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Muscle contributions to mediolateral and anteroposterior foot placement during walking

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ABSTRACT

Foot placement is critical to balance control during walking and is primarily controlled by muscle force generation. Although gluteus medius activity has been associated with mediolateral foot placement, how other muscles contribute to foot placement is not clear. Furthermore, although dynamic walking models have suggested that anteroposterior foot placement can be passively controlled, the extent to which muscles actively contribute to anteroposterior foot placement has not been determined. The objective of this study was to identify individual muscle contributions to mediolateral and anteroposterior foot placement during walking in healthy adults. Dynamic simulations of walking were developed for six older adults and a segmental power analysis was performed to determine the individual muscle contributions to the mediolateral and anteroposterior power delivered to the foot segment. The simulations revealed the ipsilateral swing limb gluteus medius, iliopsoas, rectus femoris and hamstrings and the contralateral stance limb gluteus medius and ankle plantarflexors were primary contributors to both mediolateral and anteroposterior foot placement. Muscle contributions to foot placement were found to be highly influenced by their contributions to pelvis power, which was dominated by those muscles crossing the hip joint. Thus, impaired balance control may be improved by focusing rehabilitation interventions on optimizing the coordination of those muscles crossing the hip joint and the ankle plantarflexors.

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1. Introduction

The ability to maintain dynamic balance during gait is essential for safely executing activities of daily living. The regulation of whole-body angular momentum is important for maintaining dynamic balance during walking (e.g., Herr and Popovic, 2008) and can be quantified by analyzing the time rate of change of angular momentum about the body's center-of-mass (CoM), which is equivalent to the net external moment (i.e., the cross-product between the moment arm and ground reaction force vectors). Thus, foot placement dictates the moment arm vector and plays a critical role in balance control.

Foot placement is commonly considered to be passively controlled in the anteroposterior direction (McGeer, 1990; O'Connor and Kuo, 2009) but largely regulated by active muscle control in the mediolateral direction (MacKinnon and Winter, 1993). Most studies of mediolateral foot placement during walking have focused

on gluteus medius activity in the swing (Rankin et al., 2014) and contralateral stance (Arvin et al., 2018; Kubinski et al., 2015) limbs. Greater swing phase gluteus medius activity is predictive of more lateral foot placement (Rankin et al., 2014). Gluteus medius activity during the contralateral stance phase provides feedforward control to the subsequent mediolateral foot placement of the swing limb (Arvin et al., 2018), with increased activity also associated with increased step width (Kubinski et al., 2015). However, the control of frontal plane whole-body angular momentum during walking has been shown to be regulated by several muscles (Neptune and McGowan, 2016). Gluteus medius acts to rotate the body towards the stance leg throughout stance while the vasti and ankle plantarflexors act to rotate the body towards the swing leg during early and late stance, respectively (Neptune and McGowan, 2016). In addition, due to dynamic coupling it is possible that contralateral stance leg muscles influence foot placement through contributions to pelvis motion. Thus, analyses considering the gluteus medius as the lone active controller of mediolateral balance and foot placement are likely too simplistic (Neptune and McGowan, 2016; Pandey et al., 2010). Further, the covariance of step width and step length in human walking and the small coupling between medio-

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lateral and anteroposterior foot placement predicted by passive dynamic walking models (Bauby and Kuo, 2000) suggests the active control of mediolateral foot placement likely influences anteroposterior foot placement. In addition, previous segmental power analyses have revealed that the gastrocnemius delivers energy to the leg to accelerate it forward during pre-swing and during late swing (Neptune et al., 2001), the iliopsoas accelerates the leg throughout swing (Neptune et al., 2009, 2004) and the biarticular hamstrings decelerate the leg during late swing (Neptune et al., 2004), which suggest other muscles likely play a significant role in anteroposterior foot placement.

Although analyses of individual muscle contributions to the biomechanical subtasks of walking such as body support (e.g., Anderson and Pandy, 2003; Higginson et al., 2006), forward propulsion (e.g., Liu et al., 2006; Neptune et al., 2004), and balance control (e.g., Neptune and McGowan, 2016; Pandy et al., 2010) have been performed, individual muscle contributions to foot placement remain largely unknown outside the role of the gluteus medius. Impaired foot placement control is associated with falls in older adults (Maki, 1997) and individuals with multiple sclerosis (Socie et al., 2013) and with greater fall risk in individuals post-stroke (Balasubramanian et al., 2009; Dean and Kautz, 2015). Understanding how individual muscles contribute to foot placement during walking would provide biomechanically based rationale for rehabilitation targets for those with impaired balance control. Thus, the objective of this study was to use modeling and simulation analyses to identify individual muscle contributions to mediolateral and anteroposterior foot placement during walking in healthy adults. We hypothesized that (1) mediolateral foot placement would be achieved by the contralateral stance limb gluteus medius and the ipsilateral swing limb adductors (medial placement) and by the ipsilateral swing limb gluteus medius and the contralateral stance limb vasti and plantarflexors (lateral placement), and (2), anteroposterior foot placement would be achieved by the ipsilateral swing limb iliopsoas and gastrocnemius (anterior placement) and by the ipsilateral swing limb hamstrings (posterior placement).

2. Methods

2.1. Experimental data

Kinematic, kinetic, and electromyography (EMG) data of 6 healthy adults (3 female; age: 53.5 ± 8.7 years, 79.8 ± 9.5 kg) were collected as they walked for 30 s at their self-selected speed (0.8 ± 0.3 m/s) on a split-belt instrumented treadmill (Bertec, Columbus, OH, USA). Prior to participation, each subject provided written informed consent in accordance with the Institutional Review Board of the Medical University of South Carolina. Before data collection started, participants practiced walking on the treadmill until they were comfortable with the experimental setup. Whole body kinematics were captured using 64 reflective markers by a 12-camera motion capture system (VICON, Denver, CO, USA) at 100 Hz while 3D ground reaction forces were recorded at 2000 Hz. Surface EMG electrodes (Motion Labs; Baton Rouge, Louisiana) were used to collect bilateral muscle activity at 1000 Hz from the tibialis anterior, soleus, gastrocnemius, vastus medialis, rectus femoris, lateral hamstrings, medial hamstrings, and gluteus medius. The EMG data were band-pass filtered between 20 and 500 Hz, rectified, and low-pass filtered at 50 Hz.

2.2. Musculoskeletal models & simulations

The most representative right leg gait cycle from each participant was identified using the functional median distance depth

method (Sangeux and Polak, 2015) and chosen for analysis. In OpenSim 3.3 (Delp et al., 2007), a 12 segment model with 23 degrees-of-freedom and 92 musculotendon actuators (Delp et al., 1990) was first scaled to the anthropometrics of each participant and then the model's generalized coordinates that reproduced the experimental marker data were determined using a least squares approach to minimize the distance between the experimental markers and corresponding virtual model markers (Delp et al., 2007). A residual reduction algorithm slightly adjusted model mass properties and joint kinematics to achieve more dynamically consistent kinematics and kinetics (Delp et al., 2007). Computed muscle control (CMC) was used to estimate the muscle excitations required to drive the model towards the experimentally measured kinematics (Thelen et al., 2003). The CMC excitations were constrained during swing phase using the collected EMG data. First, the EMG of each muscle from the representative gait cycle were normalized by the muscle's maximum value observed during the 30 s walking trial. Second, for each time point during the swing phase (toe-off to ipsilateral heel strike), the excitation range was set to 0.1 greater and 0.4 less than the normalized EMG (Fig. 1). The maximum muscle excitation could not exceed 1 and the minimum excitation could not fall below 0.02. The simulation results for swing phase were evaluated by visually comparing the muscle activations from CMC to the normalized EMG (Fig. 2).

2.3. Segmental power analysis

A segment power analysis was used to determine the individual muscle contributions to the mediolateral and anteroposterior power delivered to the foot segment (Neptune et al., 2001). To perform this analysis, the mechanical power each muscle generates, absorbs, or transfers to or from each segment was determined by combining the instantaneous state of the segment (i.e., current position and velocity) with the muscle-induced accelerations of the segment (Fregly and Zajac, 1996). Due to the linear transformation between segment power and acceleration (Fregly and Zajac, 1996), the segment power analysis provides a direct mapping of a muscle's contribution to a segment's motion. We defined foot placement relative to the pelvis (Balasubramanian et al., 2010), with each muscle's contribution quantified as the relative power delivered by muscle (m) to the calcaneus with respect to the pelvis during swing in the mediolateral and anteroposterior directions (i) as:

$$Power_{i,m}^{Calcaneus/Pelvis} = Power_{i,m}^{Calcaneus} - Power_{i,m}^{Pelvis} \quad (1)$$

Muscles with similar anatomical function were combined into nine muscle groups (Table 1) with the segmental power from muscles within each group being summed.

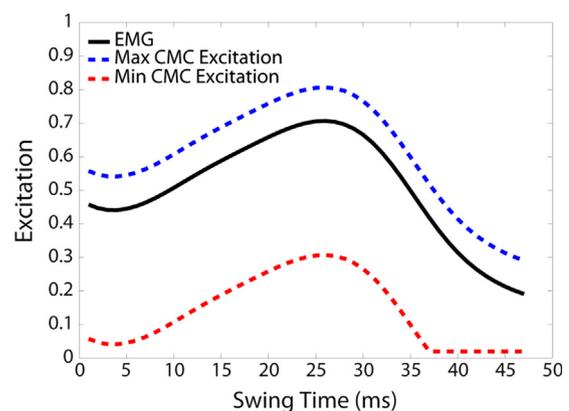


Fig. 1. Example excitation constraint used in CMC for the gluteus medius.

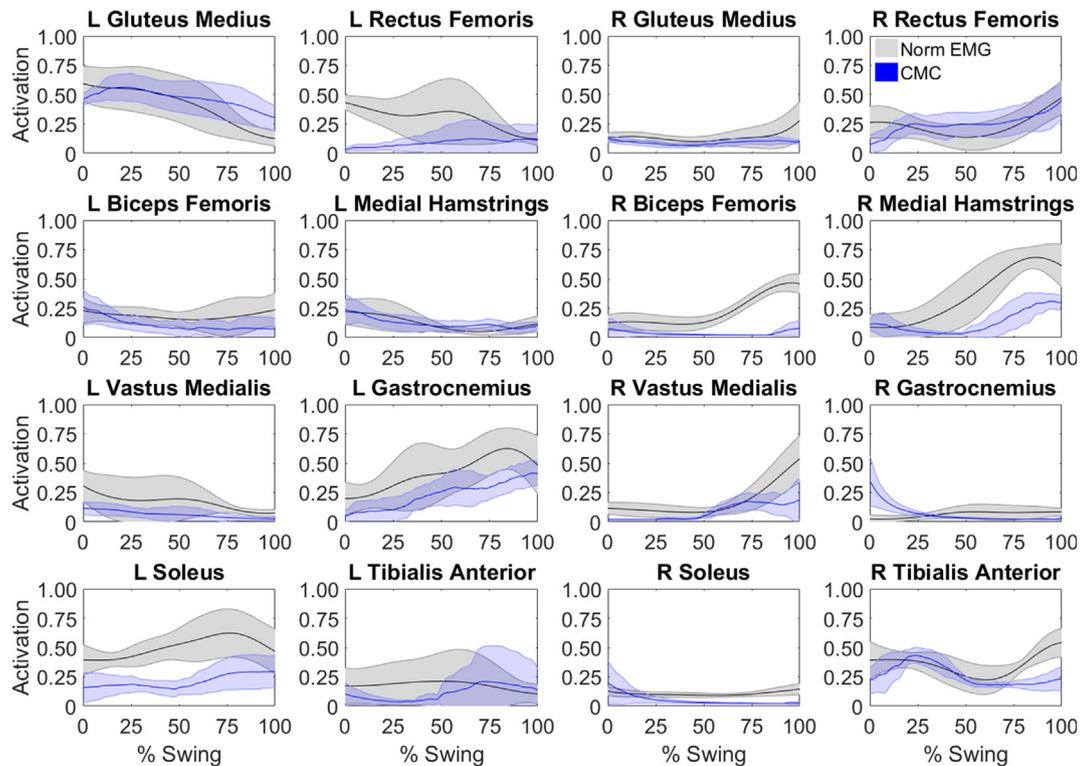


Fig. 2. Comparison of group averaged normalized EMG (Norm EMG) and CMC activations during swing phase for muscles on the left (L) and right (R) legs. The right leg is in swing and the left leg is in stance. Shaded regions represent ± 1 standard deviation.

Table 1

Muscle group definitions.

Muscle group	Muscles
Gluteus Maximus*	Superior, middle, and inferior gluteus maximus
Gluteus Medius*	Anterior, middle, and posterior gluteus medius
Gluteus Minimus*	Anterior, middle, and posterior gluteus minimus
Vasti	Vastus intermedius, vastus lateralis, vastus medialis,
Gastrocnemius†	Lateral gastrocnemius, medial gastrocnemius
Plantarflexors†	Lateral gastrocnemius, medial gastrocnemius, soleus
Adductors	Adductor brevis, adductor longus, adductor magnus
Bilateral Hamstrings	Biceps femoris longus, semimembranosus, semitendinosus
Iliopsoas	Iliacus, psoas

* Each gluteal muscle is defined by three lines of action in the model.

† The contributions of the biarticular gastrocnemius were investigated individually (Gastrocnemius group) and with the uniarticular soleus (Plantarflexors group).

Anteroposterior foot and pelvis velocities are directed anteriorly throughout swing (Fig. 3A), thus positive (negative) segmental power indicates a muscle accelerated the foot or pelvis anteriorly (posteriorly). However, the mediolateral foot velocity changes direction during swing in a manner that was inconsistent across subjects (Fig. 3B). To interpret the contribution of each muscle to mediolateral foot placement, mediolateral segmental power was defined as positive (negative) when the muscle accelerated the foot laterally (medially) with respect to the pelvis. The mediolateral and anteroposterior work performed by each muscle on the foot with respect to the pelvis was calculated by integrating the relative power over the swing phase. Mediolateral muscle work was normalized by body mass. Anteroposterior work was normalized by body mass and gait speed. Each muscle's work measures were then averaged across subjects.

3. Results

3.1. Mediolateral foot placement control

In support of our first hypothesis, the ipsilateral gluteus medius was, on average, a primary contributor to lateral foot placement and the contralateral gluteus medius and ipsilateral adductors were two of the primary contributors to medial foot placement (Fig. 4). The contralateral plantarflexors were one of the top contributors to lateral foot placement in just two of the six subjects, partially supporting our first hypothesis. However, on average, the ipsilateral erector spinae and internal obliques produced greater contributions to lateral foot placement than the contralateral plantarflexors. The ipsilateral piriformis and rectus femoris were also top contributors to lateral foot placement control while the ipsilateral iliopsoas, contralateral erector spinae and ipsilateral bilateral hamstrings were among the primary contributors to medial foot placement.

3.2. Anteroposterior foot placement control

In partial support of our second hypothesis, the ipsilateral iliopsoas and ipsilateral hamstrings were primary contributors to anterior and posterior foot placement, respectively (Fig. 5). However, contrary to our hypothesis, the ipsilateral gastrocnemius was not among the top contributors to anterior foot placement control. On the other hand, the ipsilateral plantarflexors (gastrocnemius and soleus) were a primary contributor to posterior foot placement. The ipsilateral rectus femoris, contralateral iliopsoas, contralateral plantarflexors and ipsilateral vasti were also top contributors to anterior foot placement. The contralateral and ipsilateral gluteus medius were also primary contributors to posterior foot placement, along with the contralateral gluteus maximus and hamstrings.

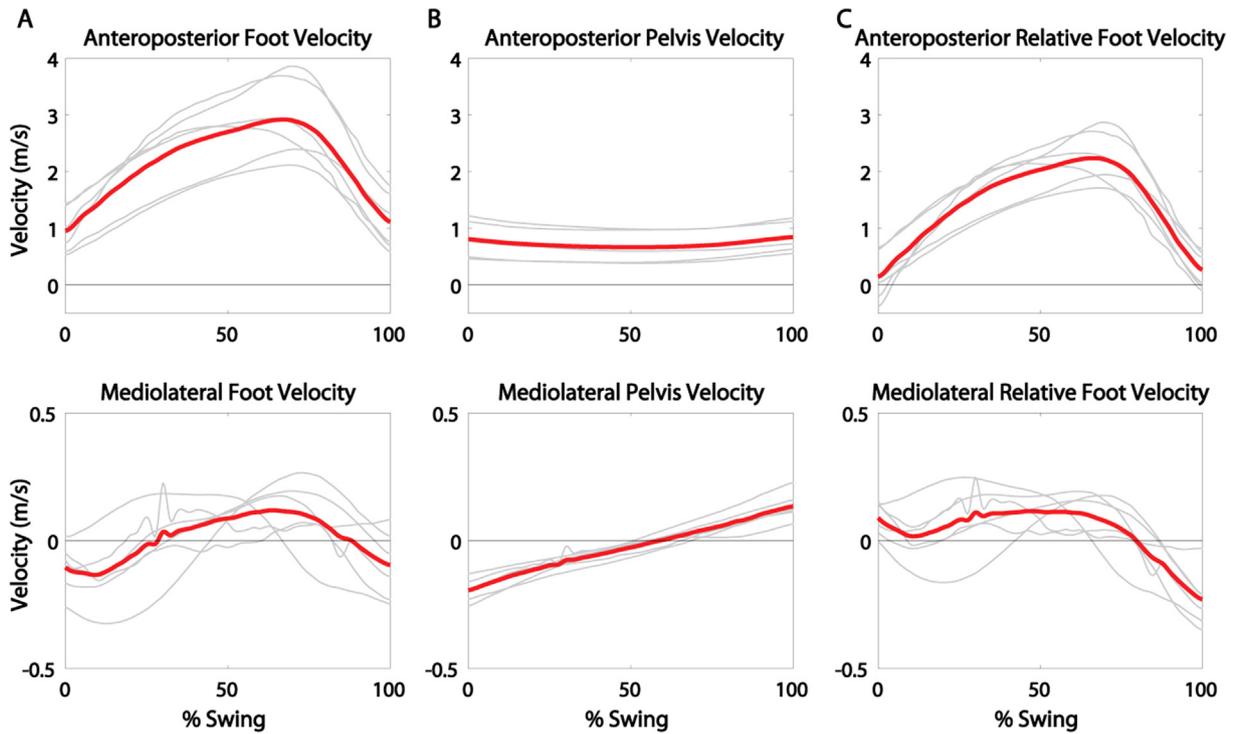


Fig. 3. Anteroposterior and mediolateral segmental velocity for (A) foot, (B) pelvis and (C) relative velocity of the foot with respect to the pelvis during swing. The gray lines represent the segmental velocities of individual subjects and the thick red line represents the group average. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

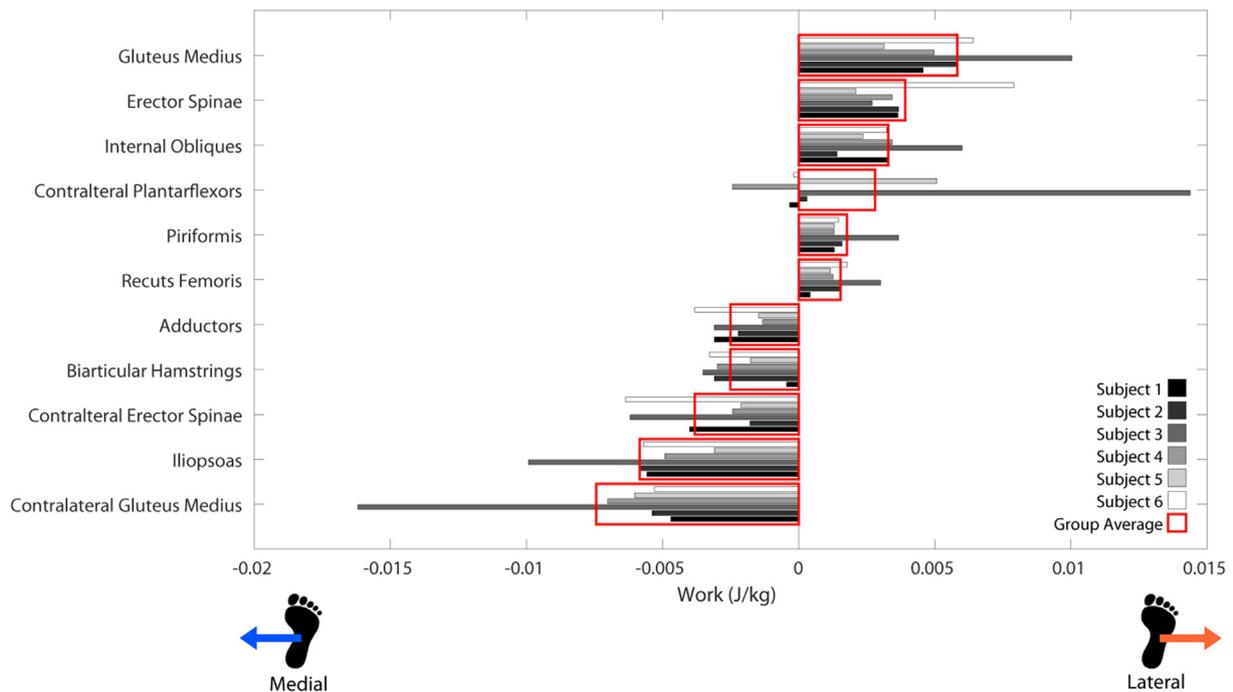


Fig. 4. Mediolateral work performed by individual muscles on the foot with respect to the pelvis of each subject (grayscale bars) and the group average (red outlined bars). Mediolateral work was normalized by body mass. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

The objective of this study was to identify the primary muscles that contribute to mediolateral and anteroposterior foot placement during walking in unimpaired individuals by analyzing the muscle

power delivered to the foot with respect to the pelvis. A muscle can influence the relative position of the foot with respect to the pelvis by delivering power to the pelvis, foot, or both segments. The majority of the muscles that contributed to mediolateral and anteroposterior foot placement generated power at both segments

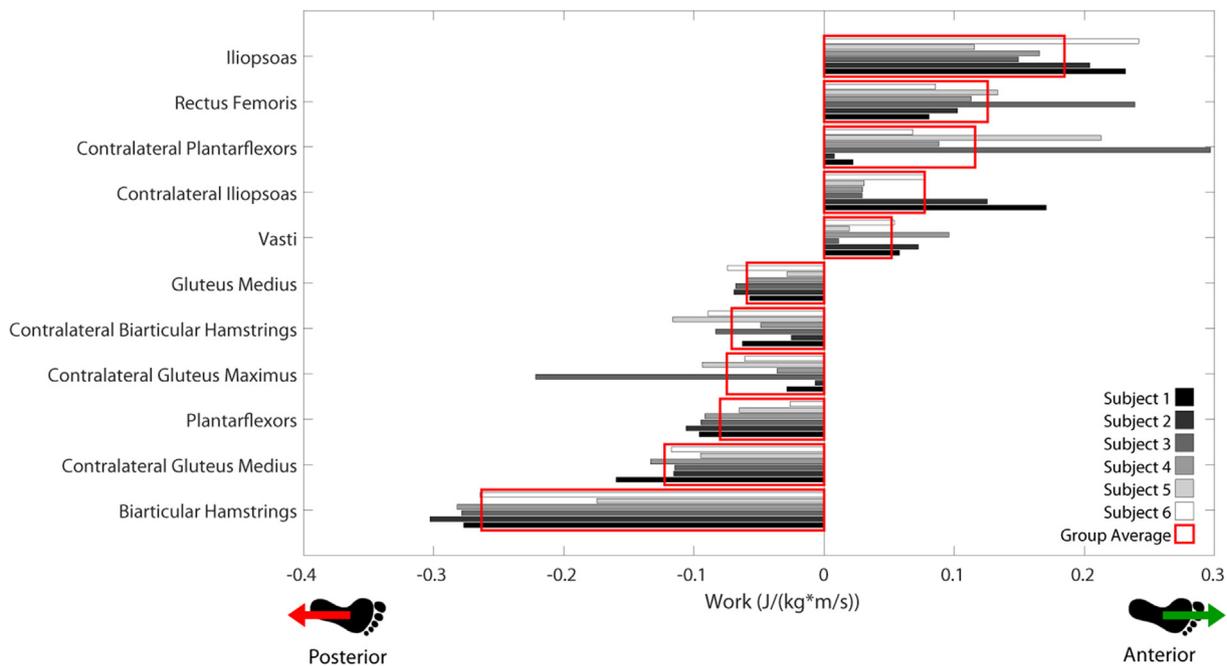


Fig. 5. Anteroposterior work performed by individual muscles on the foot with respect to the pelvis of each subject (grayscale bars) and the group average (red outlined bars). Anteroposterior work was normalized by body mass and walking speed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Fig. 6). A muscle's contribution to pelvis power tended to be greater than its contribution to foot power, which can be attributed to the greater mass of the pelvis (12.5 ± 1.5 kg) relative to the foot (1.3 ± 0.2 kg). However, the ipsilateral plantarflexors, biarticular hamstrings, rectus femoris and vasti generated greater anteroposterior power at the foot than the pelvis due to the large anteroposterior induced accelerations of the foot produced by these muscles (Fig. 7).

An important finding of this study was the large contribution of the contralateral (stance) leg muscles to foot placement. With the exception of the contralateral plantarflexors, the primary contribu-

tors to foot placement from the contralateral side cross the hip joint and attach to the pelvis. Thus, these muscles are capable of inducing large pelvis and hip joint accelerations to influence foot placement. In the mediolateral direction, the contralateral gluteus medius and erector spinae generated large lateral powers at the pelvis (Fig. 6A) and were primary contributors to swing leg hip adduction and abduction, respectively (Fig. 8A). The contralateral gluteus medius' contribution to medial foot placement resulted from its contribution to hip adduction, which resulted in medial foot power and lateral pelvis power. The contribution of the contralateral gluteus medius to lateral pelvis power is consistent with

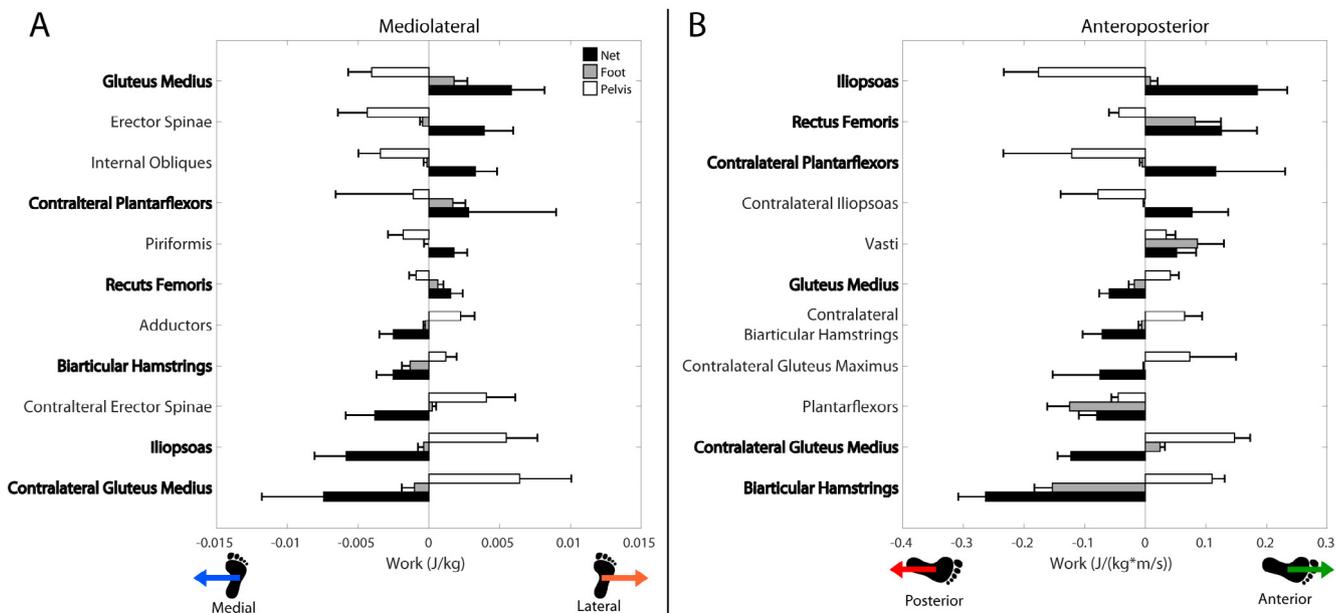


Fig. 6. Individual muscle contributions to (A) mediolateral and (B) anteroposterior work on the pelvis, foot and the relative work on the foot with respect to the pelvis (Net). Error bars represent one standard deviation. Bolded muscles were primary contributors to both mediolateral and anteroposterior foot placement.

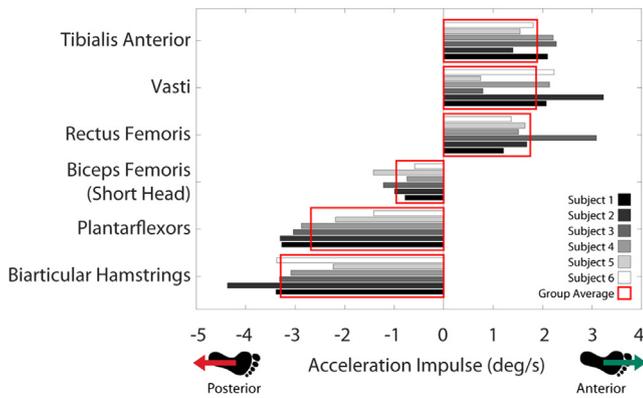


Fig. 7. Individual muscle contributions to anteroposterior foot acceleration quantified as the acceleration impulse over the swing phase for each subject (grayscale bars) and the group average (red outlined bars). The muscles shown produced the largest anterior and posterior foot acceleration impulses. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

its previously reported contribution to medial center of mass acceleration relative to the stance leg (i.e., lateral relative to the swing leg) (Pandy et al., 2010). In contrast, the contribution of the contralateral erector spinae to medial foot placement resulted from its larger contribution to lateral pelvis power than lateral foot power. In the anteroposterior direction, the contralateral plantarflexors and iliopsoas absorbed power from the pelvis while the contralateral gluteus medius, gluteus maximus and biarticular hamstrings delivered power to the pelvis (Fig. 6B). The contralateral gluteus medius, biarticular hamstrings, plantarflexors and gluteus maximus contributed to swing leg hip extension while the contralateral iliopsoas contributed to hip flexion (Fig. 8B). However, only the contralateral gluteus medius made a substantial contribution to foot power. The anteroposterior foot placement contribution of each of these contralateral muscles was in the opposite direction as its contribution to pelvis power.

Although the contralateral (stance leg) plantarflexors do not attach to the pelvis, they were primary contributors to both mediolateral and anteroposterior foot placement. The contralateral plantarflexors' contribution to lateral foot placement resulted from

its contribution to swing leg hip abduction, and thus lateral foot power and medial pelvis power. The contralateral plantarflexors' contribution to medial pelvis power is consistent with previous research demonstrating that the plantarflexors contribute to lateral center of mass acceleration, which would accelerate the pelvis medially relative to the swing leg (Pandy et al., 2010). The contralateral plantarflexors contributed to anterior foot placement by absorbing greater power from the pelvis than the foot.

Another important finding is that the control of mediolateral foot placement is not independent of the control of anteroposterior foot placement. Several muscles, including the bilateral gluteus medius muscles, the ipsilateral iliopsoas, rectus femoris and hamstrings, and the contralateral plantarflexors were primary contributors to both anteroposterior and mediolateral foot placement. In addition, our subject data showed a tendency for those who walked with a smaller anteroposterior foot placement to have a wider foot placement. However, given the small sample size in this study, additional research is needed to determine whether an association exists between foot placement in the anteroposterior and mediolateral directions. These results may further support the coupling between mediolateral and anteroposterior foot placement as shown by others (Bauby and Kuo, 2000). Moreover, the prominent contributions of the hip muscles and ankle plantarflexors to foot placement suggests that impairment of these muscle groups may compromise foot placement and balance control.

It is important to note some limitations of this study. Although we constrained CMC activations during swing to achieve activation timing consistent with experimental data, muscle activations were only constrained for muscles from which EMG was collected. Notably, adductor and iliopsoas EMG were not collected due to the difficulty of measuring reliable signals due to the higher amounts of adipose tissue in the regions of these muscles. However, the contributions of these muscles observed in this study are consistent with their reported functions in previous studies (e.g., Gottschall and Kram, 2005; Rankin et al., 2014), which provides confidence in our results. In addition, while our simulations tracked the EMG well for most muscles, differences in magnitude between CMC and EMG activations were observed for a few muscles (Fig. 2). This magnitude discrepancy can be attributed to the normalization of the EMG to the maximum activation in the walking trial. While a CMC activation of 1 represents a true maximal activation, since

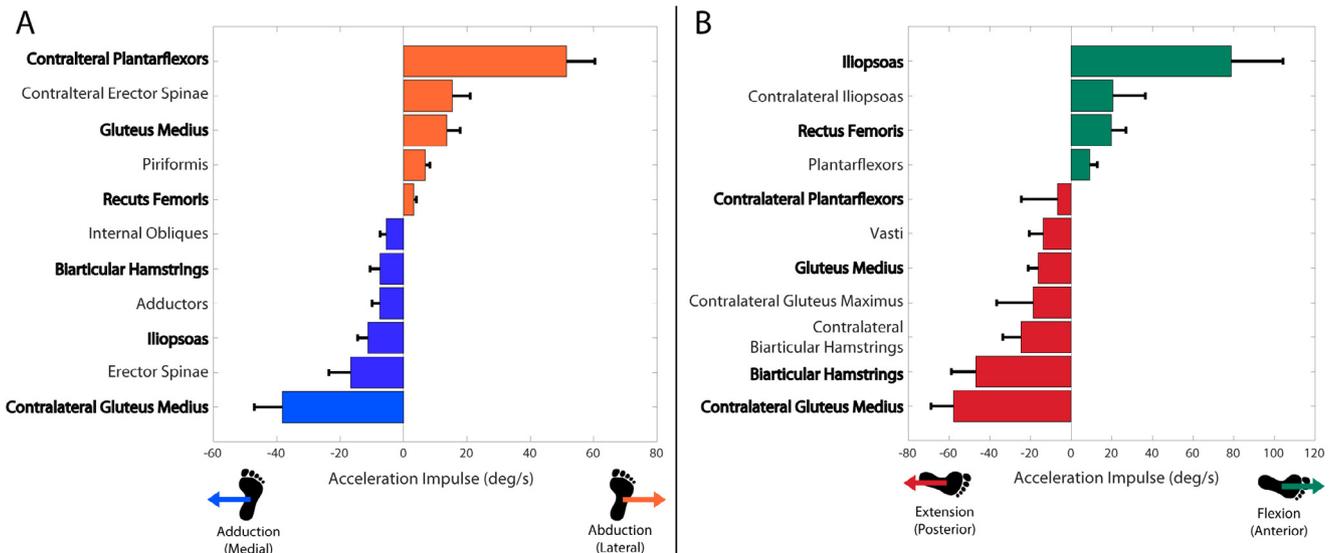


Fig. 8. Individual muscle contributions to hip (A) abduction and (B) flexion acceleration quantified as the acceleration impulse over the swing phase. Error bars represent one standard deviation. Bolded muscles were primary contributors to both mediolateral and anteroposterior foot placement.

walking is not generally considered a maximal effort task, an activation of 1 for the normalized EMG likely represents a submaximal activation level. Thus, EMG activation magnitudes may be artificially elevated. We accounted for this discrepancy by allowing the CMC excitations to vary within a larger range 0.4 below the EMG value and constraining the excitations to a smaller range 0.1 above the EMG value.

In summary, individual muscle contributions to the control of mediolateral and anteroposterior foot placement are highly influenced by their contributions to pelvis power and hip joint accelerations. Muscles that cross the hip joint attach to the pelvis and are therefore able to generate large pelvis accelerations that ultimately affect foot placement. Thus, it is not surprising that several hip muscles, along with the ankle plantarflexors, are the primary contributors to both mediolateral and anteroposterior foot placement. Furthermore, the critical role of the contralateral muscles in foot placement control suggests unilateral lower limb impairments, such as those present in individuals with post-stroke hemiparesis or a lower limb amputation, may contribute to asymmetrical foot placement and impaired balance control. Thus, balance control may be improved by focusing rehabilitation interventions on optimizing the bilateral coordination of those muscles crossing the hip joint and the ankle plantarflexors.

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Declaration of Competing Interest

None of the authors have a conflict of interest regarding the contents of this manuscript.

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