Comparison of Three Different Slip Meters under Various Contaminated Conditions

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Objectives: To challenge the problem of slipperiness, various slipmeters have been developed to assess slip hazard. The performance of in-situ slipmeter is, however, still unclear under the various floor conditions. The main objectives of this study were to evaluate the performance of three kinds of slipmeters under real conditions, and to find their dynamic and kinematic characteristics, which were compared with gait test results.

Methods: Four common restaurant floor materials were tested under five contaminants. Slipmeters and human gaits were measured by high speed camera and force plate to find and compare their dynamic and kinematic characteristics.

Results: The contact pressures and built-up ratio were below those of subjects. The sliding velocity of British Pendulum Tester was above those of subjects, while those of BOT-3000 and English XL were below those of subjects. From the three meters, the English XL showed the highest overall correlation coefficient ($r = 0.964$) between slip index and $R_a$, while the rest did not show statistical significance ($p < 0.01$) between slip index and contaminants. The static coefficient of friction obtained with the BOT-3000 showed good consistency and repeatability ($CV < 0.1$) as compared to the results for the BPT ($CV > 0.2$) and English XL ($CV < 0.2$).

Conclusion: It is unclear whether surface roughness can be a reliable and objective indicator of the friction coefficient under real floor conditions, and the viscosity of contaminants can affect the friction coefficient of the same floors. Therefore, to evaluate slipperiness, the performance of the slipmeters needed to improve.

Key Words: Floor surface, Dynamic and kinematic characteristics, Slip resistance, Field situations, Contaminants

Introduction

Slips and fall-related incidents in the workplace occur frequently and present a serious safety problem [1-3]. Occupational Health and Safety evaluation conducted in Korea showed that slips, trips and falls represented over 18% of occupational incidents in Korea [4]. Most of these incidents occurred when floor surfaces were contaminated with water, heavy oil, ice, or dust [1,2,4,5]. These contaminated conditions created insufficient friction between shoe heels/soles and floor interfaces.

In general, it is known that slip phenomena are related to various disciplines, involving biomechanics, tribology, neurophysiology, human cognition, and etc. Slip incidents are thus too complex to be understood through a single field [2].

To address the problem of slipperiness, various friction measurement devices have been developed to assess the level of slip hazard. These devices measure traction, torque, loss of energy, or the angle of inclination. Based on how they use these approaches, test devices may be categorized into drag-sled, pendulum, articulated strut, braked-wheel type testers, etc. [6].

Although many different types of friction measurement devices have been developed, there is no universally accepted...
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Test device or measuring method. Studies have shown wide disagreement about the results of these devices, even using the same floor conditions and contaminants [3,6-10]. These disparities may originate from the dynamic and kinematic characteristics of measuring devices, the physical properties of slider materials or the testing conditions (temperature, humidity). Other studies have shown strong correlation among tested devices, but different absolute values of friction coefficients [6,11]. An adequate reason for this has not yet been found.

It is known that the friction characteristics of elastomer relate to a number of factors, including normal load, tangential load, and the cone apex angle of asperity as well as the elasticity, viscoelasticity, and strength and hardness of the elastomer. The friction coefficient theoretically increases with a decrease in normal load and sliding velocity [12]. In addition, the surface roughness of slider rubber can abruptly change with wear, which will affect the friction coefficient [13,14].

Measuring devices may have different normal force, sliding velocity, slider rubber wear rate and slider conditioning procedures, and so may be expected to show different results. Normal force and sliding velocity are not at present able to be controlled. Therefore, test conditions and the slider conditioning procedure should be carefully prepared.

Most of the above studies were performed in laboratory test conditions, with few comparisons of in-situ slip testers in real contaminated conditions. The performance of these testers in real world situations thus remains unclear.

The current paper evaluates the performance of three commonly used slip meters under various real conditions, using floor materials and contaminants commonly found within the kitchen and hall areas of restaurants. The test conditions and slider conditioning procedure in this study were constantly maintained. The evaluated slip testers were the dreg-sled (BOT-3000; Regan Scientific Instruments, Southlake, TX, USA), the articulated strut (English XL; Excel Tribometers, LLC, Greer, SC, USA) and the British Pendulum Tester (BPT; All test Ltd., Melrose, UK).

Materials and Methods

Measuring devices for slip resistance properties

Three different types of slip meters were measured with force plate (Bertec 4060; Bertec Co., Columbus, OH, USA) and high speed camera (FASTCAM SA1.1; Photron Inc., San Diego, CA, USA) to examine dynamic and kinematic characteristics (Fig. 1). Slipping dynamic and kinematic characteristics of twelve subjects were also measured with the same tools.

Fig. 2 shows the dynamic and kinematic measurements of the three slip meters and human subjects. Two-dimensional markers (the yellow and black check square and circle pattern in Fig. 2) were attached to the moving parts of slip meters and the shoes of subjects. The slip phenomena were recorded with force plate (1,000 Hz) and high speed camera (1,000 fps), and then analyzed with a motion analysis program (TEMA motion; Photo-Sonic Inc., Burbank, CA, USA). The built-up ratio was calculated using the frictional force trace (force-time data) measured with force plate.

As shown in Fig. 2A, the BOT-3000 is a drag-sled type device that measures the static coefficient of friction (SCOF) of a particular surface area between its slider and the floor surface. The device can also be used to measure the dynamic coefficient of friction (DCOF) of a given surface area by adjusting its travel distance while maintaining an almost constant forward speed (0.2-0.23 m/s).
Fig. 2B shows an English XL, also called a Variable Incidence Tribometer, which is an inclined-strut slip meter driven by gas pressure. The sensor slider impacts the floor surface with force at inclined angle from the vertical direction, so that it has a horizontal component to its velocity. In the initial contact between slider and floor, the slider edge is the first contact and the slider rotates on that contact edge. The normal force is gradually increased from 0 to its maximum value. The slip index can be interpreted as a transitional COF at a contaminated condition, while the slip index can be interpreted as SCOF at a dry condition.

Fig. 2C shows a BPT, which was originally designed to simulate the action of a slipping foot (Fig. 2C). This tester uses a swinging dummy heel, which sweeps over a set area of flooring in a controlled manner [15]. The device is often used to assess the skid resistance of roads. This device measures in British Pendulum Number (BPN) values, which are fundamentally the same as DCOF at a contaminated condition. However, the time-force graph of this device showed quite similar results to the SCOF when measured on rough dry surface. In general, BPN is equivalent to DCOF × 100, but there are a number of small differences between these values. BPN is therefore generally converted into DCOF using a conversion table.

**Measuring device for surface roughness**

Surface roughness primarily records surface texture, and a value used for surface analysis [14]. In this study, a micro-roughness gauge (Surtronic Duo; Taylor Hobson Ltd., Leicester, UK) with a 5 μm radius diamond stylus was used to measure the center line average ($R_a$) and maximum height of profile ($R_z$) among a number of surface roughness parameters. The British Slip Resistance Group reported that measurement of the ‘$R_z$’ parameter allow slipperiness to be predicted for a range of common materials [15]. Other studies [16-18] have reported that ‘$R_z$’ has a strong correlation with the friction coefficient. It is generally known that the surface roughness of a floor is directly related to slip resistance in the presence of contaminants such as water or oil. Because of this, the correlation coefficients of the
surface roughness ($R_a, R_z$) were compared in this study with the slip resistance values of BPN, Slip Index, DCOF and SCOF.

**Floor and slider materials**

For floor materials, this study used ceramic, vinyl, and asphalt tile with and without a wax coating. Vinyl and asphalt tile are frequently used in restaurant dining areas, whereas ceramics are widely used in restaurant kitchens. Because devices could not use footwear (or sole) specimens, specific types of slider material were adopted to measure slip resistance properties. Slider materials for each test device were supplied by their respective manufacturers. The BPT used a 4S rubber slider (hardness 96 ± 2; shore A) for all surface conditions. Two different sliders were supplied with the BOT-3000, but only the Neolite slider (Regan Scientific Instruments, hardness 92 ± 1; shore A) was tested in this study because the leather alternative could not be used in contaminated conditions. The English XL used a Neolite slider (hardness 92 ± 1; shore A). Each slider was cleaned and conditioned before every test, according to test conditions (floors and contaminants) and was washed with ethanol solution (50%) and distilled water then dried at ambient temperature. Each slider was also conditioned with P400 grit abrasive paper and then any debris was removed with a dry soft brush. However, the sliders tested with engine oil were changed, because the chemical and physical properties of the rubber materials could have been affected by chemical reaction between rubber and engine oil.

**Surface contaminants and roughness**

Slip resistance tests were conducted under five surface conditions: dry, wet, detergent solution, soy bean oil, and engine oil (Mobil 20W-50). Table 1 shows the physical properties of the contaminants used in this study. Every contaminant was kept airtight in a constant-temperature container. The contaminants were removed with a paper towel, washed with ethanol solution (50%) and distilled water, and dried at ambient temperature for each trial. The test conditions were 23 ± 2°C and 50 ± 5 rh%, as described in KS M ISO 13287: 2008. Twelve consecutive measurements were performed for each floor and each contaminant, then the lowest and highest values were discarded and the reminders were averaged. This comprised 240 observations (4 floors × 6 contaminants × 10 accepted measurements) of COF.

To simulate wetted and detergent-spilled conditions, floor surfaces were evenly covered and thoroughly wetted with spray bottles. The used water was distilled water and the detergent solution was made of sodium hypochlorite (4 wt%) with distilled water. To simulate oil-spilled conditions, the oils were poured onto the sample floors with a syringe and spread evenly with a brush. The floor surfaces were replenished with all contaminants for every trial.

Table 2 shows the surface roughness results of the floor specimens. These results were based on the data from ten consecutive measurements at five different locations for all sample surfaces. These measurements were made in the direction of sliding to which the three slip meters were operated.

So as to prevent floor and slider surfaces roughness change through wear, all slider surfaces were conditioned with abrasive paper (grit size: P400) for every trial, while the sample floors were replaced for every test. The roughness of floor surfaces was checked and averaged for every test. The roughness of both surfaces therefore was assumed to be similar in all tests.

**Subjects**

Twelve healthy male subjects aged between 20 and 50 participated in this study. The subjects were 36.5 ± 8.54-years old (mean ± standard deviation), 171 ± 3.81 cm tall and had a mass of 72.7 ± 5.29 kg. Subjects reported no history of lower-back pain or orthopedic abnormalities of the lower extremities. Each subject wore a safety harness and the same kind of footwear. They walked over the contaminated floors, which were equipped with force plate. When they slipped, their trajectories and the reaction force of their foot were recorded with the force plate and high speed camera. Foot pressure was measured with an insole type foot pressure measurement system (Padar-X; Novel, Munich, Germany).

Prior to participation, each subject was fully informed about this study, and signed a consent form approved by the Institutional Review Board of the Korea Occupational Safety and Health Agency.

**Table 2. Summary of surface roughness results for the floor specimens**

| Tested materials          | $R_a,\mu m$ | $R_z,\mu m$ |
|---------------------------|-------------|-------------|
| Ceramic                   | 3.69 (0.79) | 16.01 (3.80) |
| Vinyl                     | 2.46 (1.28) | 6.43 (2.81)  |
| Asphalt tile A (without wax) | 1.82 (0.48) | 12.14 (2.36) |
| Asphalt tile B (with wax) | 0.90 (0.28) | 3.93 (1.25)  |

Values are mean (standard deviation).
Results

Table 3 shows the dynamic and kinematic characteristics of the three slip meters during slipping trials. Viscosity, roughness, hardness, velocity, and force were all measured. A simple equation was used to calculate the built-up ratio: the maximum normal force was divided by the time between zero and normal force at maximum level.

The contact pressures (normal force) and built-up ratios of the slip meters were below those of subjects. The sliding velocity of the BPT was above those of subjects, while those of the BOT-3000 and English XL were below.

The BPT showed the highest SCOF value (1.14) on the asphalt tile B floor, while the other slip meters showed the highest SCOF value (XL: 0.78, BOT: 1.00) on the ceramic floor under the dry condition. The ranks of SCOF values were different from each other (Table 4). The SCOF of the BPT and XL were calculated by the maximum normal force at the initial stage of

### Table 3. The specifications of slip testers and gait, measured with high speed camera

| Test device   | Normal force (N)* (pressure [kPa]) | Sliding velocity (m/s) | Built up ratio (kN/s) | Contact time prior to slip (s) |
|---------------|-----------------------------------|------------------------|-----------------------|--------------------------|
| BOT-3000      | 22 (157)                          | 0.20-0.23†             | 0.13                  | 0.6                      |
| English XL    | 18 (23)                           | 0.9-1.2                | 0.23                  | NA                       |
| BPT           | 33 (144)                          | 2.95-3.2               | 3.34                  | NA                       |
| Human subject | ~600† (100-300)                   | 1.5                    | ~10                   | 0.045                    |

BPT: British Pendulum Tester. NA: not available.
*Measured max value at point of slip. If measured on dry surface, then the results varied with inclined angle, floor materials, etc [2]. †Only dynamic test mode, ~about 70% of subject’s weight.

### Table 4. Static coefficient of friction results obtained with slip meters under the dry condition

| Test device   | Ceramic     | Vinyl       | Asphalt tile A | Asphalt tile B |
|---------------|-------------|-------------|----------------|----------------|
| BPT           | 1.02 (0.070)| 0.94 (0.031)| 0.98 (0.056)   | 1.14 (0.069)   |
| English XL    | 0.78 (0.039)| 0.74 (0.041)| 0.61 (0.057)   | 0.63 (0.065)   |
| BOT-3000      | 1.00 (0.003)| 0.95 (0.050)| 0.95 (0.058)   | 0.88 (0.065)   |

BPT: British Pendulum Tester. Values are mean (standard deviation).

### Table 5. Pearson’s correlation coefficients between roughness parameter and slip resistance values using three kinds of slip meters under the different contamination conditions

|              | $R_s$ | $R_s$ |
|--------------|-------|-------|
|              | BPT   | XL    | BOT (SCOF) | BOT (DCOF) | BPT   | XL    | BOT (SCOF) | BOT (DCOF) |
| Dry          | -0.593| 0.876 | 0.965      | -0.187     | -0.428| 0.408 | 0.870      | -0.146      |
| Wet          | 0.580 | 0.936 | 0.463      | -0.063     | 0.864 | 0.519 | 0.860      | 0.567       |
| Water-detergent | 0.647 | 0.964 | -0.186     | -0.010     | 0.964 | 0.906 | 0.459      | 0.608       |
| Soybean oil  | 0.920 | 0.945 | 0.040      | 0.966      | 0.844 | 0.658 | 0.529      | 0.909       |
| Engine oil   | -0.986| *     | -0.098     | 0.945      | -0.690| *    | 0.424      | 0.562       |
| Overall      | 0.315 | 0.964 | 0.165      | 0.027      | 0.832 | 0.603 | 0.683      | 0.560       |

BPT: British Pendulum Tester. XL: English XL, BOT: BOT-3000. SCOF: static coefficient of friction, DCOF: dynamic coefficient of friction. *Values too small for comparison.
contact between the slider and dry floor. If the floors were contaminated with fluids such as water and oil, the devices could not perfectly show any maximum friction force during the contact period.

Of the three slip meters, the English XL showed the maximum overall correlation coefficient \( r = 0.964 \) between the slip index and \( R_s \) under all floor conditions, while the others slip meters showed comparatively low correlation between slip resistance values and roughness parameters, from an overall viewpoint (Table 5).

All the slip meters used in this study showed relatively high correlation coefficients \( r = 0.817-0.987 \) between the viscosities of contaminants and slip resistance values (Table 6).

Table 6. Correlation coefficients between viscosities of contaminants and mean slip resistance values of all floors

| BPT (BPN) | XL (SI) | BOT (SCOF) | BOT (DCOF) |
|-----------|---------|------------|------------|
| 0.933     | 0.984   | 0.817      | 0.987      |

BPT: British Pendulum Tester, XL: English XL, BOT: BOT-3000, BPN: British Pendulum Number, SI: slip index, SCOF: static coefficient of friction, DCOF: dynamic coefficient of friction.

Table 7. Means (standard deviations) of all tested devices and test conditions

| Surface condition | Floor material | 4S-rubber | Neolite | Neolite |
|------------------|----------------|-----------|---------|---------|
|                  | BPT (BPN)      | XL (SI)   | BOT (SCOF) | BOT (DCOF) |
| Dry              | Ceramic        | 83.6 (5.78) | 0.78 (0.039) | 0.999 (0.003) | 0.786 (0.154) |
|                  | Vinyl          | 78.37 (2.56) | 0.74 (0.041) | 0.95 (0.050) | 0.529 (0.048) |
|                  | Asphalt tile A | 81.52 (4.66) | 0.6125 (0.057) | 0.945 (0.059) | 0.547 (0.030) |
|                  | Asphalt tile B | 93.9 (5.70) | 0.63 (0.065) | 0.876 (0.065) | 0.302 (0.090) |
| Wet              | Ceramic        | 18.93 (4.60) | 0.545 (0.079) | 0.573 (0.138) | 0.435 (0.036) |
|                  | Vinyl          | 12.37 (1.83) | 0.467 (0.107) | 0.44 (0.048) | 0.19 (0.036) |
|                  | Asphalt tile A | 22.42 (3.86) | 0.23 (0.024) | 0.65 (0.094) | 0.615 (0.031) |
|                  | Asphalt tile B | 4.32 (0.70) | 0.188 (0.042) | 0.36 (0.029) | 0.365 (0.006) |
| Detergent solution | Ceramic       | 15.52 (3.34) | 0.24 (0.055) | 0.332 (0.035) | 0.306 (0.017) |
|                  | Vinyl          | 4.98 (1.95) | 0.132 (0.020) | 0.149 (0.014) | 0.116 (0.013) |
|                  | Asphalt tile A | 15.07 (6.18) | 0.135 (0.041) | 0.48 (0.059) | 0.428 (0.062) |
|                  | Asphalt tile B | 1.33 (1.18) | 0.073 (0.013) | 0.321 (0.012) | 0.238 (0.029) |
| Soybean oil      | Ceramic        | 4.55 (1.17) | 0.065 (0.011) | 0.22 (0.012) | 0.123 (0.013) |
|                  | Vinyl          | 3.6 (0.85) | 0.026 (0.019) | 0.186 (0.009) | 0.058 (0.010) |
|                  | Asphalt tile A | 3.58 (0.72) | - | 0.41 (0.018) | 0.06 (0.014) |
|                  | Asphalt tile B | 3.36 (0.89) | - | 0.144 (0.014) | 0.02 (0.007) |
| Engine oil       | Ceramic        | 5.43 (0.87) | - | 0.192 (0.020) | 0.043 (0.009) |
|                  | Vinyl          | 6.62 (0.88) | - | 0.172 (0.008) | 0.038 (0.007) |
|                  | Asphalt tile A | 8.167 (0.56) | - | 0.397 (0.023) | 0.019 (0.003) |
|                  | Asphalt tile B | 9.5 (0.98) | - | 0.156 (0.008) | 0.01 (-) |

BPT: British Pendulum Tester, XL: English XL, BOT: BOT-3000, BPN: British Pendulum Number, SCOF: static coefficient of friction, DCOF: dynamic coefficient of friction.

Discussion

The dynamic and kinematic characteristics of three slip meters...
were measured with high speed camera and force plate, and were compared with those of human gait. The slip resistance properties of the four commonly-used floor surfaces were measured by three measuring devices under dry and contaminated conditions.

If the dynamic and kinematic characteristics of slip meters do not mimic human behavior, then the output of these meters is not reliable [11]. Based on previous literature [11] and biomechanical observation of slipping (Table 3), a slip meter’s built-up ratio, normal contact pressure, sliding velocity, and contact time prior to sliding should all be considered as relevant parameters. Generally, friction will decrease with an increase in normal contact pressure. Therefore all the slip meters used in this study over-estimated the friction between floor surface and slider. The English XL’s normal force 18 N combined with its 7.55 cm² contact area results in a contact pressure of 23 kPa, which is far below the desired pressure range of 200 to 1,000 kPa [2] and the measured pressure range of 100 to 300 kPa (Table 3). It was considered that the lowest contact pressure was demerit for English XL.

The BTP sliding velocity of 2.95 to 3.2 m/s was about twice of that of human slip velocity (Table 3). Grönqvist et al. [6] calculated the borderline slip distance \( s \) between an avoidable and unavoidable fall using Equation 1 as follows:

\[
s = \frac{v^2}{2g/\mu}
\]

Where \( g \) is the acceleration of gravity, \( v \) is the velocity of sliding, and \( \mu \) is the COF. Since the threshold value of the BPT was about 0.25 (BPN = 25) and the sliding velocity was about 3 m/s, the calculated slip distance before stopping would be 1.84 m. Strandberg and Lanshammar [19] estimated that the borderline slip distance between an avoidable and unavoidable fall is about 6 cm. Using the sliding velocity of our subjects (1.5

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**Fig. 3.** British Pendulum Number (BPN) results for the four floors in dry and contaminated conditions.

**Fig. 4.** Slip index results for the four floors in dry and contaminated conditions.

**Fig. 5.** Static coefficient of friction (SCOF) results from the BOT-3000 for the four floors in dry and contaminated conditions.

**Fig. 6.** Dynamic coefficient of friction (DCOF) results from the BOT-3000 for the four floors in dry and contaminated conditions.
m/s) and the COF (0.44) calculated from Burnfield and Power [20] in Equation 1, the calculated slip distance before stopping would be 5 cm. This result shows that if the sliding velocity of BPT is not reduced or its threshold value is not increased, BPT cannot be used to assess pedestrian slip resistance.

The built-up ratio is considered an important factor for whole-shoe devices such as the STM 603 (Satra, Northamptonshire, UK) or BST 2000 (BST Maschienen-Vertriebs, Wuppertal, Germany) and is thus an important factor for subjects, but does not apply to in-situ slip meters.

Since the contact time prior to sliding was correlated with the squeeze film effect, this factor did considerably affect the slip resistance when the floor was contaminated with fluids. Because the normal and tangential movements of the BPT and English XL happened simultaneously, their contact times could not be measured and could have been nearly zero. The contact time of the BOT-3000 was longer than those of subjects. Since this condition might increase the squeeze film effect between the slider of the BOT-3000 and floor surface, SCOF values of BOT-3000 were higher than the others when floor surfaces were contaminated with fluids (Fig. 4).

It has been reported that surface roughness is a reliable and objective indicator of the friction coefficient, despite some ambiguities about the relationship [1,16,17]. The SCOF results were thus compared with roughness under the dry condition, the results of which are presented in Table 4. The BPT showed the highest SCOF for the asphalt tile B, which had the lowest roughness ($R_z, R_a$). This is a similar result to Elleuch et al. [16], excluding the findings for ceramic material. The SCOF measured by the BOT-3000 was approximately increased with $R_z$. The English XL had the smallest SCOF as compared with the other devices and its SCOF was increased with $R_z$ except for asphalt tile B. As a result, the SCOF results from all tested devices did not coincide under the dry condition. This result could also be interpreted by the suggestion that the friction film effect is related to floor material properties as well as surface roughness. This makes it unclear whether the surface roughness tested in this study would be a reliable and objective indicator of the friction coefficient (Table 4).

The contaminants used in this study are frequently found in kitchen areas and can be considered to be factors which reduce friction at the shoe-floor interface during walking. In general, the presence of such contaminants makes measurement of slip resistance difficult due to the complex viscoelastic characteristics of the rubber involved [12]. However, all slip meters showed a relatively high correlation coefficient between the viscosities of contaminants and slip resistance values in this study. Since the hardness of slider rubbers was higher than those of a general outsole (hardness 70; shore A) and the contact pressures between slider and floor were lower than those of shoe and floor, the viscoelastic effect of the sliders from all tested devices might have been reduced. It was however considered that all the tested slip meters could distinguish the level of slip hazard for the contaminants.

The BPN showed a statistically significant difference ($p < 0.01$) between the dry and contaminated condition, but results were not statistically significant among the contaminants (Table 7). It therefore appeared that the BPT could not assess contaminant type when compared with the other two devices under the contaminated conditions [10]. The BPN measurements for all the floor materials were found to be below the danger threshold (BPN < 25) in the contaminated conditions (Fig. 3). This probably resulted from the BPT device operating at a very high sliding velocity (2.8 m/s; Table 1) and having a very short contact time (Table 3), which may not appropriately simulate typical human ambulation speed.

The English XL was able to distinguish between all the floor materials and contaminant conditions ($p < 0.01$) except those with oils (Table 7). It was therefore not suited for measuring viscous contaminants such as oil, because this device did not distinguish between the oily conditions ($p > 0.05$; Table 7). The results from this device also showed that the rougher a surface ($R_z$) became, the higher the indicated slip index was (Table 5). It therefore seemed to overcome the well-known squeeze film effect that arises from the delay between the moment of shoe contact with the surface and the initiation of horizontal motion under a wetted condition [15]. The device may thus be well suited for wetted conditions, including from detergent solutions.

The good repeatability of the BOT-3000 likely resulted from a fact that it was automatically driven forward by a powered motor and measured the SCOF using a strain gauge. As a result, human errors originating from operating and reading were minimized. The drag sled type devices similar to BOT-3000 often show wet DCOF readings that are unrealistically higher than dry ones [18]. This phenomenon could originate from the poor squeeze-film situation. Since the frictional force measurement system (the strain gauge type sensor) of the BOT-3000 seems to be sensitive to frictional vibrations and often experiences a squeeze-film effect, the reliability of this device's DCOF results could unexpected deteriorate under a wet condition [18].

Overall, the results showed that the performances of the three devices used for measuring floor slipperiness were affected by floor characteristics and the presence of contaminants on the floor.
One of the limitations of the current study is that although the slip meters used were strongly dependent on the operator, these measurements were just performed by one operator. Thus these results could not assure reproducibility, but could guarantee repeatability.

In summary, the results from the different devices were not necessarily compatible with each other for all floor material and contaminant conditions. It should be cautioned that comparing the data collected from a field investigation with different types of slip meters could be inadequate. Therefore, to evaluate slipperiness in field situations, the performance of the slip meters used in this study still need to improve.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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References

1. Li KW, Chang WR, Leamon TB, Chen CJ. Floor slipperiness measurement: friction coefficient, roughness of floors, and subjective perception under spillage conditions. Saf Sci 2004;42:547-66.
2. Chang WR, Courtney TK, Grönqvist R, Redfern M. Measuring slipperiness, human locomotion and surface factors. London, New York (NY): Taylor & Francis; 2002. 182 p.
3. Ricotti R, Delucchi M, Cerisola G. A comparison of results from portable and laboratory floor slipperiness testers. Int J Ind Ergon 2009;39:353-7.
4. The statistics of occupational injuries and diseases [Internet]. Incheon (Korea): Korea Occupational Safety and Health Agency. 2006 [cited 2012 Feb 27]. Available from: http://www.koshare.or.kr/board?tc=RetrieveBoardListCmd&boardType=A&contentId=178530&pageNum=1&urlCode=T3[Y]55516|6|46|551555|/board[N]table=&searchField=TITLE&searchInput=/.
5. Mills R, Dwyer-Joyce RS, Loo-Morrey M. The mechanisms of pedestrian slip on flooring contaminated with solid particles. Tribol Int 2009;42:403-12.
6. Grönqvist R, Hirvonen M, Tohva A. Evaluation of three portable floor slipperiness testers. Int J Ind Ergon 1999;25:85-95.
7. McElvaney LF. Proceedings of the Sixth Southeastern Safety and Health Conference and Exhibition, 1992. Atlanta (GA): Georgia Tech Research Institute; 1993. 227 p.
8. Dutrue F, Degas G. Experimental analysis of main test devices used for evaluation of skid resistance. In: Seppala P. Luopaja T, Nygård CH, Mattila M, eds. Experience to Innovation. Vol. 3. Helsinki (Finland): Finnish Institute of Occupational Health; 1997. p. 371-3.
9. Harris GW, Shaw SR. Slip resistance of floors: user’s opinions, tortus instrument readings and roughness measurement. J Occup Accid 1988;9:287-98.
10. Grönqvist R, Hirvonen M, Tohva A. Control of floor slipperiness: evaluation of three portable test devices. In: Kumar S, ed. Advances in occupational ergonomics and safety X. Amsterdam (Netherlands): IOS Press; 1998. p. 96-9.
11. Chang WR, Matz S. The slip resistance of common footwear materials measured with two slipmeters. Appl Ergon 2001;32:549-58.
12. Zhang SW. Tribology of elastomers. Tribology and interface engineering series. No. 47. San Diego (CA): Elsevier; 2004. p. 14-27.
13. Kim IJ, Smith R. Observation of the floor surface topography changes in pedestrian slip resistance measurement. Int J Ind Ergon 2000;26:581-601.
14. Kim IJ, Smith R, Nagata H. Microscopic observations of the progressive wear on shoe surfaces that affect the slip resistance characteristics. Int J Ind Ergon 2001;28:17-29.
15. Assessing the slip resistance of flooring [Internet]. Merseyside (UK): Health and Safety Executive. 2007 [cited 2009 Mar 10]. Available from: http://www.hse.gov.uk/pubns/web/slips01.pdf.
16. Elleuch R, Elleuch K, Abdelouis HB, Zahouani H. Surface roughness effect on friction behavior of elastomeric material. Mater Sci Eng A 2007;465:8-12.
17. Chang WR, Hirvonen M, Grönqvist R. The effects of cut-off length on surface roughness parameters and their correlation with transition friction. Saf Sci 2004;42:755-69.
18. Chang WR. The effect of surface roughness on dynamic friction between neolite and quarry tile. Saf Sci 1998;29:89-105.
19. Strandberg L, Lanshammar H. The dynamics of slipping accidents. J Occup Accid 1981;3:153-62.
20. Burnfield JM, Power CM. Influence of age and gender on utilized coefficient of friction during walking at different speeds. In: Marpet MI, Sapienza MA, eds. Metrology of pedestrian locomotion and slip resistance. West Conshohocken (PA): ASTM International; 2002. p. 3-16.