Musculoskeletal disorders of the lower limbs are often associated with poor hip muscle performance and altered kinematics during dynamic weight-bearing tasks. However, it is unclear whether altered lower-limb and pelvis/trunk motion, as a result of hip weakness, contributes to the development of musculoskeletal pathology and pain.\(^{11,23}\) During the stance phase of walking and hopping, the hip extensors and abductors play a complex role in control of the lower extremities, pelvis, and trunk. This includes deceleration of hip internal rotation and adduction\(^ {15}\) and maintenance of the equilibrium of the pelvis and trunk over the stance limb.\(^ {7}\) Additionally, motion at the hip, pelvis, and trunk influences kinematics and kinetics at the knee.\(^ {11,23}\) Therefore, weakness of the hip musculature may be associated with altered kinematics at the knee, hip, pelvis, and trunk.

A number of studies have examined the relationship between diminished hip muscle performance and kinematics in individuals with musculoskeletal dysfunction. For example, females with patellofemoral pain syndrome have lower maximum hip abductor and extensor torque and greater peak knee external rotation and hip adduction during the stance phase of running compared to healthy controls.\(^ {30,34}\) Similarly, hip osteoarthritis is associated with lower hip abductor strength, as well as greater pelvic drop and hip internal rotation, during the stance phase of walking.\(^ {135}\) However, cross-sectional studies of patient popula-
otions do not discriminate between weakness resulting from musculoskeletal pain or pathology and weakness that may contribute to the development of the disorder.3,23

Previous studies that have investigated the relationship between hip strength and single-joint/segment kinematics in healthy individuals have failed to account for the confounding influence of trunk motion.3,13,18,23 In the frontal plane, individuals with weak hip abductors often demonstrate greater trunk motion during the stance limb, resulting in altered moments at the hip and knee.3,20

In addition, previous studies utilizing mixed samples of male and female subjects may also have been confounded by sex-specific differences in kinematics during dynamic tasks.3,5,15,23,25 Therefore, the effect of hip muscle performance on peak kinematics of the lower limbs, pelvis, and trunk in the absence of musculoskeletal pathology remains unclear.

Analysis of the relative timing and coordination of motion between joints or segments may facilitate the identification of subtle adaptations in lower-limb, pelvis, or trunk motion associated with diminished hip muscle performance during submaximal weight-bearing tasks.10,12 Adaptations in patterns of joint or segmental coordination have the potential to alter joint loading during the stance phase of dynamic activities, and therefore may also be associated with the development of lower-limb pathologies.4,20,22 Continuous methods of analyzing coordination, such as the vector coding method, quantify patterns of coordination between segments (intersegmental coordination) or joints (interjoint coordination) across the time series of a task.25,27 Compared to single-joint and single-segment kinematics, these interjoint and intersegmental coordination analyses may have greater sensitivity to detect subtle kinematic differences between groups of subjects or between modes of gait with varying mechanical demands.

The purpose of this study was to investigate kinematics in healthy women with strong and weak hip muscle performance during the stance phase of walking at self-selected speed and rate-controlled, single-legged hopping. We hypothesized that during both walking and hopping, women with weak hip musculature would demonstrate greater peak lower-limb, trunk, and pelvis angular motion in the frontal and transverse planes, in addition to different patterns of coordination, compared to women with strong musculature.

METHODS

All participants provided written informed consent, and the Institutional Review Board of the University of Southern California approved the study procedures. Eligible participants had no history of injury or surgery in the lower extremities and spine, and no other medical condition that could affect physical activity.

Isometric hip abductor and extensor strength was tested bilaterally in healthy women using a dynamometer (PrimusRS; BTE Technologies, Hanover, MD). Hip abduction strength was tested in a sidelying position, with the test limb in neutral hip alignment and full knee extension. Hip extension strength was tested in a prone position, at 30° of hip flexion and 90° of knee flexion. Participants performed 3 trials with each lower extremity. Peak torque was averaged across the 3 trials and was normalized to participant body mass. Participants were given 3 practice trials prior to testing and consistent verbal encouragement during each trial. This protocol has a high test-retest reliability.10

Participants were stratified into a weak group (WG) or strong group (SG) if the normalized peak torque of both hip abduction and extension on their dominant limb fell outside of a 95% confidence interval. This confidence interval was calculated from the distribution of abduction and extension torque values from a database of the first 30 female participants tested in this study (mean ± SD age, 25.8 ± 1.8 years; height, 1.68 ± 0.01 m; weight, 64.3 ± 8.2 kg). Threshold values for the SG were 2.74 and 1.63 Nm·kg⁻¹ for extension and abduction, respectively. Threshold values for the WG were 1.35 and 0.77 Nm·kg⁻¹ for extension and abduction, respectively. The dominant limb was defined as the preferred leg for kicking a ball.22 The hip performance of 150 women was tested to identify 22 women who met the criteria for either the SG or the WG. These women were retained for the second phase of the study, consisting of the complete biomechanical assessment. These data were collected as part of a broader study investigating kinematics and muscle activation during a number of dynamic activities that included drop jumps and running, in addition to walking and hopping. The a priori power analysis was completed for the drop-jump task, utilizing pilot data for lumbopelvic excursion, and indicated that a total sample of 16 participants was required to achieve a power of 80% at an alpha level of .05. A conservative recruitment goal of 22 participants was selected to account for attrition. The electromyographic and kinematic data from the drop-jump task have been presented elsewhere.22

Instrumentation

Lower extremity, pelvis, and trunk kinematic data were collected using a 10-camera, 3-D motion-capture system sampling at 250 Hz (Qualisys AB, Göteborg, Sweden). Retroreflective markers were placed on bony landmarks to define the local coordinate frames of the lower extremities, pelvis, and trunk. Motion of the pelvis segment was tracked by markers on the bilateral anterior superior iliac spines, iliac crests, and at the L5-S1 interspinous space. A rigid cluster of markers placed over the spinous process of T3 was used to track the motion of the trunk, and clusters of markers on the heel counter of the shoes, shanks, and lateral thighs were used to track segmental motion of the lower extremities.

Experimental Tasks

For the walking task, participants walked

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along a walkway at a self-selected speed. Average speed during the walking trials was calculated from the time taken to pass between 2 photoelectric triggers. For the hopping task, participants performed consecutive hops on a 46 × 51-cm force plate (model OR6; Advanced Mechanical Technology, Inc, Watertown, MA), with a sampling rate of 1500 Hz, in time to a metronome. The hops were performed at a rate of 100 hops per minute, which is slower than the typical self-selected hopping rate and places a greater demand on the knee.29 Participants were required to land with the support foot fully within the force plate for at least 20 consecutive hops. All hops were performed on the participant’s dominant limb, with the arms crossed over the chest for the duration of the trial.

Data Processing
Marker coordinates and force-plate data were processed using Visual3D software (C-Motion, Inc, Germantown, MD). For the walking task, stance-phase initiation and termination on the dominant limb were identified using the heel-marker trajectories. This method of event detection was utilized to maximize the number of trials available for analysis. For the hopping task, support-phase initiation and termination were identified as the times at which the vertical ground reaction force exceeded and dropped below 20 N, respectively. A model consisting of the feet, shanks, femurs, pelvis, and trunk was constructed. Motion of the lower extremity segments was referenced to the proximal segment. Motion of the trunk and pelvis segments was referenced to the global coordinate frame and was normalized to a static calibration trial to account for individual postural alignment.22 Peak angles of the knee and hip joints and the pelvis and trunk segments in the frontal and transverse planes were calculated for 10 stance phases on the dominant limb for the walking task and for the first 10 hops for the hopping task, and were averaged across the repeated trials for each subject. The first 10 hops were selected to maximize the consistency of the task performance.

Coordination between lower extremity joints and between the trunk and pelvis segments was quantified using the vector coding technique.4,9,19 Vector coding is based on methods originally described by Sparrow et al23 to quantify coordination behavior using angle-angle plots. Coordination between 2 segments or joints is calculated as the angle of the vector between successive points on the angle-angle plot relative to the right horizontal. This provides an angle, called the coupling angle, between 0° and 360° for each successive interval of the time series. The pattern of coordination for each interval of the time series can then be defined as inphase (both segments/joints moving in the same direction at the same time), antiphasic (the 2 segments/joints moving in the opposite direction at the same time), proximal phase (motion occurring primarily in the proximal joint/segment), or distal phase (motion occurring primarily in the distal joint/segment) using 45° bin widths (FIGURE 1A).4,27 Inphase coordination is represented by coupling angles between 22.5° to 67.5° and 202.5° to 247.5°. Antiphase coordination is represented by coupling angles between 112.5° to 157.5° and 292.5° to 337.5°; proximal-phase coordination: coupling angles between 157.5° to 202.5° and 337.5° to 360°; distal-phase coordination: coupling angles between 67.5° to 122.5° and 247.5° to 292.5°. (B) Coupling joint/segment pairs in the frontal (1 and 3) and transverse (2 and 4) planes. Direction of arrows indicates direction of motion with positive values.
c Coupling 2, hip/knee motion in the transverse plane (positive values represent rotation ipsilateral to the stance limb); coupling 3, pelvis/trunk motion in the frontal plane (positive values represent tilt toward the side of the stance limb); coupling 4, pelvis/trunk motion in the transverse plane (positive values represent rotation toward the side of the stance limb) (FIGURE 1B). The amount of each coordination pattern utilized during walking and hopping for each coupling segment/joint pair was quantified as a percentage of the total coordination. This indicates the amount of each movement cycle that was spent in each of the 4 coordination patterns.

**Statistics**

Individual 2-way, repeated-measures analyses of variance were used to examine the main effects of group (between-subject factor, SG and WG) and the interaction effects of group by task (within-subject factor, walk and hop) on the dependent variables. Post hoc comparisons on significant group main effects were made using t tests for independent samples, with a Bonferroni correction for multiple comparisons, whereby the alpha level for each pairwise comparison was multiplied by the number of comparisons for that variable. Statistical significance was set at P = .05. Effect sizes for pairwise comparisons were calculated using Cohen d (PASW Statistics 18; SPSS Inc, Chicago, IL).

**RESULTS**

There was no significant difference in age, height, or weight between the groups (TABLE). Hip abductor and extensor strength was significantly greater in the SG than in the WG on both the dominant and the non-dominant limb (TABLE). Kinematic data from 3 participants were excluded due to technical issues, leaving a total of 19 subjects (SG, n = 10; WG, n = 9). Mean ± SD self-selected walking speed for the entire sample was 1.32 ± 0.18 m/s and was not significantly different between groups (P = .49).

**Single-Joint/Segment Kinematics**

There was a significant group-by-task interaction for frontal plane trunk motion. The WG demonstrated a significantly greater change in peak trunk motion during hopping compared with walking than the SG (F = 8.657, P = .009). Post hoc analyses indicated that there was no significant difference between groups during walking (WG, 2.5° ± 1.6°; SG, 1.3° ± 1.5°; P = .234). However, the WG had significantly greater trunk lateral bend toward the stance limb during the hopping task than the SG (WG, 7.9° ± 2.1°; SG, 4.1° ± 2.0°; P = .002; d = 1.88). A group-by-task interaction was also evident for ipsilateral pelvic tilt (F = 8.079, P = .011). There was a trend toward the WG demonstrating a greater amount of ipsilateral tilt during hopping (walking: WG, 2.0° ± 1.3°; SG, 2.5° ± 1.1°; P = .756; hopping: WG, 11.0° ± 2.1°; SG, 9.0° ± 2.0°; P = .108).

**Coordination**

There was a significant effect of group for hip/knee transverse plane coordination (coupling 2: antiphase, F = 7.376; P = .015; inphase, F = 8.22; P = .011; hip phase, F = 10.311; P = .005). During walking, the WG utilized less inphase coordination between the hip and knee in the transverse plane (WG, 22.4% ± 6.4%; SG, 29.4% ± 2.7%; P = .036; d = 1.45) and greater primarily hip motion than the SG (WG, 23.2% ± 6.1%; SG, 15.7% ± 2.0%; P = .036; d = 1.70) (FIGURE 2). The WG had significantly greater antiphase coordination between the hip and knee in the transverse plane during hopping than the SG (WG, 30.2% ± 7.1%; SG, 17.0% ± 10.4%; P = .03; d = 1.47) (FIGURES 2 and 3). There was also a significant effect of group for coordination between the pelvis and the trunk in the frontal plane (coupling 3: inphase coordination, F = 5.44; P = .032). Although the WG utilized more inphase coordination between the trunk and the pelvis in the frontal plane than the SG during hopping, the difference was not statistically significant (WG, 10.0% ± 5.3%; SG, 5.4% ± 1.8%; P = .066; d = 1.19). In addition, there was a group-by-task interaction for the amount of inphase coordination utilized in the transverse plane between the pelvis and the thorax (F = 5.983, P = .026). The WG demonstrated less inphase coordination than the SG during hopping (WG, 33.00% ± 18.5%; SG, 47.90% ± 8.72%; P = .028).

**DISCUSSION**

This study indicates that, in healthy young women, hip muscle performance does not affect peak kinematics of the hip or knee during walking or rate-controlled hopping. However, those women specifically selected as being at the extreme of strong or weak hip musculature do demonstrate signifi-

### TABLE

**Subject Demographics and Hip Strength**

<table>
<thead>
<tr>
<th></th>
<th>WG (n = 9)</th>
<th>SG (n = 10)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>23.44 ± 3.54</td>
<td>24.10 ± 3.51</td>
<td>.68</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>61.16 ± 6.49</td>
<td>58.57 ± 5.32</td>
<td>.35</td>
</tr>
<tr>
<td>Height, m</td>
<td>1.67 ± 0.05</td>
<td>1.66 ± 0.06</td>
<td>.75</td>
</tr>
<tr>
<td>Dominant hip abduction, N·m·kg⁻¹</td>
<td>0.67 ± 0.09</td>
<td>1.22 ± 0.13</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Dominant hip extension, N·m·kg⁻¹</td>
<td>1.17 ± 0.18</td>
<td>2.97 ± 0.13</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Nondominant hip abduction, N·m·kg⁻¹</td>
<td>0.76 ± 0.14</td>
<td>1.87 ± 0.19</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Nondominant hip extension, N·m·kg⁻¹</td>
<td>1.21 ± 0.22</td>
<td>2.94 ± 0.35</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

*Abbreviations: SG, strong group; WG, weak group. Values are mean ± SD.*
cantly different patterns of coordination between the hip and knee and the trunk and pelvis.

By demonstrating little relationship between isometric strength and peak hip and knee joint kinematics, the results of this study are consistent with the findings of previous studies investigating individuals at the extremes of typical hip muscle performance.3,4,23 Previous studies using healthy subjects have demonstrated changes in lower extremity kinematics after the hip musculature is fatigued.2,8 However, the kinematics observed after fatigue in these studies may in part represent a short-term response to a novel, localized loss of muscle performance rather than the purely habitual movement strategy for that individual.

In this study, the weaker participants did demonstrate increased frontal plane trunk motion in the direction of the stance limb during hopping. It is possible that if this trunk lateral bend had been constrained during hopping, a greater group difference in peak lower-limb kinematics would have emerged. The fact that this strategy was not evident during walking gait is reflective of the higher mechanical demands of the rate-controlled slow-hopping task.

The quantification of coordination patterns in this study permitted greater insight into differences between groups than the single-joint/segment peak kinematics. During weight-bearing tasks, the coordination between joints or segments is in part constrained by the morphology of the joints and associated soft tissues.6,32 However, the kinematics of multiple segments or joints are also coordinated as part of a motor control strategy or synergy.15 Despite the lack of group differences in peak hip or knee kinematics, the coordination analyses indicated differences in patterns of lower extremity coordination between the SG and the WG. The WG demonstrated significantly greater antiphase coordination between the hip and knee in the transverse plane compared with the SG during hopping. The antiphase coordination pattern, consisting of simultaneous hip internal rotation and knee external rotation, occurred during both the deceleration and acceleration components of the hop stance phase in the WG. This pattern of coordination may result in increased patellofemoral joint stress23,24 and therefore suggests a mechanism for the development of patellofemoral joint pain in individuals with weak hip musculature.

Interestingly, in the present study, there were also differences between the groups in transverse plane lower extremity coordination during the less mechanically demanding walking task. The WG used less inphase hip and knee rotation than the SG, and also spent a greater amount of time utilizing primarily hip motion (hip phase) than the SG. These differences were driven primarily by a pattern of relative external rotation of the hip during midstance in the WG that did not occur in the SG. Powers et al.24 also demonstrated decreased hip internal rotation during walking in individuals with patellofemoral pain compared with controls. They suggested that this could be a compensatory mechanism to minimize the lateral forces on the patella. The present study indicates that this finding may also be related to hip muscle performance.

Limitations
This study utilized a relatively small sample size. However, the large effect sizes for group differences in a number of variables suggest that the study was adequately powered. As our study aimed to investigate women with contrasting hip muscle performance, the generalizability of these results to individuals with less extreme muscle performance may be limited. The strength thresholds for inclusion in the study were calculated a priori after initially testing only 30 participants. However, utilizing strength data calculated from all 150 study participants would have resulted in a smaller sample due to larger standard deviations in the entire cohort data. Further, due to the time required to screen all 150 subjects, retaining subjects for biomechanical testing might have been difficult. It should also be noted that as the criterion for stratification to the SG and WG in this study was the performance of the hip extensors and abductors, it is possible that...
differing performance in other lower extremity or trunk musculature may have contributed to the group differences. In particular, the adaptations in transverse plane coordination patterns may also be associated with poor hip rotator performance. In addition, this study did not control for habitual physical or sporting activity in the participants and did not investigate the nondominant limb.

CONCLUSION

This study helps to clarify the relationship between hip muscle performance and lower-limb, pelvis, and trunk kinematics in young women. In the absence of the confounding influences of pain or pathology, hip weakness is not associated with significant differences in peak kinematics in the lower limbs, pelvis, or trunk during walking. Compensatory frontal plane trunk motion in weak subjects may reduce the effect of weak hip musculature on lower-limb kinematics during hopping. The significantly different lower-limb and pelvis/trunk coordination patterns during both walking and hopping in the weak participants suggest subtle adaptations to diminished hip performance even in young, healthy women during submaximal motor tasks. Further research is needed to establish the relationship between these coordination adaptations and joint loading or the development of musculoskeletal pathology.

KEY POINTS

FINDINGS: Healthy women with poor hip muscle performance have different coordination, but not different peak lower-limb kinematics, during walking and hopping compared to women with strong hip muscle performance.

IMPLICATIONS: The differences in kinematics previously observed in patients with musculoskeletal disorders may be more related to pain or pathology than hip muscle weakness. However, the adaptations in trunk motion and in patterns of lower-limb and trunk coordination evident in this study may contribute to the development of musculoskeletal disorders.

CAUTION: This study only investigated young, healthy women, selected to be at the extreme ranges of hip muscle performance, performing submaximal tasks. In addition, the interpretation of the data relies on a premise that functional tasks require a common pattern of coordination.

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