278*	$KEM = 0.120 - 0.024_{SEX*} + 0.000_{KFLEXEXC} - 0.001_{HFLEXEXC*} + 0.006_{QUADTRQ} + 0.006_{HAMTRQ} - 0.026_{QUADPRE} - 0.014_{HAMPRE} - 0.004_{QUADPOST} + 0.013_{HAMPOST}$
ASF	SEX, $KFLEX_{EXC}$, $HFLEX_{EXC}$, KEM, $QUAD_{TRQ}$, HAM_{TRQ}; $QUAD_{PRE}$, HAM_{PRE}, $QUAD_{POST}$, and HAM_{POST}		0.565*	$ASF = 0.426 - 0.037_{SEX} + 0.003_{KFLEXEXC*} - 0.005_{HFLEXEXC*} + 1.805_{KEM*} + 0.059_{QUADTRQ} - 0.032_{HAMTRQ} - 0.199_{QUADPRE} - 0.119_{HAMPRE} + 0.173_{QUADPOST*} - 0.082_{HAMPOST}$

* Significant R^2 value or regression coefficient, $P < 0.05$.

greater quadriceps preactivation was a significant but weak predictor of greater hip flexion excursion. Results for knee joint flexion excursion revealed no significant contributions of muscle strength and activation. Once accounting for sex (R^2 = 7.1%, P = 0.0 18), neither quadriceps and hamstring strength (R^2 change = 2.5%, P = 0.370) nor pre- and postlanding activation (R^2 change = 2.9%, P = 0.674) contributed significantly to $KFLEX_{EXC}$ (overall R^2 = 12.5, P = 0.206).

Table 4 presents the parameter estimates for the full regression model when examining the neuromuscular and kinematic contributions to KEM. Once accounting for sex and individual differences in $KFLEX_{EXC}$ and $HFLEX_{EXC}$ (R^2 = 24.4%, P < 0.001), neither thigh muscle strength (R^2 change = 1.9%, P = 0.407) nor pre- and postlanding activation (R^2 change = 1.5%, P = 0.836) was significant predictor of KEM. On the basis of the prediction equation from the first step in the model, being a female (P = 0.001) and going through less

$HFLEX_{EXC}$ (P = 0.003) were significant predictors of greater KEM. These relationships held once accounting for thigh strength and activation (both P = 0.006). Table 5 presents the parameter estimates for the full regression model when examining the collective contributions to ASF. Once accounting for sex, $KFLEX_{EXC}$, $HFLEX_{EXC}$, and KEM (R^2 = 48.5%, P < 0.001), thigh muscle strength did not explain any additional variance in ASF (R^2 change = 0.7%, P = 0.631), but thigh muscle activation did (R^2 change = 7.3%, P = 0.032). Parameter estimates from the full model (overall R^2 = 56.5%) indicate that once accounting for sex (P = 0.226), individuals who go through less $HFLEX_{EXC}$ (P < 0.001) but greater $KFLEX_{EXC}$ (P = 0.039) and who have greater normalized KEM (P < 0.001) and $QUAD_{POST}$ (P = 0.004) experience greater ASF. It should be noted that when all other factors were removed from the regression model, the individual's sex and their quadriceps and hamstring muscle activation during the drop jump explained only 15.5% of the variance (P = 0.030), with lower $QUAD_{PRE}$ and higher $QUAD_{POST}$ predicting higher ASF. In an effort to provide collective summary of the findings from each of the regression models, Table 6 lists the dependent variable examined, the predictor variables entered, and the final R^2 and regression equations obtained from each model.

DISCUSSION

Our primary findings revealed that females who had lower BMI and produced lower quadriceps and hamstring torque relative to the same body mass demonstrated greater quadriceps and hamstring activation amplitudes both before and after ground contact during the initial landing of a drop jump. Although lower thigh muscle strength was a moderate predictor of greater pre- and postquadriceps activation amplitudes in females, it was a weak-to-moderate predictor in males. Further, although sex differences in strength and landing activation patterns were accompanied by greater hip and knee flexion excursions and peak KEM during a drop jump in females compared with males, thigh muscle activation patterns were rather poor predictors of these kinematic and kinetic differences, even when accounting for strength differences. Ultimately, our findings revealed that regardless of an individual's sex and relative thigh strength, greater peak ASF were experienced during the deceleration phase of a drop jump when individuals demonstrated less hip flexion and greater knee flexion excursions and greater peak quadriceps activation and internal KEM. These results suggest that kinematic and kinetic variables played a greater role in producing anterior tibial shear forces at the knee than quadriceps activation amplitude.

Thigh strength predicting pre- and postlanding muscle activation amplitudes.

The first aim of this study was to examine whether sex differences in thigh muscle strength may explain the quadriceps dominant activation patterns that have often been observed in females. It is well accepted that females compared with males have lower strength to body weight as a result of a lower proportion of fat-free mass for the same body weight. The lack of a "neuromuscular spurt" (increased vertical jump height and increased ability to attenuate landing force in males) in females as compared with males during maturation has been suggested to be a contributing factor in female bias in ACL injury (24). Due to this disadvantage, we hypothesized that weaker females may be required out of necessity to activate their thigh muscles to a higher level to control the same comparative body mass to a male during a given functional task. Although this hypothesis was supported, only moderate relationships were observed in females and weaker relationships observed in males. The lack of strength in these relationships may in part be due to the nature of the landing task. Because both males and females drop jumped from the same height, this task may have been more challenging for females, thereby requiring more of their available strength to perform the task. Further, the relationship between strength and activation may become more apparent when performing tasks with increasing quadriceps demands. Although the ground reaction forces exerted against the body in this study averaged 2.2 body weights, higher ground reaction forces have been observed during sport-specific maneuvers, including landing with a single leg (3.4 bodyweights) (27) and landing in a stiff manner during a drop jump (4.1 bodyweights) (40). Further studies are needed to explore the magnitude of these relationships during more challenging tasks that may occur during physical activity. Future studies should also examine these relationships using more functional strength assessments. Although we specifically chose to use isometric strength tests to best isolate the strength of the quadriceps and hamstrings, it is unknown if results would be different using more dynamic, field-based measures of strength. Continued evaluations in this area may lead us to developing more appropriate tasks for risk factor screening and identification of muscular deficiencies.

Future studies should also explore the role that body composition plays in the relationships between isometric strength and dynamic muscle activation. Although BMI was used in this study and is considered as a good estimate of body composition and relative body fat (34), this value is simply based on the overall weight of the individual compared with their height. Therefore, individuals with a greater than average weight would have a higher calculated BMI, whether this be due to a higher than average amount of body fat versus a higher than average amount of lean muscle mass. A more precise assessment of body composition that allows for a more accurate estimation of available lean mass to total body weight may yield stronger relationships between strength and muscle activation during a dynamic task.

Thigh strength and activation as predictors of sagittal plane kinematics and kinetics.
Previous studies have reported that females demonstrate greater quadriceps activation patterns during landing (4,23) and cutting tasks (21,31), which are not always accompanied by greater hamstring activation. Females are also reported to have decreased knee flexion angles (4,12,19,21) and greater KEM (5,28,31) and ASF (5,39) during similar landing and cutting tasks compared with males. These finding are often combined to suggest that females who land with greater quadriceps activation and lower knee flexion angles may experience stiffer landings leading to greater KEM and shear forces at the knee, thus placing the ACL at greater risk for injury. However, the direct relationships between quadriceps activation and these kinematic and kinetic variables have rarely been examined. Of the studies that report both hip and knee flexion excursions along with muscle activation amplitude during landing or cutting tasks, they consistently report greater quadriceps activation in females compared with males, but some observe less hip (4) and knee flexion angles (4,21) whereas others observe equivalent knee flexion angles in females (23,28,31). With regard to the amount of hamstring activation in females versus males, these studies have noted lower (21), equal (23,31), or greater (4,28) hamstring activation in females compared with males. Therefore, our second goal was to directly examine the relationships between neuromuscular, kinematic, and kinetic variables during the drop jump task while accounting for individual thigh strength differences.

Our findings revealed that the quadriceps dominant activation pattern we observed in females, once controlling for individual differences in thigh strength and hamstring activation patterns, was not related to sagittal plane knee and hip kinematics. Although we were unable to compare these findings to similar tasks, our results are consistent with Wojtys et al. (36,37) who observed lower thigh strength to body weight and lower sagittal plane and torsional knee stiffness in females compared with males during maximal muscle activations, but no relationship between the strength and activation levels and the ability to resist knee motions. However, our findings are limited to thigh strength and activation, and future studies should account for potential differences in gastrocnemius or posterior hip strength and activation, which also contribute in controlling sagittal plane motions.

Given the lack of relationships between sagittal plane hip and knee kinematics and thigh strength and activation, we then accounted for both neuromuscular (quadriceps and hamstring strength and pre- and postlanding activation amplitudes) and kinematic variables ($KFLEX_{EXC}$ and $HFLEX_{EXC}$) when examining potential predictors of adverse knee kinetics (i.e., greater KEM and ASF). As in previous studies (4,28,31), we observed a greater peak internal KEM in females compared with males but no differences in ASF. Although females had a greater relative increase in hamstring versus quadriceps activation from pre- to postlanding, neither thigh muscle strength nor activation amplitude significantly predicted KEM. The strongest predictors of greater KEM during the landing were being female and less $HFLEX_{EXC}$, suggesting that sex differences in body position rather than thigh muscle control may be the driving force behind larger peak KEM during the deceleration phase of landing. This is supported by recent studies that indicate a forward lean of the trunk (i.e., moving the center of mass more anterior) results in increased hip and knee flexion (3), decreased knee extensor and increased plantar flexor and hip extensor moments (15,29), and greater hamstring activation relative to the quadriceps (15,33) when compared with more upright or backward leaning postures. However, it should be noted that we did not account for the activation of the rectus femoris in this analysis. Although a smaller muscle than the two vasti muscles, accounting for this two joint muscle may have yielded a stronger relationship with KEM.

When we examined the collective contributions to ASF, both kinematic and neuromuscular variables were significant predictors in the model, although the contribution of strength and activation was relatively small compared with biomechanical factors. Our prediction model for ASF in large part agrees with the work of Sell et al. (28), who found that greater integrated EMG activity of the vastus lateralis along with sex (female), greater peak postground reaction force, decreased external knee flexion moment, and greater knee flexion angle were significant predictors of greater ASF. As was found in our model, the coefficients in the final model similarly suggest that the unique contribution of quadriceps activation to ASF, although significant, is relatively small compared with kinematic and kinetic contributions. Although we did not account for the posterior ground reaction force in our model, we did account for hip flexion excursion, which again would suggest a more upright (vs forward) position of the trunk may be an important contribution to adverse knee forces.

An upright trunk has been associated with changes in distal function. When investigating adaptations in response to an added mass to the trunk during drop jumps, results revealed that subjects adapted by either landing in a position of trunk extension or trunk flexion (~10° difference) (17). Specifically, those subjects landing in a more upright or trunk extended position demonstrated 1 1% less hip angular impulses and 18% less hip energy absorption. Thus, a more upright or extended position of the trunk may place greater energy dissipation demands on the knee and ankle. Similarly, in a study of sex differences in single leg landing mechanics, it was reported that females used a more upright, higher peak vertical GRF ankle-dominated strategy during landing that was theorized to put the noncontractile structures of the more proximal lower extremity joints (such as the ACL) at risk for injury as the large extensor muscles absorbed less energy (27). These studies along with the current investigation provides further evidence that the joints of the lower extremity interact in a kinetic chain to maintain postural control during athletic tasks, suggesting that a multifactorial approach is needed when attempting to determine when an individual joint may be at risk of injury.

In summary, our findings suggest that individual differences in thigh muscle strength explained some of the variance in quadriceps and hamstring activation levels as measured with sEMG during a functional task. However, even when accounting for strength differences, we did not support the long-held theory that greater quadriceps activation in females contributes to lower hip and knee flexion angles or greater peak KEM. Although postlanding quadriceps activation was a small but significant contribution to the prediction model for knee ASF, the observed predictors for both KEM and ASF indicate that multiple factors determine movement patterns that result in potentially adverse knee forces. When considering current risk factor screening and prevention strategies, these findings would suggest that 1) more focus should be placed on positional or postural differences of the trunk, hip, and knee during landing for their potential to increase sagittal plane knee joint loads contributing to ACL strain, and 2) evidence of greater quadriceps activation amplitude in females may simply reflect the presence of muscle weakness rather than increased knee extensor forces, and therefore strategies to improve overall thigh muscle strength (i.e., both quadriceps and hamstrings) should be considered.

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