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Contribution of center of mass–center of pressure angle tangent to the required coefficient of friction in the sagittal plane during straight walking

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ABSTRACT

In human bipedal walking, the peak value of the traction coefficient (i.e., the ratio of the shear force component to the vertical force component exerted on the floor) produced shortly after heel contact is termed as the required coefficient of friction (RCOF). Based on a bipedal inverted pendulum model, with a whole-body center of mass (COM) and reaction forces applied at the center of pressure (COP) of standing feet, RCOF in the sagittal plane ($RCOF_y$) can be expressed as the sum of the tangent of the COM–COP angle and a residual term (*RT*), mainly comprising the moment around COM. In this study, we investigated the contribution of the tangent of the COM–COP angle to $RCOF_y$ during straight walking. The study involved four healthy young adult males. The participants were asked to walk on a 5-m long carpeted walkway. Each participant performed nine trials, i.e., three walking speeds (1, 1.4, and 1.9 m/s) × three step lengths (0.55, 0.75, and 0.95 m). COM was estimated using motion capture. COPs for the left and right feet were measured using eight force plates embedded in the walkway. $RCOF_y$ was calculated from the anterior–posterior and vertical ground reaction force components measured using the force plates. We found that the tangent of the COM–COP angle accounted for 91%–124% of the $RCOF_y$ value. This percentage tended to decrease with increasing walking speed ($p < 0.05$). The magnitude of *RT* accounted for only 5.3%–24% of $RCOF_y$. These results suggest that the tangent of the COM–COP angle dominantly determines $RCOF_y$.

1. Introduction

Slips are the most frequent events leading to falls at home and workplace [1–3]. Slips occur if the tangential force applied to the floor during walking reaches the friction force at the shoe–floor interface; slips do not occur when the tangential force is less than the friction force during the stance phase of the gait cycle. Thus, the ratio of the tangential force to the vertical force applied to the floor, i.e., the traction coefficient, must be less than the coefficient of friction at the shoe–floor interface to prevent slipping [4]. The traction coefficient, calculated from the ground reaction forces exerted between the shoe and floor while walking on a dry, uncontaminated surface, has been used to identify the location during the gait cycle where slipping occurs. The required coefficient of friction (RCOF) is the peak value of the traction coefficient obtained at weight acceptance, which usually occurs shortly after heel contact by the leading foot [5]. RCOF is recognized as the minimum coefficient of friction necessary at the interface between the shoe and floor to sustain human locomotion [6–9]; thus, RCOF is an important factor related to slipping during walking.

Therefore, research is increasingly focused on the relationship between RCOF and gait kinematics. Published studies [10–13] indicate that RCOF is affected by walking speed, step length, and heel-contact velocity. It was shown that the tangent of the angle between the leg and a line perpendicular to the floor affects RCOF [6,14]. Burnfield and Powers [15] asserted that the inclination angles of the line connecting the whole-body center of mass (COM) to the center of pressure (COP; termed the COM–COP angle) is a predictive kinematic variable of RCOF during straight walking. Similarly, Yamaguchi et al. [8,12] demonstrated that the tangent of the COM–COP angle strongly correlates with RCOF during straight walking [12] as well as during turning, gait termination, and gait initiation [8]. Thus, the tangent of the COM–COP angle is a good predictor of RCOF, the examination of which may improve our understanding of the correlation between individuals' anthropometric and gait characteristics and the onset of slipping. However, till date, no study has expounded the theoretic rationale behind the high correlation between the tangent of the COM–COP angle and RCOF. Furthermore, the quantitative contribution of the tangent of the COM–COP angle to RCOF has not been investigated.

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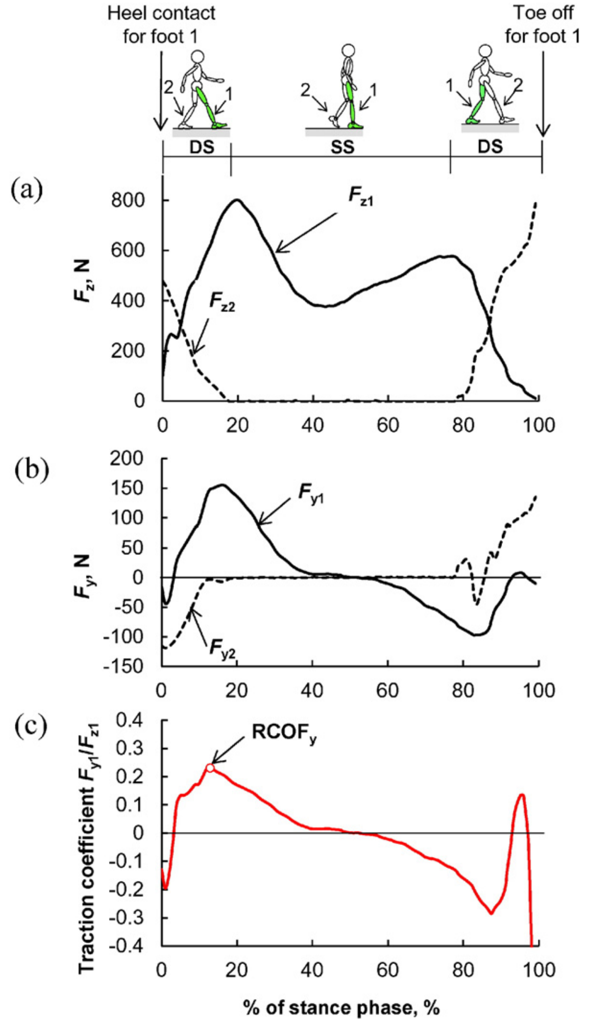

Fig. 1. Typical time course of (a) vertical ground reaction forces (F_z); (b) anterior–posterior ground reaction forces (F_y) for the leading foot (foot 1) and trailing foot (foot 2); and (c) traction coefficient (F_{y1}/F_{z1}) for foot 1 from heel contact to toe off. DS and SS represent double support and single support, respectively.

Fig. 1 shows the typical ground reaction force components and traction coefficient during the stance phase of the gait cycle (i.e., from heel contact to toe off for a single foot) in the sagittal plane. As shown in Fig. 1, the peak of the traction coefficient in the sagittal plane ($RCOF_y$) is produced in the final phase of the double-support period. To analyze the effect of the tangent of the COM–COP angle on $RCOF_y$, we assumed a bipedal inverted pendulum model, with all mass at the COM location and reaction forces applied at COP during double support (Fig. 2). When we consider the sagittal plane with y and z coordinates, where y is the horizontal axis and z is the vertical axis, the moment equation is as follows:

$$M_x = F_{z1}(y_{COP1} - y_{COM}) + F_{z2}(y_{COP2} - y_{COM}) - F_{y1}z_{COM} + F_{y2}z_{COM} \tag{1}$$

where F_{y1} and F_{y2} are the horizontal ground reaction forces of the leading and trailing feet, respectively; F_{z1} and F_{z2} are the vertical ground reaction forces of the supporting feet; y_{COM}, y_{COP1} and y_{COP2} are the y coordinates of COM and COPs of the supporting feet; M_x is the moment around COM in the sagittal plane; and z_{COM} is the height of COM. The traction coefficient for the leading foot in the sagittal plane (F_{y1}/F_{z1}) is derived from Eq. (1) as follows:

$$\frac{F_{y1}}{F_{z1}} = \tan\theta_{x1} + RT \tag{2}$$

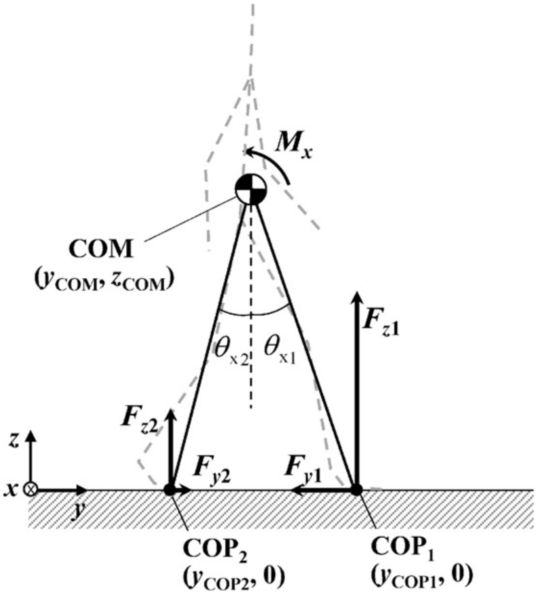

Fig. 2. Bipedal inverted pendulum model in the sagittal plane, with all mass at the center of mass location and reaction forces applied at the center of pressure for leading and trailing feet during a double-support period.

$$\text{where} \quad RT = \frac{F_{z2}}{F_{z1}}\tan\theta_{x2} + \frac{F_{y2}}{F_{z1}} - \frac{M_x}{F_{z1}z_{COM}}, \tag{3}$$

$$\tan\theta_{x1} = \frac{y_{COP1} - y_{COM}}{z_{COM}}, \quad \text{and} \tag{4}$$

$$\tan\theta_{x2} = \frac{y_{COP2} - y_{COM}}{z_{COM}} \tag{5}$$

where θ_{x1} and θ_{x2} are the angles of inclination of the lines connecting COM to COPs of supporting feet.

Thus, in the sagittal plane, the traction coefficient for the leading foot in the sagittal plane (Eq. (2)) is theoretically equivalent to the sum of the tangent of the COM–COP angle of the leading foot ($\tan\theta_{x1}$) and the residual term (RT). The strong correlation between the tangent of the COM–COP angle and RCOF evident experimentally can be accounted for by the assumption that the term of the tangent of the COM–COP angle is dominant in Eq. (2).

Therefore, in this study, we aimed to test this assumption. Specifically, we quantitatively investigated the contribution of the tangent of the COM–COP angle and RT in Eq (2). According to published studies [10–13], the tangent of the COM–COP angle of the leading foot and RT may be affected by walking conditions such as step length and gait speed. Therefore, we controlled these factors and systematically investigated the contribution of the tangent of the COM–COP angle to $RCOF_y$.

2. Methods

2.1. Participants

This study involved four healthy young adult males aged 24.3 ± 3.3 years (range: 22–29 years), 1.74 ± 5.3 m in height (range: 1.69–1.81 m), and weighing 69 ± 15.4 kg (range: 56–88 kg). Informed consent was obtained from each participant.

2.2. Experimental procedures

Gait trials were performed on a 5-m long carpeted walkway. Eight force plates (OR6-5; Advanced Mechanical Technology, Inc., Watertown, MA, USA) were located approximately 2 m from the start position for collecting ground reaction forces, as shown in Fig. 3. An eight-