

MODELING THE ONSET OF SLIP DURING WALKING

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Introduction

Slips are a leading cause of falls and injuries in the home and work environments¹. During walking, the forces generated by the body are transmitted through the foot to the floor. In order to prevent a slip, sufficient friction (traction) is required at the foot floor interface. The probability of a slip event rises as either the friction that a person utilizes (COF_U) increases or the friction that is available from the floor surface (COF_A) decreases². In the research setting, a person's COF_U during walking is calculated from force plate recordings. The COF_U is defined as the ratio between the shear and vertical components of the ground reaction force. The COF_A of the floor surface can be measured using a device called a tribometer. Ultimately, the onset and outcomes of slips are determined by dynamic interactions between human and environmental factors.

Purpose

The objective of this work was to develop a dynamic model of slipping in order to determine the interaction between human (center of mass (CM) velocity; COF_U) and environmental factors (COF_A) on slip outcome using an experimentation and dynamic simulation approach.

Significance

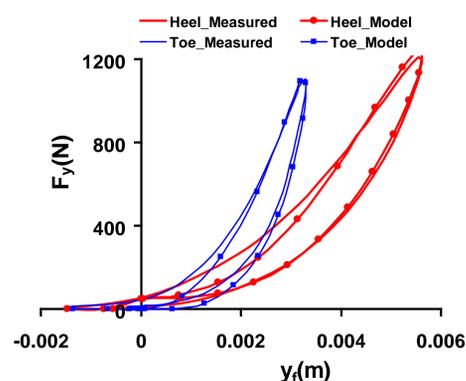
The reduction of deaths from falls has been identified as a national priority in Healthy People 2010 Objectives for Improving Health. Modeling and simulation can be used to identify specific individuals or environmental conditions that pose the greatest risk for slip onset and could serve as a basis for proactive human (gait, strengthening) and environmental (footwear, flooring) interventions to reduce the risk of falls and injuries.

Experimentation

Experimental kinematic (120Hz, VICON), kinetic (1200Hz, AMTI), and video data were recorded simultaneously as a healthy 30 year old female (height 1.59 m; mass 65.7 kg) walked at a self-selected speed under conditions of normal and reduced floor surface slip resistance. The subject wore a fall-arresting body harness to ensure safety, and was provided with a pair of walking shoes (Rockport model MWT18) for use during testing. Following multiple non-slip walking trials, WD-40 was applied to the surface of the force platform to initiate a forward heel slip. Whole body center of mass velocity in the horizontal direction (CMV_x) was calculated from kinematic data. The peak COF_U value during weight acceptance was determined from ground reaction forces recorded during speed matched non-slip walking trials. The COF_A of the clean and contaminated floor surface was measured using a variable incidence tribometer (English XL). To determine the material properties associated with the forefoot and heel regions of Rockport walking shoes, ten separate pairs were tested (MTS 858 Test System). The average vertical force-deformation relationships from material testing were modeled using an exponential function:

$$F_y = k|y_f|^{2.45} + C|y_f|^{1.8} \dot{y}_f + 50$$

with $k = 3.8 \times 10^8$ (heel), 8.4×10^8 (toe) and $C = 2.0 \times 10^7$ (heel), 9.0×10^7 (toe).



Model

A two-dimensional 8-segment model representing the combined head and torso, arms, and right and left thighs, shanks, and feet plus non-linear visco-elastic elements representing the shoe/floor contact forces at the heel and toe region was formulated as a differential equation of the form:

$$M(q)\ddot{q} + V(q, \dot{q}) + G(q) = Q + \left[\frac{\partial P_l}{\partial q} \right]^T \lambda_l + \left[\frac{\partial P_r}{\partial q} \right]^T \lambda_r$$

q = Generalized coordinates

Q = Generalized forces

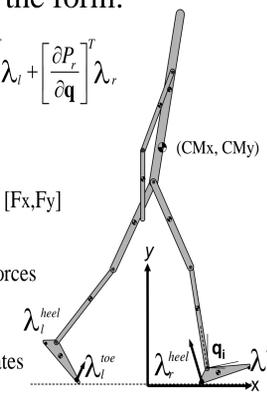
λ_l, λ_r = Reaction constraint forces = $[F_x, F_y]$

$M(q)$ = Mass matrix

$V(q, \dot{q})$ = Centrifugal and Coriolis forces

$G(q)$ = Gravitational forces

$\frac{\partial P_l}{\partial q}, \frac{\partial P_r}{\partial q}$ = Contact position coordinates



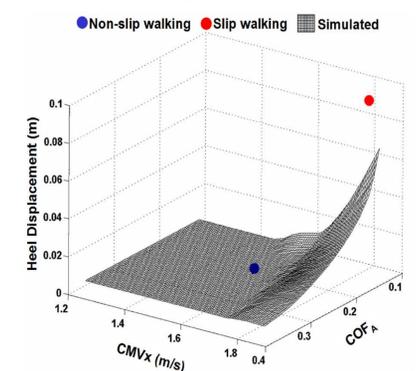
The model was implemented using a dynamics simulation software package (ADAMS, Mechanical Dynamics). Initial model conditions from measured values were used. Experimental joint kinematics data from walking trials served as model input. The stiffness (k) and damping (C) constant values in the vertical contact force model (F_y) were determined from the shoe testing results. The coefficient of friction (COF_A) range of the horizontal contact force model ($F_x = COF_A * F_y$) were determined from experimental results and subsequently varied in the simulation study.

Simulation

A simulation study was performed to assess the influence of CMV_x and floor surface slip resistance on the magnitude of slips. The CMV_x at heel strike was incrementally adjusted for each available slip resistance value (COF_A). At each simulated condition, the stance leg heel horizontal displacement 400ms after heel strike was determined. The result showed the causal relationship between these mechanical conditions and the magnitude of forward heel displacement. The simulated region was then compared with the experimentally observed non-slip and slip walking trials.

Results

The peak COF_U during non-slip walking trials (●) was $\mu = 0.246 (\pm .014)$ while the available slip resistance (measured with the tribometer) was $\mu = 0.88$. The available slip resistance during the slip walking trial (●) was $\mu = 0.17$. In this condition CMV_x at heel strike = 1.9 m/s resulted in 0.1m heel displacement. From the simulation study (■), maximum slip onset (heel displacement = 0.08m) occurred at lowest slip resistance ($\mu = 0.1$) and highest heel strike CM velocity (CMV_x = 1.81 m/s). At the experimentally observed velocity (CMV_x = 1.61m/s), the slip resistance ($\mu < 0.1625$) resulted in a slip condition. In order to minimize forward heel slip displacement at faster CM velocities, greater available slip resistance was required.



Discussion

Both greater horizontal CM velocity and reduced floor surface slip resistance were associated with increased simulated forward heel displacement during walking. Future work will be directed at further model development and determining the impact of other human (e.g., impact angle of the leg, strength) and environmental factors (shoe stiffness) on slip onset and recovery potential.

References

1. Berg et al (1997). Age and Ageing, 26(4), 261-268.
2. Hanson et al (1999). Ergonomics, 24(12), 1619-1633.