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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—39 females and 39 males were measured for isometric quadriceps and hamstring strength, and were instrumented to obtain sEMG, 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 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 knee extensor moments. 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 knee extensor moments during the landing.

Conclusions—While thigh muscle strength explained some of the variance in quadriceps and hamstring activation levels as measured with sEMG, we failed to support the hypothesis that these neuromuscular factors are strong predictors of sagittal plane hip and knee flexion excursions or knee extensor moments. Although greater quadriceps activation amplitude was a significant predictor of greater anterior tibial shear forces, its contribution was relatively small compared to kinematic and kinetic variables.

Keywords

Quadriceps dominance; ACL risk factors; landing biomechanics; peak torque to body weight

INTRODUCTION

The greater risk of non-contact anterior cruciate ligament (ACL) injury in physically active females compared to 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. Based

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on available literature, expert consensus in 2006 suggested that females have quadriceps dominant activation strategies(11), based on studies where females compared to 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 pre(4,23) and post(21,31) ground contact. This quadriceps dominant activation pattern is thought to be a major contributing factor to ACL injury, as high levels of quadriceps activation and low levels of hamstring activation during a concentric contraction is 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 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(5,28,31) observed in females compared to 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 knee extensor moments and knee joint forces. Sigward et al(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 external net knee flexor moments, but no difference in knee flexion angles. While 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 7 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.

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 to 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 an 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 knee extensor moments and anterior shear forces, 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 if 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, knee extensor moments 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 years, 162.9 ± 6.8 cm, 58.8 ± 7.8 kg) and 39 males (22.6 ± 2.6 years, 177.8 ± 10.1 cm, 81.7 ± 14.0 kg) were measured for body mass index 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 weeks prior to actual testing. All females were tested during the first 6 days 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. Prior to 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 (Nm). 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 2 fingers breadth proximal to the medial malleolus. Knee extension and flexion torque was 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-second MVIC trials were obtained for both knee extension and knee flexion with a 30 second 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 1mV/V, frequency bandwidth of 10 to 1000Hz, common mode rejection ratio of 90dB min at 60Hz, input resistance of 1 M Ω , 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 20mm. Myoelectric data were acquired, stored and analyzed using DataPac 2K2 lab application software (Version 3.13, Run Technologies, Mission Viejo, CA). The skin was shaved and thoroughly cleaned with isopropyl alcohol, and the electrodes were then placed midway between the motor point and the distal tendon of the lateral quadriceps (LQ), medial quadriceps (MQ), medial hamstrings (MH), 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, USA) were attached with double-sided tape and

elastic wrap over the anterior mid-shaft of the third metatarsal, the mid-shaft of the medial tibia, and the lateral aspect of the mid-shaft 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 method.(18) Knee joint centers were calculated as the centroid of the medial and lateral femoral epicondyles and ankle joint centers were calculated as the centroid of the medial and lateral malleoli. All kinematic data were collected at 100 Hz using the Motion Monitor software (Innovative Sports Training, Chicago, IL, USA).

Once instrumented and digitized, 5 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 take-off position in which the toes were aligned along the leading edge of the wooden platform and the hands 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 regards 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 prior to 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 5 successful drop jumps. All data were synchronized using the software's trigger sweep acquisition mode, using a foot contact threshold of 10N 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 following the maximal vertical jump.

Data Reduction and Analyses

Quadriceps and hamstring torque data were recorded as the mean of the peak torques obtained over the 3 MVIC trials for each muscle group and normalized to the subject's body mass and reported in Newton-meters per kilogram of body mass (Nm/kg). To estimate body composition (34), body mass index (BMI) was calculated as the body weight in kilograms divided by the square height in meters. To analyze muscle activation amplitude, the sEMG signal of the LQ, MQ, LH and MH were band pass filtered from 10 Hz 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 5 landing trials were ensemble averaged, and the peak RMS amplitude obtained from each muscle during the 150 ms immediate before (pre-activation) and after (post activation) initial ground contact of the first landing phase were obtained. These amplitudes were then normalized using the average of the peak sEMG amplitudes obtained over the 3 MVIC trials (%MVIC). Normalized activation amplitudes obtained from the medial and 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 subsequently low-pass filtered at 12 Hz using a 4th 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 5 drop jump trials. Kinetic data were low-pass filtered at 60 Hz using a 4th order, zero-lag Butterworth filter, and peak knee extensor moment and anterior tibiofemoral shear force data were obtained between the point of initial ground contact and 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 ($\text{Nm} \times \text{BW}^{-1} \times \text{Ht}^{-1}$), and shear force data were normalized to weight (%BW).

Independent samples t-tests compared males and females on BMI, initial hip ($\text{HFLEX}_{\text{INIT}}$) and knee ($\text{KFLEX}_{\text{INIT}}$) flexion angles, hip ($\text{HFLEX}_{\text{EXC}}$) and knee flexion ($\text{KFLEX}_{\text{EXC}}$) 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 2×2 repeated measures ANOVA examined sex differences in quadriceps (QUAD_{TRQ}) and hamstring (HAM_{TRQ}) muscle peak torque relative to body mass. A $2 \times 2 \times 2$ repeated measures ANOVA compared males and females on quadriceps and hamstring pre- (QUAD_{PRE} , HAM_{PRE}) and post ($\text{QUAD}_{\text{POST}}$, HAM_{POST}) landing 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 post landing activation once accounting for BMI and reciprocal muscle activation (e.g. accounting for post landing hamstring activation when predicting post landing quadriceps activation). Because the means and distributions of the muscle activation variables differed so widely by sex, and the known sex differences in BMI, we ran separate regression models for males and females, as we did not feel it would be sufficient to simply control or adjust for sex when examining these relationships. All analyses were evaluated at $P < .05$. Power calculations determined that with a sample of 39 subjects for each analyses, and a maximum of 4 independent variables, we had 80% power to detect a multiple R^2 of .25.(6) This criteria was considered acceptable since a large effect would be required to establish thigh strength as a meaningful and accurate predictor of quadriceps activation.

To address our second goal, separate planned stepwise linear regression models were constructed to examine the extent to which muscle strength and activation contributed to sagittal plane kinematics ($\text{HFLEX}_{\text{EXC}}$, $\text{KFLEX}_{\text{EXC}}$) and kinetics (KEM, ASF) once accounting for other sex dependent factors. In order to parse out the contributions of muscle strength and activation to $\text{HFLEX}_{\text{EXC}}$ and $\text{KFLEX}_{\text{EXC}}$ during the drop jump, sex was entered on the first step, strength variables (QUAD_{TRQ} and HAM_{TRQ}) were entered on the second step, and muscle activation amplitudes (QUAD_{PRE} , HAM_{PRE} , $\text{QUAD}_{\text{POST}}$, HAM_{POST}) were entered 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 $\text{HFLEX}_{\text{EXC}}$ and $\text{KFLEX}_{\text{EXC}}$ in the model, and these variables were included in the first step along with sex. To examine the neuromuscular contributions to ASF, the individual's sex, $\text{HFLEX}_{\text{EXC}}$, $\text{KFLEX}_{\text{EXC}}$ and KEM were first controlled for and entered on the first step, followed by strength (QUAD_{TRQ} and HAM_{TRQ}) on the second step, and muscle activation (QUAD_{PRE} , HAM_{PRE} , $\text{QUAD}_{\text{POST}}$, HAM_{POST}) on the third step. Based on 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 .25.(6)

RESULTS

Means and standard deviations (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 ($P=.001$) but no interaction between sex and muscle ($P=.739$) indicated that females produced 15.6% lower knee extensor and flexor torque (11.8% and 17.2% for the quadriceps and hamstring, respectively) for the same relative body mass compared to males. When comparing males and females on quadriceps and hamstring muscle activation during the initial landing of the drop jump, significant effects for sex ($P<.001$), and sex by muscle ($P=.047$) and sex by muscle by landing phase ($P=.016$) interactions were revealed. Post hoc analyses indicated that females had greater quadriceps and hamstring activation amplitude both pre- and post landing compared to males. However, the three-way interaction revealed that while females had 27% and 29% more QUAD_{PRE} and HAM_{PRE} during the pre-activation phase, the relative sex difference decreased for QUAD_{POST} (females 13% > males) but increased for HAM_{POST} (females 54% > males) during the post landing phase (Figure 1). Table 1 also presents the means and standard deviations and 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 anterior shear force were observed. Figure 2 demonstrates the kinematic and kinetic time course of a representative trial.

Table 2 and Table 3 present the parameter estimates for the full regression model separated by sex when predicting quadriceps pre- and post landing activation and hamstring pre- and post landing activation, respectively. When examining the extent to which an individual's muscle strength was associated with their quadriceps pre- and post landing activation amplitudes during the drop jump, QUAD_{TRQ} and HAM_{TRQ} explained an additional 17.2% (Sign R^2 Change, $P=.032$; Overall $R^2 = 23.7\%$, $P=.050$) and 22.2% (Sign R^2 Change, $P=.006$; Overall $R^2 = 38.0\%$, $P=.002$) of the variance in females for pre- and post landing respectively, and 11.4% (R^2 Change, $P=.120$; Overall $R^2 = 14.3\%$, $P=.247$) and 13.7% (R^2 Change, $P=.079$; Overall $R^2 = 14.7\%$, $P=.233$) of the variance in males for pre- and post landing 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 , $P=.038$) and QUAD_{POST} (-0.406 , $P=.012$) in females, and QUAD_{POST} (-0.405 , $P=.032$) in males. In each case, these estimates indicate that lower quadriceps torque to body mass predicted greater quadriceps activation amplitude. When predicting pre and post landing 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, $P=.080$; Overall $R^2 = 19.2\%$, $P=.116$) and 2.6% (R^2 Change, $P=.589$; Overall $R^2 = 17.7\%$, $P=.146$) of the variance in females for pre- and post landing respectively, and essentially none of the variance in males (HAM_{PRE}: R^2 Change = 0%, $P=.984$; Overall $R^2 = 4.7\%$, $P=.790$) (HAM_{POST}: R^2 Change = 0.8%, $P=.875$; Overall $R^2 = 3.3\%$, $P=.884$). The parameter estimate for HAM_{TRQ} was only significant (-0.388 , $P=.034$) when predicting HAM_{PRE} in females, indicating that lower hamstring torque to body mass was related to greater hamstring pre-activation prior to the landing.

Results for the prediction of HFLEX_{EXC} during the drop jump reveal that once accounting for sex ($R^2=6.1\%$, $P=.029$) and quadriceps and hamstring strength (R^2 Change = 2.5%, $P=.370$), pre- and post landing activation explained an additional 7.8% of the variance (F Change, $P=.170$, Overall $R^2=16.5\%$, $P=.071$). While the overall model was not significant, the parameter estimate for QUAD_{PRE} was significant (0.347, $P=.024$) once controlling for these other variables, indicating greater quadriceps pre-activation 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 ($R^2=7.1\%$, $P=.018$), neither quadriceps and hamstring strength (R^2 Change = 2.5% , $P=.370$) or pre- and post landing activation (R^2 Change = 2.9% , $P=.674$) contributed significantly to $KFLEX_{EXC}$ (Overall $R^2=12.5$, $P = .206$).

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 $HFLEX_{EXC}$ ($R^2 = 24.4\%$, $P<.001$), neither thigh muscle strength (R^2 Change = 1.9% , $P=.407$) or pre- and post landing activation (R^2 Change = 1.5% , $P=.836$) were significant predictors of KEM. Based on the prediction equation from the first step in the model, being a female ($P=.001$) and going through less $HFLEX_{EXC}$ ($P=.003$) were significant predictors of greater KEM. These relationships held once accounting for thigh strength and activation (both $P=.006$). 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 ($R^2 = 48.5\%$, $P <.001$), thigh muscle strength did not explain any additional variance in ASF (R^2 change = 0.7% , $P=.631$), but thigh muscle activation did (R^2 change = 7.3% , $P=.032$). Parameter estimates from the full model (overall $R^2 = 56.5\%$) indicate that regardless of sex ($P=.226$), individuals who go through less $HFLEX_{EXC}$ ($P<.001$) but greater $KFLEX_{EXC}$ ($P=.039$) and who have greater normalized KEM ($P<.001$) and $QUAD_{POST}$ ($P=.004$) 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 ($P=.030$), 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 BMIs and produce lower quadriceps and hamstring torque relative to the same body mass, demonstrated greater quadriceps and hamstring activation amplitudes both prior to and following ground contact during the initial landing of a drop jump. While lower thigh muscle strength was a moderate predictor of greater pre and post quadriceps activation amplitudes in females, it was a weak to moderate predictor in males. Further, while sex differences in strength and landing activation patterns were accompanied by greater hip and knee flexion excursions and peak knee extensor moments during a drop jump in females compared to 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 anterior shear forces 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 knee extensor moments. 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 Post Landing 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 to 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 to males during maturation has been suggested

to be a contributing factor in female bias in ACL injury.(24) Because of 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. While 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. While 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. While 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 difference 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. While BMI was used in this study and is considered a good estimate of body composition and relative body fat(34), this value is simply based on the overall weight of the individual compared to 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 totally 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) greater knee extensor moments(5,28,31) and anterior shear forces (5,39) during similar landing and cutting tasks compared to 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 knee extensor moments 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/or knee flexion excursions along with muscle activation amplitude during landing or cutting tasks, they consistently report greater quadriceps activation in females compared to males, but some observe less hip(4) and knee flexion angles(4,21) while others observe equivalent knee flexion angles in females.(23,28,31) In regards 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 to 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 Woytys et al.(36,37) who observed lower thigh strength to body weight and lower sagittal plane and torsional knee stiffnesses in females compared to males during maximal muscle activations, but no relationship between 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 post landing 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 to males but no differences in ASF. Although females had a greater relative increase in hamstring versus hamstring activation from pre to post landing, neither thigh muscle strength or 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 knee extensor moments 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 to 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 relative small compared to 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 post ground reaction force, decreased external knee flexion moment and greater knee flexion angle were significant predictors of greater anterior shear force. 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 to kinematic and kinetic contributions. While 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 (versus 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 ($\sim 10^\circ$ difference).(17) Specifically, those subjects landing in a more upright or trunk extended position demonstrated 11% 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 non-contractile 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 a multifactorial approach is needed when attempting to determining 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 knee extensor moments. While post landing 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 / 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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Figure 1.

Comparison of males and females on quadriceps and hamstring pre and post landing muscle activation (%MVIC) during the initial landing of the drop jump. *Indicates females > males. †Indicates the relative sex difference increased from pre to post landing activation for the hamstring muscles but decreased for the quadriceps muscles.

Figure 2.

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

Table 1

Means and standard deviations for measures of body mass index, thigh muscle strength, and biomechanical outcome variables during a double leg drop jump landing.

	Females (N = 39)	Males (N = 39)	
	Mean ± SD	Mean ± SD	P-Value
Body Mass Index	22.2 ± 2.4	25.8 ± 3.3	<.001 *
Quadriceps Torque (Nm/kg)	2.2 ± 0.4	2.5 ± 0.3	<.001 *
Hamstring Torque (Nm/kg)	1.7 ± 0.2	2.0 ± 0.3	<.001 *
Initial Knee Flexion Angle (deg)	17.0 ± 5.9	17.3 ± 6.5	.844
Knee Flexion Excursion (deg)	71.6 ± 10.0	65.5 ± 12.1	.018 *
Initial Hip Flexion Angle (deg)	25.3 ± 6.4	22.9 ± 9.1	.185
Hip Flexion Excursion (deg)	48.0 ± 13.7	40.1 ± 17.2	.029 *
Peak Knee Extensor Moment (Nm x BW ⁻¹ xHt ⁻¹)	0.087 ± 0.029	0.072 ± 0.028	.026 *
Peak Anterior Tibial Shear Force (%BW)	68.6 ± 9.7	66.6 ± 15.6	.492

* Significant difference between sex (P≤.05)

Table 2

Regression coefficients from the full regression model when predicting pre- and post landing quadriceps activation based on quadriceps and hamstring peak torque (Nm/kg) once accounting for body mass index and reciprocal hamstring activation.

Variable	Females (N = 39)			Males (N = 39)		
	Parameter Estimate	Standard Error	t-Value	P-Value	Parameter Estimate	Standard Error
Pre-Landing Activation						
Intercept	.455	.178	2.559	.015	.028	.152
Body Mass Index	-.005	.005	-0.928	.360	.003	.003
Hamstring Pre-Activation	.250	.205	1.218	.231	.142	.190
Quad Peak Torque	-.071	.033	-2.158	.038*	-.055	.033
Ham Peak Torque	-.030	.063	-0.480	.634	.077	.040
Post Landing Activation						
Intercept	2.229	.515	4.328	.000	1.240	.501
Body Mass Index	-.025	.016	-1.562	.127	-.009	.012
Hamstring Post-Activation	.172	.129	1.332	.192	-.058	.420
Quad Peak Torque	-.252	.095	-2.654	.012*	-.271	.121
Ham Peak Torque	-.172	.173	-0.994	.327	.233	.148

* Significant regression coefficient, $P < .05$

Table 3

Regression coefficients from the full regression model when predicting pre- and post landing hamstring activation based on quadriceps and hamstring peak torque (Nm/kg) once accounting for body mass index and reciprocal quadriceps activation levels.

Variable	Females (N = 39)			Males (N = 39)		
	Parameter Estimate	Standard Error	t-Value	P-Value	Parameter Estimate	Standard Error
Pre-Landing Activation						
Intercept	.313	.149	2.100	.043	.216	.122
Body Mass Index	-.003	.004	-0.652	.519	-.003	.003
Quad Pre-Activation	.167	.137	1.218	.231	.114	.152
Quad Peak Torque	.042	.028	1.508	.141	-.002	.031
Ham Peak Torque	-.106	.048	-2.207	.034*	-.004	.038
Post Landing Activation						
Intercept	1.089	.811	1.342	.188	.043	.222
Body Mass Index	-.020	.021	-0.946	.351	.005	.005
Quad Post Activation	.289	.217	1.332	.192	-.010	.070
Quad Peak Torque	-.032	.135	-0.235	.816	.017	.053
Ham Peak Torque	-.200	.225	-0.891	.379	.013	.063

* Significant regression coefficient, $P < .05$

Table 4

Regression coefficients from the full regression model when examining neuromuscular and kinematic contributions to peak knee extensor moment (N=78)

Variable	Parameter Estimate	Standard Error	t-Value	P-Value
Peak Knee Extensor Moment				
Intercept	.120	.040	3.029	.003
Sex	-.024	.008	-2.837	.006*
Knee Flexion Excursion	.000	.000	0.491	.625
Hip Flexion Excursion	-.001	.000	-2.831	.006*
Quad Peak Torque	.006	.010	0.671	.505
Ham Peak Torque	.006	.013	0.479	.633
Quad Pre-Activation	-.026	.056	-0.465	.643
Ham Pre-Activation	-.014	.055	-0.249	.804
Quad Post Activation	-.004	.017	-0.259	.796
Ham Post Activation	.013	.015	0.879	.383

* Significant regression coefficient, $P < .05$

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	Standard Error	t-Value	P-Value
Peak Anterior Tibial Shear Force				
Intercept	.426	.145	2.930	.005
Sex	-.037	.030	-1.223	.226
Knee Flexion Excursion	.003	.002	2.110	.039*
Hip Flexion Excursion	-.005	.001	-3.934	.000*
Knee Extensor Moment	1.805	.417	4.325	.000*
Quad Peak Torque	.059	.033	1.785	.079
Ham Peak Torque	-.032	.044	-0.711	.480
Quad Pre-Activation	-.199	.195	-1.021	.311
Ham Pre-Activation	-.119	.188	-0.632	.529
Quad Post Activation	.173	.058	2.988	.004*
Ham Post Activation	-.082	.052	-1.593	.116

* Significant regression coefficient, $P < .05$

Table 6

Summary of findings from each of the regression models examined, noting the dependent variable examined, the predictor variables entered (PV) and the final R² value and regression equation obtained.

Dependent Variable	Predictor Variables	SEX	R ² Value	Final Regression Equation
QUAD _{PRE}	BMI, HAM _{PRE} , QUAD _{TRQ} , HAM _{TRQ}	Female	.237 [*]	QUAD _{PRE} = 0.455 - .005 ^{BMI} + . 250 ^{HAMPRE} - .071 ^{QUADTRQ} - . 030 ^{HAMTRQ}
		Male	.143	QUAD _{PRE} = 0.028 + .003 ^{BMI} + . 142 ^{HAMPRE} - .055 ^{QUADTRQ} + . 077 ^{HAMTRQ}
QUAD _{POST}	BMI, HAM _{POST} , QUAD _{TRQ} , HAM _{TRQ}	Female	.380 [*]	QUAD _{POST} = 2.229 - .025 ^{BMI} + . 172 ^{HAMPST} - .252 ^{QUADTRQ} - . 172 ^{HAMTRQ}
		Male	.147	QUAD _{POST} = 1.240 - .009 ^{BMI} - . 058 ^{HAMPST} - .271 ^{QUADTRQ} - . 233 ^{HAMTRQ}
HAM _{PRE}	BMI, QUAD _{PRE} , QUAD _{TRQ} , HAM _{TRQ}	Female	.192	HAM _{PRE} = 0.313 - .003 ^{BMI} + . 167 ^{QUADPRE} + .042 ^{QUADTRQ} - . 106 ^{HAMTRQ}
		Male	.047	HAM _{PRE} = 0.216 - .003 ^{BMI} + . 114 ^{QUADPRE} - .002 ^{QUADTRQ} - . 004 ^{HAMTRQ}
HAM _{POST}	BMI, QUAD _{POST} , QUAD _{TRQ} , HAM _{TRQ}	Female	.177	HAM _{POST} = 1.089 - .020 ^{BMI} + . 289 ^{QUADPOST} - .032 ^{QUADTRQ} - . 200 ^{HAMTRQ}
		Male	.033	HAM _{POST} = .043 + .005 ^{BMI} - . 010 ^{QUADPOST} + .017 ^{QUADTRQ} + . 013 ^{HAMTRQ}
HFLEX _{EXC}	SEX, QUAD _{TRQ} , HAM _{TRQ} ; QUAD _{PRE} , QUAD _{POST} , HAM _{PRE} , HAM _{POST}		.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} , HAM _{POST}		.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} , HAM _{POST}		.278 [*]	KEM = .120 - .024 ^{SEX} + . 000 ^{KFLEXEXC} - .001 ^{HFLEXEXC} + . 006 ^{QUADTRQ} + .006 ^{HAMTRQ} - . 026 ^{QUADPRE} - .014 ^{HAMPRE} - 004 ^{QUADPOST} + .013 ^{HAMPOST}
ASF	SEX, KFLEX _{EXC} , HFLEX _{EXC} , KEM, QUAD _{TRQ} , HAM _{TRQ} ; QUAD _{PRE} , HAM _{PRE} , QUAD _{POST} , HAM _{POST}		.565 [*]	ASF = .426 - .037 ^{SEX} + . 003 ^{KFLEXEXC} - .005 ^{HFLEXEXC} + 1.805 ^{KEM} + .059 ^{QUADTRQ} - . 032 ^{HAMTRQ} - .199 ^{QUADPRE} - . 119 ^{HAMPRE} + .173 ^{QUADPOST} - . 082 ^{HAMPOST}

* Denotes significant R^2 value or regression coefficient, $P < .05$