Insufficient Hamstring Strength Compromises Landing Technique in Adolescent Girls

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ABSTRACT

WILD, C. Y., J. R. STEELE, and B. J. MUNRO. Insufficient Hamstring Strength Compromises Landing Technique in Adolescent Girls. Med. Sci. Sports Exerc., Vol. 45, No. 3, pp. 497–505, 2013. Purpose: Women sustain more anterior cruciate ligament (ACL) ruptures than men, and this gender disparity is apparent from pubertal onset. Although the hamstring muscles play a vital role in ACL protection during landing by restraining anterior tibial motion relative to the femur, it is unknown whether hamstring strength affects landing biomechanics during a functional movement. This study aimed to determine whether pubescent girls with lower hamstring strength displayed different lower limb biomechanics when landing from a leap compared with girls with higher hamstring strength. Methods: Thirty-three healthy girls, age 10–13 yr, in Tanner stage II (pubertal onset) and 4–6 months from their peak height velocity were recruited. The concentric and the eccentric isokinetic strength of the hamstring and quadriceps muscles were assessed. On the basis of peak concentric hamstrings torque, participants were divided into a lower (peak torque < 45 N·m) and higher (peak torque > 60 N·m) strength group. Participants performed a functional landing movement, during which ground reaction forces (1000 Hz), lower limb electromyography (1000 Hz), and kinematic data (100 Hz) were collected. Results: Girls with lower hamstring strength displayed significantly (P < 0.05) greater knee abduction alignment, reduced hip abduction moments, and greater ACL loading at the time of the peak anteroposterior ground reaction forces compared with their stronger counterparts. Conclusions: Girls with reduced hamstring strength appear to have a decreased capacity to control lower limb frontal plane alignment. This reduced capacity appears to contribute to increased ACL loading and, in turn, increased potential for injury. Key Words: GROWTH SPURT, INJURIES, LOWER LIMB, ACL, BIOMECHANICS

Acute rupture of the anterior cruciate ligament (ACL) is a common and devastating knee injury, 70% of which are sport related (9). Within the same sport, women are two to eight times more likely to rupture their ACL through noncontact mechanisms compared with men (3). This gender disparity in ACL rupture rate is apparent from the onset of puberty (36), a time of life which is accompanied by a large influx of hormones in combination with the adolescent growth spurt (26). The rapid and sizeable increases in height and limb length (29), combined with the large influx of hormones during puberty (26), could play a role in the etiology of noncontact ACL ruptures in this population.

A common noncontact ACL injury mechanism occurs when athletes rapidly decelerate when landing from a jump, particularly during landings that involve a horizontal approach (28). During such landings, an anterior drawer force is imparted to the tibia as the quadriceps muscles are contracted in an attempt to prevent the knee from collapsing upon initial contact with the ground. This quadriceps contraction exacerbates anterior tibial translation, which the ACL attempts to restrain (10). In addition to anterior tibial translation, the ACL is also strained during abduction and rotation of the knee, which are also commonly observed during landing tasks (18,27,28).

As antagonists to the quadriceps muscles, the hamstring muscles play a highly important role in stabilizing the knee joint during landing tasks (20). Because of the posterior and superior attachment of the hamstring muscles on the tibia and fibula, contracting the hamstring muscles during landing can impart a posterior tibial drawer force, thereby acting as a synergist to the ACL during anterior tibial translation (10). The ability of the hamstring muscles to cause medial and lateral rotation at the knee (32) as well as control coronal plane knee motion (25) highlights the potential of the hamstring muscles to also protect the ACL against high rotational and abduction strain. A significant reduction in coronal plane knee moments experienced during landing have been reported in women after a training intervention, whereby significant increases in hamstring strength were observed (20). This confirms the important role of the hamstring muscles in protecting the knee as well as the ACL against
potentially high external abduction loads during landing (20). Interestingly, men are suggested to use their hamstring muscles more effectively to protect the ACL compared with women, contracting their muscles so that the peak hamstring muscle activity better coincides with the high tibiofemoral shear forces experienced during landing (10). Therefore, although the potential protective role of the hamstring muscles during landing in adults is understood (10,20,31), it is unknown whether adolescents are able to effectively use their hamstring muscles to protect their ACL during their growth spurt or whether changes in muscle strength during puberty compromise landing technique.

Ahmad et al. (2) collected peak isometric hamstring and quadriceps muscle strength data using a handheld dynamometer and reported that adolescent girls (2 yr postmenarche) displayed lower hamstring-to-quadriceps ratios (0.51) compared with their mature male counterparts (0.69) and compared with prepubescent boys and girls (0.63 and 0.58, respectively). Furthermore, although the mechanism is not well understood, lower hamstring-to-quadriceps ratios have been shown to contribute to greater lower limb valgus and tibial rotation angles during dynamic movements, which can also increase loading of the ACL (19). Recently, it has been shown that lower reported hamstring-to-quadriceps ratios in women with ACL injury compared with male controls are due to lower hamstring muscle strength, with no differences in quadriceps strength (30). This emphasizes the need to further determine whether changes in hamstring strength during puberty alter landing mechanics of adolescent girls, ultimately placing them at an increased risk of ACL injury.

Interestingly, previous research has demonstrated that boys experience a defined “spurt” in muscle strength development during puberty, particularly evident in hamstring muscle strength, although this strength spurt is not apparent in girls (2,5,18). The rapid growth of the lower limbs during puberty results in an increase in the inertial properties of the lower limb segments (16). This, in turn, requires greater muscular torque to control the limbs during dynamic landing movements. We speculate that this lack of a strength spurt in girls during puberty, paired with lower hamstring-to-quadriceps ratios, may provide further explanation for the increased risk of noncontact ACL ruptures in adolescent girls.

Although adolescent girls display lower hamstring-to-quadriceps ratios during puberty without a defined strength development spurt, it is unknown whether hamstring strength affects landing mechanics in girls from the onset of puberty. Furthermore, most previous studies in this field have investigated the landing technique of young girls performing bilateral drop-landing maneuvers (18,19). Given that the ACL primarily restrains anterior and thus horizontal tibial translation, a movement that has a horizontal approach to the landing is more ecologically valid compared with drop landings when developing implications for ACL injury mechanisms in women. Therefore, the purpose of this study was to determine whether pubescent girls with lower hamstring strength displayed different lower limb biomechanics when landing after performing a horizontal leap movement compared with girls with higher hamstring strength. It was hypothesized that girls with lower hamstring strength would display significantly lower hamstring-to-quadriceps ratios as well as significantly different lower limb kinematics and kinetics, including higher ACL loading and altered muscle activation patterns, during landing compared with girls with higher hamstring strength.

METHODS

Participants. Ninety healthy female volunteers between ages 10 and 13 yr were initially screened for their Tanner stage of pubertal development (39) as well as the estimated time they were from reaching their peak height velocity (peak growth in height, called maturity offset) to determine pubertal onset (26). Each girl’s Tanner stage was self-assessed using modified Tanner stage diagrams (39), and maturity offset was estimated using a sex-specific multiple regression equation (29). Thirty-three girls satisfied the inclusion criteria (pubertal onset (38); Tanner stage II of pubic hair development and maturity offset = −4 to 6 months) and were recruited as participants. Girls were excluded if they did not satisfy the developmental inclusion criteria, had a lower limb injury that prevented them from participating in physical activity or sport, or had begun menstruating. The University of Wollongong Human Research Ethics Committee (HE08/281) approved all study procedures, and the participants and their parents/guardians provided informed written and verbal consent before the girls participated in the study.

Isokinetic lower limb strength. After completing a standardized 5- to 10-min warm-up on a cycle ergometer (Monark Model 818E, Varberg, Sweden), each participant’s hamstring and quadriceps strength was assessed using an isokinetic dynamometer (KinCom; Chattanooga Inc., Chattanooga, TN), following standardized procedures (13,23). In brief, the participants were seated with their trunk reclined at 10° from the vertical, and the lever arm axis of the dynamometer was aligned with the lateral knee joint line of each participant’s dominant limb (13). Lower limb dominance was determined as the landing limb each participant used when they were asked to perform a vertical jump, taking off from two legs and landing on one leg (37), which remained the test limb for the duration of the testing session.

After adequate familiarization, participants performed four separate tests at 180°s−1 from 10° to 90° of knee flexion to assess concentric and eccentric hamstring and quadriceps strength. During each test, the lever arm moved back and forth for a total of six cycles. During the first two cycles, participants were asked to relax (0% effort); during cycles 3–4, participants were asked to exert 25% effort; and during cycles 5–6, participants were asked to exert 100% effort. Participants performed one test for each of the strength measures (concentric hamstrings, eccentric hamstrings, concentric quadriceps, and eccentric quadriceps) in a randomized order. The peak torque and the torque later
calculated to correspond to the knee angle displayed at the time of the peak anteroposterior ground reaction force (GRF) during the landing task were recorded. Hamstring-to-quadriceps ratios were then calculated for each participant, including the peak concentric ratios ($H_{\text{conc}}/Q_{\text{conc}}$) for comparison with the literature and the functional ratios ($H_{\text{conc}}/Q_{\text{con}}$) corresponding to the knee angles displayed at the time that the peak anteroposterior GRF was generated during landing (13). Participants were allowed adequate rest between each trial to reduce the effects of fatigue on peak torque values.

**Landing task.** After preparation, adequate jump task familiarization was carried out. Participants then performed a horizontal leap whereby they jumped as far forward as they were able, taking off from two legs and landing on the force platform with their test limb only (see Fig. 1). During the horizontal leap task, each participant placed their arms across their chest to reduce any effect that arm motion had on landing technique (14) and focused on a picture on the wall to prevent “targeting” of the force platform. Participants performed 5–7 successful trials (landing within the confines of the force platform) of the horizontal leap movement, and fatigue was avoided by providing ample rest periods when required.

**Data collection and analysis.** During the horizontal leap movement, the three orthogonal components of the GRF generated by each participant upon landing were measured (1000 Hz) using a calibrated multichannel force platform (Type 9281B, 600 × 400 mm; Kistler, Winterthur, Switzerland), embedded in the laboratory floor and amplified using a Kistler Multichannel charge amplifier (Type 9865A; Kistler). The raw GRF data were filtered using a fourth-order zero-phase-shift Butterworth digital low-pass filter ($f_c = 14$ Hz; determined using residual analysis [40]), before calculating the lower limb kinematics and joint moments (6). Three-dimensional ankle, knee, and hip joint angles (whereby positive angles were defined as dorsiflexion, eversion, and forefoot abduction for the ankle; and flexion, abduction, and external rotation for the knee and hip), were then calculated at the times of initial contact, peak vertical GRF, and peak anteroposterior GRF to determine lower limb kinematics during the impact phase of landing.

The raw kinematic, GRF, free moment, and center of pressure data were then filtered using a fourth-order zero-phase-shift Butterworth digital low-pass filter ($f_c = 14$ Hz; determined using residual analysis [40]), before calculating the lower limb kinematics and joint moments (6). Three-dimensional ankle, knee, and hip internal joint moments at the time of initial contact, peak vertical GRF, and peak anteroposterior GRF were calculated using an inverse dynamics approach (40) and normalized to each participant’s body mass. Positive moments were defined as dorsiflexion, eversion, and forefoot abduction for the ankle, extension, abduction, and external rotation for the knee and flexion, abduction, and external rotation for the hip. An estimation of ACL force during landing was calculated using a validated two-dimensional knee joint model (27). The relative contributions of the hamstring and quadriceps muscle forces were calculated using equations for tendon orientation as a function of knee joint angle (17). These contributions were added to the resultant anterior–posterior knee joint load to obtain an estimate of the anterior drawer force. Finally, ACL forces were estimated by dividing the anterior drawer force by the line of action of the ACL, also calculated as a function of knee angle (17). The magnitude and timing of the peak ACL forces ($F_{\text{ACL}}$), normalized to body weight (BW), and the magnitude of $F_{\text{ACL}}$ at the time of the peak anteroposterior GRF were calculated to characterize potential ACL loading during landing.

Activity of medial gastrocnemius (MG), tibialis anterior (TA), vastus medialis (VM), rectus femoris (RF), semitendinosus (ST), and biceps femoris (BF) of each participant’s dominant lower

![FIGURE 1—Horizontal leap movement.](Image)
limb were recorded using bipolar Ag-AgCl surface electrodes (2-cm interelectrode spacing, Blue Sensor Type M-OOS; Medicotest, Olstykke, Denmark) following standard preparation (11). A reference electrode was placed on the tibial tuberosity of the dominant lower limb. Electromyographic signals from the electrodes were relayed to a Telemyo transmitter (1000 Hz, bandwidth 16–500 Hz; Noraxon, Scottsdale, AZ) and then to a Telemyo receiver via an antenna. The EMG data were then analyzed using a custom-written LabVIEW software program (EMGAlyser V3, 2011). Raw signals were firstly inspected to discard trials contaminated with noise or movement artifact. After signal offset removal, raw EMG signals were filtered using a zero-phase-shift fourth-order high-pass Butterworth filter \( f_c = 15 \text{ Hz} \) full-wave rectified and filtered using a low-pass Butterworth filter \( f_c = 20 \text{ Hz} \) to obtain linear envelopes (mV) closely representing the muscle tension curves (10,40). The filtered EMG signals were visually inspected, using a threshold detector of 8%, to determine the timing of muscle onsets relative to initial contact as well as the timing of peak muscle activity. The kinematic, GRF, and EMG data were time synchronized during data collection using First Principles software (Version 1.2.2; Northern Digital).

**Statistical analyses.** To assess whether hamstring strength affected landing biomechanics, the 33 participants were divided into a lower hamstring strength group (peak torque < 45 N·m; \( n = 11 \)) and a higher hamstring strength group (peak torque > 60 N·m; \( n = 11 \)) based on the peak concentric hamstring strength results (see Fig. 2). The 11 participants whose peak hamstring torque was measured to be between 45 and 60 N·m were removed from further analysis to ensure a significant between-group difference in hamstring strength \( (P = 0.012; \text{see Table 1 for participant characteristics}) \). Jump distance during the experimental landing task was similar between the two participant groups \( (P = 0.840; 1.22 \pm 0.12 \text{ and } 1.20 \pm 0.19 \text{ m for the lower and higher strength groups, respectively}) \). The sample size provided sufficient statistical power (>80%) to detect significant main effects at \( P \leq 0.05 \) between the two groups when comparing lower limb strength and landing biomechanics (4).

Mean and SD values of the lower limb isokinetic strength, kinematics, moments, ACL force, and EMG variables were calculated for the lower and higher hamstring strength groups. Independent samples t-tests were then applied to the data to determine whether there were any significant \( (P \leq 0.05) \) differences in the lower limb landing biomechanics displayed by the lower hamstring strength group relative to their higher hamstring strength counterparts during the horizontal leap movement. Although multiple comparisons were made, no adjustment to the alpha level was deemed necessary given the exploratory nature of the present study and because such adjustments may increase the likelihood of Type II errors (34). All statistical procedures were conducted using

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lower Strength</th>
<th>Higher Strength</th>
<th>( P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (cm)</td>
<td>150.0 ± 4.7</td>
<td>150.5 ± 6.4</td>
<td>0.850</td>
</tr>
<tr>
<td>Leg length (cm)</td>
<td>71.3 ± 3.7</td>
<td>70.7 ± 4.7</td>
<td>0.746</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>36.4 ± 2.4</td>
<td>43.7 ± 4.6</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Tanner stage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>II</td>
<td>0.614</td>
<td></td>
</tr>
<tr>
<td>Concentric hamstring torque (N·m)</td>
<td>42.5 ± 8.2</td>
<td>70.8 ± 9.1</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Concentric quadriceps torque (N·m)</td>
<td>85.4 ± 12.9</td>
<td>88.3 ± 26.2</td>
<td>0.741</td>
</tr>
<tr>
<td>Normalized concentric hamstring torque (N·m·kg(^{-1}))</td>
<td>1.0 ± 0.1</td>
<td>1.8 ± 0.2</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Normalized concentric quadriceps torque (N·m·kg(^{-1}))</td>
<td>2.3 ± 0.4</td>
<td>2.1 ± 0.6</td>
<td>0.203</td>
</tr>
</tbody>
</table>

**FIGURE 2—Frequency distribution of the concentric hamstring torque (N·m) for all 33 participants.**

**FIGURE 3—Mean ± SD for the hamstring-to-quadriceps ratios, including peak concentric \( (H_{\text{con}}:Q_{\text{con}}) \) and functional (corresponding to knee angles during landing; \( H_{\text{con}}:Q_{\text{con}} \)) ratios for the lower and higher concentric hamstring strength groups. *Significant between-group difference at \( P \leq 0.05 \).**
the Statistical Package for the Social Sciences (Version 17; SPSS Inc., Chicago, IL).

RESULTS

Hamstring-to-quadriceps ratios. The hamstring-to-quadriceps ratios calculated for the two hamstring strength groups are displayed in Figure 3. Overall, participants with lower hamstring strength displayed significantly lower $H_{\text{con}}:Q_{\text{con}}$ ($P = 0.011$) and $H_{\text{con}}:Q_{\text{ecc}}$ ($P = 0.010$) ratios compared with the higher hamstring strength group.

Kinematic results and joint moments. Although no between-group differences were noted for the ankle kinematics or moments (see Fig. 4A), the lower hamstring strength group displayed significantly lower hip extension moments at the time of initial contact ($P = 0.014$; Fig. 4C). In the frontal plane, girls with lower hamstring strength displayed significantly greater knee abduction at the time of peak vertical ($P = 0.050$) and peak anteroposterior ($P = 0.030$) GRF. Although no between-group differences were evident for knee abduction moments, girls with lower hamstring strength displayed significantly ($P = 0.050$) lower hip abduction moments at the time of peak vertical GRF (see Fig. 4).

A between-group difference ($P = 0.041$) was displayed for transverse plane biomechanics, such that girls with lower hamstring strength displayed knee internal rotation at the time of the peak anteroposterior GRF, whereas girls with higher hamstring strength displayed knee external rotation at this same point in time. This was also the case at the time of the peak vertical GRF, although this difference was not significant ($P = 0.062$). Girls with lower hamstring strength displayed significantly ($P = 0.001$) lower knee external rotation moments at the time of initial contact compared with their higher hamstring strength counterparts. A significant between-group difference was also evident for hip external rotation at the time of the peak anteroposterior

![Figure 4](image_url)

FIGURE 4—Mean ± SD for the three-dimensional ankle (A), knee (B), and hip kinematics (C) and normalized joint moments at the time of initial contact (IC), peak vertical GRF ($F_V$), and peak anteroposterior ($F_{AP}$) GRF for the lower and higher hamstring strength groups. *Significant between-group difference at $P \leq 0.05$. 

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GRF ($P = 0.037$) as well as hip external rotation moments at the time of peak vertical GRF ($P = 0.050$; see Fig. 4C).

**ACL loading.** No between-group differences were noted for timing of the peak $F_{ACL}$ (59.6 ± 13.7 and 65.8 ± 12.3 ms for the lower and higher hamstring strength groups, respectively; $P = 0.315$) or the magnitude of the normalized $F_{ACL}$ at the time of the peak vertical GRF (0.97 ± 1.21 and 1.14 ± 0.65 BW for the lower and higher hamstring strength groups, respectively; $P = 0.702$). However, girls with lower hamstring strength displayed significantly ($P = 0.034$) greater normalized $F_{ACL}$ at the time of the peak anteroposterior GRF (3.0 ± 1.3 BW) compared with girls with higher hamstring strength (1.7 ± 0.9 BW).

**Muscle activation.** There were no between-group differences in the timing of muscle onsets relative to initial contact or timing of peak muscle activity, although high within-group variation was evident (see Table 2). Interestingly, although not significant, girls with lower hamstring strength displayed peak ST and medial gastrocnemius activity before initial contact, which was not evident in the higher hamstring strength group (see Table 2).

## DISCUSSION

The hamstring muscles play a vital role in protecting the ACL during functional landing movements (10). The purpose of this study was to determine whether pubescent girls with lower hamstring strength displayed different lower limb biomechanics when landing after performing a horizontal leap movement compared with girls with higher hamstring strength. The results of the study confirmed that, as hypothesized, girls with lower hamstring strength modified their landing biomechanics compared with girls with higher hamstring strength, which will be discussed in detail below.

Conventional hamstring-to-quadriceps ($H_{con}/Q_{con}$) ratios are frequently used as an indicator of balance between the flexor and extensor muscles surrounding the knee (1,13). As hypothesized, our results revealed significantly lower $H_{con}/Q_{con}$ ratios in the lower hamstring strength group, relative to their higher strength counterparts. Interestingly, both groups displayed similar absolute and normalized peak quadriceps torque (see Table 1), and these values are comparable with those of Ramos et al. (35), who reported isokinetic quadriceps torque data collected at 180°·s⁻¹ in pubescent girls. This highlights the fact that the lower strength group were not “weaker” all round, but rather the between-group differences seen in the $H_{con}/Q_{con}$ ratios were due specifically to differences in hamstring strength. A decrease in hamstring strength relative to quadriceps strength is thought to be associated with an increased risk of lower limb injuries, as $H_{con}/Q_{con}$ ratios less than 0.75 at 180°·s⁻¹ have been shown to correlate with greater injury incidence in female athletes (24). This indicates that girls with lower hamstring strength may be placed at a greater risk of injury, given that their $H_{con}/Q_{con}$ ratio was found to be less than 0.6 (see Fig. 3). During deceleration from a landing, however, the quadriceps muscles eccentrically rather than concentrically control knee flexion, while the concentric hamstrings torque aids to reduce anterior shear forces experienced at the proximal tibia (1). Therefore, to assess dynamic functionality at the knee in terms of ACL injury risk during a landing, it is important to examine $H_{con}/Q_{ecc}$ ratios as opposed to the more conventional $H_{con}/Q_{con}$ ratios (1).

In the present study, girls with lower hamstring strength demonstrated almost two fold lower $H_{con}/Q_{ecc}$ ratios compared with their higher hamstring strength counterparts (see Fig. 3). Although these ratios are well above the previously reported $H_{con}/Q_{con}$ (24) and $H_{con}/Q_{ecc}$ (1) ratios, to our knowledge no research has calculated the $H_{con}/Q_{ecc}$ ratios corresponding with the knee angle displayed during landing, thus making comparisons to the literature difficult. However, our results suggest that girls with lower hamstring strength may have a reduced capacity for their hamstring muscles to protect the ACL during a dynamic landing movement. Whether girls with lower hamstring strength compensate for this strength deficit via modifying their landing biomechanics compared with girls with higher hamstring strength is discussed below.

Previous research has shown that foot placement during a landing may be implicated in the occurrence of noncontact ACL injuries, such that athletes with ACL injury tend to land with less ankle plantarflexion and adopt a more flatfoot alignment, postulated to increase abduction and rotation at

### TABLE 2. Mean ± SD and $P$ values for the timing of muscle onset and peak muscle activity relative to initial contact for the lower ($n = 11$) and higher ($n = 11$) hamstring strength groups.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Muscle</th>
<th>Lower Strength</th>
<th>Higher Strength</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of muscle onset relative to initial contact (ms)</td>
<td>MG</td>
<td>−183.4 ± 78.6</td>
<td>−163.7 ± 40.5</td>
<td>0.491</td>
</tr>
<tr>
<td></td>
<td>TA</td>
<td>−157.9 ± 72.7</td>
<td>−169.4 ± 93.6</td>
<td>0.762</td>
</tr>
<tr>
<td></td>
<td>VM</td>
<td>−154.5 ± 71.3</td>
<td>−143.6 ± 58.6</td>
<td>0.707</td>
</tr>
<tr>
<td></td>
<td>RF</td>
<td>−80.5 ± 54.4</td>
<td>−99.7 ± 105.2</td>
<td>0.620</td>
</tr>
<tr>
<td></td>
<td>BF</td>
<td>−172.7 ± 27.4</td>
<td>−165.5 ± 28.6</td>
<td>0.569</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>−171.5 ± 59.5</td>
<td>−201.5 ± 139.4</td>
<td>0.538</td>
</tr>
<tr>
<td>Time of peak muscle activity relative to initial contact (ms)</td>
<td>MG</td>
<td>−25.0 ± 47.6</td>
<td>8.5 ± 51.4</td>
<td>0.148</td>
</tr>
<tr>
<td></td>
<td>TA</td>
<td>113.0 ± 102.8</td>
<td>131.9 ± 178.4</td>
<td>0.774</td>
</tr>
<tr>
<td></td>
<td>VM</td>
<td>74.1 ± 55.1</td>
<td>69.8 ± 13.7</td>
<td>0.810</td>
</tr>
<tr>
<td></td>
<td>RF</td>
<td>78.4 ± 64.9</td>
<td>61.3 ± 11.8</td>
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<td></td>
<td>BF</td>
<td>60.2 ± 68.7</td>
<td>79.7 ± 88.6</td>
<td>0.640</td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>−43.8 ± 79.6</td>
<td>65.1 ± 173.7</td>
<td>0.243</td>
</tr>
</tbody>
</table>

A negative value indicates that the muscle onset or peak activity occurred before initial contact.

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the knee (7). Contrary to this belief, both groups in the present study displayed similar ankle kinematics and kinetics (see Fig. 4A). This highlights the need to determine whether deficits in hamstring strength contribute to between-group differences in knee and hip biomechanics during landing in adolescent girls.

The hamstring muscles can decrease anterior tibial translation and, in turn, loading on the ACL, and thus influence sagittal plane motion at the knee and hip (10). Although girls with lower hamstring strength displayed lower hip extension moments at the time of initial contact, we speculate that, based on previously reported moment data (15), a between-group difference of 0.3–0.5 N·m·kg⁻¹ seen in the present study is not functionally relevant. Interestingly, girls with lower hamstring strength experienced significantly greater estimated ACL forces (almost double) at the time of the peak anteroposterior GRF compared with their higher hamstring strength counterparts. Therefore, given that the participants displayed no differences in sagittal plane biomechanics, it is important to examine the differences in frontal and transverse plane kinetics or kinematics, which may provide greater insight into the between-group difference in ACL loading.

Increased knee abduction (valgus) angles have been shown to contribute to higher knee abduction loads, which, in turn, have been shown to predict ACL injury risk (19). Girls with lower hamstring strength in the present study displayed greater knee abduction angles at the time of the peak vertical and the peak anteroposterior GRF compared with their higher hamstring strength counterparts. Although the 4° between-group difference in knee abduction angle may not seem to be substantial, previous research has shown that a difference as little as 2° in frontal plane alignment reduced the injury threshold (defined as the maximal sustainable GRF before injury occurs) by 1 BW (8). This suggests that girls with lower hamstring strength may be exposed to a greater injury risk because of their greater knee abduction alignment during landing.

Despite greater knee abduction alignment in girls with lower hamstring strength during landing, no differences were evident in frontal plane knee loading (see Fig. 4). It is acknowledged that trunk and hip motion can affect biomechanics of the knee and ankle (21). In fact, Jacobs et al. (22) reported an association between lower peak isometric hip abductor torque (5.8% and 7.2% BW × height for women and men, respectively) and increased knee valgus motion (7.3° and 3.3° for women and men, respectively) during a dynamic landing movement in women compared with men. Girls with lower hamstring strength in the present study displayed significantly lower hip abduction moments at the time of the peak vertical GRF, despite similar frontal plane hip kinematics. The net internal moments calculated in the present study represent the contribution of the body’s soft tissues to oppose the external load on each joint. This decreased hip abduction moment displayed by girls with lower hamstring strength may suggest a reduced ability of the hip abductor muscles to control and reduce frontal plane knee motion during the landing movement (22), potentially contributing to an increased risk of ACL injury. As we did not assess hip abductor muscle activity in the present study, further research is warranted to assess this notion.

Palmieri-Smith et al. (33) reported an association between greater knee valgus angles and the lateral thigh musculature activity (vastus lateralis: partial regression coefficient = −1.397, P value = 0.013; BF: partial regression coefficient = −1.760, P value = 0.008). Conversely, lower knee valgus angles were associated with heightened medial thigh muscle activation (VM: partial regression coefficient = 2.197, P value = 0.009). Given the abduction and adduction moment arms of the lateral and medial thigh musculature, respectively (25), this may explain the increased knee valgus angles typically displayed by women compared with men when landing (18,22). However, despite this association, no between-group differences in the timing of hamstring or quadriceps activation were evident in the present study. Although vastus lateralis activity was not collected in the present study, these results suggest that there are no between-group differences in the activation of the lateral (BF) and medial thigh muscles (VM and ST) and therefore may not be the contributing factor to the greater knee abduction alignment displayed by girls with lower hamstring strength.

Increased knee rotation, particularly internal rotation, has shown to be potentially injurious to the ACL (28). Results from the present study revealed a significant difference in the transverse plane knee alignment at the time of the peak anteroposterior GRF, such that participants with lower hamstring strength displayed knee internal rotation and those with higher hamstring strength displayed knee external rotation (see Fig. 4B). Interestingly, despite a lack of significance (most likely due to the large variation in the data), girls with lower hamstring strength displayed peak ST activity before initial contact, whereas this peak activity occurred after initial contact in girls with higher hamstring strength (see Table 2). We speculate this earlier ST peak activity may be contributing to greater knee internal rotation in girls with lower hamstring strength (32), potentially contributing to a greater ACL injury risk (28). However, because of the large between-subject variation in EMG results, further research involving a significantly larger cohort is recommended to verify this claim.

Although a between-group difference in ACL force was detected, this study used a two-dimensional knee model to estimate ACL force. Because of the association between knee abduction, internal rotation alignment, and ACL injury risk, further research using a more comprehensive knee model, which incorporates knee frontal and transverse plane motion, is recommended. In addition, the present study was limited in that it did not assess the strength or activation of the hip abductor muscles or motion of the torso, both of which are known to affect the biomechanics of the lower limbs (21). Furthermore, it is acknowledged that the present study did not examine the intensity of muscle recruitment, and results are only based around the temporal aspects of muscle recruitment. Thus, further research is recommended.
in these areas to provide a greater understanding of factors affecting lower limb biomechanics during landing.

Overall, it was found that girls who had lower concentric hamstring strength displayed significantly lower hamstring-to-quadriceps ratios, reduced hip abduction moments, greater knee abduction alignment, and similar muscle activation patterns during the landing phase of a horizontal landing movement relative to their counterparts with higher hamstring strength. Given that the differences in landing biomechanics displayed by girls with lower compared with higher concentric hamstring strength were evident from the onset of puberty, as indicated by Tanner stage II, further research is warranted to determine how landing technique changes throughout the adolescent growth spurt. In summary, girls with reduced hamstring strength appear to have a decreased capacity to control lower limb frontal plane alignment. This reduced capacity appears to contribute to the increased ACL loading and, in turn, increased potential for injury.

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