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The Influence of Hip Strength on Lower-Limb, Pelvis, and Trunk Kinematics and Coordination Patterns During Walking and Hopping in Healthy Women

Jo Armour Smith
Chapman University, josmith@chapman.edu

John M. Popovich
Michigan State University

Kornelia Kulig
University of Southern California

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Comments
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Key Words: coordination, muscle performance, **hopping,** gait.

INTRODUCTION

Musculoskeletal disorders of the lower limbs are often associated with both poor hip muscle performance and altered kinematics during dynamic tasks. However, it is still unclear whether altered lower limb or pelvis/trunk motion as a result of hip weakness contributes to the development of musculoskeletal pathology and pain.[13,25] During the stance phases of activities such as walking, running or 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[16] and maintenance of the equilibrium of the pelvis and trunk over the stance limb.[8] Additionally, motion at the hip, pelvis and trunk influences kinematics and kinetics at the knee.[13,25] Therefore, weakness of the hip musculature may be associated with altered kinematics at the knee, hip, pelvis or trunk.

A number of studies have examined the relationship between diminished hip muscle performance and kinematics in patients with musculoskeletal dysfunction. For example, females with patellofemoral pain syndrome (PFP) have decreased maximum hip abductor and extensor torque and increased peak knee external rotation and increased hip adduction during the stance phase of running compared with healthy controls.[30,34] Similarly, hip osteoarthritis is associated with decreased hip abductor strength as well as increased pelvic drop and hip internal rotation during the stance phase of walking.[2,33] However, cross sectional studies of patient populations do not discriminate between weakness resulting from musculoskeletal pain or pathology and weakness that may have contributed to the original development of the disorder.[4,25]

Existing studies that have investigated the relationship between hip strength and single joint/segment kinematics in healthy subjects have failed to account for the confounding influence of trunk motion in persons with weak hip musculature.[4,14,19,25] In the frontal plane, subjects with weak hip abductors often demonstrate increased trunk motion towards the stance limb,[23,25] resulting in altered moments at the hip and knee.[4,21] In addition, existing studies utilizing mixed samples of male and female subjects may also have been confounded by sex-specific differences in kinematics during dynamic tasks.[4,6,16,25,26] 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, or coordination, of motion occurring between joints or segments may facilitate identification of subtle adaptations in lower limb, pelvis or trunk motion associated with diminished hip muscle performance during sub-maximal tasks.[11,12] 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.[5,11,32] Continuous methods of analyzing coordination, such as the vector coding method, quantify patterns of coordination between segments (inter-segmental coordination) or joints (inter-joint coordination) across the time-series of a task.[1,27] These types of coordination analyses may have greater sensitivity to detect subtle kinematic differences between groups of subjects, or between modes of gait with varying mechanical demands, than single joint/segment kinematics.

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 **University of Southern California** Institutional Review Board approved the study procedures. Eligible participants were free from any history of injury or surgery to the lower extremities and spine or other medical conditions affecting physical activity.

Isometric hip abductor and extensor strength were tested bilaterally in healthy women using a dynamometer (Primus RS, BTE Technologies, Hanover, MD). Hip abduction strength was tested in a side lying position with the test limb in neutral hip alignment and full knee extension. Hip extension strength was tested in a prone position with 30° and 90° of hip and knee flexion respectively.[23,30] Participants performed three trials with each leg. Peak torque was averaged across the three trials and was normalized to participant body mass. **Participants were given three practice trials prior to testing, and consistent verbal encouragement was provided during each trial. This protocol has high test-retest reliability.**[17]

Participants were stratified to a weak or strong group 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 (age 25.8 ± 1.8 years, height 1.68 ± 0.01 m, weight 64.3 ± 8.2 kg). Threshold values for the strong group (SG) were 2.74 and 1.63 N m·kg^{-1} for extension and abduction respectively. Threshold values for the weak group (WG) were 1.35 and 0.77 N m·kg^{-1}. The dominant limb was defined as the preferred leg for kicking a ball.[23,28] **The hip performance of 150 women was tested in order to find 22 that 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 EMG during a number of dynamic activities that included drop jumps and running in addition to walking and hopping. The EMG and kinematic data from the drop jump task have been presented elsewhere.[23] 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 0.05. A conservative recruitment goal of 22 participants was selected to account for attrition.**

Instrumentation

Lower extremity, pelvis and trunk kinematic data were collected using a ten-camera three-dimensional motion capture system sampling at 250 Hz (Qualisys AB, Gothenburg, Sweden). Retro-reflective 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 shoe, shanks and lateral thighs were used to track segmental motion of the lower extremities.

Experimental tasks

For walking gait, participants walked along a walkway at self-selected speed. Average speed during the walking trials was calculated from the time taken to pass between two photoelectric triggers. **For the hopping task, participants performed consecutive hops on a 46cm by 51cm force plate (AMTI OR-6, Watertown, MA, sampling rate 1500Hz) in time with a metronome.** Hops were performed at a rate of 100 hops per minute. This hopping rate is slower than typical self-selected hopping rate, and induces greater demand on the knee than self-selected hopping.[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 leg and the arms were crossed over the chest for the duration of the trial.

Data processing

Marker coordinates and force plate data were processed using Visual 3D™ (C-Motion Inc., MD). For walking, stance phase initiation and termination on the dominant leg were identified using the heel marker trajectories. For hopping, support phase initiation and termination were identified as the moment the vertical ground reaction force exceeded or 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.[23] Peak **angles** of the knee and hip joints and the pelvis and trunk segments in the frontal and transverse planes were calculated for ten stance phases on the dominant leg for walking and for the first ten hops for hopping and were averaged across the repeated trials for each subject. **The first ten hops were selected in order 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.[5,10,20] **Vector coding is based on methods originally described by Sparrow et al.** [31] **to quantify coordination behavior using angle-angle plots. Coordination between two 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 degrees for each successive interval on the time series. The pattern of coordination for each time interval across the time series can then be defined as in-phase (both segments/joints moving in the same direction at the same time,); anti-phase (both segments/joints moving in the opposite direction at the same time); proximal phase (motion occurring primarily in the proximal joint/segment); distal phase (motion occurring primarily in the distal joint/segment) using 45° bin widths (Figure 1a).[1,5] In-phase coordination is represented by coupling angles between 22.5 – 67.5° and 202.5 – 247.5°. Anti-phase coordination is represented by coupling angles between 112.5 – 157.5° and 292.5 – 337.5°. Proximal phase coordination is represented by coupling angles between 157.5 – 202.5° and 337.5 – 360°. Distal phase coordination is represented by coupling angles between 67.5 – 112.5° and 247.5 to 292.5°.**[5]

The vector coding technique was utilized in this study as, unlike other continuous methods of coordination analysis such as continuous relative phase, it does not require amplitude normalization of kinematic data and therefore can be more easily interpreted relative to the original kinematics, and is appropriate for both discrete and oscillatory motor tasks.[22] **For both walking and hopping, coordination was quantified between the following joint/segment pairs: Coupling 1: Hip/knee motion in the frontal plane (positive values = abduction); Coupling 2: Hip/knee motion in the transverse plane (positive values = rotation ipsilateral to the stance limb); Coupling 3: Pelvis/trunk motion in the frontal plane (positive values = tilt towards the side of the stance limb); Coupling 4: Pelvis/trunk motion in the transverse plane (positive values = rotation towards 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 four coordination patterns.**

Statistics

Individual two-way repeated measures ANOVA were used to examine the main effects of group (between subjects factor; SG, WG) and the interaction effects of group by task (within subjects factor; walk, 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, with statistical significance set at $p \leq 0.05$. Effect sizes for pairwise comparisons were calculated using Cohen's d **(PASW Statistics 18, IBM Corp., Armonk, NY).**

RESULTS

There was no significant difference in age, height or weight between the groups (Table 1). 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 1). Kinematic data from three 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) $m \cdot s^{-1}$ and was not significantly different between groups (p = 0.49).

Single joint/segment kinematics

The only significant main effect of group for peak single-joint/segment kinematics was in frontal plane trunk motion (F = 13.19, p = 0.002). Post-hoc analyses indicated that there was no significant difference between groups during walking (WG = 2.5 (1.6)°, SG = 1.3 (1.5)°, adjusted p = 0.234). However, the WG had significantly greater trunk lateral bend towards the stance limb during the hopping task than the SG (WG = 7.9 (2.1)°, SG = 4.1 (2.0)°; adjusted p = 0.002, effect size d = 1.88). In addition, the WG demonstrated a significantly greater change in peak trunk motion during hopping compared with walking than the strong group (ordinal interaction, F = 8.657, p = 0.009). A **disordinal** group by task interaction was also evident for ipsilateral pelvic tilt. The WG demonstrated less ipsilateral pelvic tilt than the SG during walking and a greater amount of ipsilateral tilt during hopping (Walking, WG = 2.0 (1.3)°, SG = 2.5 (1.1)°; Hopping, WG = 11.0 (2.1)°, SG = 9.0 (2.0)°, F = 8.079, p = 0.011).

Coordination

There was a significant effect of group for hip/knee transverse plane coordination (coupling 2; anti-phase (F = 7.376, p = 0.015), in-phase (F = 8.22. p = 0.011), hip phase (F = 10.311 p = 0.005)). During walking, the WG utilized less in-phase coordination between the hip and knee in the transverse plane (WG = 22.4 (6.4)%, SG = 29.4 (2.7)%, adjusted p = 0.036, d = 1.45) and greater primarily hip motion than the SG (WG = 23.2 (6.1)%, SG = 15.7 (2.0)%, adjusted p = 0.036, d = 1.70) (Figure 2). The WG had significantly greater anti-phase 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)%, adjusted p = 0.03, 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; in-phase coordination, F = 5.44, p = 0.032). The WG tended to utilize more in-phase coordination between the trunk and the pelvis in the frontal plane than the SG during hopping (WG = 10.0 (5.3)%, SG = 5.4 (1.8)%, adjusted p = 0.066, d = 1.19). In addition, the WG demonstrated a smaller change in the amount of in-phase coordination utilized in the transverse plane between the pelvis and the thorax between walking and hopping than the SG (ordinal interaction, p = 0.026).

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, women with strong or weak hip musculature do demonstrate significantly 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**, this present research **supports** the findings of other studies investigating subjects at the extremes of typical hip muscle performance.[4,15,19] Some previous studies using healthy subjects have demonstrated changes in lower extremity kinematics after the hip musculature is fatigued.[3,9] **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 subject.**

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.[7,32] However, the kinematics of multiple segments or joints are also coordinated as part of a motor control strategy or synergy.[18] 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 weak subjects demonstrated significantly greater anti-phase coordination between the hip and knee in the transverse plane compared with the SG during hopping. The anti-phase 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 stress[25,34] and therefore suggests a mechanism for the development of PFP in subjects with weak hip musculature.

Interestingly, in this 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 in-phase 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 mid-stance in the WG that did not occur in the SG. Powers et al.,[24] also demonstrated decreased hip internal rotation during walking in subjects with PFP compared with controls. They suggested that this may be a compensatory mechanism to minimize the lateral forces on the patella. **This 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 testing only an initial 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 non-dominant limb.

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 sub-maximal motor tasks. Further research is needed to establish the relationships 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 with 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 performing sub-maximal 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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TABLE 1. Subject demographics and hip strength. (WG = weak group, SG = strong group).

	WG (n=11)	SG (n=11)	p
Age (years)	23.91 (3.96)	23.91 (3.21)	1.00
Weight (kg)	60.43 (6.18)	59.44 (6.82)	0.70
Height (m)	1.66 (0.04)	1.66 (0.06)	0.77
Dominant hip abduction ($N \cdot m \cdot kg^{-1}$)	0.67 (0.08)	1.81 (0.13)	<0.001
Dominant hip extension ($N \cdot m \cdot kg^{-1}$)	1.14 (0.19)	2.96 (0.13)	<0.001
Non-dominant hip abduction ($N \cdot m \cdot kg^{-1}$)	0.75 (0.13)	1.84 (0.20)	<0.001
Non-dominant hip extension ($N \cdot m \cdot kg^{-1}$)	1.18 (0.22)	2.93 (0.34)	<0.001

All values mean (± SD)

FIGURE 1(a). Exemplar angle-angle plot and detail from plot demonstrating calculation of coupling angle and categorization of coupling angles for a single coupling pair into coordination patterns using 45° bin widths. In-phase coordination, coupling angles between 22.5 – 67.5° and 202.5 – 247.5°; anti-phase coordination, coupling angles 112.5 – 157.5° and 292.5 – 337.5°; proximal phase coordination, coupling angles 157.5 – 202.5° and 337.5 – 360°; distal phase coordination, coupling angles 67.5 – 112.5° and 247.5 to 292.5°. **FIGURE 1(b)**. Coupling joint/segment pairs in the frontal (1 & 3) and transverse (2 & 4) planes. Direction of arrows indicates direction of motion with positive values.

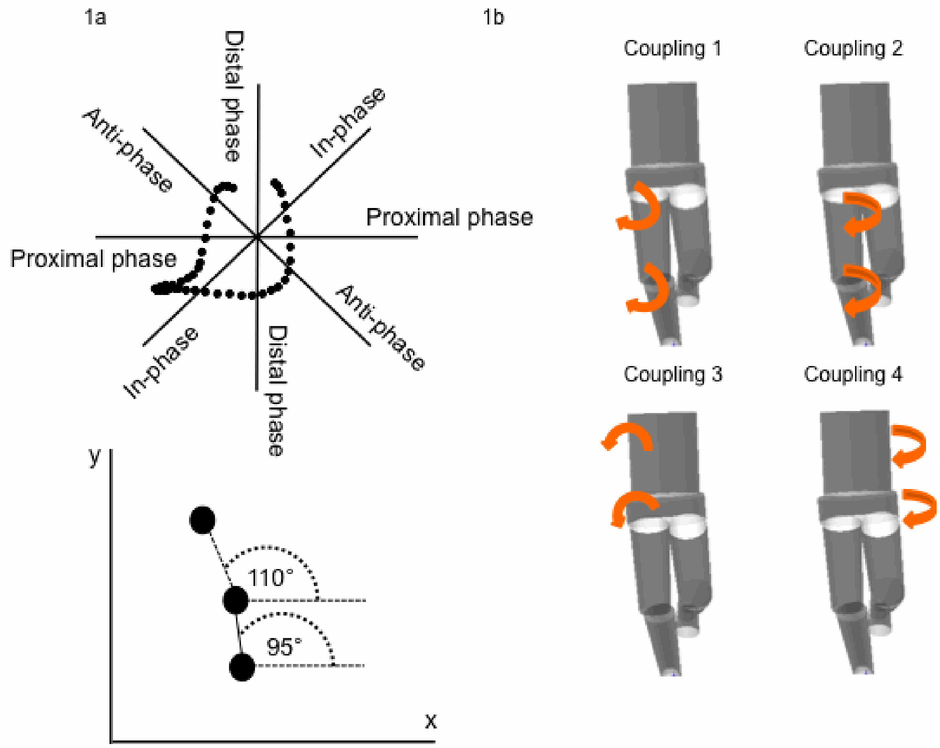


FIGURE 2. Coordination pattern between the hip and knee in the transverse plane during stance phase of hopping and walking; weak group (WG, n = 9) and strong group (SG, n = 10), each coordination pattern expressed as a % of total stance phase. * = significant difference between groups.

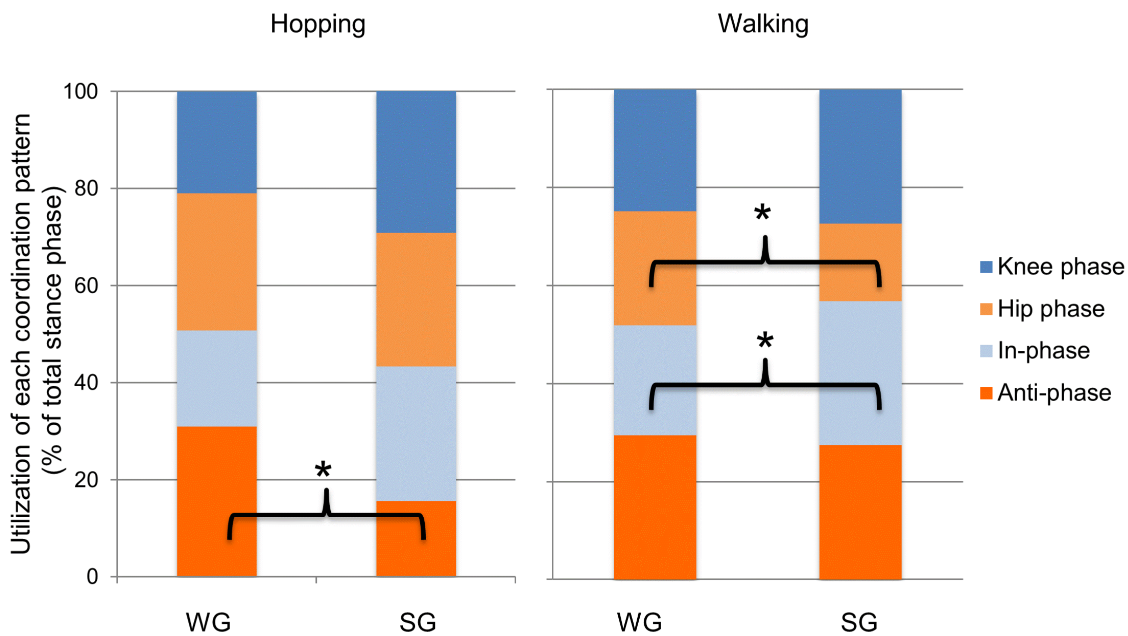
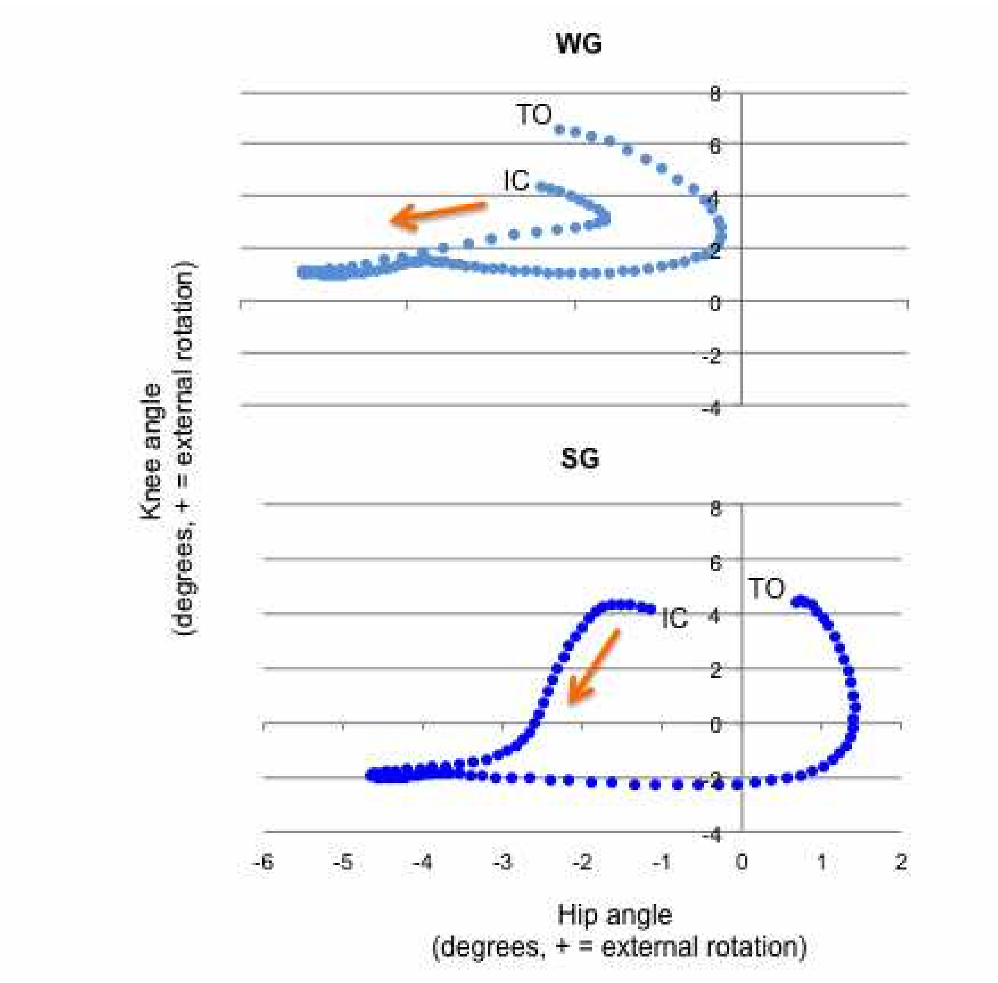


FIGURE 3: Angle-angle plots between the hip and knee in the transverse plane during hopping; weak group (WG, n = 9) and strong group (SG, n = 10). IC = initial contact, TO = toe-off, arrows indicate direction of motion.



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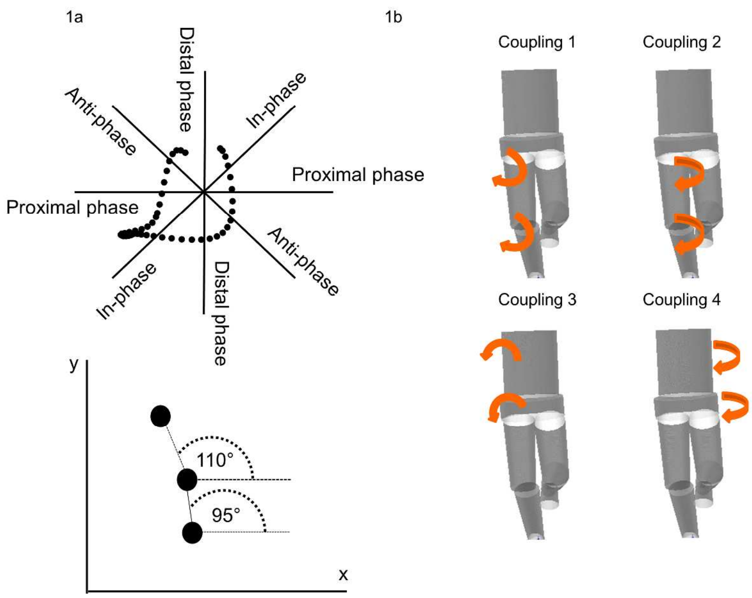

FIGURE 1(a). Exemplar angle-angle plot and detail from plot demonstrating calculation of coupling angle and categorization of coupling angles for a single coupling pair into coordination patterns using 45° bin widths. In-phase coordination, coupling angles between 22.5 – 67.5° and 202.5 – 247.5°; anti-phase coordination, coupling angles 112.5 – 157.5° and 292.5 – 337.5°; proximal phase coordination, coupling angles 157.5 – 202.5° and 337.5 – 360°; distal phase coordination, coupling angles 67.5 – 112.5° and 247.5 to 292.5°. FIGURE 1(b). Coupling joint/segment pairs in the frontal (1 & 3) and transverse (2 & 4) planes. Direction of arrows indicates direction of motion with positive values.
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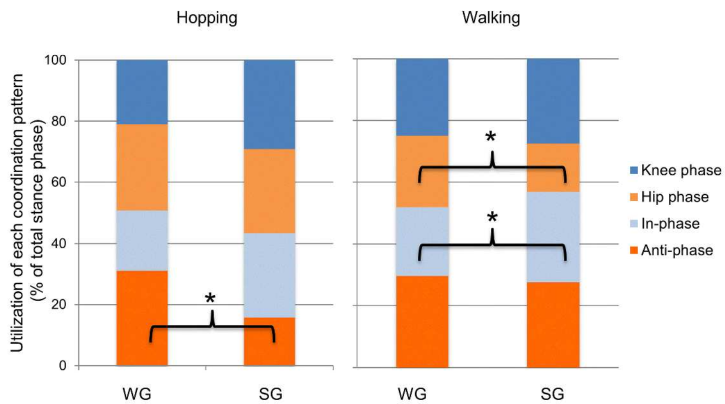

FIGURE 2. Coordination pattern between the hip and knee in the transverse plane during stance phase of hopping and walking; weak group (WG, n = 9) and strong group (SG, n = 10), each coordination pattern expressed as a % of total stance phase. * = significant difference between groups.
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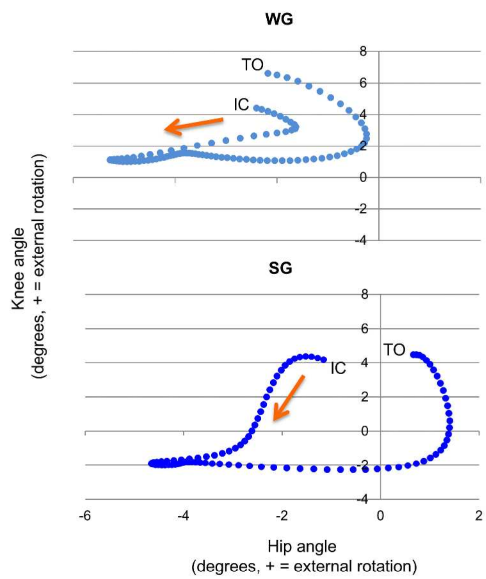

FIGURE 3: Angle-angle plots between the hip and knee in the transverse plane during hopping; weak group (WG, n = 9) and strong group (SG, n = 10). IC = initial contact, TO = toe-off, arrows indicate direction of motion.
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