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injuries are estimated to occur in 17%–79.3% of runners (36). Biomechanical running evaluations may potentially identify injury risk factors and aid in injury prevention (31). Proximal factors are now being studied more widely due to the nature of closed kinetic chain mechanics. During running, sufficient strength is required in hip and trunk musculature to maintain stability in all three planes of movements. Specifically, hip abductors and external rotators assist in maintaining a level pelvis and prevent hip adduction movements. Specifically, hip abductors and external rotators assist in maintaining a level pelvis and prevent hip adduction movements. Specifically, hip abductors and external rotators assist in maintaining a level pelvis and prevent hip adduction movements. Specifically, hip abductors and external rotators assist in maintaining a level pelvis and prevent hip adduction movements. 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Specifically, hip abductors and external rotators assist in maintaining a level pelvis and prevent hip adduction movements. Specifically, hip abductors and external rotors assist in maintaining a level pelvis and prevent hip adduction and movement during single-limb support. Hip adductor strength and pelvic drop (r = 0.66) and hip adduction (r = 0.86) during single-leg squats (38). Hip strength is also predictive of injury status in a variety of populations. For example, in a cohort of collegiate athletes, those who reported injuries during the season had weaker hip musculature than those who were not injured (19). In addition, decreased hip abduction strength has been found in individuals with a history of lower extremity injuries including patellar femoral pain syndrome (16) and iliotibial band syndrome (13). However, the influence of hip strength on thorax motion has not been well established during running.

With the proximal segments (pelvis, thorax, arms, and head) comprising approximately 60% of the total body mass (3), the movement and control of these segments relative to the lower extremities influence the location of the total body center of gravity, ground reaction forces, and energetics during running (22). In a closed kinetic chain, the motion of one segment must influence the motion of adjacent segments. Accordingly, movement of the pelvis should influence the motion of the thorax during the stance phase of running. If the strength of the hip musculature is correlated to the motion of the pelvis during dynamic tasks, hip strength should therefore influence the amount of thorax

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motion. This relationship has yet to be established. Therefore, the purpose of the present study was to determine the relationship between hip isokinetic strength and thorax and pelvic motion during treadmill running. We hypothesized that, as hip strength increased, thorax and pelvic range of motion (ROM) would decrease during treadmill running. A secondary purpose of this study was to identify if differences in these variables exist between male and female cross-country runners. Females, compared to males, have increased axial thorax rotation when calculated in relation to the pelvis (32). Therefore, we further hypothesized that female runners would exhibit decreased isokinetic hip strength and increased thorax and pelvic ROM compared to males.

METHODS

Twenty-four collegiate cross-country runners participated in this study (male \(n=14\), age 20.2 ± 1.2 yr, height 177.8 ± 6.7 cm, mass 64.0 ± 4.2 kg; female \(n=10\), age 19.5 ± 1.5 yr, height 153.9 ± 30.5 cm, mass 53.7 ± 4.3 kg). Informed written consent was obtained from each subject in accordance with the protocol approved by the Institutional Review Board. Data were collected immediately before the fall cross-country season. Subjects were excluded if they were currently under medical supervision and not fully cleared to participate in a structured running program. Inclusion criteria consisted of current participation on a collegiate cross-country team and self-reported free from pain during testing. Weekly mileage was greater than 30 miles for all subjects with an average of 64 ± 18 miles wk\(^{-1}\).

Hip abductor strength was assessed in a standing position with the trunk perpendicular to the floor and hip aligned with the axis of rotation of the dynamometer (System III; Biodex Medical Systems, Shirley, NY). Using bilateral upper extremity support, the subject pushed outward into hip abduction against a padded buttress for five repetitions, isokinetically at 120° s\(^{-1}\). Hip extensor strength was assessed in a standing position (System II; Biodex Medical Systems) with the patient leaning forward over a padded wedge that was used to obtain 10° of thorax anterior lean with 90° of knee flexion of the testing limb. Using bilateral upper extremity support, the subject pushed backward against a padded buttress for five repetitions, isokinetically at 120° s\(^{-1}\). Peak torque was recorded for hip abduction and hip extension.

Thorax and pelvis motion were calculated during two different running speeds on a custom built treadmill (2.12 m length by 0.91 m width running surface). Self-selected speed (SS) was initially determined by asking each subject what pace he/she would select for an easy 20-min run. The speed was then adjusted, if requested by the subject, after a short acclimation period of less than 2 min. The average speed during SS trials was 3.58 ± 0.26 m s\(^{-1}\) with a range of 2.95–3.8 m s\(^{-1}\). A prescribed speed (PS) of exactly 3.58 m s\(^{-1}\) was determined a priori and used immediately following the self-selected trial. The prescribed speed was similar to the averaged SS trials, which is a commonly selected light training pace of a 7.5 min mile\(^{-1}\). A 1-min trial was collected at each speed.

Reflective markers were placed on the pelvis (right ASIS, left ASIS, and sacrum) and thorax (posterior cluster of three markers) to calculate three-dimensional angular displacement relative to the global laboratory coordinate system during treadmill running (Fig. 1). Three-dimensional marker trajectories were collected with Cortex (Motion Analysis Corporation, Santa Rosa, CA) using a motion analysis system with 10 digital cameras (Eagle cameras; Motion Analysis Corporation). The video data were collected at 240 Hz. The motion analysis system was calibrated based on the manufacturer’s recommendations. Marker trajectories were filtered at a cutoff frequency of 12 Hz (low-pass fourth-order filter).
TABLE 1. Correlation analysis of segment angles of the thorax and pelvis to isokinetic strength of the hip extensors and abductors.

<table>
<thead>
<tr>
<th></th>
<th>Hip Extensor Strength</th>
<th>Hip Abductor Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prescribed speed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelvic tilt</td>
<td>-0.21</td>
<td>-0.35*</td>
</tr>
<tr>
<td>Pelvic obliquity</td>
<td>-0.50*</td>
<td>-0.50*</td>
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<tr>
<td>Pelvic rotation</td>
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<td>-0.23</td>
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<tr>
<td>Trunk flexion</td>
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</tr>
<tr>
<td>Trunk lateral lean</td>
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<td>0.16</td>
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<tr>
<td>Trunk rotation</td>
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<td>-0.57**</td>
</tr>
<tr>
<td>Self-selected speed</td>
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<td></td>
</tr>
<tr>
<td>Pelvic tilt</td>
<td>-0.31*</td>
<td>-0.32*</td>
</tr>
<tr>
<td>Pelvic obliquity</td>
<td>-0.49*</td>
<td>-0.44*</td>
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<tr>
<td>Pelvic rotation</td>
<td>-0.003</td>
<td>-0.22</td>
</tr>
<tr>
<td>Trunk flexion</td>
<td>-0.22</td>
<td>-0.14</td>
</tr>
<tr>
<td>Trunk lateral lean</td>
<td>-0.11</td>
<td>0.25</td>
</tr>
<tr>
<td>Trunk rotation</td>
<td>-0.60*</td>
<td>-0.53*</td>
</tr>
</tbody>
</table>

Correlation analysis of segment angles of the thorax and pelvis to isokinetic strength of the hip extensors and abductors. Significant correlations less than or equal to \( r = 0.48 \), based on the total number of subjects \( n = 24 \), exhibit a power less than 0.8. Prescribed speed was 3.58 m\( \cdot \)s\(^{-1} \) for all subjects. Self-selected speed average was 3.58 m\( \cdot \)s\(^{-1} \) with a range from 2.95 to 3.8 m\( \cdot \)s\(^{-1} \).

*Significant correlation coefficient at \( P = 0.05 \).

RESULTS

Correlations between Strength and Trunk Motion

Correlation analyses revealed that hip extensor strength and hip abductor strength were both significantly correlated with total ROM of pelvic obliquity and thorax axial rotation during stance phase of running (Table 1). Specifically, at both running speeds, as hip abductor strength increased, pelvic obliquity motion decreased (Fig. 2; SS \( r = -0.44 \), \( P = 0.002 \); PS \( r = -0.50 \), \( P < 0.001 \)). In addition, hip extensor strength showed a similar relationship with moderate negative correlation of \( r = -0.60 \) (PS \( P < 0.001 \)) and \( r = -0.59 \) (PS \( P < 0.001 \)) for thorax axial rotation ROM during SS and PS, respectively (Fig. 2). Pelvic obliquity ROM had a moderate to high correlation with thorax axial rotation ROM for both SS (\( r = 0.74 \), PS \( r < 0.001 \)) and PS (\( r = 0.75 \), PS \( r < 0.001 \)).

Sex Differences

Female runners exhibited greater pelvic obliquity (SS 13.1° ± 2.6°, PS \( P < 0.001 \); SS 13.9° ± 2.7°, PS \( P < 0.001 \)) and thorax axial rotation (SS 34.5° ± 7.0°, PS \( P < 0.001 \); SS 35.4° ± 7.2°, PS \( P < 0.001 \)).
DISCUSSION

We hypothesized that, as hip strength increased, thorax and pelvic motion would decrease during treadmill running in a cohort of collegiate cross-country runners. This hypothesis was supported as the subjects in the current study exhibited significant negative correlations of hip abductor and extensor strength to pelvic and thorax ROM. From a neuromuscular standpoint, enhanced strength of the pelvic gluteus maximus and gluteus medius neuromuscular efficiency during a single-leg lateral drop landing and stabilization test. The training group used a specialized training device with the subjects’ feet planted on the ground, standard and diagonal, as they performed concentric and eccentric trunk rotation exercise.

While in the current study we did not assess thigh motion. Souza et al. (35) found subjects with decreased hip extension strength had increased femoral internal rotation during running. Further, Heinert et al. (15) found that an uninjured female cohort with weaker hip abductor muscles demonstrated significantly increased maximum knee abduction angle and knee abduction angle \(P = 0.008\) at initial contact and toe-off as compared to the stronger female subject group. It is likely that internal femoral rotation, femoral adduction, pelvic tilt, and thorax axial rotation exhibit some form of coupling during stance. For instance, during initial ground contact during running, the trunk is near maximum posterior axial rotation on the contralateral side of the stance.
limb and then undergoes maximum forward rotation near toe-off. If femoral internal rotation and adduction increases as the limb moves through stance phase, the thorax will have increased rotation at toe-off to maintain forward directed motion. Moreover, in the presence of decreased hip strength, there will likely be increased thorax axial rotation.

The kinematics of running have been extensively investigated (25,27,31). Pontzer et al. (29) measured 24° of trunk rotation during 3.0-m·s$^{-1}$ running in 10 healthy adults. This is similar to the current study’s findings of male average trunk rotation (23°) but lower than the female average trunk rotation (35°) found. Pelvic tilt (5°–7°) and pelvic obliquity (9°–14°) ROM in our current cohort were similar to published results (25,31).

Sex differences were evident in our cohort in hip strength and pelvic and thorax motion. Previous studies support that females have increased lower extremity frontal plane motion in a variety of movements, including during the stance phase of running when compared to male counterparts (2,7,8,10–12,18,20,28,32,33). However, sex differences in transverse plane trunk axial rotation during running are modestly reported in the literature. In support of our current findings, Schache et al. (32) compared running mechanics between sexes and found that females had increased axial trunk rotation (marker rod positioned over the twelfth thoracic spinous process) when calculated in relation to the pelvis. Interestingly, these differences were primarily explained by sex as opposed to a variety of anthropometric and dynamic variables (32). In a later study, Saunders et al. (30) report increasing speed leads to reduced axial rotation across sexes; however, their study is limited by both a paucity of total subjects ($n = 7$) and female subjects ($n = 1$), which limits comparisons to the current study.

Average hip strength differences between male and female groups were similar to previous studies. Using the same hip abduction strength procedure on 21 females, Myer et al. (23) found average peak hip abduction strength of 0.99 N·m·kg$^{-1}$, which is similar to the hip strength found on our female population. Jacobs et al. (17) studied hip abduction function in males and females and found that females had significantly decreased peak torque when compared to males. Males have been found to have 41% higher maximum hip extension strength than females do (14). While the mechanism is not fully understood, an increase in hip strength has been shown to decrease frontal and transverse plane lower extremity motion in running (34). This supports our findings that the amount of hip strength relates to the amount of rotation and obliquity in neighboring joints. Dowson et al. (4) measured hip extension isokinetic strength at 190°·s$^{-1}$ in a population of sprinters. They found average peak strength relative to body mass as 2.92 N·m·kg$^{-1}$, which is higher than the average found in this study, which may be explained by the difference in population.

Clinically, the relationship between strength and function is often investigated in runners. The results of this study indicate that a significant inverse relationship exists between hip strength and rotations in the frontal and transverse planes during treadmill running. In addition, in patients with large movement excursions in the transverse plane, which are easily identified during visual gait observations, clinicians should pay close attention to potential gluteal strength deficits. This important relationship should be further explored with investigations targeting the effects of gluteal strengthening on lumbopelvic trunk rotation and any corresponding effects on pain, biomechanics, and function.

It is important to note that all running analyses in the current study were performed on a treadmill and therefore may not be generalizable to overground running. Treadmill analyses were used to standardize running conditions across all subjects. We assessed pelvic drop as a segmental angle in relation to the global laboratory coordinate system. Several studies have reported hip abduction/adduction as thigh rotation about the pelvis. Therefore, relative pelvic obliquity (drop) motion may pertain to several reports of hip frontal plane motion that are reported as joint angles. In addition, the use of segmental angles for both the pelvis and thorax should be carefully interpreted when comparing against other biomechanical conventions.

In conclusion, we identified moderate correlations in hip extensor and hip abductor strength and pelvic and thorax motion during running. The potential that a causal relationship may exist should be further investigated with randomized trials that target gluteal strengthening. In addition, females exhibited decreased strength and increased pelvic and thorax motion compared to males. While not in the scope of this study, future work should identify the effects of thorax motion on lower extremity mechanics and risk of overuse running injuries.

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There is no conflict of interest for each author of this study.

The results of this study do not constitute endorsement by the American College of Sports Medicine.

REFERENCES


