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Individual muscle contributions to circular turning mechanics

Jessica D. Ventura [a,*], Glenn K. Klute [b], Richard R. Neptune [c]

[a] Department of Kinesiology, Gordon College, Wenham, MA, USA
[b] Department of Veterans Affairs, Puget Sound Health Care System, Seattle, WA, USA
[c] Department of Mechanical Engineering, The University of Texas at Austin, Austin, TX, USA

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ABSTRACT

Turning is an activity of daily living that involves both the acceleration of the body center-of-mass (COM) towards the center of curvature and rotation of the pelvis towards the new heading. The purpose of this study was to understand which muscles contribute to turning using experimentation, musculoskeletal modeling and simulation. Ten healthy adults consented to walk around a 1-m radius circular path at their self-selected walking speed and then along a straight line at the same speed. Forward dynamics simulations of the individual subjects during the turning and straight-line walking tasks were generated to identify the contributions of individual muscle groups to the body mediolateral and anterior–posterior COM acceleration impulse and to the pelvis angular acceleration impulse. The stance leg gluteus medius and ankle plantarflexor muscles and the swing leg adductor muscles were the primary contributors to redirect the body's COM relative to straight-line walking. In some cases, contributions to mediolateral COM acceleration were modulated through changes in leg orientation rather than through changes in muscle force. While modulation of the muscle contributions generally occurred in both the inner and outer legs, greater changes were observed during inner single-leg support than during outer single-leg support. Total pelvis angular acceleration was minimal during the single-support phase, but the swing leg muscles contributed significantly to balancing the internal and external rotation of the pelvis. The understanding of which muscles contribute to turning the body during walking may help guide the development of more effective locomotor therapies for those with movement impairments.

1. Introduction

Walking not only requires the execution of biomechanical functions such as body support, forward propulsion and leg swing, but it also requires the ability to change direction and navigate obstacles by turning. Turning involves both the acceleration of the body center-of-mass (COM) towards the center of curvature and the rotation of the pelvis towards the new heading. To accelerate the COM in the direction of the turn, the medial ground reaction force (GRF) of the outer leg increases relative to straight-line walking and the inner leg GRF changes direction from a medial to lateral force during the entire stance phase (Orendurff et al., 2006). These changes in the mediolateral GRFs occur through modulation of intersegmental joint work, which for healthy adults involves increased sagittal plane ankle work of the outer leg and coronal hip work of the inner leg (Ventura et al., 2011). However, it is not clear which individual muscles are responsible for the observed changes in the GRFs.

Previous electromyographic (EMG) measurements have revealed that while turning following straight-line walking, healthy adults increase activity of the soleus (SOL) and decrease activity of the peroneus longus in the outer leg (Courtine and Schieppati, 2003b). Studies comparing steady-state turning with straight-line walking have found that young healthy adults decrease their self-selected walking speed when turning (Courtine et al., 2006; Duval et al., 2011; Chen et al., 2013), which would seemingly correspond with a decrease in muscle activity (Hof et al., 2002). However, Chen et al. (2013) and Courtine et al. (2006) measured an increase in EMG amplitude of the outer leg medial gastrocnemius (GAS) during turning relative to straight-line walking. Courtine et al. (2006) also measured an increase in outer leg gluteus medius (GMED) and tibialis anterior (TA) and inner leg lateral GAS amplitude. Duval et al. (2011) measured an increase in GMED amplitude of the inner leg during stance and of the outer leg during swing. However, these EMG studies could not reveal how these muscles contribute to the mechanics of the turning task.

Recent computer simulation studies of straight-line walking have found GMED to be the primary contributor to the body medial COM acceleration (Pandy et al., 2010; Allen and Neptune, 2012; John et al., 2012). When turning, a contribution to the medial COM acceleration from the inner (outer) leg translates to

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[*] Correspondence to: Department of Kinesiology, Gordon College, 255 Grapevine Road, Wenham, MA 01984, USA. Tel.: +1 978 867 4570; fax: +1 978 867 4585.
E-mail address: jessica.ventura@gordon.edu (J.D. Ventura).
URL: http://gordon.academia.edu/JessicaVentura (J.D. Ventura).

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an outward (inward) COM acceleration. Therefore, one would expect that activity of muscles of the inner leg that contribute to the medial GRF would decrease and those of the outer leg would increase. Thus, the finding of increased inner leg GMED activity during the stance phase of a turn (Duval et al., 2011) is surprising while the finding of increased outer leg GMED activity (Courtine et al., 2006) is expected. The simulations also identified SOL and GAS as primary contributors to lateral COM acceleration (Pandy et al., 2010; Allen and Neptune, 2012; John et al., 2012), which does not appear to support the increase in EMG activity of these outer leg muscles during turning (Courtine and Schieppati, 2003b; Courtine et al., 2006; Chen et al., 2013). It is important to note that the contribution of the plantarflexors to mediolateral COM acceleration may change as the leg rotates relative to the body COM, which differs between straight-line walking and turning (Courtine and Schieppati, 2003a; Taylor et al., 2005), and that turning strategies differ (i.e., Taylor et al., 2005). Therefore, muscle contributions to COM acceleration may change between walking along a straight path and various turning techniques. In addition, SOL accelerates the knee into extension during pre-swing (Fox and Delp, 2010; Pandy et al., 2010), which is an important biomechanical function executed during turning (Taylor et al., 2005; Orendurff et al., 2006). Computational modeling and simulation of a turning task is necessary to understand how the findings of EMG studies relate to COM acceleration during a turn, as the kinematic differences between straight-line walking and turning will likely affect muscle function.

Pelvis rotation into a turn is primarily accomplished by internal rotation of the hip joint and foot segment during inner leg stance and external rotation of the hip joint and foot segment during outer leg stance. Anterior GMED and iliopsoas (IL) contribute to internal hip rotation while posterior GMED, gluteus maximus (GMAX), and SOL contribute to external hip rotation in straight-line walking (Pandy et al., 2010). Increased contributions from these muscles during the appropriate region of the gait cycle would appear needed to facilitate pelvis rotation in the direction of the turn. The swing leg also plays an important role in the body's trajectory during walking (Winter, 1995). As the swing leg unloads and travels in the direction of the turn, the activity from muscles controlling leg swing, namely the hip flexors and abductors, may also contribute to pelvis rotation. The observed increase in outer leg GMED activity during swing (Duval et al., 2011) may be an indication of its increased contributions to pelvis rotation while turning.

The objective of this study was to understand how individual muscles function in synergy to perform the turning task relative to straight-line walking. Specifically, we generated forward dynamics simulations of 10 subjects walking along a circular path of a constant 1-m radius and straight-line walking and compared individual muscle contributions from both the stance and swing legs to the body COM mediolateral and anterior–posterior acceleration impulses and the pelvis angular acceleration impulse. Walking along a constant 1-m radius circle at steady-state was chosen because it represents a typical turn radius found in daily ambulation and minimized the confounding effects of acceleration and deceleration of transient turns (i.e., Courtine and Schieppati, 2003a; Taylor et al., 2005). Glaister et al. (2007) divided turns typical of daily walking into four phases (initiation, continuation, termination and adjustment). The task presented in this study would be classified as the continuation phase of a turn, and while the results may shed light on muscle function during other turns, they cannot be directly applied to the transient turning phases.

Based on previous studies (Courtine et al., 2006; Pandy et al., 2010; Ventura et al., 2011; Allen and Neptune, 2012), we expected the outer stance leg GMED to increase its contribution to mediolateral COM acceleration and pelvis rotation during the turn relative to straight-line walking. Based on the observed increase in SOL activity during outer leg stance (Courtine and Schieppati, 2003b) and its role in hip external rotation (Pandy et al., 2010), we expected the contributions of SOL would increase during outer leg stance and decrease during inner leg stance. We also expected there would be

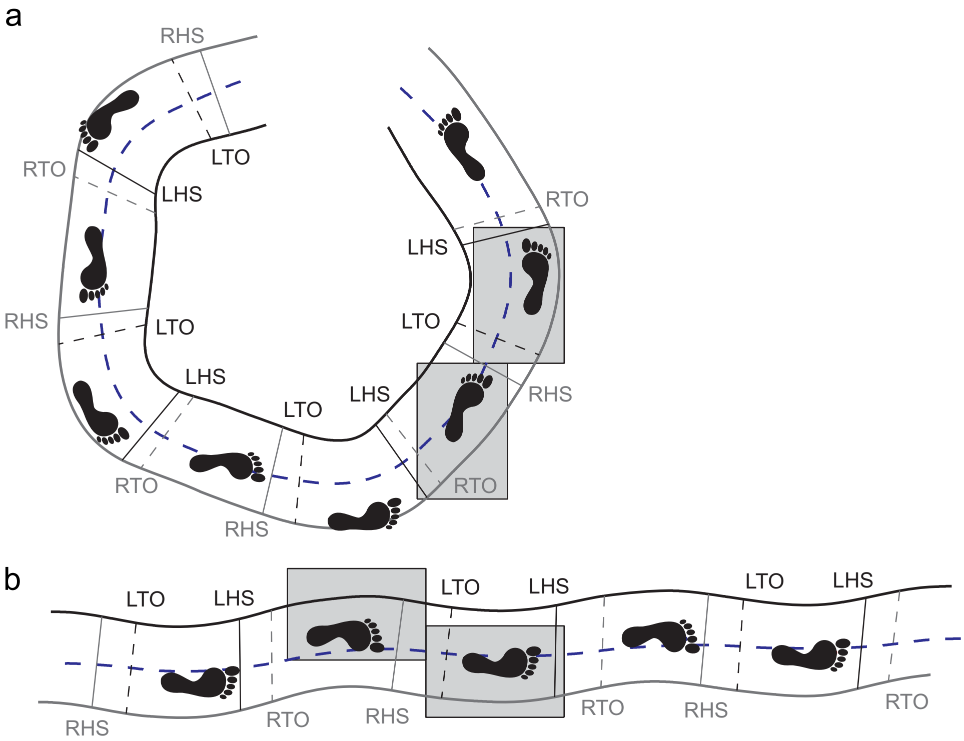

Fig. 1. Characteristic (a) turning and (b) straight-line walking paths, depicted by the force plates (shaded rectangles), COM path (dashed line), left (black) and right (grey) shoulder paths and foot positions. Left and right toe off (LTO and RTO, respectively) and left and right heel strike (LHS and RHS, respectively) events are shown by lines (dashed and solid, respectively) joining the shoulder positions.

Table 1
Muscle groups used in the musculoskeletal model. Muscles were modeled using a Hill-type muscle actuator (Zajac, 1989) and grouped with other muscles based on biomechanical function for data analysis. All but the Trunk muscle group were evaluated separately for the right and left legs.

Group	Muscles
Trunk	Erector spinae, external oblique, internal oblique
IL	Iliacus, psoas
GMED	Gluteus medius anterior, middle, and posterior
GMAX	Gluteus maximus superior, middle, and inferior
ADD	Adductor magnus superior, middle, and inferior, adductor longus
SAR	Sartorius
HAM	Semimembranosus, biceps femoris long head, biceps femoris short head
RF	Rectus femoris
VAS	Vastus intermedius, lateralis, and medialis
GAS	Gastrocnemius lateralis and medialis
SOL	Soleus
TP	Tibialis posterior, flexor digitorum longus
TA	Tibialis anterior, extensor digitorum longus

greater contributions from the swing leg hip muscles to pelvis angular acceleration during both inner leg (hip flexors and adductors) and outer leg (hip flexors and abductors) single support. Finally, because muscles that contribute to mediolateral COM acceleration and pelvis angular acceleration also contribute to anterior–posterior COM acceleration (Pandy et al., 2010; John et al., 2012), we expected there would be changes in muscle contributions to the anterior–posterior COM acceleration that mirrored changes in the other two directions. Understanding how individual muscles contribute to turning has important implications for designing effective locomotor therapies that target specific muscle groups for those with movement impairments.

2. Methods

Ten healthy adults (4 females, 6 males; age 44 ± 14 yr; height 1.73 ± 0.10 m; mass 78 ± 21 kg) participated in this study. All participants were free from walking impairments and provided written informed consent to a protocol approved by the governing Institutional Review Boards. The experimental protocol has been previously described in detail (Segal et al., 2009) and is briefly presented here.

2.1. *Experimental data collection*

Thirty-eight reflective markers were placed bilaterally on the arms, legs, trunk and head of the participants, consistent with Vicon's Plug-In-Gait model (Oxford Metrics, Oxford, England). Kinematic data were collected using a 10-camera Vicon 612 system at a minimum rate of 120 Hz. GRFs were collected at 1200 Hz from two consecutive Kistler force plates (Wintethur, CH) embedded in a level, circular walkway. Participants walked around a 1-m radius circular path at their self-selected walking speed (Fig. 1a). Participants began walking a few steps before the force plates in order to achieve a steady-state walking pattern. The participants repeated the trial until three force plate contacts were recorded in both the clockwise and counter-clockwise directions. Walking speed tangential to the path was determined using the velocity of the posterior superior iliac spine marker of the outer leg. Participants then walked along a straight path at the same walking speed until three force plate contacts were recorded (Fig. 1b).

The experimental data were processed using Visual3D (C-Motion, Germantown, MD). Kinematic and kinetic data were low-pass filtered using a 4th-order Butterworth filter with cut-off frequencies of 6 Hz and 20 Hz, respectively. Segment joint angles were determined from marker trajectories using standard inverse kinematic techniques.

2.2. *Musculoskeletal models and simulations*

Musculoskeletal models and forward dynamic simulations of each participant during the turning and straight-line walking tasks were developed using OpenSim 3.0 (Delp et al., 2007). The musculoskeletal model had 21 degrees-of-freedom and was scaled to match the anthropometric measurements of each subject obtained from the marker positions. The model was driven by 60 Hill-type muscle-tendon actuators (Table 1).

A computed muscle control algorithm solved for the muscle excitations to drive the dynamic musculoskeletal model to track the experimental kinematics. An induced acceleration analysis (Dorn et al., 2011; Lin et al., 2011) determined the contributions of individual muscle groups to the body mediolateral and anterior–posterior COM accelerations and to the pelvis angular acceleration. The average contribution of each muscle was multiplied by the time over which it acted (i.e., the acceleration impulse was calculated) to determine its contribution over the gait cycle. The muscle contributions to mediolateral and anterior–posterior COM acceleration impulse were expressed in the pelvis reference frame, with the medial direction pointing inward during outer leg stance and outward during inner leg stance. Because the simulation of an entire stance phase required three consecutive steps on the force plates (which was not possible with our experimental setup), only the muscle contributions of the left leg (arbitrarily chosen) during outer leg and inner leg single support were analyzed.

2.3. *Statistical analysis*

Data from the subject simulations were used to test our expectations. A within-subject one-factor (leg) with three levels (inner and outer leg during turning, left leg (arbitrarily chosen) during straight-line walking) repeated measures analysis of variance was used to identify differences in muscle contributions to the mediolateral COM acceleration impulse using SPSS Statistics 20 (IBM Corp., Armonk, NY). When significant differences were found, pairwise comparisons with a Bonferroni adjustment for multiple comparisons were used to determine which conditions were significantly different from each other. The analysis was repeated for muscle contributions to the anterior–posterior COM acceleration impulse and pelvis angular acceleration impulse. As the Bonferroni adjustment was made by multiplying the *p*-value by the number of comparisons, a familywise significance level of 0.05 was used for all statistical comparisons.

3. Results

3.1. *Mediolateral acceleration*

The primary contributor to the medial COM acceleration impulse was the stance leg GMED, with smaller contributions from the stance leg tibialis posterior (TP) and swing leg adductors (ADD, Fig. 2). The primary contributors to the lateral acceleration impulse were the stance leg IL, GAS, ADD and SOL and swing leg GMED. Contributions from stance leg GMED and swing leg ADD to the medial acceleration impulse were significantly lower for the inner support leg than for the straight and outer support legs (Table 2). Contributions from the stance leg GAS and SOL to the lateral acceleration impulse were significantly lower for the outer support leg than for the straight and inner support legs. Contributions from the stance leg GAS were significantly greater for the inner support leg than for the straight leg. Contributions from stance leg ADD to the lateral acceleration impulse were significantly lower for the inner support leg than for the straight and outer support legs. Contributions from swing leg GMED to the lateral acceleration impulse were significantly greater for the outer support leg than for the straight support leg and contributed to the medial acceleration impulse for the inner support leg.

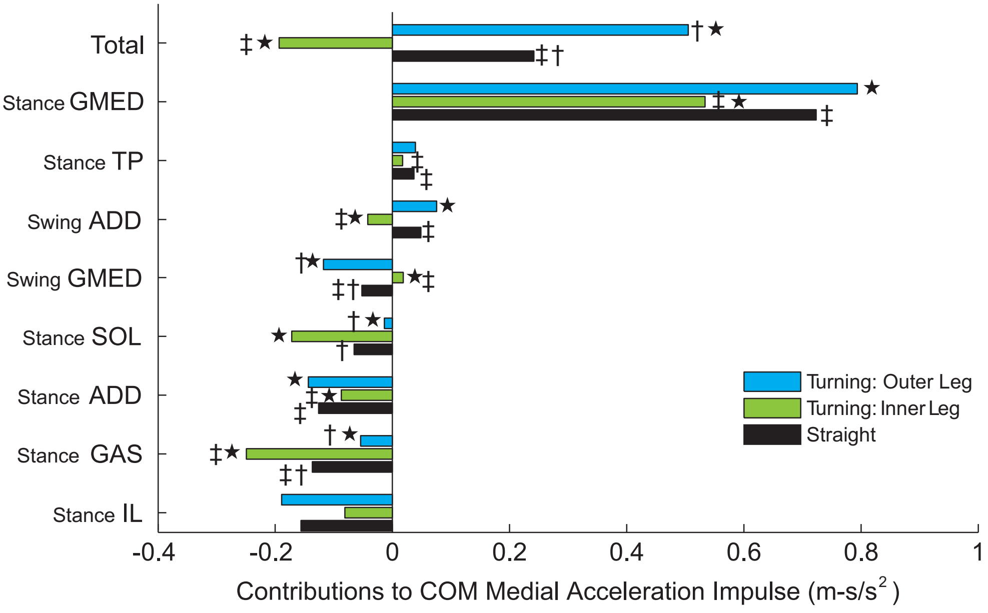

Fig. 2. The primary contributors to the body COM acceleration impulse in the mediolateral direction during single leg support of the outer leg and inner leg when turning and when walking along a straight path. Total is the sum of all muscles and gravity. Significant differences between the outer and inner leg conditions are denoted with ★; significant differences between the outer leg and straight conditions are denoted with †; and differences between the inner leg and straight conditions are denoted with ‡.

Table 2
Statistical analysis of the primary contributors to acceleration impulse of the COM (m-s/s^2) during single-leg support of the outer leg and inner leg while turning and during single-leg support while walking along a straight path.

Muscle	**Mean ± STD COM acceleration impulse (mm-s/s^2)**			***p*-Value**		
Medial	**Turning: outer leg**	**Turning: inner leg**	**Straight**	**Outer v inner**	**Outer v straight**	**Inner v straight**
Total	505 ± 25	−193 ± 29	242 ± 17	< 0.001	< 0.001	< 0.001
Stance leg GMED	794 ± 59	534 ± 51	724 ± 47	0.015	–	0.007
Stance leg TP	39 ± 6	17 ± 9	37 ± 7	–	–	0.048
Swing leg ADD	76 ± 8	−42 ± 21	49 ± 10	0.001	–	0.001
Swing leg GMED	−118 ± 20	19 ± 16	−52 ± 10	< 0.001	0.035	0.001
Stance leg SOL	−14 ± 20	−172 ± 42	−65 ± 20	0.03	0.004	–
Stance leg ADD	−143 ± 19	−87 ± 13	−126 ± 15	0.006	–	0.001
Stance leg GAS	−54 ± 13	−249 ± 32	−137 ± 25	< 0.000	0.001	0.001
Stance leg IL	−189 ± 36	−81 ± 90	−156 ± 67	–	–	–
Anterior						
Total	−41 ± 8	−43 ± 11	−31 ± 10	–	–	–
Stance leg HAM	176 ± 28	302 ± 42	242 ± 51	0.003	–	–
Stance leg IL	147 ± 34	138 ± 24	176 ± 35	–	–	–
Stance leg TA	79 ± 7	71 ± 8	74 ± 8	–	–	–
Gravity	36 ± 15	13 ± 16	36 ± 16	–	–	–
Swing leg GMED	−67 ± 17	−17 ± 10	−44 ± 14	–	–	–
Stance leg RF	−127 ± 17	−120 ± 9	−119 ± 7	–	–	–
Stance leg VAS	−181 ± 18	−227 ± 19	−212 ± 16	0.004	–	0.026
Stance leg SOL	−234 ± 16	−239 ± 15	−253 ± 17	–	–	–

3.2. *Anterior–posterior acceleration*

The primary contributors to the anterior COM acceleration impulse were the stance leg hamstrings (HAM), IL and TA and gravity (Fig. 3). The primary contributors to the posterior acceleration impulse were the stance leg SOL, vasti (VAS) and rectus femoris (RF) and to a lesser extent the swing leg GMED. Stance leg HAM had a greater contribution to the anterior acceleration impulse during inner support leg compared to the outer support leg (Table 2). Stance leg VAS had a lower contribution to the posterior acceleration impulse during the outer support leg compared to the inner and straight support legs.

3.3. *Pelvis angular acceleration*

The primary contributors to the pelvis internal angular acceleration impulse were swing leg IL and ADD and stance leg GMED and VAS (Fig. 4). The primary contributors to the pelvis external angular acceleration impulse were the stance leg IL and swing leg GMED, GMAX and VAS. Contributions from the swing leg ADD to the internal angular acceleration impulse were significantly lower for the outer support leg than for the straight and inner support legs and greater for the inner support leg than for the straight support leg (Table 3). Contributions from the stance leg IL to the external angular acceleration impulse were greater for the outer

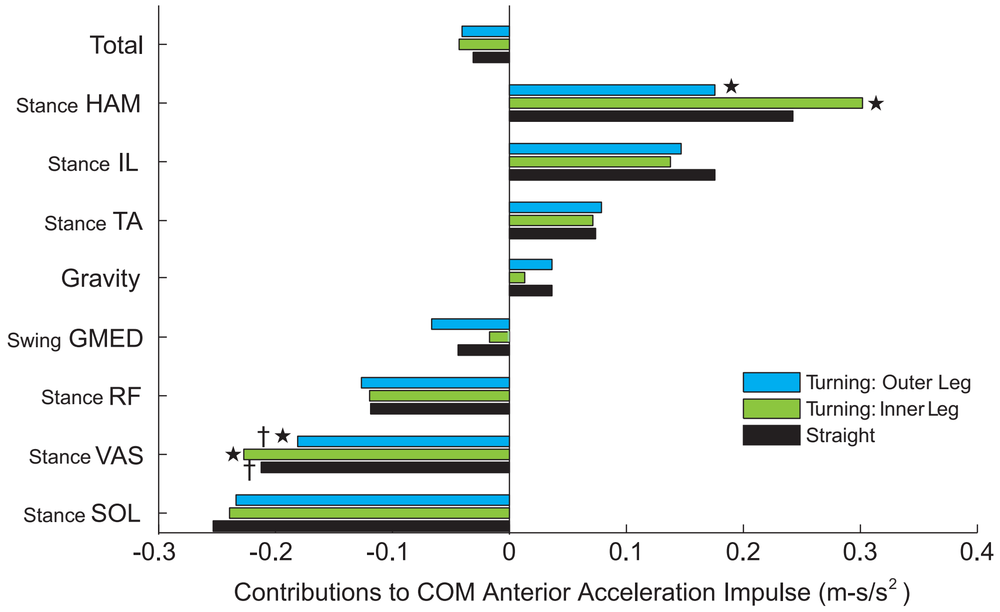

Fig. 3. The primary contributors to the body COM acceleration impulse in the anterior–posterior direction during single leg support of the outer leg and inner leg when turning and when walking along a straight path. Total is the sum of all muscles and gravity. Significant differences between the outer and inner leg conditions are denoted; and significant differences between outer leg and straight conditions are denoted with †.

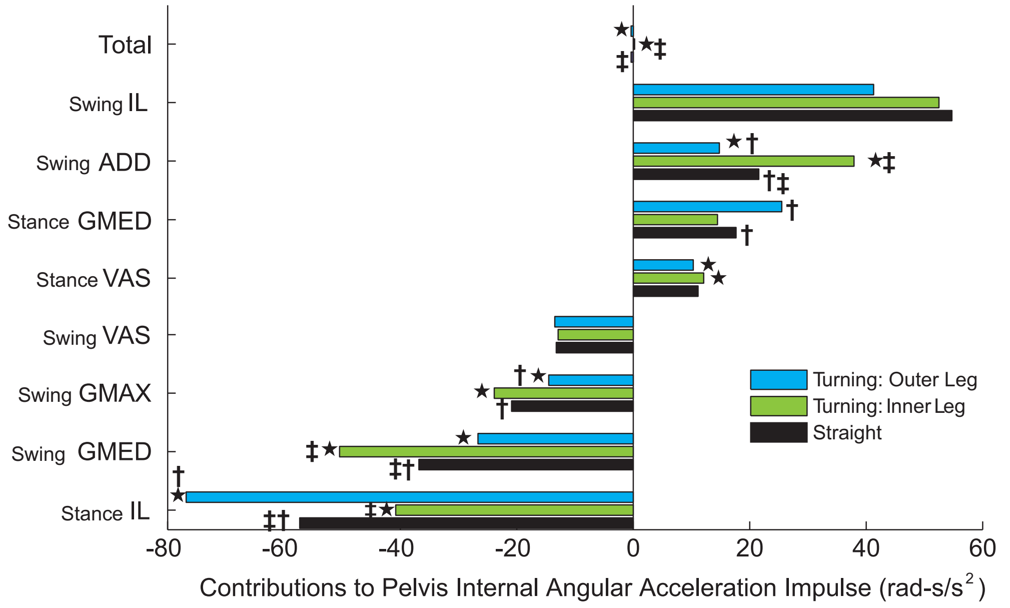

Fig. 4. The primary contributors to the pelvis angular acceleration impulse in the internal–external direction during single leg support of the outer leg and inner leg when turning and when walking along a straight path. Total is the sum of all muscles and gravity. Significant differences between the outer and inner leg conditions are denoted with ★; significant differences between the outer leg and straight conditions are denoted with †; and differences between the inner leg and straight conditions are denoted with ‡.

support leg than for the straight and inner support legs and lower for the inner support leg than for the straight support leg. Contributions from the swing leg GMED and GMAX were greater for the outer support leg than for the inner support leg.

4. Discussion

To help confirm the findings of the current model and simulations, the muscle contributions during level, straight-line walking were compared with previous studies (Figs. 2–4; Neptune et al., 2004; Liu et al., 2006; Pandy et al., 2010; Allen and Neptune, 2012). Consistent to what has been previously reported, the stance leg GMED contributes significantly to the medial COM acceleration and stance leg IL, ADD, GAS and SOL to the lateral COM acceleration. The stance leg HAM, IL and TA contribute to the anterior COM acceleration and stance leg SOL, VAS, and RF to the posterior COM. Muscle contributions to pelvis rotation have not been previously reported. Contributions to pelvis internal rotation during outer leg stance and to pelvis external rotation during inner leg stance act to redirect the body torso to the new heading. Absolute internal (external) pelvis rotation is caused by relative external (internal) rotation of the stance leg joints. Stance leg IL contributed to external pelvis rotation during straight-line walking (Fig. 4), which

Table 3
Statistical analysis of the primary contributors to angular acceleration impulse of the pelvis (rad-s/s^2) during single-leg support of the outer leg and inner leg while turning and while walking along a straight path.

Muscle	**Mean ± STD COM acceleration impulse (rad-s/s^2)**			***p*-Value**		
Internal rotation	**Turning: outer leg**	**Turning: inner leg**	**Straight**	**Outer vs. inner**	**Outer vs. straight**	**Inner vs. straight**
Total	−0.34 ± 0.07	0.17 ± 0.04	−0.42 ± 0.40	< 0.001	–	< 0.001
Swing leg IL	41.3 ± 4.3	52.5 ± 5.4	54.7 ± 4.5	–	–	–
Swing leg ADD	14.8 ± 2.2	37.8 ± 4.2	21.5 ± 2.8	0.002	0.024	0.002
Stance leg GMED	25.5 ± 4.2	14.5 ± 4.4	17.6 ± 3.6	–	0.044	–
Stance leg VAS	10.3 ± 1.0	12.1 ± 1.0	11.1 ± 1.0	0.03	–	–
Swing leg VAS	−13.5 ± 1.6	−12.9 ± 1.8	−13.2 ± 1.6	–	–	–
Swing leg GMAX	−14.5 ± 1.4	−23.9 ± 2.2	−20.9 ± 2.0	0.005	0.004	–
Swing leg GMED	−26.7 ± 3.3	−50.4 ± 4.9	−36.8 ± 3.4	0.012	–	0.007
Stance leg IL	−76.8 ± 4.9	−40.8 ± 1.9	−57.3 ± 3.5	< 0.001	0.001	0.005

is consistent with the contributions to internal hip rotation generated by IL as reported by Pandy et al. (2010). The same study reported that the anterior and posterior muscle groups of GMED had a net contribution to hip internal rotation, whereas stance leg GMED contributes to pelvis internal rotation in the current study.

Our expectation that outer stance leg GMED contributions to mediolateral COM would significantly increase during the turn about a 1-m radius circular path was not supported (Fig. 2, Table 2); rather, inner stance leg GMED contributions were significantly decreased. While our expectations that outer stance leg GMED would increase its contribution to pelvis rotation was supported (Fig. 4, Table 3), there was almost no net pelvis angular acceleration during the single-leg support phase due to significant changes in contributions by the swing leg ADD and stance leg IL in the opposite direction. Likewise, increased contributions from swing leg GMED and GMAX during inner leg stance support our third expectation that there would be greater contributions from the swing leg hip muscles to pelvis angular acceleration, but their effects were offset by increased opposing contributions to outward pelvis rotation.

In support of our second expectation, contributions from the stance leg SOL to lateral COM acceleration changed to direct the body COM towards the center of curvature although not by the means expected (Fig. 2, Table 2). Contributions from SOL and GAS to mediolateral COM acceleration decrease during outer leg support, which appears to disagree with previous studies that measured an increase in outer leg SOL and GAS activity during turning, both during steady-state and transitional turns (Courtine and Schieppati, 2003b; Courtine et al., 2006; Chen et al., 2013). Because SOL and GAS contribute to lateral COM acceleration, an increase in outer leg plantarflexor activity should oppose the turning movement. However, during turning the difference in leg rotation angle influenced the functional roles of the muscles. For example, the contributions from the ankle plantarflexors to lateral COM acceleration increase when the leg is rotated internally during mid and late stance, as during inner leg support, and decrease when the leg is rotated externally, as during outer leg support (Fig. 5; i.e., Taylor et al., 2005). Statistical analysis of the average SOL and GAS force production showed no significant difference between the outer leg, inner leg and straight conditions (SOL: 556 ± 60 N, 606 ± 115 N and 580 ± 96 N; GAS: 680 ± 106 N, 816 ± 149 N and 750 ± 144 N). More likely, differences in leg angle (rather than muscle activity) modulated the plantarflexor contributions to the lateral COM acceleration to execute the turn.

Our final expectation that muscles that change their contributions to the mediolateral COM acceleration impulse would also change their contributions to body support (vertical COM acceleration) and forward propulsion (anterior–posterior COM acceleration) was not fully supported. There were no significant differences in the contribution of SOL to the anterior–posterior COM acceleration impulse during turning, although there were significant differences in its contribution to the mediolateral COM acceleration impulse. Again, while there is no significant difference in force production by SOL, the differences in leg angle (Fig. 5) allowed SOL to contribute to mediolateral COM acceleration without significantly compromising contributions to anterior–posterior COM acceleration. Similarly, stance leg HAM contributed more to the anterior COM acceleration impulse in inner leg support, while also contributing less to lateral COM acceleration impulse (outer leg: −31 ± 4 mm-s/s^2; inner leg: −6 ± 8 mm-s/s^2; $p=0.001$). These differences in contributions to the COM acceleration impulses were due to differences in leg angle across conditions (Fig. 5) as the HAM forces did not significantly change. Thus, during turning the muscle contributions in the mediolateral and anterior–posterior directions were found to be modulated independently through changes in leg angle rather through changes in muscle force.

Another interesting finding was the greater differences between the muscle contributions to the medial COM acceleration impulses during the inner leg and straight conditions than between the outer leg and straight conditions (Table 2). For example, the stance leg GMED, TP and ADD and swing leg ADD medial COM acceleration impulse contributions differed significantly from straight-line walking for the inner condition but not for the outer condition. Further analysis of the simulations showed that this occurred even though the time spent in inner single-leg support was similar to the time spent in single-leg support during straight-line walking (inner: 451 ± 10 ms; straight: 445 ± 13 ms; $p=1.000$) while the time spent in outer leg support was shorter than in inner leg support (outer: 414 ± 10 ms; $p=0.009$). When walking along a straight path, the COM accelerates medially during right leg support and again during left leg support, causing a sinusoidal pattern about the straight-line trajectory (Fig. 1). When turning, one accentuates this medial acceleration when supported on the outer leg and reverses it when supported on the inner leg (Fig. 2). Because the inner leg muscles accelerate the COM in the direction opposite to the one during straight-line walking, modulation of the inner leg muscle function may be more critical than modulation of outer leg muscle function. This is consistent with the finding that the inner leg GRF changes direction from a medial force during straight-line walking to a lateral force in a turn, whereas the outer leg GRF only increases in magnitude (Orendurff et al., 2006).

An important finding of this study was the role of the swing leg muscles to the generation of mediolateral COM acceleration and redirection of the pelvis during both straight-line walking and continuous turning on a level surface. During single leg support, the stance leg not only actively directs the walking motion but also reacts to the movement of the swing leg (Winter, 1995). Swing leg ADD was found to be an important contributor to the medial COM acceleration impulse and the external pelvis angular acceleration

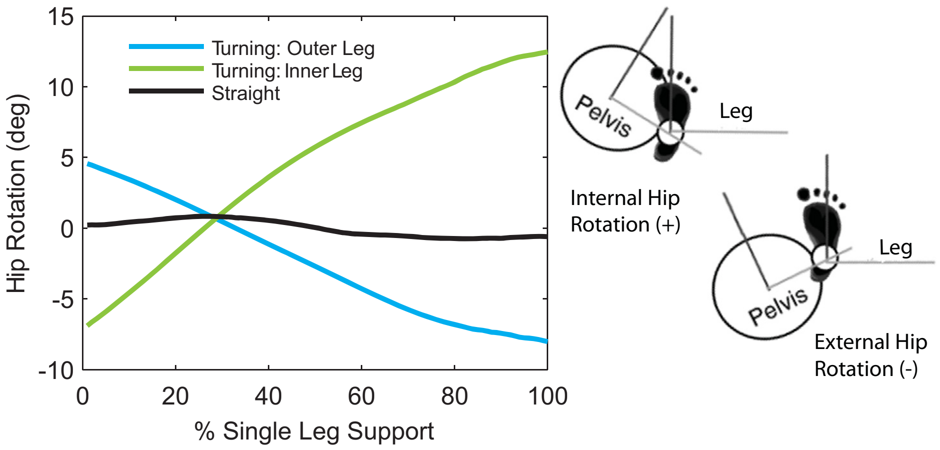

Fig. 5. Hip rotation angle of the stance leg during single leg support of the outer leg and inner leg when turning and when walking along a straight path. A positive angle indicates that the stance leg is rotated internally with respect to the pelvis.

impulse (Figs. 2 and 4). Swing leg GMED is an important contributor to the posterior COM acceleration impulse and the external pelvis angular acceleration impulse (Figs. 3 and 4). Pelvis internal angular acceleration is also driven by the swing leg IL and external rotation by GMAX and VAS (Fig. 4). Thus, analyzing the swing leg during walking may be especially important for subjects with various movement disorders.

A potential limitation of the study is that we did not simulate the double support phase due to our experimental set-up that made collecting consecutive force plate hits difficult. However, the majority of the inward COM acceleration occurs during single-leg support of the outer leg with minimal acceleration occurring from the inner leg (Fig. 1), suggesting that analysis of the single-support phase is most important. The muscle contributions to pelvis angular acceleration impulses were likely the most affected by the omission of the double support phases, as the pelvis angular acceleration occurred primarily during the step-to-step transition (Fig. 1). Another potential limitation is that we did not have EMG data to compare with the simulation excitations. However, the muscle excitations compare fairly well with published EMG data (e.g., Winter and Yack, 1987) and we chose to group the muscles into functional groups (Table 1) to help offset potential differences in excitation timing of individual muscles.

In summary, significant changes in muscle coordination from straight-line walking are needed to successfully complete a steady-state turn about a 1-m circular path. The stance leg GMED and plantarflexor (TP, GAS and SOL) muscles and swing leg ADD act to redirect the body's COM in the direction of a turn. Significant changes by the stance leg GMED and swing leg GMED and GMAX to pelvis angular acceleration were offset by changes in the swing leg ADD and stance leg IL in single-leg support, resulting in a very small difference in total angular acceleration of the pelvis during turning and straight-line walking. While modulation of muscle function generally occurs in both the inner and outer legs, greater changes were observed during inner single-leg support than during outer single-leg support. These results provide insight into which muscles contribute to turning the body while walking and may help guide the development of more effective locomotor therapies that target specific muscle groups for those with movement disorders.

Conflict of interest statement

There is no conflict of interest regarding the publication of this manuscript.

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