Evaluation for slip resistance of floor sheets and shoe sole with newly developed mobile friction measurement system

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In general, slip-resistant floors and shoes become a necessity. To develop and design floors and shoes with high slip resistance, precise measurement of the coefficients of friction between actual floors and shoes under comparable test conditions to real walking conditions is essential. Slip initiation relates to the static coefficient of friction (SCOF), and slip continuity relates to the dynamic coefficient of friction (DCOF). According to previous studies, SCOF and DCOF values of more than 0.4 are preferable for locomotion without slips and falls. The authors have recently developed a cart-type mobile measurement system for both SCOF and DCOF at the shoe-floor interface. The slip resistance of commercially available flooring sheets and shoe soles was evaluated using this new system. On the basis of the friction test, a rough surface with hard particles had a high SCOF (0.72±0.06) and DCOF (0.55±0.02), i.e. a high slip-resistant floor surface, when a flat outsole without patterns slid on it. Approximately the same slip resistance was obtained when a commercially available safety shoe sole was tested, regardless of flooring type.

Practitioner Summary: This study included the development of a cart-type mobile measurement system for the coefficients of friction at the shoe-floor interface, and indicated the efficacy of this system in evaluating the slip resistance of floors and shoes.

Keywords: Slip resistance, measurement system, floor, shoe, coefficient of friction

1. Introduction

In Japan, the number of fatalities resulting from falling accidents has exceeded that of traffic accidents. The victims of these accidents are almost always elderly people (Kawajiri et al., 2001). In the industrial field, the proportion of fatalities resulting from falling accidents was more than 20\% of all fatalities. Therefore, falling accidents have become a significant problem for society. Slip is one of the leading causes of falling accidents (Courtney et al., 2001). Thus, high slip-resistant flooring and shoes are required. To develop these floors and shoes, it is necessary to evaluate the slip resistance. Slip initiation relates to the static coefficient of friction (SCOF), and slip continuity relates to the dynamic coefficient of friction (DCOF). According to previous studies, SCOF and DCOF values of more than 0.4 are preferable for locomotion without slips and falls (Pilla, 2003, Grönqvist et al., 2003, Nagata et al., 2009). Therefore, precise measurement of the friction coefficients between actual floors and shoes under comparable test conditions to real walking conditions is necessary for evaluating their slip resistance. Until now, there have been several measurement systems related to the assessment of slipperiness at the shoe-floor interface (Chang et al., 2001). However, a measurement system that satisfies all requirements does not exist.

In the present study, the authors have developed a mobile system to measure both SCOF and DCOF at the shoe-floor interface. Furthermore, the slip resistance of commercially available flooring sheets and shoe soles was evaluated using this new system.

2. Development of a mobile SCOF/DCOF measurement system for the shoe-floor interface

The newly developed system is a cart-type system, as shown in Fig. 1. This system was designed with several considerations: portability, measurement in a narrow space, measurement at slope, comparable normal load and sliding velocity conditions to real walking condition, measurement of both SCOF and DCOF at the same time and measurement against a variation in sliding velocity. The real walking condition includes 500 N of normal load (JIS T8101, 2006) and 0–1.0 m/s of sliding velocity (Chang et al., 2001). The traction forces were measured with a load cell coupled to a connecting rod. An acceleration sensor was placed on
top of the test footwear. The angle of slope was measured using an angular sensor. The time of slip onset was determined by the moving velocities, which were calculated from the integrated acceleration. Variations in sliding velocities occurred easily because of the cart-type system, resulting in the occurrence of an inertial force. The coefficient of friction, \( \mu \), at the shoe-floor interface, corrected for the inertial force and the angle of slope, is expressed as

\[
\mu = \frac{f_h}{f_n} = \frac{F - m(g \sin \theta + a_h)}{mg \cos \theta}
\]

where \( f_h \) is the horizontal reaction force, \( f_n \) is the vertical reaction force, \( F \) is the traction force required to drag the test footwear, \( m \) is the total mass of the test footwear with mechanical foot and weight, \( g \) is the gravity acceleration, \( \theta \) is the slope angle (ascent is positive) and \( a_h \) is the horizontal acceleration against the floor surface.

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Figure 1. Schematic diagram of the newly developed mobile SCOF/DCOF measurement system for shoe-floor interfaces.

Figure 2 shows as example of time variations in sliding velocity, acceleration and coefficient of friction between a flat shoe and commercially available flooring sheet obtained using the system and equation. We were able to measure SCOF from the onset of slip. DCOF was measured against the sliding velocities, with variation. Furthermore, the corrected coefficients of friction were different from the uncorrected ones, which indicated that inertial forces could not be ignored in this system. The corrected coefficients of friction were confirmed to have good match with those obtained from a force plate. The SCOF between the test shoe and test floor was 0.45. Therefore, this combination had a high slip resistance at slip initiation. In contrast, the DCOF at a sliding velocity of 0.2 m/s was 0.27. The sliding velocity was based on a criterion for safety shoes in Japan (JIS T8101, 2006). This combination had a risk, which was a continuing slip after a slip onset. Thus, the slip resistance of actual floors or shoes can be evaluated using this system.
Figure 2. Time variations in sliding velocity, acceleration and coefficient of friction. The test shoe had a flat surface without any tread pattern. The shoe sole was made from nitrile-butadiene rubber with a Shore hardness of A80 and a surface roughness $R_a$ of 0.04 $\mu$m. The test flooring sheet was for outside slopes, which had a parallelogram block pattern. The total mass of the footwear with mechanical foot and weight was 52.5 kg. The slope angle was 0°. The lubrication condition was a 90 wt% of glycerol solution ($\eta = 0.122$ Pa·s at 20°C).

3. Evaluation of the slip resistance of flooring sheets and shoe soles

As test floors, six commercially available flooring sheets were selected (Fig. 3). Floor A had a smooth surface without any block pattern. Floor B included hard particles in the surface. The direction and interval of each block pattern was different among floors C to E. The block pattern of floor C was oval and its height was approximately 300 $\mu$m. Floor D had a parallelogram block pattern with a height of 500 $\mu$m. This floor was used in Section 2. Floor E had a tightly arranged half-cylinder pattern with a height of approximately 600 $\mu$m. Floor F had grid-like grooves with a height of approximately 1000 $\mu$m. As test shoes, we selected those with a flat outsole and no block pattern as well as commercially available safety shoes (Fig. 4). The flat-soled shoe was used in Section 2. The safety shoe sole had a Shore hardness of A56. The total mass of footwear and weight was the same as in Section 2. The flooring sheets were set on a level floor and covered with a 90 wt% glycerol solution.
SCOFs for the flat shoes are shown in Fig. 5. The error bars indicate the maximum and minimum coefficients of friction among the results collected under the same experimental conditions, and the plots show the average values. The SCOF of floor A was the lowest (0.14±0.06), and that of floor B was the highest (0.72±0.06). Fluid film between the flat shoe and floor A was not removed, because the local contact pressures in the flat-flat interface were low. In contrast, the fluid film between the flat shoe and floor B was easily removed, because the local contact pressures at the interface were high due to the included hard particles. For floors C, D and E, the roughness of the block patterns was thought to contribute to the high SCOFs, which were about 0.60. Figure 6 shows the relationships between the DCOFs and the sliding velocities. The DCOFs of floor A increased with sliding velocity. However, the maximum value was 0.21. Floor F had almost the same low values of DCOF against the sliding velocity. The deep grooves on floor F acted as oil pockets. Conversely, the DCOFs of floors B, C, D and E decreased with increasing sliding velocity. For these floors, hydrodynamic lubrication components at the contact interfaces increased with the sliding velocity. The DCOFs of floor D were smaller than those of floor A at sliding velocities over 0.5. Floors C and E exhibited DCOFs of about 0.35 at low sliding velocities and about 0.25 at high sliding velocities. The DCOFs of floor B were high (more than 0.40), at sliding velocities of up to 0.5 m/s.
The relationships between SCOFs and DCOFs for the flat shoes are shown in Fig. 7. Floors A and F showed low SCOFs (≤ 0.4) and low DCOFs (≤ 0.4). Therefore, these floors were considered to have poor slip resistance, which were deemed unsafety. Floors C, D and E showed high SCOFs (> 0.4) but relatively low DCOFs (≤ 0.4). In contrast, floor B showed a high SCOF (> 0.4) and high DCOF (> 0.4). This floor was considered to have a high slip resistance.
SCOFs for the safety shoes are shown in Fig. 8. The SCOF of floor D was 0.38±0.10. Floors B and C showed a SCOF of about 0.35. The others exhibited low values of SCOF values (about 0.30). Figure 9 shows the relationships between DCOFs and sliding velocities for the safety shoes. The DCOFs of floor B decreased as sliding velocity increased. Conversely, the other floors had almost the same low DCOF values against the sliding velocity. There were fewer differences in DCOF for the safety shoes than there were for the flat shoes on the various floors.
Figure 9. Relationships between DCOFs and sliding velocities for the safety shoes.

The relationships between SCOFs and DCOFs for the safety shoes are shown in Fig. 10. For the safety shoes, all floors showed low SCOFs (≤ 0.4) and low DCOFs (≤ 0.4). Therefore, all floors did not have sufficient slip resistance against the safety shoes. The block patterns of the safety shoes were considered to have a huge effect on the frictional properties between the shoe sole and the floor.

Figure 10. Relationship between SCOFs and DCOFs for the safety shoes.
4. Conclusions

In the current study, we developed a mobile system to measure both SCOF and DCOF between a floor and shoe interface under normal load and sliding velocity conditions comparable to real walking conditions. This system can measure SCOF from the onset of slip and also can measure DCOF against the sliding velocities, with variation. The newly developed measurement system could identify the difference in slip resistance of commercially available flooring sheets slid against flat soled shoes. The floor with hard particles in the surface was considered to have a high slip resistance against the flat shoe sole because of high values of SCOF and DCOF (more than 0.4). On the other hand, none of the floors used in this study had sufficient slip resistance against the safety shoes. This means that the block pattern of these shoes had a huge effect on the frictional properties between the shoe sole and the floor, compared with the flat shoe sole. Although further study is needed, these results indicate the efficacy of this new measurement system in evaluating the slip resistance of shoes and floors surfaces.

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