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Individual muscle contributions to circular turning mechanics

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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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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

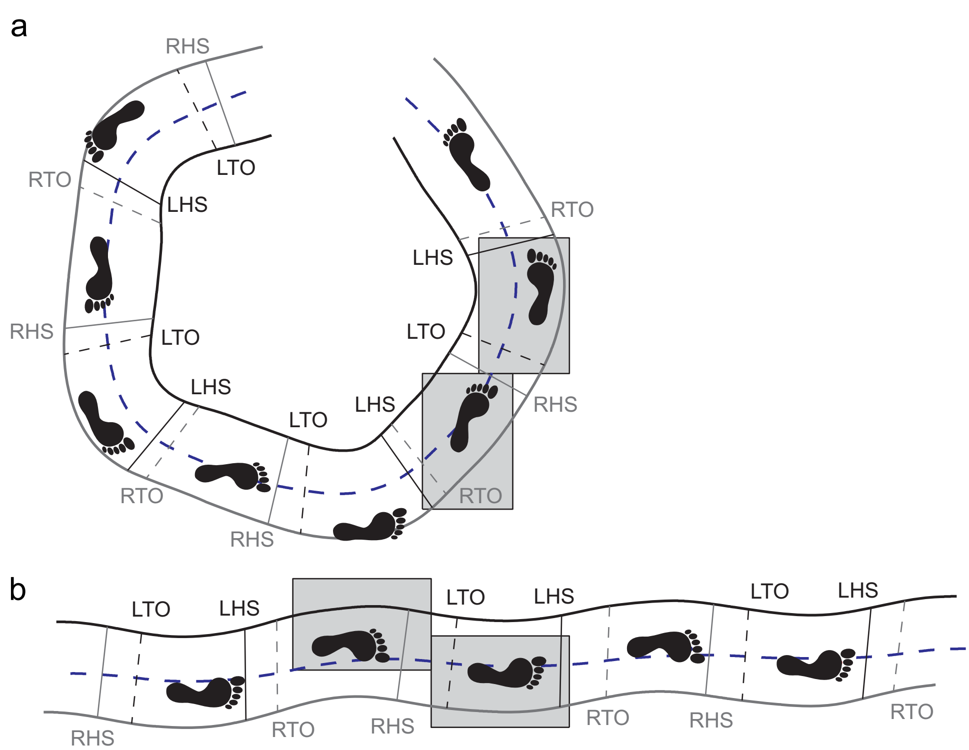

Fig. 1. Characteristic (a) turning and (b) straight-line walking paths, depicted by the force plates (shaded rectangles), COM path (dashed line), left (black) and right (grey) shoulder paths and foot positions. Left and right toe off (LTO and RTO, respectively) and left and right heel strike (LHS and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