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Gender differences in walking and running on level and inclined surfaces

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Abstract

Background. Gender differences in kinematics during running have been speculated to be a contributing factor to the lower extremity injury rate disparity between men and women. Specifically, increased non-sagittal motion of the pelvis and hip has been implicated; however it is not known if this difference exists under a variety of locomotion conditions. The purpose of this study was to characterize gender differences in gait kinematics and muscle activities as a function of speed and surface incline and to determine if lower extremity anthropometrics contribute to these differences.

Methods. Whole body kinematics of 34 healthy volunteers were recorded along with electromyography of muscles on the right lower limb while each subject walked at 1.2, 1.5, and 1.8 m/s and ran at 1.8, 2.7, and 3.6 m/s with surface inclinations of 0%, 10%, and 15% grade. Joint angles and muscle activities were compared between genders across each speed–incline condition. Pelvis and lower extremity segment lengths were also measured and compared.

Findings. Females displayed greater peak hip internal rotation and adduction, as well as gluteus maximus activity for all conditions. Significant interactions (speed-gender, incline-gender) were present for the gluteus medius and vastus lateralis. Hip adduction during walking was moderately correlated to the ratio of bi-trochanteric width to leg length.

Interpretation. Our findings indicate females display greater non-sagittal motion. Future studies are needed to better define the relationship of these differences to injury risk.

Keywords: Gender differences; Walking and running mechanics; Kinematics; Hip muscles; EMG; Anthropometry

1. Introduction

When compared to males, females are almost twice as likely to sustain a running injury, such as patellofemoral pain syndrome, iliotibial band syndrome or gluteus medius injury (Geraci and Brown, 2005; Taunton et al., 2002). While the reasons for the gender discrepancies in these injury rates (females: 62–76%; males: 24–32%) are not fully understood (Taunton et al., 2002), gender differences in lower extremity kinematics during running have been suggested as a contributing factor (Ferber et al., 2003; Schache et al., 2003).

During running, females demonstrate greater frontal and transverse plane motions than males. Specifically, females exhibit greater peak hip internal rotation and adduction (Ferber et al., 2003), as well as greater peak knee valgus or abduction (Ferber et al., 2003; Malinzak et al., 2001). This increased non-sagittal plane motion has been suggested to contribute to various running-related injuries, such as patellofemoral pain and iliotibial band syndrome, wherein females are predominantly affected (Fredericson et al., 2000; Leetun et al., 2004; Niemuth et al., 2005; Noehren et al., 2007).

Previous investigations have determined gender differences in hip motion also exist during walking (Hurd et al., 2004; Kerrigan et al., 1998), indicating this observation is not specific to the running gait. However, it is not known how these kinematic differences between genders

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will respond when gait speed is systematically manipulated in the same subject pool. It is possible that the gender differences in joint motion may remain consistent as gait speed is increased, or may progressively increase with speed due to increased mechanical demands (Belli et al., 2002; Chiu and Wang, 2007; Whittington et al., 2007). Similarly, increased surface inclination will create a greater challenge (Roberts and Belliveau, 2005) which may emphasize the gender differences in motion; however, the effect of surface inclination has not yet been determined.

Given the identified gender differences in joint kinematics, it is likely that gender differences in underlying muscle activities are also present. For example, during specific tasks such as a side-step maneuver or a stop jump, females have been reported to display increased quadriceps activity (Chappell et al., 2007; Sigward and Powers, 2006) with reduced activity in the gluteus maximus (Zazulak et al., 2005) compared to males. While gender differences in muscle activity have been identified during running (von Tscharner and Goepfert, 2003), it is unclear if they persist across running speeds and whether the differences in muscle activity are associated with the joint kinematic differences.

In addition to potential gender discrepancies in muscle activity during locomotion, gender-specific morphology of the pelvis and thigh may also contribute to the gender related differences found in motion. For example, the larger hip width to femoral length ratio observed in females has been suggested to increase hip adduction (Ferber et al., 2003). Despite this intuitive claim, the relationship between hip and pelvis anthropometrics and the gender differences in lower extremity motion has not been well defined (Krivickas, 1997; Schache et al., 2005).

The purpose of this study was to systematically evaluate gender differences in lower extremity gait kinematics as a function of speed and surface incline. Both walking and running speeds were evaluated to provide a comprehensive assessment. Muscle activity patterns were also evaluated during each movement condition to provide insight regarding the neuromuscular coordination strategies related to the kinematics. Finally, we investigated the relationship between hip and pelvis anthropometrics and joint kinematics to assess whether skeletal structure may explain potential gender differences in movement.

2. Methods

2.1. Subject

Thirty four healthy volunteers familiar with treadmill running agreed to participate in this study (Table 1). All subjects were either experienced runners or regularly participated in aerobic conditioning. Subjects were excluded if they reported prior surgery to lower extremity or back, and/or had current pain during normal walking and/or running. The testing protocol was approved by the Institutional Review Board at the University of Wisconsin-Madison and subjects provided informed consent in accordance with institutional policies.

Table 1
Subject characteristics and anthropometric measures (mean (SD))

	Males	Females
n	17	17
Age	22.0 (4.8)	24.9 (4.8)
Height (cm)*	182.3 (8.0)	165.9 (8.5)
Mass (kg)*	79.8 (13.0)	60.1 (5.9)
BMI	24.0 (3.1)	21.9 (2.8)
Leg length (cm)*	88.5 (5.1)	80.0 (4.6)
Femur length (cm)*	44.6 (2.7)	40.6 (2.1)
Bi-trochanteric width (cm)	31.0 2.1)	30.3 (2.2)
normalized*	35.1 (2.1)	37.9 (3.1)
Bi-iliac width (cm)*	27.0 (2.0)	25.5 (1.6)
normalized	30.6 (2.3)	32.0 (2.6)
Hip joint center width (cm)*	19.4 (1.4)	18.1 (1.6)
normalized	21.9 (1.6)	22.6 (2.3)

Normalized values were relative to leg length (%).
* Significant gender differences ($P < 0.05$).

2.2. Experimental protocol

Whole body kinematics were recorded using 40 reflective markers placed on each subject, with 21 located on anatomical landmarks. In addition, the subjects had electromyography (EMG) surface electrodes placed according to Basmajian and Blumenstein (1989) on the hip adductors, gluteus medius, gluteus maximus and vastus lateralis muscles of the right lower limb. After the markers and EMG electrodes were in place, each subject walked at 1.2, 1.5, and 1.8 m/s and ran at 1.8, 2.7, and 3.6 m/s with surface inclinations of 0%, 10%, and 15% grade. The order of speed–incline combinations was randomized for each subject, with approximately 10 s of data (a minimum of five strides) recorded for each condition. A quiet standing trial was performed to establish segment lengths, joint centers and joint coordinate systems, along with a circumduction movement of each subject's leg to estimate the location of their functional hip joint center (Piazza et al., 2004).

2.3. Anthropometrics

Pelvis and lower extremity anthropometrics were measured (cm) on all subjects using an anthropometer (Holtain Ltd., United Kingdom). The measures included: leg length (greater trochanter to the lateral malleolus of the fibula), femur length (greater trochanter to the knee joint space), and bi-trochanteric and bi-iliac width (Wall-Scheffler et al., 2006). The hip joint center width was determined using the right and left estimates of the functional hip joint centers from the circumduction trial.

2.4. Data acquisition

Three-dimensional kinematics were collected at 200 Hz using an 8-camera passive marker system (Motion Analysis Corporation, Santa Rosa, CA, USA). Kinematic data were low pass filtered using a bidirectional, 4th order Butterworth filter with a cutoff frequency of 12 Hz. Foot contact and toe-off times were ascertained by identifying a contact-induced or push-off induced vertical acceleration and jerk of the heel and the 5th metatarsal markers that occurred at the time of foot strike and toe-off. This approach was validated with extensive pressure sensitive foot switch data on one subject.

EMG activities were recorded at 2000 Hz (synchronously with kinematics) using single differential, surface electrodes with an inter-electrode distance of 10 mm (DE-2.1, DelSys, Inc., Boston, MA, USA). Each electrode preamplified the signal and was interfaced to an amplifier unit (Bagnoli-16, DelSys, Boston, MA, USA; CMRR > 84 dB at 60 Hz; input impedance > 100 MΩ). The EMG signals were subsequently full-wave rectified and low pass filtered using a bidirectional, 6th order Butterworth filter with a cutoff frequency of 50 Hz. Integrated EMGs over the entire gait cycle and terminal swing–initial loading were calculated using the trapezoidal method. The terminal swing–initial loading was defined as the final 10% of the gait cycle (terminal swing) and the initial half of the subsequent stance phase, 20% for running and 30% for walking. EMG signals for each subject were normalized to the average of the respective muscle activity across the entire gait cycle of that subject's slowest walking speed on a level surface.

2.5. Musculoskeletal model

The body was modeled as a 14-segment, 31 degree of freedom (DOF) articulated linkage. Anthropometric properties of the segments were scaled to each individual using the subject's height, mass, and segment lengths (de Leva, 1996). Each hip was modeled as a ball and socket joint with three DOF. The knee was represented as a one DOF joint, in which the tibiofemoral translations and non-sagittal rotations were constrained functions of the knee flexion–extension angle (Walker et al., 1988). The ankle–subtalar complex was represented by two revolute joints aligned with anatomical axes (Delp et al., 1990). For each trial, joint angles were computed at each time step using a global optimization routine to minimize the sum of squared error between the measured and model marker positions (Lu and O'Connor, 1999).

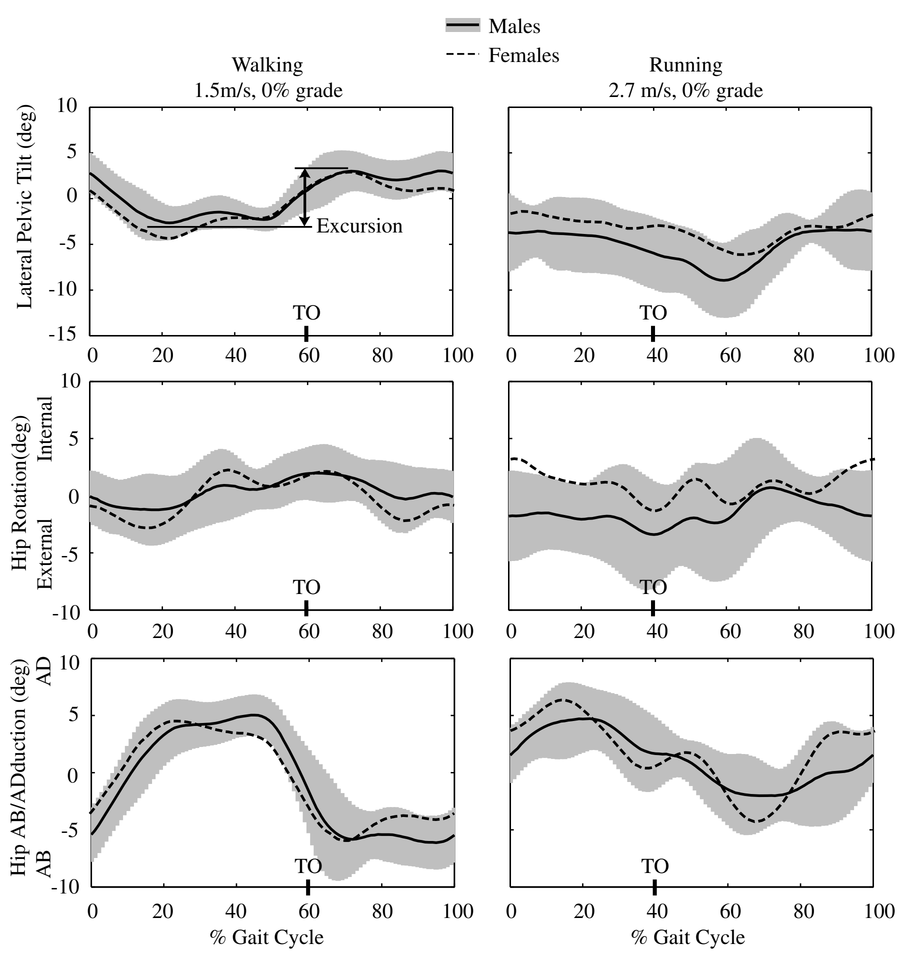

Fig. 1. Average lateral pelvic tilt, hip internal rotation, and hip adduction during walking (1.5 m/s) and running (2.7 m/s) for males and females on a level surface (shaded region is ±1 SD for males). Peak hip internal rotation and adduction, as well as hip adduction excursion, were greater in females than males during walking and running ($P < 0.05$). In addition, females displayed a significantly greater lateral pelvic tilt excursion than males during walking ($P < 0.05$). TO designates toe-off.

2.6. Outcome measures

Based on previously reported gender differences in running kinematics, we focused our analyses of gender differences to the hip and knee joints, as well as the pelvis. Specific variables that were calculated include the peak angles during stance phase for lateral pelvic tilt, hip flexion, hip adduction, hip internal rotation, and knee flexion; as well as the excursions (max. to min. difference) over the entire gait cycle for lateral pelvic tilt, hip adduction, and hip rotation. Similarly, the analysis of muscle activations was limited to the gluteus maximus and medius, vastus lateralis, and the hip adductors. For the anthropometric correlations, height, mass, and BMI were included (as gross measures of scale) along with the specific pelvis and leg measures. Pelvic breadth measures were expressed as absolute and relative to leg length.

2.7. Statistics

Kinematic and muscle activity variables were assessed for each dependent variable using a 3-factor (gender, speed and incline) ANOVA with repeated measures (speed and incline) (STATISTICA 6.0, StatSoft, Inc., Tulsa, OK, USA). Post-hoc analyses of significant interactions and main effects were further investigated using Tukey's HSD. Anthropometric measures were compared between males and females using an independent *t*-test. Spearman's rank order was used to determine the relationship between muscle activity and kinematic variables that showed a gender effect, as well as between the anthropometric measures and same kinematic variables. Significance for all analyses was established at $P < 0.05$.

3. Results

3.1. Joint kinematics

Females displayed significantly greater peak hip internal rotation ($P < 0.04$) and adduction ($P < 0.001$) during stance, as well as hip adduction excursion ($P < 0.02$), compared to males at all walking and running speeds and surface inclinations (Fig. 1 and Tables 2 and 3). Lateral pelvic tilt excursion was also greater in females during all speed–incline conditions for walking only ($P < 0.001$). Peak knee flexion during stance was ~5° greater in females compared

Table 2
Peak kinematic measures (deg) for males and females during walking and running at all speeds and inclines (mean (SD))

Speed (m/s)	Incline (% grade)					
	0		10		15	
	Male	Female	Male	Female	Male	Female
Peak lateral pelvic tilt						
Walk						
1.2	3.8 (2.2)	3.9 (2.1)	3.9 (2.2)	4.1 (1.7)	4.0 (2.3)	4.5 (2.2)
1.5	3.9 (2.0)	4.3 (2.0)	4.2 (2.0)	4.5 (2.0)	4.9 (2.2)	5.5 (2.2)
1.8	4.1 (2.1)	4.7 (2.3)	4.6 (2.0)	5.5 (2.0)	6.2 (2.3)	6.8 (2.0)
Run						
1.8	3.3 (2.0)	3.8 (2.4)	4.2 (1.8)	4.5 (2.3)	5.3 (2.0)	5.4 (2.7)
2.7	3.8 (2.0)	4.0 (2.4)	5.3 (1.9)	5.5 (2.4)	6.0 (1.9)	6.3 (2.7)
3.6	4.7 (2.1)	4.7 (2.5)	5.9 (2.1)	5.6 (2.5)	6.5 (2.4)	6.4 (2.5)
Peak hip internal rotation[a]						
Walk						
1.2	−0.9 (4.5)	3.1 (4.3)	−0.2 (4.3)	2.9 (4.2)	0.1 (4.0)	2.6 (4.1)
1.5	−0.1 (5.4)	3.4 (5.0)	−0.1 (4.5)	3.1 (4.3)	0.3 (3.7)	3.2 (4.6)
1.8	0.1 (4.9)	3.9 (5.4)	−0.4 (4.7)	3.5 (4.8)	0.7 (4.0)	3.5 (5.0)
Run						
1.8	1.4 (4.0)	4.5 (3.6)	1.8 (3.5)	4.7 (4.1)	2.4 (3.4)	5.0 (3.7)
2.7	1.6 (3.4)	5.2 (4.3)	2.2 (3.4)	5.5 (3.6)	1.9 (3.4)	4.6 (3.7)
3.6	2.4 (3.3)	6.2 (4.3)	2.5 (2.9)	5.3 (4.0)	1.7 (3.1)	4.1 (3.8)
Peak hip adduction[a]						
Walk						
1.2	6.2 (2.0)	7.7 (1.9)	5.2 (2.2)	7.2 (2.1)	5.1 (2.0)	7.3 (2.2)
1.5	6.1 (1.6)	8.0 (1.9)	5.2 (1.9)	7.6 (2.6)	4.9 (2.0)	8.0 (2.3)
1.8	6.1 (1.6)	8.5 (2.0)	5.3 (1.7)	8.5 (2.5)	5.9 (2.2)	9.1 (2.3)
Run						
1.8	6.0 (2.5)	9.0 (2.2)	7.0 (1.8)	9.9 (3.3)	7.5 (1.8)	10.4 (3.0)
2.7	7.2 (2.3)	10.0 (3.0)	8.3 (2.2)	11.5 (2.9)	8.5 (2.2)	11.7 (2.9)
3.6	8.1 (2.2)	11.0 (3.0)	9.0 (2.3)	12.5 (3.1)	9.0 (2.6)	12.4 (3.3)

[a] Significant gender differences at all speeds and surface inclinations for walking and running ($P < 0.05$).

to males during all speed–incline conditions of walking only ($P < 0.01$), while peak hip flexion during stance was not different between genders (walking, $P = 0.62$; running, $P = 0.60$).

3.2. Muscle activity

Gluteus maximus activity across the stride cycle was significantly greater for females compared to males during walking ($P < 0.001$) and running ($P < 0.001$) at all speed–incline conditions (Fig. 2). This gender difference was also present specifically during terminal swing–initial loading for running ($P < 0.01$), while a significant gender by incline interaction was found during walking ($P < 0.03$). Post-hoc assessment of the interaction revealed males progressively increased gluteus maximus activity with surface incline during walking while females did so to a lesser extent (Fig. 2).

A significant speed by gender interaction was present for gluteus medius activity across the stride cycle ($P < 0.03$) and during terminal swing–initial loading ($P < 0.03$) of running, indicating females increased activity with speed to a greater extent than males (Fig. 3). Greater vastus lateralis activity during terminal swing–initial loading of running ($P < 0.02$) was also present in females compared to males at all speed–incline conditions; while a significant gender by incline interaction was found for vastus lateralis activity across the stride cycle of running ($P < 0.05$) (Fig. 4). Hip adductor activity was consistent between genders during all walk–run conditions.

3.3. Anthropometry

Absolute anthropometric measures for males were significantly greater than females ($P < 0.05$) (Table 1). Absolute bi-trochanteric width, while not significantly different between genders, was greater in females compared to males when normalized to leg length ($P < 0.01$).

3.4. Correlations

Gluteus maximus activity was significantly correlated ($r = 0.34$ to 0.57, $P < 0.05$) to hip adduction excursion during walking and running speeds at 0% and 10% inclines

Table 3
Excusion of the kinematic measures (deg) for males and females during walking and running at all speeds and inclines (mean (SD))

Speed (m/s)	Incline (% grade)					
	0		10		15	
	Male	Female	Male	Female	Male	Female
Lateral pelvic tilt excursion[*]						
Walk						
1.2	6.9 (2.4)	9.0 (2.1)	7.3 (2.4)	9.0 (2.5)	7.8 (2.6)	9.8 (2.0)
1.5	7.2 (1.7)	9.7 (1.9)	7.4 (2.3)	10.1 (2.3)	9.3 (2.5)	11.7 (2.0)
1.8	7.6 (1.9)	10.4 (1.9)	8.3 (2.4)	11.9 (1.9)	12.2 (3.2)	14.0 (2.0)
Run						
1.8	5.6 (2.0)	7.9 (3.5)	8.0 (2.0)	9.0 (4.2)	9.6 (2.7)	10.7 (4.2)
2.7	6.8 (2.3)	8.5 (4.3)	9.9 (2.7)	11.2 (4.5)	11.0 (2.9)	12.5 (4.3)
3.6	8.2 (2.7)	9.6 (4.3)	10.7 (3.1)	11.6 (4.7)	12.1 (3.5)	13.3 (4.6)
Hip rotation excursion						
Walk						
1.2	8.9 (2.9)	9.6 (2.1)	8.7 (2.3)	9.5 (2.5)	8.6 (1.8)	9.7 (2.7)
1.5	10.2 (2.8)	10.9 (3.1)	8.2 (1.6)	9.6 (2.3)	9.1 (3.0)	10.5 (2.0)
1.8	11.0 (3.9)	11.4 (3.5)	8.7 (3.1)	10.5 (2.7)	9.7 (4.4)	11.2 (2.6)
Run						
1.8	7.9 (2.8)	9.7 (3.9)	8.7 (2.6)	10.0 (3.7)	9.6 (2.9)	11.3 (3.4)
2.7	8.8 (2.9)	10.5 (4.2)	10.5 (3.7)	12.5 (5.0)	10.3 (3.3)	12.5 (4.2)
3.6	10.0 (3.1)	12.1 (5.4)	10.9 (3.4)	12.4 (4.3)	10.5 (3.6)	13.6 (4.8)
Hip adduction excursion[a]						
Walk						
1.2	11.6 (3.7)	14.1 (2.8)	9.6 (2.4)	12.9 (2.3)	10.0 (2.2)	13.5 (1.9)
1.5	12.0 (2.4)	15.2 (2.0)	10.2 (2.1)	14.0 (2.4)	10.6 (2.2)	15.2 (2.2)
1.8	12.8 (2.7)	16.0 (1.7)	10.8 (2.1)	15.5 (2.4)	13.0 (3.0)	16.9 (2.5)
Run						
1.8	7.8 (3.4)	10.8 (3.7)	10.4 (1.8)	12.3 (3.8)	12.2 (2.1)	14.4 (3.9)
2.7	9.4 (2.7)	11.9 (3.8)	13.0 (2.4)	15.3 (3.8)	14.2 (2.6)	16.8 (3.9)
3.6	10.9 (2.6)	13.7 (3.7)	14.4 (2.8)	16.8 (4.6)	15.2 (3.1)	18.0 (4.5)

[*] Significant gender differences at all speeds and surface inclinations for walking only ($P < 0.05$).
[a] Significant gender differences at all speeds and surface inclinations for walking and running ($P < 0.05$).

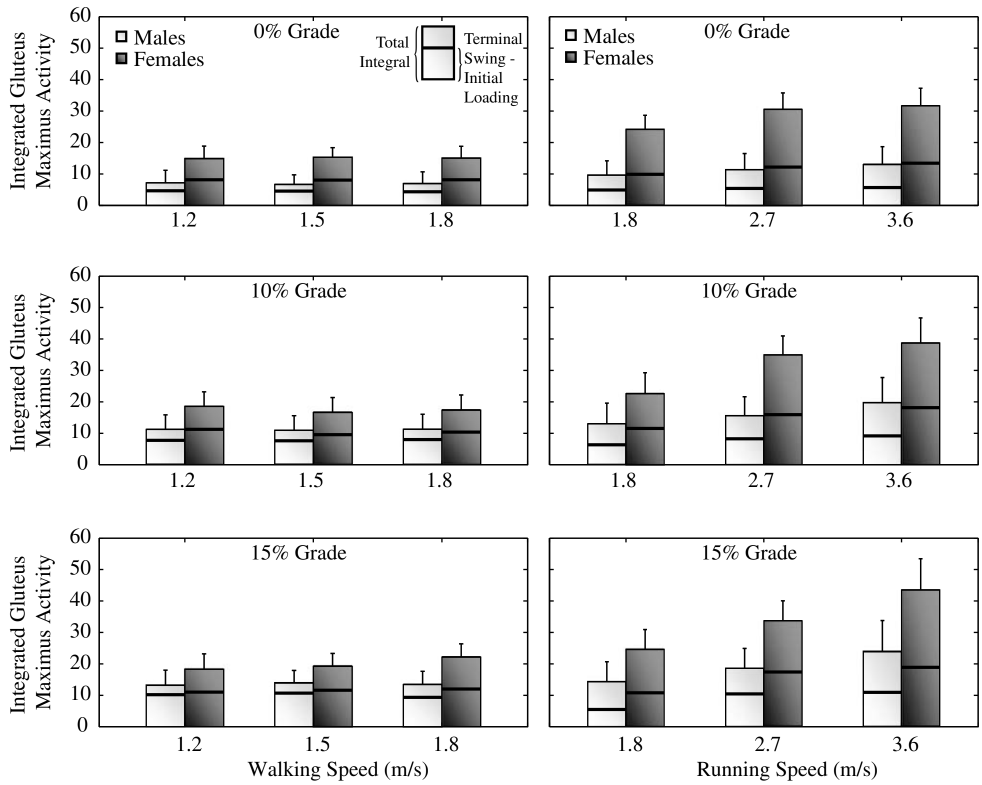

Fig. 2. Integrated gluteus maximus activity across the stride cycle was significantly greater for females compared to males during walking ($P < 0.001$) and running ($P < 0.001$) at all speeds and inclines. This gender difference was also present during the terminal swing–initial loading of running ($P < 0.01$), with a gender by incline interaction during the terminal swing–initial loading of walking ($P < 0.03$). The entire bar represents the integrated muscle activity across the stride cycle while that occurring during the terminal swing–initial loading is depicted as the portion below the horizontal line.

only. Gluteus medius activity was not significantly correlated with either peak hip adduction or total excursion.

Subject mass ($r = -0.41$ to -0.60; $P < 0.05$) and BMI ($r = -0.37$ to -0.61; $P < 0.05$) were negatively correlated to peak hip adduction during walking and running at all speeds and surface inclinations. Bi-trochanteric width normalized to leg length was correlated to hip adduction excursion during all walking speeds and inclines ($r = 0.37$ to 0.63; $P < 0.05$) In addition, femur length was negatively correlated to lateral pelvic tilt excursion during walking at 0% and 10% surface inclinations ($r = -0.35$ to -0.41; $P < 0.05$).

4. Discussion

Females displayed significantly greater non-sagittal hip and pelvis motion during walking and running across a range of speeds and inclines, whereas sagittal motion at the hip was consistent between genders. In addition, gluteus maximus activity was consistently greater in females during walking and running, while gluteus medius activity during the terminal swing–initial loading of running differed in response to speed between genders.

Our results are consistent with other studies that found gender differences in non-sagittal hip and pelvis kinematics in healthy populations for walking and running (Cho et al., 2004; Ferber et al., 2003; Hurd et al., 2004; Schache et al., 2003; Smith et al., 2002). While these studies focused on level surface walking and running, our findings indicate that the gender differences in joint kinematics extend across a range of gait speeds and surface inclinations. Since increases in speed and surface incline increase the mechanical demands at the hip (Belli et al., 2002; Roberts and Belliveau, 2005; Whittington et al., 2007), gender differences observed during level ground walking and running were anticipated to increase with speed and incline. While this was not observed for joint kinematics, several muscles activities did show this predicted response. Females displayed a greater increase in the gluteus medius and vastus lateralis activity than males as either speed (e.g. gluteus medius across stride and terminal swing–initial loading during running) or incline (e.g. vastus lateralis across stride during running) increased. Conversely, males showed a greater increase in gluteus maximus activity with increasing surface inclination during the terminal swing–initial loading of walking. The gender-specific response of these muscles to changes in speed and incline supports the concept that as task challenge increases, males and females utilize different neuromuscular strategies (von Tscharner and Goepfert, 2003).

Besides the gender-specific response of particular muscles to changing speed and incline, overall gender differences were also observed. Specifically, gluteus maximus activity in females was approximately twice that of males during all

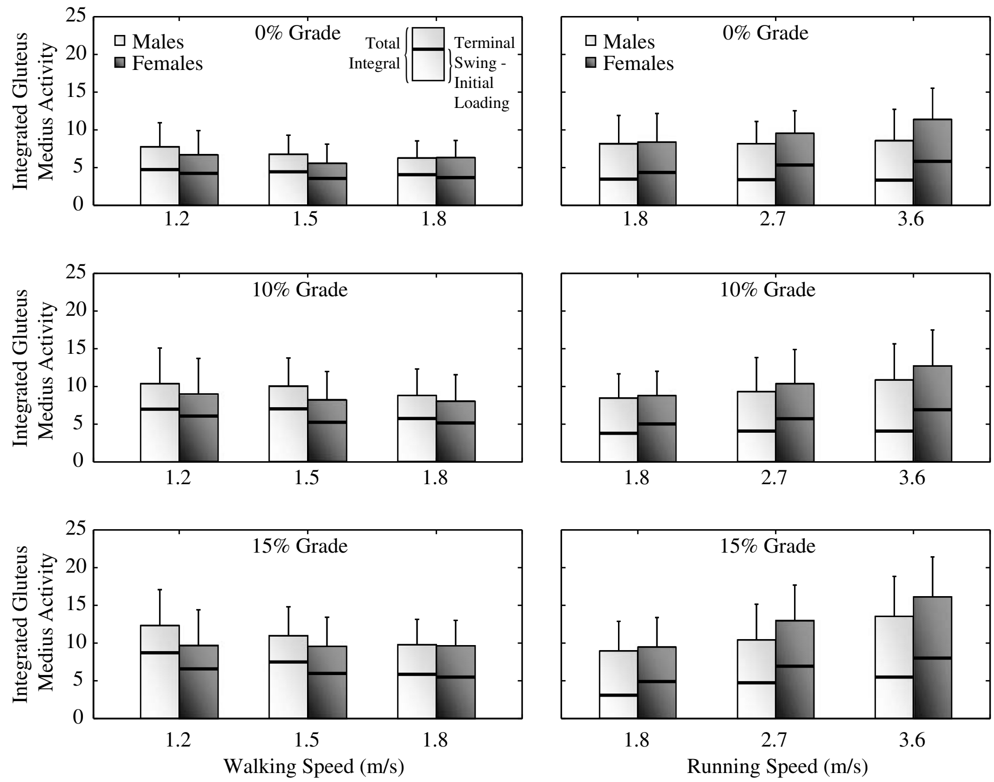

Fig. 3. Integrated gluteus medius activity across the stride cycle was similar between genders during walking ($P = 0.23$) and running ($P = 0.29$). However, a significant gender by speed interaction ($P < 0.03$) was present across the stride cycle ($P < 0.03$) and during the terminal swing–initial loading ($P < 0.03$) of running, as gluteus medius activity increased with running speed among females, while remaining invariant across speed in males. The entire bar represents the integrated activity across the stride cycle while that occurring during the terminal swing–initial loading is depicted as the portion below the horizontal line.

speed–incline conditions. This increased activity may be reflective of the greater peak hip internal rotation observed among females, although these two variables were not significantly correlated. Nonetheless, the increased utilization of the gluteus maximus supports the observed increase in hip extension moment and positive work in females during running compared to males (Ferber et al., 2003).

The similar gluteus medius activation between genders was somewhat unexpected considering the observed differences in pelvis lateral tilt excursion and hip adduction. Increased frontal plane hip motion combined with hip abductor weakness has been suggested as a possible factor in patellofemoral pain syndrome (Ireland et al., 2003; Robinson and Nee, 2007), iliotibial band syndrome (Fredericson et al., 2000; Noehren et al., 2007) and other common running-related injuries (Cichanowski et al., 2007; Leetun et al., 2004; Niemuth et al., 2005). Of interest, however, was the observed gender-specific response to increased running speed. While males maintained a fairly consistent level of gluteus medius activity across running speeds, females displayed a progressive increase in activity with speed.

Muscle activity continued to increase even during the most challenging speed–incline condition (3.6 m/s at 15%) suggesting that neither males nor females had reached their muscular limit. However, given the greater absolute levels of activation observed in females, they are likely working at greater percentage of maximum and possibly more susceptible to fatigue effects. Prior studies involving fatigue have demonstrated kinematic adjustments following an exhaustive run (Derrick et al., 2002; Miller et al., 2007), as well as an increased risk for running-related injury (Bradley et al., 2002; Gabbett, 2004). Additional work is needed to determine if females are more susceptible to these fatigue induced changes.

While most anthropometric variables were not associated with the joint motions, BMI and normalized bi-trochanteric width showed a significant linear relation to hip adduction. Increased BMI was associated with increased peak adduction during both walking and running, while increased bi-trochanteric to leg length ratio was associated with increased hip adduction excursion during walking only. Similar to other investigations, the relationship between pelvic anthropometrics and hip adduction did not extend to running (Heiderscheit et al., 2000; Schache et al., 2005). Thus, the value of anthropometrics in assessing risk of running-related injury remains questionable (Ilahi and Kohl, 1998; Schache et al., 2005).

In addition to non-sagittal gender differences in motion at the hip, we observed greater peak knee flexion during the stance phase of walking in females. Despite a similar peak knee flexion angle during running between genders, females had greater vastus lateralis activity during the

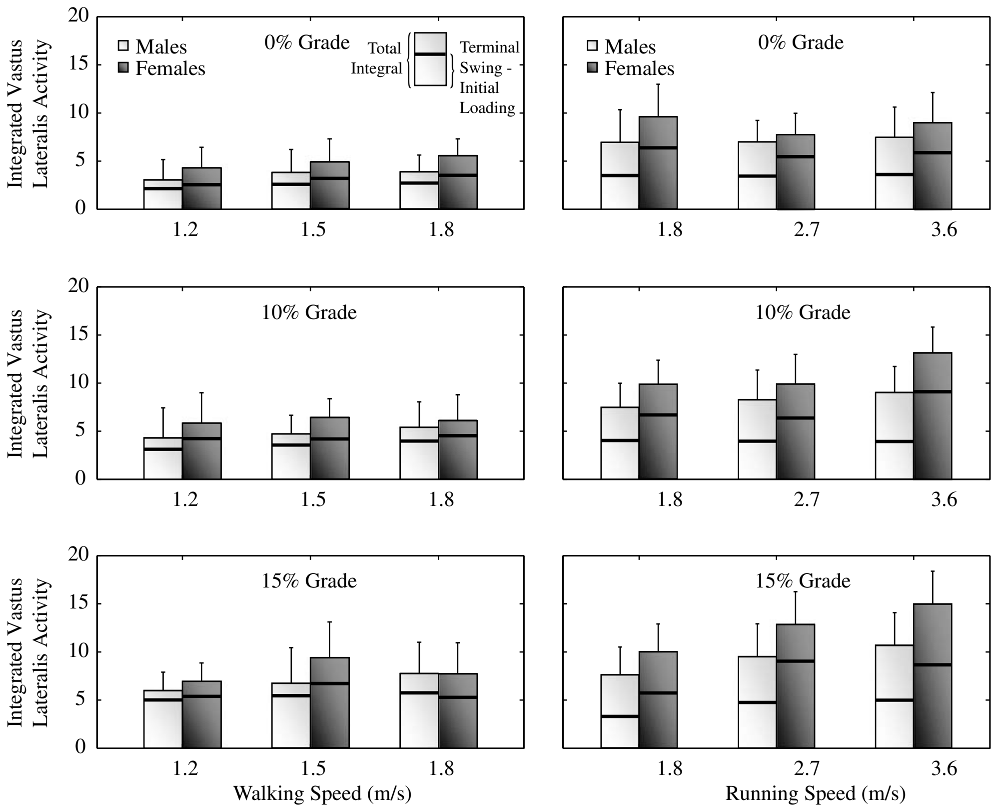

Fig. 4. Integrated vastus lateralis activity across the running stride cycle showed a significant gender by incline interaction ($P < 0.05$) with females having a larger increase in activity as incline increased. During the terminal swing–initial loading of running, females had significantly greater activity than males ($P < 0.02$) at all speed–incline condition. No gender effects were observed during walking ($P = 0.31$). The entire bar represents the integrated activity across the stride cycle while that occurring during the terminal swing–initial loading is depicted as the portion below the horizontal line.

terminal swing–initial loading. While there are discrepancies in the literature regarding sagittal plane motion at the knee between genders (Ferber et al., 2003; Kerrigan et al., 1998; Malinzak et al., 2001), greater quadriceps activity among females has been reported for specific tasks (Chappell et al., 2007; Sigward and Powers, 2006). It is possible that an increase in vastus lateralis activity observed in our study, could be due to a decrease in knee flexor moment, similar to that observed in females during a side-step maneuver (Sigward and Powers, 2006), however we did not estimate joint moments. It is also quite possible that the greater vastus lateralis activity observed in our study is a consequence that females require increased muscle activity to sustain their motion at the same speed/incline as males.

Although others have observed greater non-sagittal knee motion in females compared to males (Ferber et al., 2003; Malinzak et al., 2001), we modeled the knee as a one degree of freedom joint with the non-sagittal motions computed as a function of the flexion–extension angle; thus limiting our ability to assess potential gender differences at the knee. Subjects were also asked to walk and run at fixed speeds rather than self-select preferred speeds. Since males typically have a faster maximum walking and running speed (Cheuvront et al., 2005), females were likely performing at a greater percentage of their maximum effort during each speed–incline condition. However, post-hoc analyses indicated that these gender differences persisted when pairwise comparisons were performed between speeds representative of similar relative effort (e.g. females at slower walking–running speeds compared to males at faster walking–running speeds).

While our findings clearly indicate females display greater non-sagittal motion at the hip with an accompanied increase in hip muscle activity, the relationship between these gender differences and injury risk is uncertain. As all of our subjects were without recent injury, it is possible that these are simply intrinsic gender differences and are unrelated to future injury risk. However, a recent prospective study has found that increased hip adduction motion was predictive of future running-related injury in female runners (Noehren et al., 2007). Thus, it would seem that the gender differences observed in the current study may at least partially contribute to the increased incidence of running-related injuries in females.

In summary, we observed clear gender differences in hip kinematics and muscle activity across a variety of walking and running speeds and surface inclinations. Females displayed greater peak hip internal rotation and adduction, as well as gluteus maximus activity for all walk and run conditions. In addition, a progressive increase in gluteus medius activity with running speed was observed for females compared to males. While our findings indicate females display greater non-sagittal motion at the hip with an accompanied increase in hip muscle activity, the relationship between these gender differences and injury risk is uncertain.

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