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Ankle torque control that shifts the center of pressure from heel to toe contributes non-zero sagittal plane angular momentum during human walking

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ABSTRACT

A principle objective of human walking is controlling angular motion of the body as a whole to remain upright. The force of the ground on each foot (*F*) reflects that control, and recent studies show that in the sagittal plane *F* exhibits a specific coordination between *F* direction and center-of-pressure (CP) that is conducive to remaining upright. Typical walking involves the CP shifting relative to the body due to two factors: posterior motion of the foot with respect to the hip (stepping) and motion of the CP relative to the foot (foot roll-over). Recent research has also shown how adjusting ankle torque alone to shift CP relative to the foot systematically alters the direction of *F*, and thus, could play a key role in upright posture and the *F* measured during walking. This study explores how the CP shifts due to stepping and foot roll-over contribute to the observed *F* and its role in maintaining upright posture. Experimental walking kinetics and kinematics were combined with a mechanical model of the human to show that variation in *F* that was not attributable to foot roll-over had systematic correlation between direction and CP that could be described by an intersection point located near the center-of-mass. The findings characterize a component of walking motor control, describe how typical foot roll-over contributes to postural control, and provide a rationale for the increased fall risk observed in individuals with atypical ankle muscle function.

1. Introduction

From a whole-body perspective, the mechanical objective of walking is to use the legs to move the body though space while preserving upright posture. That postural task necessitates regulation of whole-body angular position, which has received relatively little attention beyond observational studies of angular motion during human walking (Popovic et al., 2004; Bennett et al., 2010; Herr and Popovic, 2008). Irregular control of angular body motion is related to an increased risk of falling (Nott et al., 2014; Simoneau and Krebs, 2000), but the mechanism by which humans regulate angular motion while walking is poorly understood. One outcome of neuromuscular control is ankle torque, which is important for maintaining appropriate angular body motion (Pijnappels et al., 2005). Studies of subjects with a history of falling have shown atypical ankle muscle function when compared to non-fallers (LaRoche et al., 2010; Pijnappels et al., 2005; Simoneau and Krebs, 2000; Skelton et al., 1999, 2002). Application of this evidence to improve fall prevention strategies and gait rehabilitation requires a more precise understanding of how ankle function combines with the other neuromechanical interactions to produce typical walking behavior. Therefore, this paper presents a model of a potential mechanism by which neuromuscular control of the hip, knee and ankle torques and segmental mechanics enable control of sagittal-plane angular posture during human walking.

Previous walking studies of sagittal-plane whole-body angular position have focused on characterizing the force of the ground on the foot (*F*) through stance (Maus et al., 2010; Gruben and Boehm, 2012b). The effect of neuromuscular control acting on the body (a mechanical linkage) is reflected in both the motion of the body and the net force acting on the body. The previous work chose to quantify *F* and investigated how properties of *F* such as location of application (center of pressure, CP) and direction (Fig. 1) co-vary during walking to preserve upright posture.

These CP and direction properties of *F* are key features of gait to observe when focusing on how people prevent tipping over, because they determine the torque of *F* about the center-of-mass (CM) during unaided walking. *F* is the only force acting on the body during unaided walking that can produce torque about the

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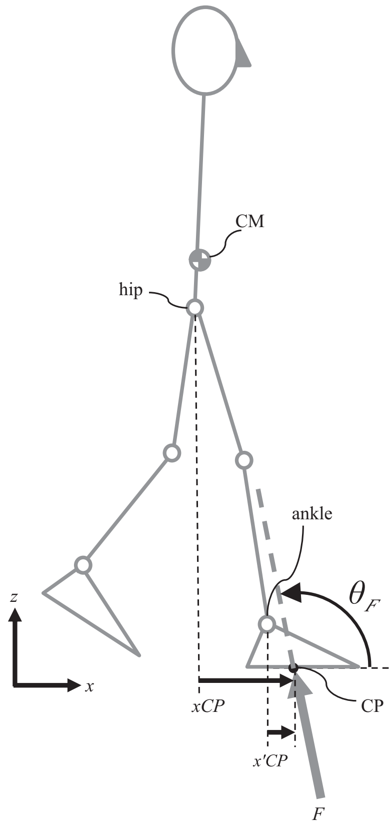

Fig. 1. Factors contributing to *xCP* location. The location of the CP of *F* expressed relative to a vertical line through the hip (*xCP*) depends on (1) the foot location relative to the hip and (2) the location of CP relative to the foot (*x′CP*). A vertical line through the ankle joint was used to reference *x′CP*. The direction of *F* (θ_F) was expressed relative to the *x* axis.

CM, and thus, is directly related to the whole-body angular acceleration that determines whether someone tips over. Characterization of *F* through the gait cycle with respect to the CM, then, is sufficient on a whole-body level to characterize how the system prevents tipping over. Discussion in previous reports of walking studies has been limited to this characterization of the overall nervous system output provided by observing the *F* relative to the CM. Those studies have shown that the *F* direction and location (CP) co-vary in a pattern that is common across individuals (Maus et al., 2010; Gruben and Boehm, 2012b). That typical nervous system control results in a systematic pattern of non-zero angular acceleration alternating in sign such that it averages zero (Herr and Popovic, 2008). Through the single limb stance phase of the gait cycle, the CP varies from anterior to posterior relative to the vertical line through the CM. Through the same time, the direction of *F* begins angled backward (the *F* has a horizontal component directed posteriorly) with a line-of-action passing anterior to the CM, is then vertical, and finally is angled forward with a line-of-action passing posterior to the CM (Fig. 2) (Maus et al., 2010; Gruben and Boehm, 2012b). That characterization of the typical pattern of *F* variation was shown to promote upright posture, because it produced a torque in the direction needed to pitch the body toward upright throughout most of the gait cycle.

The present study initiated a more detailed investigation of *F* during walking by focusing on the contributions to CP position. During single limb support, the motion of the CP relative to a vertical line through the hip can be dissected into two factors; (1) posterior motion of the stance foot relative to the hip (stepping), and (2) motion of the CP with respect to the foot (foot roll-over) (Fig. 1). The foot roll-over factor is typically described as heel-to-toe, as the foot initially contacts the floor with the CP near the heel and leaves the ground with the CP near the toe. Heel-to-toe and alternate CP patterns such as those used in toe walking (Crenna et al., 2005) and speed change (Orendurff et al., 2008)

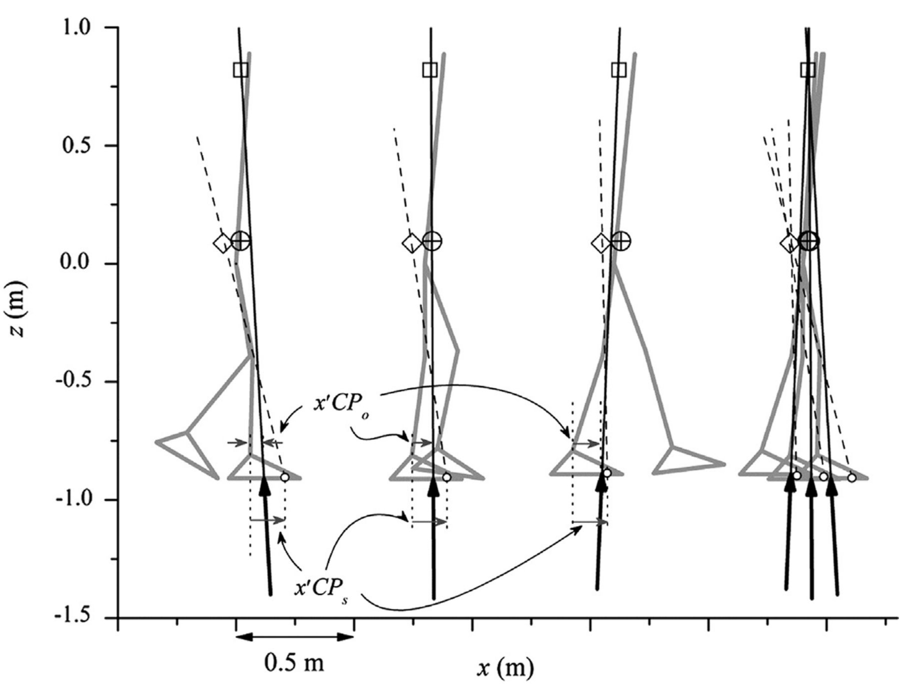

Fig. 2. Characteristics of the *observed F* and of the *modified F* that is positioned at a specified $x'CP_s$. In the three left figures, different instants from a representative walking cycle are shown with both the *observed F* (bold line-of-action and vector) and line-of-action of the *modified F* (dashed line) that results from selecting ankle torque to position the CP at the specified point ($x'CP_s$, open circle). The *observed F* lines-of-action pass from the observed CP ($x'CP_o$) to near a DP (square that is fixed with respect to the hip across postures). The *modified F* lines-of-action pass near the point *xi* (diamond that is fixed with respect to the hip across postures) after shifting the CP to the same specified point on the foot ($x'CP_s$, open circle) but keeping the same body segment positions, velocities, and knee and hip torques as observed at each of the three instants. The right panel shows the three instants superimposed with the hip at the origin of the reference frame to illustrate the proximity of the *observed F* lines-of-action to the DP and the proximity of the *modified F* lines-of-action to *xi*.