The Mechanical Principle of Slipping When Walking on Motion Surface with Different Acceleration

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Abstract. The contact force and the required friction coefficient were tested when people walking on motion platform with different accelerations by gait friction tester, forces acting on the body in different gait phases were analyzed, and the effect of the platform acceleration on mechanical principle of slipping was discussed. The results showed that the peak value of the required coefficient of friction (RCOF1) in landing phase increased with increasing of platform acceleration when people walking on accelerated motion platform, which was easy to slip; The peak value of the required coefficient of friction (RCOF2) in taking off phase decreased with larger acceleration, and the slipping tendency decreased. The required coefficient of friction could be decreased by adjusting the gait parameters and the motion of the body gravity center to reduce the possibility of slipping.

Introduction

The slipping and falling accidents are serious problem often happened in workplace and daily life, which lead to great economic cost and psychological pain [1-3]. Many researches were done to reduce the tendency of slipping [4-7]. Slipping happens more easily when people walking on moving, swing vehicles such as ship, train, plan and offshore platform [8].

Studies showed that the ground reaction forces acting on the foot were lateral force FX, sagittal force FY and normal force FZ. There was a peak value in landing phase and taking off phase of each curve respectively [9, 10]. The required coefficient of friction (RCOF) could be achieved by the level component divided by the normal component of the contact force between foot and ground [11]. Slipping would be happened if the required coefficient of friction (RCOF) exceeded the static friction coefficient (us) between ground and the shoe sole. So larger peak value of RCOF made people slip easily [12]. That is, the tendency of slipping increased with $ΔCOF = \mu_s - RCOF$ increasing.

Physical and mathematical models of centrobaric motion trajectory were established by analyzing and simplifying the feature of human body walking in literature [13]. Gait cycle consisted of single support phase and double support phase when people walking, the trajectory of body center of mass (BCOM) in different phases was shown in Fig.1. The trajectory in single support phase was arc AC, which center was the center of pressure (COP) of the left foot, and the radius 11 is the height of the body center of mass (BCOM) when people standing upright, and in double support phase the trajectory was arc CE with radius of trunk length around the head. The horizontal component $a_{xy}$ and normal component $a_{yz}$ of inertial acceleration were shown in Fig.1 when people walking in different phases.

In literature [13], mechanism of slipping and falling was analyzed during walking on level and slope according to the force and moment equilibrium. On the basis of these, how the acceleration affected the required coefficient of friction was analyzed in this paper, and the effect of the acceleration on mechanism of slips and falls was discussed too.
Methods

Apparatus
A self-developed step friction tester (SFT) was used to collect data. The SFT was composed of a 6-degree-of-freedom electromechanical motion platform and two force plates. The upper platform was a walkway with 1.5m wide and 5.0m long, the material of the walkway was steel plate with regular juts on its surface. Two force plates were installed in the middle of the walkway along the length. The structure of the experimental apparatus and force plates were shown in Fig.2. The kinematic data of the platform and the ground reaction forces of subjects walking on the test surfaces were sampled and recorded at 1000 Hz.

Experimental Design and Procedure
The platform reciprocated continuously along the Y axis, the equation of motion was \( X = A \sin(2\pi ft) \), and that of the acceleration was \( a = \ddot{X} = -4\pi^2 f^2 A \sin(2\pi ft) \), \( a_{\text{Max}} = 4\pi^2 f^2 A \), where \( A, f, \) and \( t \) were amplitude, frequency and time of the platform motion respectively. The motion amplitude was 0.3m, the maximum acceleration were 0 m/s², 0.118 m/s², 0.473 m/s², 1.065 m/s² respectively.

Twenty males took part in this experiment. The average and standard deviation of weight, height and age for all participants were 68.2 ± 7.77kg, 175.1 ± 6.19 cm, 22.1 ± 1.73 years respectively. The platform started to move first, each of subject was allowed to be familiar with the motion first, and then was instructed to walk at 1.2m/s speed (controlled by metronome) and 0.7m step length, same shoes were used (the sole was rubber). All subjects completed the trials at different accelerations and completed 10 times repeatedly at each of accelerations. The gait parameters that the subject walking direction was opposite to that of the platform acceleration were chosen to study.

Data Analysis
The ground reaction force values were normalized to body weight (BW). The required coefficient of friction (RCOF) values were gotten from the detected contact force which in lateral was \( RCOF_{x} = \frac{F_{x}}{F_{z}} \), in anterior–posterior was \( RCOF_{y} = \frac{F_{y}}{F_{z}} \) and the integrated coefficient of friction was \( RCOF = \frac{F_{x} + F_{y}}{F_{z}} \). The peak value of RCOFX, RCOFY, RCOF in landing phase and taking phase were \( RCOF_{X1} \) and \( RCOF_{X2} \), \( RCOF_{Y1} \) and \( RCOF_{Y2} \), \( RCOF_{1} \) and \( RCOF_{2} \).

Results and Discussion

The Analysis of Slipping Mechanism
When walking direction was opposite to that of the platform acceleration \( a \), the inertia force \( F=ma \) would act on the subject and the direction was same to that of walking. The forces acting on the subject in single phase AB (landing phase) were shown in Fig.3a. Point O was the body center of mass
(BCOM), the forces acting on it include gravity \( G \) \( (G=mg) \), inertia force \( F_{ge} \), \( F_{gy} \), \( F_{gy} \), and \( F \), where \( m \) was the mass of the subject. Point \( P \) was the pressure center of sole (COP), the forces acting on it included the support force \( N \), friction force \( f \), where \( N=F_{gz} \), \( f=F_{gy}.h \) was the vertical distance from point \( O \) to walkway, \( y \) was the distance from \( P \) to the intersection point of vertical line through BCOM and the walkway, \( \theta \) was the angle between the line \( OP \) and the gravity line, the value of \( h, y \) and \( \theta \) changed continuously during walking.

![Figure 5. Force analysis in single support phase.](image)

The walking process was dynamic, the BCOM lifted up and down gradually, the forces and gait parameters were not constant. The BCOM must be balanced dynamically to prevent slipping, that was, the forces and the moments acting on the body should be zero \( (\sum F=0, \sum M=0) \) according to the force and moment balance principle, so the equations (1) and (2) could be gotten as follows:

\[
\begin{align*}
F_{ge} + F_y - f & = 0 \\
F_{ge} + N - G & = 0 \\
f \cdot h - N \cdot y & = 0
\end{align*}
\]

\[
R_{COF} = \frac{f}{N} = \frac{y}{h} = \frac{F_{ge} + F_y}{G-F_{gy}} = \tan \theta
\]

The equation (2) showed that the friction force \( f = F_{gy} + F_{gy} \) increased with the acceleration increasing in single support phase AB when the direction of platform acceleration was opposite to that of walking, the required coefficient of friction \( R_{COF} \) \( R_{COF} = \frac{f}{N} = \tan \theta \) increased, and \( \Delta_{COF} = \mu - R_{COF} \) decreased, so the slipping tendency increased. The horizontal component of acceleration \( a_{gy} \) of BCOM should be decreased when walking to decrease \( F_{gy} \) and \( f \), which would reduce the value of RCOF, so the tendency of slipping would be decreased. The height of BCOM \( h \) could be decreased by enlarging the step length to satisfy the equation (1) to reduce the possibility of slipping.

Force analysis in single support phase BC was shown in Fig.3b, the direction of \( F_{gy} \) was opposite to that of walking. According to the force and moment balance principle, equations (3) and (4) could be gotten as follows:

\[
\begin{align*}
f + F_y - F_{gy} & = 0 \\
F_{gy} + N - G & = 0 \\
f \cdot h - N \cdot y & = 0
\end{align*}
\]

\[
R_{COF} = \frac{f}{N} = \frac{y}{h} = \frac{F_{gy} - F_y}{G-F_{gy}} = \tan \theta
\]

Equation (4) showed that the friction force \( f = F_{gy} - F_y \) acting on tiptoe decreased with the acceleration increasing in single support phase BC, the required coefficient of
friction $RCOF = \frac{f}{N} = \tan \theta$ decreased, and $\Delta COF = \mu_r - RCOF$ increased, so the tendency of slipping backward decreased. Slipping forward would be happened if the acceleration increased to $F_a = ma \geq F_{g},$ because the equilibrium of equation (3) was not satisfied.

The inertia force $F_{gy}$ should be increased by adjusting the velocity of BCOM when the acceleration of platform increased to ensure balance. To some extent, larger $h,$ smaller step length could satisfy the equation (3), which could reduce the possibility of slipping.

The Effect of Platform Acceleration on Slipping

The friction coefficient $RCOF_x$ in lateral changed little with the increasing of platform acceleration $r=0.30 \ p \ 0.01$ during walking (shown in Fig.4a). The integral friction coefficient $RCOF$ was determined by the sagittal $RCOF_y,$ the tendency of them was consistent when platform acceleration increasing (shown in Fig.4b and 4c). The peak value $RCOF_1$ increased and $\Delta COF = \mu_r - RCOF$ decreased with larger acceleration, and the heel was easy to slip backward (shown in Fig.4c). The friction force $f_1$ must be increased to balance the increasing of the inertia force $F_a,$ which to satisfy the equilibrium of force and moment instantly, the value of $RCOF_1$ increased, and the possibility of slipping increased. The peak value $RCOF_2$ decreased and $\Delta COF = \mu_r - RCOF$ increased with larger acceleration, the slipping tendency of tiptoe decreased. These because the direction of $f_2$ was same to that of $F_a,$ the equilibrium equations of force and moment could be satisfied by reducing $f_2.$

![Figure 4. The required coefficient of friction (RCOF) under different accelerations.](image)

Conclusion

(1) In landing phase, the peak value $RCOF_1$ increased by the increasing of platform acceleration when people walking on the platform with negative acceleration motion, the danger of slipping increased; Peak value $RCOF_2$ in taking off phase decreased with larger platform acceleration, and the slipping tendency decreased.

(2) The peak value of the required coefficient of friction could be decreased by adjusting the horizontal acceleration of BCOM $a_{gy},$ which changed inertia force $F_{gy}$ and friction force $f_1$ and $f_2,$ and the slipping tendency would be decreased. At the same, the equilibrium equation of force and moment could be satisfied by adjusting the step length to reduce the possibility of slipping.

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Reference


