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The Role of Center of Mass Kinematics in Predicting Peak Utilized Coefficient of Friction During Walking*

ABSTRACT: Slips frequently occur when the friction required between the foot and floor exceeds available surface slip resistance. To date, the ability to identify variables that predict an individual's friction needs during walking, or utilized coefficient of friction (COF_U), remains limited. Understanding COF_U in the context of pedestrian/walkway accidents is important as individuals who demonstrate higher COF_U are at a greater risk of slipping. This study determined if whole body center of mass (CM) kinematics were predictive of peak COF_U during walking. Ground reaction forces and kinematic data were recorded simultaneously as subjects walked. Stepwise regression analysis determined that the combination of the subject's CM-to-center-of-pressure angle and CM anterior (i.e., forward) velocity predicted 62% of the variance in peak COF_U during weight acceptance ($p < 0.001$). The identified relationships between CM kinematics and peak COF_U provide insight into how gait and individual anthropometric characteristics may increase risk for slip initiation.

KEYWORDS: forensic science, slips and falls, walking, utilized coefficient of friction

Slips have been identified as a leading cause of falls and injuries in the home (1,2) and work (2–4) environments. During walking, forces generated by the body are transmitted through the foot to the floor. In order to prevent a slip, sufficient friction at the foot-floor interface is required. When the shear forces applied to the floor surface exceed the available friction at the foot-floor interface, a slip becomes imminent (5,6). Conversely when the available friction exceeds the utilized friction, no slip will occur.

In the research setting, an individual's friction needs during walking, or utilized coefficient of friction (COF_U), is calculated from ground reaction force (GRF) data recorded using force plates (Fig. 1*a*) (7). The COF_U is defined as the ratio between the shear (resultant of the fore-aft and medial–lateral forces) and vertical components of the ground reaction force recorded as a person walks across a dry, non-contaminated surface (Fig. 1*b*) (8). Understanding utilized friction in the context of pedestrian/walkway accidents is important as persons or groups of individuals who demonstrate higher COF_U are at the greatest risk of slipping (6).

Currently, the ability to identify predictors of peak COF_U, and thus risk of slip initiation, remains limited. Two factors that have been proposed to increase COF_U during weight acceptance are the angle of impact of the leg with the ground (9) and walking speed (10–12).

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Ekkebus and Killey (9) proposed that the impact angle of the leg with the ground, calculated from measures of step and leg length, could be used to predict peak COF_U. In their model, the leg was equated to a rigid strut that transmitted forces to the ground during walking. The authors theorized that the tangent of the angle formed by the leg at heel contact (using the hip joint center as a reference point) would be equal to the ratio of shear to vertical forces, and thus be predictive of peak COF_U at weight acceptance. According to this model, greater impact angles would result in higher peak COF_U. Many state laws and building codes have established that a static COF of $\mu = 0.50$ represents the minimum slip resistance threshold for safe flooring surfaces based, in part, on estimates of peak COF_U derived from this model (8,13). Subsequent investigations, however, have revealed that while the impact angle of the leg does serve as a significant predictor of friction needs, it accounts for only 18–27% of the variance in peak COF_U (11,14). Additionally, the Ekkebus and Killey model has been shown to overestimate peak COF_U by 86% at slow walking speeds and up to 131% at fast walking speeds (14).

Cavagna and Margaria (15) proposed that greater angles of inclination of the line connecting the whole body center of mass (CM) to the center of pressure (CP) would contribute to higher anterior shear forces during walking. These authors suggested that greater angles of inclination between the CM and CP resulting from faster walking speeds, could be associated with greater anterior shear forces during weight acceptance. Unfortunately, the authors did not calculate peak COF_U, so it is unknown what impact, if any, the CM-to-CP angle ($CM–CP_{Angle}$) would have on the prediction of peak COF_U.

Walking speed also has been theorized to influence COF_U; however, the published literature relating walking speed to COF_U is conflicting. While a number of authors have found that peak COF_U increases with faster walking speeds (11,12,16), others have reported that walking speed is not related to peak COF_U (17,18). Small sample sizes, non-homogeneous populations, and differences in study design, may explain, in part, the differences found across studies.

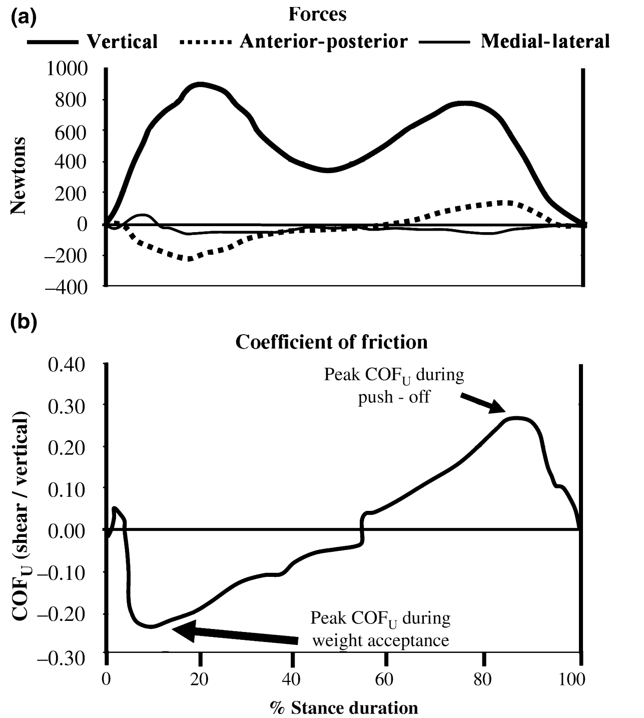

FIG. 1—*Stance phase ground reaction forces (a) and utilized coefficient of friction (b) for a single stride during walking at a self-selected velocity. Utilized coefficient of friction peaks during weight acceptance when a braking force is required to prevent the foot from slipping anterior (i.e., when the anterior–posterior component of the ground reaction force is directed posteriorly and the COF_U has a negative value), and in push-off when a propulsive force is contributing to limb advancement (i.e., when the anterior–posterior component of the ground reaction force is directed anteriorly and the COF_U has a positive value).*

Walking speed in the above noted studies was calculated as the average velocity over a fixed distance; however, it is possible that the instantaneous velocity at the time of peak COF_U may be a stronger predictor of peak COF_U. For example, Pai and Iqbal (19) modeled the relationship between the instantaneous velocity of the CM in the anterior (i.e., forward) direction, the location of the CM relative to the base of support, and the ability to maintain dynamic stability. The authors reported that with increasingly posterior locations of the CM relative to the foot, greater instantaneous CM velocities in the anterior direction would be required to maintain stability.

Based on the findings of Cavagna and Margaria (15), and Pai and Iqbal (19), subtle variations in the relative location as well as velocity of the CM would be expected to influence the forces applied to the floor and therefore slip potential. Although it is conceivable that measures describing the relative location of the total body center of mass as well as the anterior velocity during walking could serve as better predictors of COF_U, there are no data to support this premise. The purpose of this study was to determine the extent to which the $CM–CP_{Angle}$ of inclination and the CM velocity could be used to predict peak COF_U during the weight acceptance phase of level walking. It was hypothesized that both greater $CM–CP_{Angles}$ of inclination as well as a faster anterior CM velocity would contribute to higher peak COF_U values. Once the relationship between CM kinematics and peak COF_U has been established, then it may be possible to identify individual anthropometric and gait characteristics that combine to increase the risk of slip onset.

Methods

Subjects

Forty-nine persons (28 males, weight range, 67–116 kg; 21 females, weight range 52–135 kg) between the ages of 22 and 40, participated in this study (Table 1). Subjects were recruited from the student population at the University of Southern California (Los Angeles, California), as well as by word of mouth in the local Los Angeles area. Prior to participation, each subject was fully informed of the nature of the study, and signed an informed consent form approved by the Institutional Review Board of the University of Southern California Health Sciences Campus. Only subjects capable of independent ambulation without assistive devices were included. Subjects with known neurologic or orthopedic conditions that would interfere with gait were excluded from the study.

Instrumentation

All walking trials were conducted on a 10-m walkway with the middle 6 m designated for data collection. Light sensitive triggers were used to initiate and terminate data collection as subjects traversed the length of the walkway. Three-dimensional motion analysis was performed using a six-camera motion analysis system (VICON, Oxford Metrics Ltd., Oxford, England). Kinematic data were sampled at 120 Hz and recorded digitally on a Pentium III 1 GHz personal computer. Reflective markers (20 mm spheres) placed over specific anatomical locations (see below) were used to calculate the CM location.

Ground reaction forces (vertical, anterior–posterior, and medial–lateral) were recorded using a single AMTI force plate (Model OR6-6-1; AMTI Corp., Newton, MA). The force plate was covered with smooth vinyl composition tile in order to camouflage its location within the walkway. Force plate data were sampled at 1200 Hz, and recorded on a Pentium III 1 GHz personal computer using a 64-channel analog-to-digital converter.

Procedures

Each subject was provided with a pair of walking shoes (Rockport World Tour, model M/W WT18; The Rockport Company, LLC, Ronks, PA) for use during testing. To allow placement of the markers directly on the skin of the trunk and extremities, male subjects wore only sports shorts, while female subjects wore sports shorts and a sports bra.

All testing was performed within the Musculoskeletal Biomechanics Research Laboratory at the University of Southern California. To estimate CM location, selected anthropometric measures were obtained including: subject height and mass, bilateral leg length, knee width, ankle width, shoulder offset (vertical distance from base of the reflective marker that was placed over the acromio-clavicular joint to the origin of the clavicle), elbow width, wrist width, and hand thickness (distance between dorsal and palmer surface of hand at level of third metacarpal).

TABLE 1—*Selected subject characteristics (SD).*

	Male (n = 28)	Female (n = 21)	Combined (n = 49)
Age (years)	27.4 (4.4)	25.1 (2.8)	26.4 (3.9)
Height (cm)	180.1 (7.4)	165.7 (8.1)	173.9 (10.5)
Weight (kg)	86.3 (13.3)	67.7 (18.0)	78.3 (17.9)

Thirty-seven reflective markers were then taped to the following body landmarks: sterno-clavicular notch, xyphoid process, C7 and T10 spinous processes, right mid-scapula, as well as bilaterally over the acromio-clavicular joint, lateral humerus, lateral humeral epicondyle, radial and ulnar styloids, dorsal surface of the third metacarpal, anterior and posterior superior iliac spines, lateral thigh, lateral femoral epicondyle, lateral tibia, lateral malleolus, second metatarsal head, and posterior calcaneous. A head band was used to secure four markers bilaterally over the temple and posterior cranium, forming a plane horizontal with the floor when the subject looked forward.

A static calibration trial was recorded to define marker relationships necessary for subsequent kinematic modeling. During the static trial, subjects stood stationary in the center of the calibration field for 5 sec.

Next, subjects were allowed several practice trials to accommodate to the markers and head band. All subjects were instructed to walk at a comfortable speed, with kinematic and force plate data being recorded simultaneously. A trial was considered successful if the subject's right foot landed within the force plate and all 37 markers were visible throughout stance on the force plate.

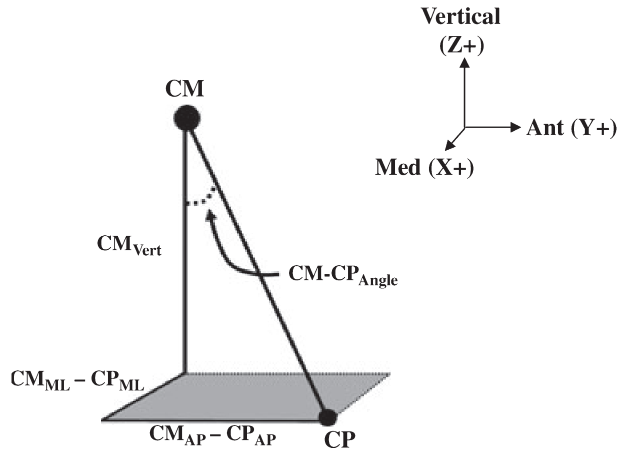

FIG. 2—*Center of mass (CM) to center of pressure (CP) relationships studied. Abbreviations: CM_{AP}–CP_{AP}, absolute distance between center of mass and center of pressure in the anterior–posterior direction (y-coordinate); CM_{ML}–CP_{ML}, absolute distance between center of mass and center of pressure in the medial–lateral direction (x-coordinate); CM_{Vert}, absolute distance between center of mass and center of pressure in vertical direction (z-coordinate); CM–CP_{Angle}, angle of center of mass to center of pressure (expressed relative to vertical).*

Data Analysis

Reflective markers were identified manually using VICON 370 Workstation software (Oxford Metrics, Ltd.) and then automatically digitized. Kinematic data were filtered using Woltring's general cross-validatory quintic spline routine (predicted MSE = 20). A fifteen segment model (VICON Plug-in-Gait; Oxford Metrics, Ltd.), consisting of six lower extremity links, six upper extremity links, two links for the trunk and one for the head, was used to estimate the location of the CM (*x*, medial–lateral; *y*, anterior–posterior; and *z*, vertical coordinates). Masses of each segment were calculated as a proportion of the total body mass using anthropometric relationships reported by Dempster (20) as well as subject specific anthropometric measures recorded by the investigator. The weighted sum of the center of mass of each of the fifteen individual segments was then used to compute the 3-D location of the whole body CM. CM displacement data and ground reaction forces were imported into DataPac software (v. 2K2; Run Technologies, Mission Viejo, CA) for further analysis.

The velocity of the CM in the anterior–posterior direction ($CM_{Vel\ AP}$) was calculated in DataPac using the first derivative of the CM *y*-displacement data. Digitally acquired vertical, anterior–posterior, and medial–lateral forces were filtered in DataPac using a fourth order, 45 Hz, low pass Butterworth filter with a zero-lag compensation (21). The center of pressure coordinates (*x*, *y*) were calculated in Data Pac using standard formulas provided by the force plate manufacturer.

The COF_U was calculated by dividing the resultant shear force (computed from the anterior–posterior, F_{AP}, and medial–lateral, F_{ML}, forces) by the vertical force (F_{Vert}) (Equation 1).

$$COF_U = \frac{\sqrt{F_{AP}^2 + F_{ML}^2}}{F_{Vert}} \quad (1)$$

During weight acceptance, the peak COF_U value resulting from a shear force that would contribute to the foot sliding *anteriorly*, was identified. To avoid spurious COF_U values resulting from division by small numbers, the data were screened and only COF_U data in which the vertical GRF's exceeded 50 N were analyzed (7). The onset of stance was defined as the time at which the vertical ground reaction force exceeded 5 N, and the cessation of stance was defined as the time at which the vertical ground reaction force fell below a 5 N threshold.

The CM–CP_{Angle} was defined as the angle formed by the following three points: CP, CM, and the vertical projection of the CM onto the ground surface (Fig. 2). The position of the CM relative to the CP at the time of peak COF_U was calculated in the anterior–posterior (CM_{AP}–CP_{AP}), medial–lateral (CM_{ML}–CP_{ML}), and vertical (CM_{Vert}) directions (Fig. 2). The CM–CP_{Angle}, was referenced to vertical, and was calculated using (Equation 2):

$$CM - CP_{Angle} = \mathrm{ArcTan}\frac{\sqrt{(CM_{ML} - CP_{ML})^2 + (CM_{AP} - CP_{AP})^2}}{CM_{Vert}} \quad (2)$$

Statistical Analysis

Descriptive statistics (mean, standard deviation, minimum, and maximum) were calculated for all variables assessed. To determine whether CM–CP_{Angle} and $CM_{Vel\ AP}$ were predictive of the peak COF_U during weight acceptance, stepwise regression analysis using a forward stepwise procedure was performed. Specifically, the independent variables were sequentially entered into the prediction model if they met the criteria. The first variable to enter into the model was the one with the highest correlation with the dependent variable. A variable only entered the model if the probability of the *F*-ratio was less than 0.05 (probability of *F* to enter = 0.05). A variable was removed from the model if the probability of the *F*-ratio for the resulting model exceeded 0.10 (probability of *F* to remove = 0.10).

Independent variables at the instant of peak COF_U during weight acceptance included the relative position of the CM to the CP (CM–CP_{Angle}), as well as the velocity of the CM in the anterior–posterior direction ($CM_{Vel\ AP}$). Peak COF_U was the dependent variable. All statistics were calculated using the SPSS 10.0 statistical software (SPSS Inc., Chicago, IL).

TABLE 2—*Center of mass kinematic variables at time of peak utilized coefficient of friction during weight acceptance (n = 49).*

Kinematic Variables	Mean	SD	Minimum	Maximum
$CM_{Vel\ AP}$ (m/sec)	1.6	0.2	1.3	2.0
$CM\text{-}CP_{Angle}$ (°)	13.6	2.3	9.4	18.9

$CM_{Vel\ AP}$, velocity of center of mass in the anterior–posterior direction (+, anterior); $CM\text{–}CP_{Angle}$, angle of center of mass to center of pressure (expressed relative to vertical).

Results

On the average, self-selected walking velocity of the participants was 1.6 ± 0.2 m/sec (range, 1.2–2.0 m/sec). The mean peak COF_U was μ = 0.23 ± 0.03 (range, μ = 0.14–0.34), and occurred 90 msec following initial contact (range, 33–143 msec). At the instant of peak COF_U, the CM was always located posterior (mean = 0.227 m), medial (mean = 0.052 m) and superior (mean = 0.970 m) to the CP. The CM velocity at the time of peak COF_U averaged 1.6 m/sec in the anterior direction. The average $CM\text{–}CP_{Angle}$ at the time of peak COF_U was 13.6° (Table 2).

Relation between CM Kinematic Variables and Peak COF_U

The $CM\text{–}CP_{Angle}$ at the instant of peak COF_U was the best predictor of peak COF_U during weight acceptance ($r = 0.750$; $p < 0.001$), accounting for 56% of the variance. Greater $CM\text{–}CP_{Angles}$ were associated with higher peak COF_U (Fig. 3). The $CM_{Vel\ AP}$ also was a significant predictor of peak COF_U ($r = 0.591$; $p < 0.001$) with faster $CM_{Vel\ AP}$ being associated with higher peak COF_U (Fig. 4). The combination of the subject's $CM\text{–}CP_{Angle}$ and the $CM_{Vel\ AP}$ improved the prediction of peak COF_U, and together explained 62% of the variance ($r = 0.784$; $p < 0.001$; Fig. 5; Table 3).

Discussion

Recognition of factors that contribute to high COF_U during walking is essential for identification of individuals and/or situation-specific circumstances which present the greatest risk for slip onset. Consistent with the initial hypothesis of this study, both the $CM\text{–}CP_{Angle}$ and $CM_{Vel\ AP}$ were significant predictors of peak COF_U.

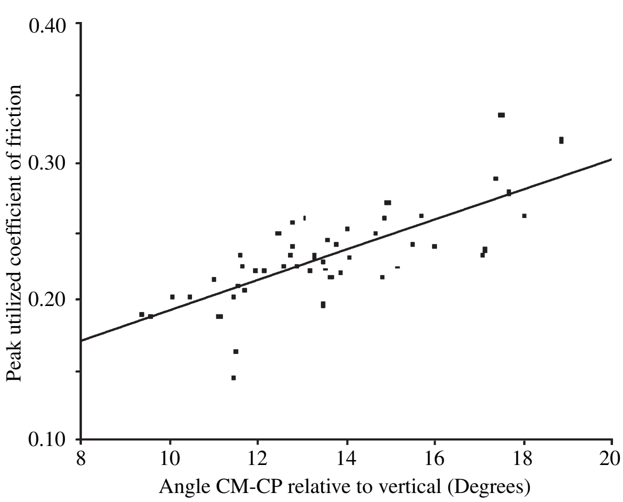

FIG. 3—*Scatter plot and fit showing the relationship between $CM\text{–}CP_{Angle}$ and peak utilized coefficient of friction ($r = 0.750$; $R^2 = 0.563$; $p < 0.001$).*

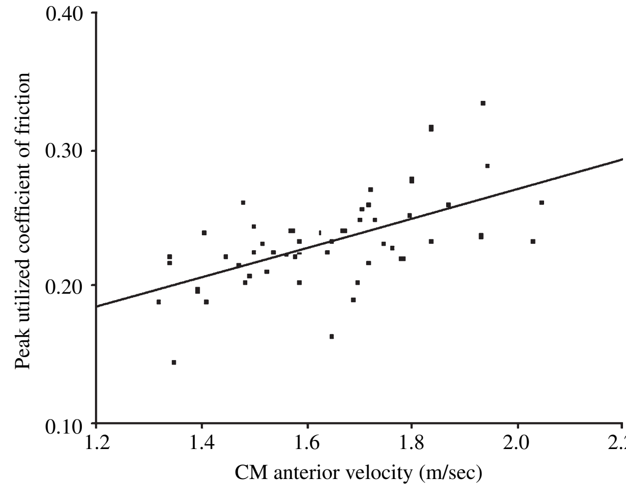

FIG. 4—*Scatter plot and fit showing the relationship between $CM_{Vel\ AP}$ and peak utilized coefficient of friction ($r = 0.591$; $R^2 = 0.349$; $p < 0.001$).*

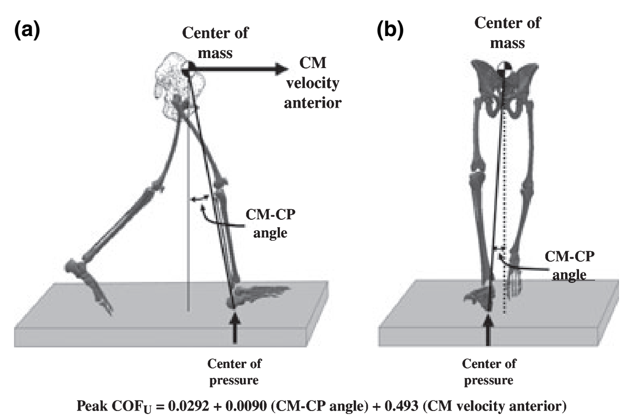

FIG. 5—*Significant predictors of peak utilized coefficient of friction during weight acceptance from sagittal (a) and frontal (b) perspective. The $CM\text{–}CP_{Angle}$ (expressed relative to vertical) in combination with the CM velocity in the anterior direction accounted for 62% of variance in peak COF_U ($r = 0.784$; $p < 0.001$).*

TABLE 3—*Simple and partial correlation coefficients for center of mass kinematic variables and peak utilized coefficient of friction.*

	Utilized COF	
Kinematic Variables	*r*	*r* (partial)
$CM\text{-}CP_{Angle}$	0.750*	0.634
$CM_{Vel\ AP}$	0.591*	0.345

*Correlations significant at $p < 0.001$ level.

The $CM\text{–}CP_{Angle}$ was the best predictor of peak COF_U, with larger $CM\text{–}CP_{Angles}$ being associated with greater peak COF_U. The finding that peak COF_U increased with greater $CM\text{–}CP_{Angles}$ is consistent with the basic premise proposed by Ekkebus and Killey (9). These authors proposed that increases in the initial contact impact angle of the limb with the ground would be associated with greater peak COF_U.

The Ekkebus and Killey (9) model, however, was based on assumptions that likely contributed to the inability to accurately predict peak COF_U. For example, these authors viewed the leg as a rigid strut which would transmit forces to the ground with a ratio of shear to vertical forces proportional to the angle of impact. In actuality, however, the leg is not a rigid strut as motion (22,23) at the knee and ankle occurs between the time of initial contact and the time of peak COF_U (24,25). In addition, the Ekkebus and Killey model (9) used the hip joint center and foot to define the angle of inclination, while the current study used the alignment of the CM to the CP at the instant of peak COF_U. In the current model, the $CM–CP_{Angle}$ accounted for 56% of the variance in peak COF_U during walking compared to the model proposed by Ekkebus and Killey which accounted for less than 30% of the variance (11,14).

Instantaneous velocity of the CM in the anterior direction ($CM_{Vel\ AP}$) also was a significant predictor of peak COF_U, with greater $CM_{Vel\ AP}$ being associated with higher peak COF_U. While the $CM_{Vel\ AP}$ represented the instantaneous velocity of the CM at the instant of peak COF_U, post-hoc analysis revealed a strong correlation to each subject's average walking speed ($r = 0.942$; $p < 0.001$).

The finding of faster $CM_{Vel\ AP}$ being associated with higher peak COF_U is consistent with a number of previously reported average over-ground velocity-COF_U relationships (11,12,16); however, others have not found this relationship to be consistent (17,18). Fendley and colleagues (16) noted a fair positive correlation ($r = 0.41$; $p < 0.001$) between walking speed and peak COF_U in a single male subject walking at speeds ranging from approximately 102 to 160 m/min. Similarly, Skiba (12) reported that peak COF_U increased with walking speed, though specific subject data were not provided.

Burnfield and Powers (11) reported that average peak COF_U increased from $\mu = 0.22$ at the slow walking speed (57 m/min) to $\mu = 0.26$ at a fast walking speed (132 m/min) in their study of 60 subjects between the ages of 23 and 79 years. However, the variation with speed differed for the male and female subjects. In males, the average peak COF_U increased from $\mu = 0.20$ at the slow speed to $\mu = 0.28$ at the fast speed. In females, the average peak COF_U ($\mu = 0.24$) did not change across the three walking speeds. Tisserand (17) reported that peak COF_U during weight acceptance (range, $\mu = 0.08–0.15$) did not demonstrate a significant relationship to walking speed in a study of three subjects walking at speeds ranging from 90 to 165 m/min. As the age and gender of this limited number of subjects was not reported, it is difficult to compare these results to other studies.

Three mechanisms can be used to increase walking velocity, lengthening stride, increasing cadence, or a combination of both (14,22,26–28). Increasing velocity by lengthening stride, would likely lead to a greater $CM–CP_{Angle}$ as the CP would be farther anterior to the CM. Based on the results of the current study, a greater $CM–CP_{Angle}$ would contribute to a higher COF_U than would have resulted from the $CM_{Vel\ AP}$ increase alone. Such findings suggest that individuals who increase stride length to achieve a faster walking velocity may experience greater increases in peak COF_U compared to those who increase cadence to achieve a faster walking speed.

The findings of the current investigation also suggest that person-specific anthropometric characteristics may increase an individual's risk for slip initiation. Individuals with shorter legs who take similar length steps as individuals with longer legs could conceivably have increased $CM–CP_{Angles}$, due to the lowered height of the CM. Such results suggest that individuals with shorter legs who take longer steps may experience higher peak COF_U during weight acceptance than individuals with longer legs taking a similar step length. In addition, significant trunk leans which alter the CM location relative to the CP may also contribute to differences in peak COF_U across individuals. Further research is needed to test these assumptions.

Conclusions

In summary, both $CM–CP_{Angle}$ and $CM_{Vel\ AP}$ served as predictors of peak COF_U during weight acceptance. The identified relationships between CM kinematics and peak COF_U provide insight into how gait and individual anthropometric characteristics may increase risk for slip initiation in certain individuals. However, only 62% of the variance in peak COF_U could be explained by the model, suggesting further investigation is required to identify other factors that influence COF_U values.

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