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Abstract

The purpose of this study was to identify alterations in preparatory muscle activation patterns across different drop heights in female athletes. Sixteen female high school volleyball players performed the drop vertical jump from three different drop heights. Surface electromyography of the quadriceps and hamstrings were collected during the movement trials. As the drop height increased, muscle activation of the quadriceps during preparatory phase also increased ($p < .05$). However, the hamstrings activation showed no similar increases relative to drop height. Female athletes appear to preferentially rely on increased quadriceps activation, without an increase in hamstrings activation, with increased plyometric intensity. The resultant decreased activation ratio of the hamstrings relative to quadriceps before landing may represent altered dynamic knee stability and may contribute to the increased risk of ACL injury in female athletes.

Keywords

electromyography; drop vertical jump; anterior cruciate ligament; knee injury; co-contraction

Female athletes suffer anterior cruciate ligament (ACL) injuries at a greater rate than males participating in the same landing and pivoting sports (Arendt & Dick, 1995; Malone et al., 1993). Decreased dynamic neuromuscular control of the knee or active restraint likely contributes to increased risk of ACL injury in female athletes (Hewett et al., 2005). Decreased neuromuscular control of the joint may increase the stress on passive ligamentous structures, including the ACL, in a manner that may ultimately exceed the failure strength of the ligament (Li et al., 1999; Markolf et al., 1978).

Increased hamstrings force has been shown, in vitro, to greatly decrease relative strain on the ACL during the exion phase of simulated jump landings (Withrow et al., 2008). Increased strength and recruitment of the hamstrings musculature may also decrease excessive frontal plane rotations (Lloyd & Buchanan, 2001). Female athletes demonstrate increased frontal plane motion and moments during a variety of athletic maneuvers compared with males (Ford et al., 2003, 2005, 2006; Hewett et al., 2006; Kernozek et al., 2005; McLean et al., 2004). Decreased ability to control external frontal plane loads in female athletes may be the symptom of decreased co-contraction of the hamstrings and quadriceps musculature in female athletes (Hewett et al., 2008). Accordingly, increased quadriceps activation with decreased relative hamstrings activation may contribute to the increased risk of ACL injury in female athletes (Hewett et al., 2005; Myer et al., 2008).

The current study aims to determine the relationship between hamstrings and quadriceps activation during plyometric activities with increasing drop heights in female athletes. Specifically, the purpose was to identify alterations in muscle activation strategies across three different drop heights of a drop vertical jump. The primary hypothesis was that muscle activation would be greater at higher drop heights during the preparatory phase of landing in the quadriceps, but not the hamstrings, musculature. Secondly, we hypothesized that muscle activation would be greater at greater drop heights during the reactive phase of landing in the quadriceps but not the hamstrings. An increase in quadriceps activation, in the absence of increased hamstrings activation may be indicative of a preferential extensor activation pattern in females during increased intensity of plyometric activity.

Methods

Subjects

Sixteen female high school volleyball players volunteered to participate in this study (height 169 ± 5 cm, mass 61.7 ± 5.4 kg). Informed written consent, approved by Cincinnati Children’s Hospital institutional review board, was obtained from the parent or parental guardian of each subject. Child assent was also obtained from each subject before participation.

Instrumentation

A telemetry surface electromyography system (TeleMyo 2400, Noraxon) was used to record muscle activity on the right lower extremity. A custom backpack was worn by each subject during data collection to secure the electromyography transmitter. The unit specifications included an amplifier gain of 2000, hardware bandpass filter of 10–500 Hz, an input impedance of >1MΩ and a common-mode rejection ratio of >100 dB.

A 10-camera motion analysis system (Eagle cameras, Motion Analysis Corporation, Santa Rosa, CA) was used to capture three-dimensional marker trajectories of the right lower extremity. Ground reaction force was captured with one force platform (AMTI, Watertown, MA) embedded in the laboratory floor. The trials were collected in EVaRT (Version 5, Motion Analysis Corporation, Santa Rosa, CA) with synchronized video (240 Hz) and analog data (force and electromyography; 1200 Hz).

Procedures

The testing was completed during a single session. The subject's skin was prepared by shaving hair that was present and vigorously cleansing the location with an alcohol swab. Disposable, self-adhesive Ag/AgCl dual electrodes with sensor diameter of 1 cm and interelectrode distance of 2 cm (Noraxon #272, Scottsdale, AZ) were applied to five muscles on the right lower extremity: hamstrings (semitendinosus, biceps femoris) and quadriceps (rectus femoris, vastus medialis, and vastus lateralis). Electrode placement was determined using protocols described previously in the literature (Boling et al., 2006; Cram et al., 1998) and confirmed by visually inspecting waveforms on an oscilloscope (MyoResearch, Noraxon) using standard manual muscle testing protocols. Wires were secured with elastic tape to reduce movement artifact during testing.

Maximum activation was recorded from each muscle during a maximum voluntary isometric contraction. Subjects were seated on a dynamometer (Biodex Medical Systems, Shirley, NY) with the trunk perpendicular to floor, the hip flexed to 90°, and the knee flexed to 60° (Brindle et al., 2002). Practice trials were performed on the dynamometer with both visual and verbal cues on their technical performance. Each subject performed three maximum effort isometric contractions of the quadriceps and hamstrings muscle groups. Each isometric contraction lasted 5 s with a 30-s rest between each trial. For the dynamic trials, three trials of a drop vertical jump were performed at three randomly presented drop heights (15 cm, 30 cm, and 45 cm). Participants were instructed to drop directly down off the box with both feet leaving the box at the same time and as soon as they touched the ground to immediately perform a maximum vertical jump. The first landing on the force platform (i.e., the drop from the box) was used for analysis.

Thirty-seven reflective markers were placed on the subject, as previously described (Ford et al., 2007), with a minimum of three markers per lower extremity segment. A static trial was collected in which the subject was instructed to stand still in the anatomical position with foot placement standardized. This static measurement was used as each subject's neutral (zero) alignment.

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Data Analysis

Raw electromyography data were filtered to remove movement artifact with a fourth-order, high-pass Butterworth filter with 30-Hz cutoff (Besier et al., 2003). Each rectified signal was then filtered with a fourth-order low-pass Butterworth filter with a 6-Hz cutoff to generate a linear envelope for each muscle (Besier et al., 2003; Winter, 2005). Linear envelope data were divided by the maximum electromyography signal obtained during the 5-s maximum voluntary isometric contraction trials, which were processed in the exact same manner, resulting in a normalized signal. Electromyography data during dynamic trials are represented as the percentage of maximum muscle activation. Vertical ground reaction force data were used to calculate initial contact with the ground immediately after the subject dropped from the box. Initial contact was defined when vertical ground reaction force first exceeded 10 N. Preparatory and reactive phases were operationally defined as 100 ms before initial contact and 100 ms after initial contact, respectively (Fagenbaum & Darling, 2003; Palmieri-Smith et al., 2008).

Normalized electromyography signal was used to calculate the average and peak magnitude for each individual muscle during the preparatory and reactive phases. In addition, a hamstrings-to-quadriceps activation ratio was calculated during the preparatory and reactive phases. Specifically, this first involved the calculation of an average hamstrings (semitendinosus, biceps femoris) and an average quadriceps (vastus medialis, vastus lateralis, rectus femoris) time series signal. Secondly, the time series hamstrings-to-quadriceps activation ratio was calculated (hamstrings/quadriceps). The average ratio during each phase was then calculated. Data analysis was performed in MATLAB (Version 7.5, The Mathworks Inc., Natick, MA).

Right hip and knee exion angles were calculated during the drop vertical jump at each box height within Visual3d (Version 4.0, C-Motion, Inc., Germantown, MD) (Ford et al., 2007). Marker trajectories from each trial were filtered at a cutoff frequency of 12 Hz (low-pass fourth-order Butterworth filter). Based on our kinematic analysis convention, hip and knee exion angles are positive. Maximum vertical ground reaction force was calculated after initial contact during the drop vertical jump landing.

Statistical Procedures

Statistical analyses were conducted in SPSS (Version 15.0, SPSS Inc. Chicago, IL). Statistical means and standard deviations from each drop height for each variable were calculated. Multiple one-way repeated-measures ANOVAs were used to assess the effect of drop height (15 cm, 30 cm, and 45 cm) on the dependent variables during the preparatory phase and reactive phase. An alpha level of 0.05 was chosen a priori to indicate statistical significance. A Bonferroni adjustment was performed based on the number of dependent variables (11) for each hypothesis ($p < 0.0046$ was significant). Secondary analyses were conducted on maximum vertical ground reaction force, hip exion angle at initial contact, and knee exion angle at initial contact with one-way repeated-measures ANOVAs. Post hoc pairwise comparisons were performed, with Bonferroni adjustments, to determine if differences between the three drop heights were significantly different, adjusting significance at $p \leq .0167$.

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Results

Preparatory Phase

Figure 1 shows the hamstrings and quadriceps electromyography 100 ms before landing through 100 ms after initial contact. In the preparatory phase before landing, the average hamstrings-to-quadriceps ratio decreased as the drop height increased (15 cm, 1.9 ± 1.6; 30 cm, 1.6 ± 1.5; 45 cm, 0.9 ± 0.6; $p = .004$, Figure 1). A significant 53% decrease in hamstrings-to-quadriceps ratio was found from the 15-cm box to the 45-cm box ($p = .008$). At the lower drop heights, the average activity of the hamstring was greater than the average activity of the quadriceps. In contrast, at the highest drop height (45 cm), the quadriceps were higher than the hamstrings (Figure 1).

Increased average preparatory quadriceps muscle activation was observed with increased drop heights within the vastus medialis ($p < .001$), vastus lateralis ($p < .001$), and rectus femoris ($p = .004$) muscles (Table 1). Conversely, the magnitude of average muscle activation of the hamstrings did not change across drop heights within the semitendinosus or biceps femoris (Table 1). Similar results were found with peak muscle activation during the preparatory phase. The peak vastus lateralis ($p < .001$) and rectus femoris ($p = .002$) muscle activities were significantly greater with increased box height (Table 1).

Reactive Phase

Significant differences were not observed in average hamstrings-to-quadriceps ratio during the reactive phase with increased box height (15 cm, 0.6 ± 0.7; 30 cm, 0.4 ± 0.3; 45 cm, 0.4 ± 0.3; $p = .104$, Figure 1). Average rectus femoris activity significantly increased when the box height was increased ($p = .001$; Table 2). Similar results were found with the peak muscle activity of two quadriceps muscles, rectus femoris ($p = .004$), and vastus medialis ($p = .003$; Table 2). The peak vastus medialis activity significantly increased 25% from the 15-cm to 45-cm box height ($p = .005$). Significant differences were not observed with increased box height in average or peak hamstrings activity (semitendinosus, biceps femoris, Table 2) during the reactive phase.

Initial Contact Kinematics and Ground Reaction Force

Figure 2 presents the averaged time series from 100 ms before ground contact to 100 ms after ground contact of the vertical ground reaction force, hip exion angle, and knee exion angle. Maximum vertical ground reaction force during landing increased at each intensity level (15 cm, 928.4 ± 181.6 N; 30 cm, 1,080.0 ± 158.1 N; 45 cm, 1,379.7 ± 189.6 N; $p < .001$), as was expected. Interestingly, hip exion angle at initial contact significantly decreased as the drop height increased (15 cm, 34.4 ± 8.0°; 30 cm, 29.2 ± 7.1°; 45 cm, 27.2 ± 8.0°; $p < .001$). No differences were found in knee exion angle at initial contact for each drop height (15 cm, 24.4 ± 8.3°; 30 cm, 22.3 ± 6.1°; 45 cm, 22.1 ± 5.6°; $p = .17$).

Discussion

The purpose of this study was to evaluate the influence of task intensity on relative muscle activation strategies during landing in female athletes. The current study used increased drop

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height as a mechanism to increase the overall external load on the lower extremity. Correspondingly, the observed increase in vertical ground force with greater drop heights indicates that the activity incrementally increased the load on the lower extremity. The increased quadriceps muscle activation in response to greater demand on the lower extremity to decelerate the body center of mass when landing from greater heights occurred, confirming the hypothesis. However, no concomitant changes in hamstrings amplitude were found to match increased drop height intensity or increased quadriceps activation as was hypothesized. ACL injury occurs under high dynamic loading of the knee joint, when active muscle stiffness does not adequately dampen joint loads (Beynnon & Fleming, 1998). Thus, the lack of similar activation increases from the hamstrings may increase injury risk in female athletes.

Dynamic, or active, stiffness of the neuromuscular system includes both feed-forward and feedback motor control loops (Lephart et al., 2002). Feed-forward neuromuscular control is likely developed during previously repeated movement patterns and activates muscles around the joint before excessive loading in order to absorb force and to decrease stress on the ligaments (Beard et al., 1993). Motor control strategies that rely on feedback loops (reactive) alter muscle activation in response to situations that load the lower extremity joints (Dyhre-Poulsen et al., 1991). The electromechanical time delays that are inherent in feedback mechanisms likely limit the effectiveness of muscular joint protection during dynamic movements (Lephart & Fu, 2000). Therefore, we analyzed muscle activity immediately before landing, in addition to during landing in the current study. Preparatory muscle activity can stiffen joints before unexpected perturbations and can be learned and adjusted through integration of previous movement experiences or training (Beard et al., 1993; Dietz et al., 1981; Dyhre-Poulsen et al., 1991; Wojtys & Huston, 1994). Decreased relative hamstrings strength and recruitment of the hamstrings musculature may be related to an increased risk of ACL injury (Myer et al., 2008). The subjects demonstrated preferential quadriceps, not hamstrings, recruitment as the drop height increased during the precontact and postcontact phases. This preferential muscle activation strategy may create increased loads directly to the ACL as the plyometric activities became more demanding (Withrow et al., 2008).

Sex differences have been previously identified during a variety of tasks, with females demonstrating increased activation of the quadriceps relative to the antagonistic hamstrings musculature (Hanson et al., 2008; Hewett et al., 1996; Malinzak et al., 2001; Padua et al., 2005; Sell et al., 2007; White et al., 2003; Wojtys et al., 1996; Youdas et al., 2007). While additional loading conditions may be related to shear load, the disproportional recruitment of the knee extensors may increase anterior shear force at the low knee exion angles (Markolf et al., 1995; Myer et al., 2005). In the current study, females showed an increase in quadriceps activation as the ground reaction force increased. The quadriceps, through the anterior pull of the patellar tendon on the tibia, contributes to ACL loading when knee exion is less than 45° (Markolf et al., 1995; Renstrom et al., 1986). The knee exion angle at initial contact of landing during the drop vertical jump has been previously reported as approximately 20° (Chaudhari et al., 2007; Ford et al., 2007; Myer et al., 2006). Our data are similar at initial contact with the knee exion angle approximately 23° over all the drop heights. Therefore, during the initial loading conditions of landing, it is hypothesized that increased muscular co-contraction before initial contact would be beneficial during the reactive phases by increasing actual muscular force while the knee is less than 45°. Adequate co-contraction of the knee exors may balance contraction of the quadriceps, compress the joint, and limit high knee extension and abduction torques immediately after ground contact (Hewett et al., 1996). Muscle co-contraction compresses the joint, due in part to the concavity of the medial tibial plateau, which may protect the ACL against anterior drawer (Imran & O’Connor, 1997). Increased balance in strength and recruitment of the knee flexor relative to the knee extensor musculature may protect the ACL (Hewett et al., 1996).

Similar mechanisms apply to muscular protection against torsional loading, in which sex differences have been identified (Wojtys et al., 2003). Wojtys et al. demonstrated that maximal rotations of the tibia were greater in women than in men in both passive and active muscle states (Wojtys et al., 2003). Females exhibited less muscular protection of the knee ligaments under internal rotation loading than did males (Wojtys et al., 2003). In addition, during single-leg landing maneuvers, females increase quadriceps while decrease gluteus maximus activity (Zazulak et al., 2005).

High valgus knee torques have been correlated with increased ground reaction forces (Hewett et al., 1996, 1999, 2005) and increased risk of ACL injury (Ford et al., 2003; Hewett et al., 2005; Malinzak et al., 2001; McLean et al., 2004). The systematic increase in drop height in the current study led to higher ground reaction forces. Different muscle activation strategies of quadriceps and hamstrings (quadriceps alone, hamstrings alone, and co-contraction) may be used to control the valgus (external abduction) forces at the knee (Li et al., 1999; Lloyd et al., 2005). Therefore, the findings of this study indicate that females preferentially rely on increased quadriceps activation without an increase in hamstrings activation to decelerate the body center of mass and absorb higher ground reaction forces before performing a maximum vertical jump.

Muscular co-contraction did not increase during the reactive phase of landing as the drop height increased. Similarly, hamstrings muscle activation did not increase during the reactive phase of landing. Within the first 100 ms of landing, the maximum ground reaction force and estimated peak ACL force typically occur, making this the most hazardous phase of a landing (Kernozek & Ragan, 2008). However, based on electromechanical delay, muscular activation patterns before landing are partially responsible for the actual muscular force during landing. Males can reach a relative isometric force level, compared with females, in a shorter amount of time (Blackburn et al., 2009). Therefore, hamstrings may need to be activated earlier to produce the critical level of force to maintain knee stability.

Hip exion angle at initial contact significantly decreased as the drop height increased, resulting in a greater hip extended position during landing from the highest box. Differences have been previously reported in hip exion during a drop vertical jump, with females exhibiting decreased hip exion at initial contact compared with males (Ford et al., 2010). Decreased hip exion may play an important role in the mechanical efficiency of the hamstrings muscles in relation to the quadriceps (Shultz, 2007). For example, increased activation of the quadriceps and decreased activation of the hamstrings have been reported with an extended hip and trunk posture compared with a flexed hip and trunk (Shultz, 2007; Wilk et al., 1996). Although we did not measure trunk position, this may explain how increased quadriceps activation may relate to a more extended hip posture as the drop height increased.

One potential limitation to the generalizability of this study was the use of a singular landing task performed at different landing intensities. While other studies have examined cutting and medial/lateral movements, we chose to focus on a landing task to better control the intensity levels (drop heights). Future studies that vary the intensity during cutting and pivoting may be warranted. A final limitation to the current study was that only female athletes were examined during the landing trials. Therefore, sex differences in quadriceps and hamstrings activation based on landing intensity cannot be concluded from this study. Both male and female athletes may increase knee extensor force to counteract the greater impact velocity due to the higher drop heights.

In conclusion, female athletes preferentially rely on increased quadriceps activation, without an increase in hamstrings activation, with increased plyometric intensity. The decreased hamstrings-to-quadriceps muscle activation before landing may represent altered neuromuscular control patterns and may contribute to the increased risk of ACL injury in female athletes. This observed preferential quadriceps muscle activation pattern supports previous findings of motor control alterations with quadriceps bias in this population (Zazulak et al., 2005). Preferential quadriceps muscle activation may be modifiable with specific training that could possibly yield a protective dynamic coactivation for the static stabilizers.

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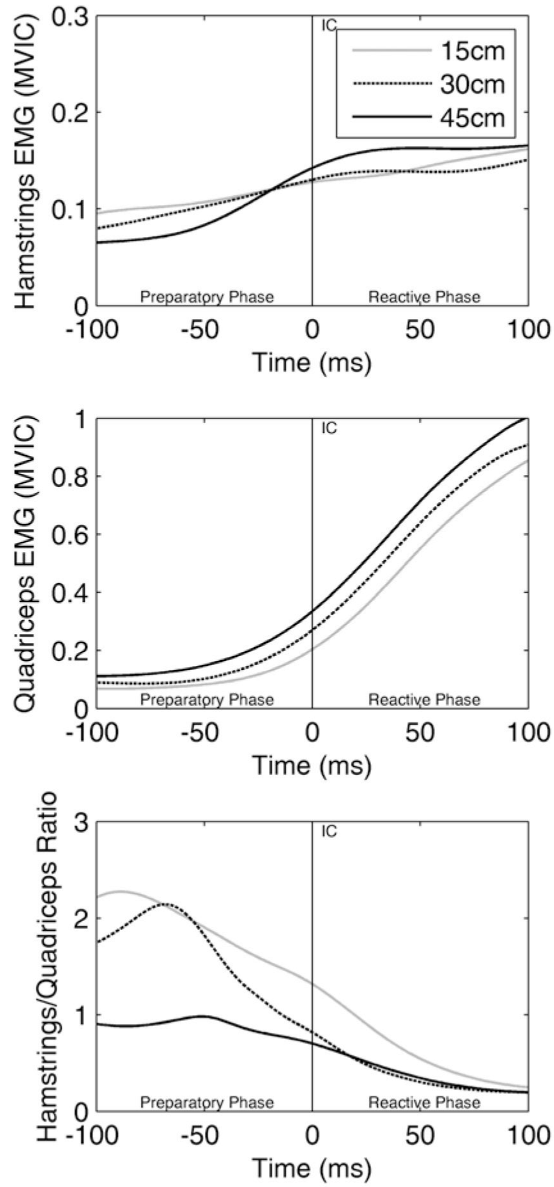

Figure 1.

Hamstrings, quadriceps, and hamstrings/quadriceps ratio time series averaged for each subject during the 15-cm, 30-cm, and 45-cm box drop landing. Hamstrings electromyography was calculated from the average of the semitendinosus and biceps femoris signals over time. Quadriceps electromyography was calculated from the average of the vastus medialis, vastus lateralis, and rectus femoris signals over time. IC—initial contact, MVIC—maximum voluntary isometric contraction, EMG—electromyography.

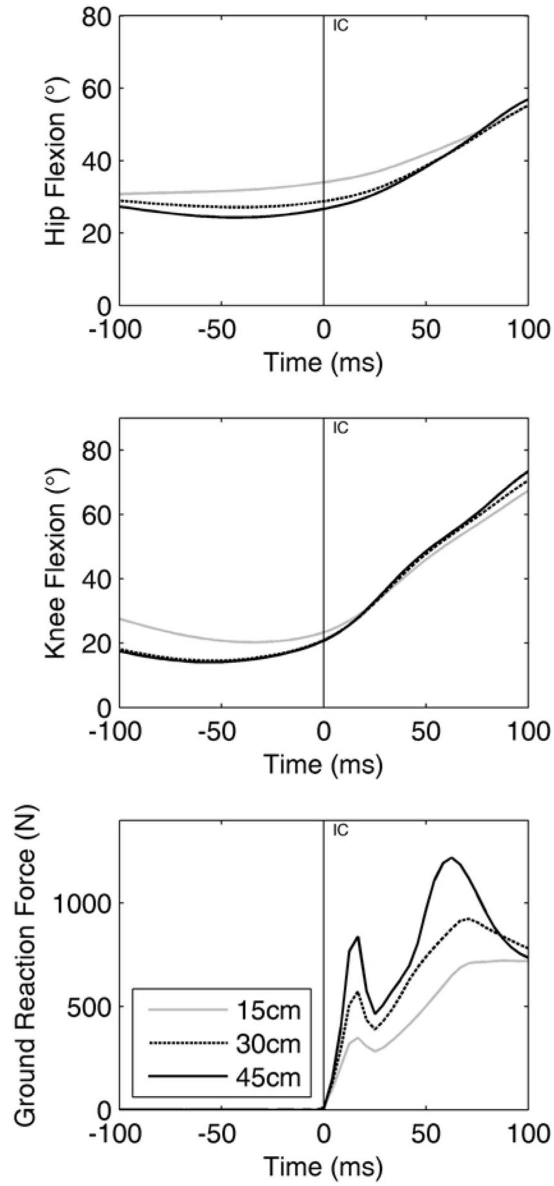

Figure 2.

Hip and knee exion–extension and vertical ground reaction force time series averaged for each subject during the 15-cm, 30-cm and 45-cm box drop landing. By convention, knee exion and hip exion are positive. IC—initial contact.

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Table 1

Preparatory EMG

	Average Preparatory EMG (%MVIC)				Maximum Preparatory EMG (%MVIC)			
	15 cm	**30 cm**	**45 cm**	***p* value**	**15 cm**	**30 cm**	**45 cm**	***p* value**
Semitendinosus	12.7 ± 9.4	11.2 ± 10.5	10.1 ± 5.7	0.236	19.4 ± 11.7	18.2 ± 17.1	18.1 ± 11.8	0.784
Biceps femoris	9.2 ± 5.1	9.6 ± 5.7	8.3 ± 4.3	0.102	13.7 ± 5.9	13.6 ± 7.5	13.3 ± 7.6	0.916
Vastus medialis	8.8 ± 4.1^{b,c}	11.8 ± 5.5^{a,c}	17.9 ± 10.4^{a,b}	<0.001*	20.9 ± 12.8	27.5 ± 11.7	38.0 ± 25.3	0.007
Vastus lateralis	8.5 ± 4.2^{b,c}	11.2 ± 5.1^{a,c}	15.5 ± 8.5^{a,b}	<0.001*	20.2 ± 10.9^{b,c}	25.3 ± 9.6^{a}	31.7 ± 17.6^{a}	<0.001*
Rectus femoris	12.6 ± 7.6^{c}	15.8 ± 10.6	18.7 ± 11.4^{a}	0.004*	25.1 ± 10.3^{b,c}	31.2 ± 15.7^{a}	34.5 ± 19.5^{a}	0.002*

Note. Electromyography (EMG) data are represented as percentage of maximum voluntary isometric contraction (%MVIC).

[*] Denotes statistically significant effect of drop height ($p < 0.0046$).

[a,b,c] Denote statistically significant post hoc pairwise comparison of 15-cm, 30-cm, or 45-cm height, respectively ($p < 0.0167$).

Table 2

Reactive EMG

	Average Reactive EMG (%MVIC)				Maximum Reactive EMG (%MVIC)			
	15 cm	**30 cm**	**45 cm**	***p* value**	**15 cm**	**30 cm**	**45 cm**	***p* value**
Semitendinosus	14.8 ± 7.4	15.4 ± 11.4	18.2 ± 10.1	0.033	22.2 ± 10.2	22.2 ± 16.9	24.5 ± 12.5	0.474
Biceps femoris	14.0 ± 10.8	12.5 ± 8.2	13.9 ± 9.4	0.439	20.3 ± 14.7	17.6 ± 11.5	18.5 ± 11.0	0.324
Vastus medialis	59.2 ± 32.0	70.9 ± 31.1	79.7 ± 41.5	0.008	97.7 ± 46.1[c]	108.9 ± 42.0	122.2 ± 57.8[a]	0.003*
Vastus lateralis	55.2 ± 29.1	58.0 ± 26.0	65.9 ± 34.3	0.059	90.9 ± 46.2	90.5 ± 42.8	97.2 ± 45.7	0.439
Rectus femoris	49.4 ± 21.9[b,c]	59.0 ± 27.4[a]	65.1 ± 30.2[a]	0.001*	75.5 ± 33.5[c]	83.2 ± 38.5	95.3 ± 36.5[a]	0.004*

Note. Electromyography (EMG) data are represented as percentage of maximum voluntary isometric contraction (%MVIC).

* Denotes statistically significant effect of drop height.

a,b,c Denotes statistically significant post hoc pairwise comparison of 15-cm, 30-cm, or 45-cm height, respectively.