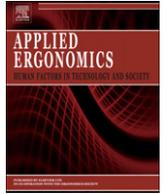


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Functional levels of floor surface roughness for the prevention of slips and falls: Clean-and-dry and soapsuds-covered wet surfaces

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ABSTRACT

Literature has shown a general trend that slip resistance performance improves with floor surface roughness. However, whether slip resistance properties are linearly correlated with surface topographies of the floors or what roughness levels are required for effective slip resistance performance still remain to be answered. This pilot study aimed to investigate slip resistance properties and identify functional levels of floor surface roughness for practical design applications in reducing the risk of slip and fall incidents. A theory model was proposed to characterize functional levels of surface roughness of floor surfaces by introducing a new concept of three distinctive zones. A series of dynamic friction tests were conducted using 3 shoes and 9 floor specimens under clean-and-dry as well as soapsuds-covered slippery wet environments. The results showed that all the tested floor–shoe combinations provided sufficient slip resistances performance under the clean-and-dry condition. A significant effect of floor type (surface roughness) on dynamic friction coefficient (DFC) was found in the soapsuds-covered wet condition. As compared to the surface roughness effects, the shoe-type effects were relatively small. Under the soapsuds-covered wet condition, floors with 50 μm in R_a roughness scale seemed to represent an upper bound in the functional range of floor surface roughness for slip resistance because further increase of surface roughness provided no additional benefit. A lower bound of the functional range for slip resistance under the soapsuds-covered wet condition was estimated from the requirement of $\text{DFC} > 0.4$ at $R_a \cong 17 \mu\text{m}$. Findings from this study may have potential safety implications in the floor surface design for reducing slip and fall hazards.

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1. Introduction

Slips and falls are one of the leading categories of non-traffic incidents in terms of serious injuries and fatalities. They can happen to anyone but are more common and significant as we get older. More than one third of adults 65 and older fall each year in the United States (Hornbrook et al., 1994; Hausdorff et al., 2001). About 2.2 million nonfatal fall injuries among the older adults were treated in emergency departments and more than 581,000 of these patients were hospitalized (CDC, 2010). In 2007, 18,000 people 65 and older died from unintentional fall injuries (CDC, 2010). The death rates from falls among older men and women have risen sharply over the past decade (Stevens, 2006). There is no doubt that falls are one of the leading causes of morbidity and mortality in the

older populations and consequently a major threat to the wellbeing and quality of life to the elderly people. They are also a primary cause of workplace injuries as well as being one of the leading causes of injury related deaths for the workers age 65 and over (Berg et al., 1997; Layne and Landen, 1997; Larry, and Pollack, 2004).

There have been prolonged efforts to identify and understand the main causes of fall incidents throughout the world (Redfern et al., 2001). It has been found that one of the most common precipitating events leading to a fall is loss of traction or slip resistance between the shoe soles/heels and floor surfaces. As a result, the shoe sole-floor grip or slip resistance property has been measured as a coefficient of friction (COF). Hence, knowledge about friction demand and friction available is recognized as one of the major factors for fall safety evaluation. Despite many years of investigation and fabrication of numerous testing machines for the slip resistance measurement, none of them is internationally adopted as a standard model yet, because each of them has some advantages and disadvantages in its design and testing performance. In fact, because each testing instrument has different

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concepts, systemic parameters and mechanical principles, it can be misleading to adopt a reference COF value without any citation to the instrument used for the slip resistance measures.

Recent studies have highlighted the importance of surface roughness on slip resistance evaluations and measured a number of surface roughness parameters to identify any correlations between the surface coarseness and slip resistance properties (Harris and Shaw, 1988; Proctor and Coleman, 1988; Stevenson et al., 1989; Manning et al., 1991; Proctor, 1993; Manning and Jones, 1994; Grönqvist, 1995; Jones et al., 1995; Rowland et al., 1996; Wilson, 1996; Manning et al., 1998; Chang, 1998, 1999, 2000, 2001, 2002; Fendley et al., 1999; Chang and Matz, 2000; Kim and Smith, 2000, 2003; Kim et al., 2001; Kim, 2004a,b; Kim, 2006a,b; Kim and Nagata, 2008a,b). As stated in those studies, there are convincing evidences that surface roughness on the shoe and floor surfaces affect slipperiness significantly. Surface roughness provides necessary drainage spaces to avoid squeeze film formations under lubricated conditions. Proper tread patterns on the heel surfaces could also improve traction properties by providing void spaces for the removal of contaminants and leading to an increase in direct contact with the floor surfaces. Therefore, macro-roughness or tread patterns have been commonly designed into the heel areas, but they become inadequate quickly after being worn.

On the other hand, topographic characteristics of the floor surfaces could rather drastically enhance the traction performance than ones of the shoes (Kim et al., 2001; Kim, 2004a,b) because the floor surfaces may provide sharper, taller and tougher asperities in their surface features than the shoes. These topographic characteristics may extend upward through any lubricating films sufficiently to engage with the bottom areas of the heel surfaces in a manner like sandpaper. While increasing the slip resistance properties of floor surfaces would be desirable as a general rule, a very high coefficient of friction (COF) may impede safe and comfortable ambulation (Chaffin et al., 1992). In addition, maintaining or increasing the floor surface roughness requires high processing costs. However, studies and guidelines on the functional levels of floor surface roughness required for optimal slip resistance performance are scarce. The objectives of this study were to investigate the effects of floor surface roughness on slip resistance performance under different environmental and shoe-type conditions, and identify functional levels of floor surface roughness as practical design information for the reduction of slip and fall incidents.

2. Main theory

2.1. Background

Almost all surfaces are rough on a microscopic scale and the variations in surface profiles could be represented by a random arrangement of peaks and valleys. When a shoe heel contacts a floor surface, it could be assumed that two such surfaces would touch only at tiny discrete areas where their highest asperities are in contact, as illustrated in Fig. 1(a). Because elastic modulus of the shoe soles/heels is considerably lower than that of flooring materials, there would be an interlocking mechanism between the shoe heel and floor surface (Fig. 1(b)). If the shoe heel slides on the floor surface, then the heel surface would be ruptured, deformed and ploughed by the wedge-shaped hard asperities of the floor surface. In this model, peak heights of the floor surface would be a vital factor affecting the heel contact-sliding mechanism. Therefore, high-peak related roughness parameters of the floor surface and their effects on slip resistance properties were mainly considered in this study.

For the high-peak related roughness parameters, R_t (maximum peak-to-valley height) and R_{tm} (maximum mean peak-to-valley

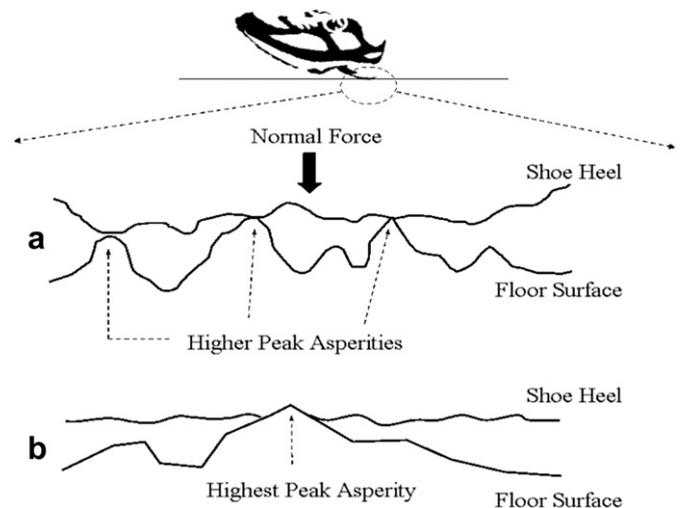


Fig. 1. Schematic diagrams for the detailed images of the contact-sliding interface between a shoe heel and a floor surface – (a) initial contact state and (b) interlocking mechanism.

height) were considered together with R_a (centre line average), which is the most widely used roughness parameter (Bibby, 1974; Thomas, 1999). The three roughness parameters have been previously used for assessing the effects of floor surface roughness on slip resistance performance (Harris and Shaw, 1988; Proctor, 1993; Manning and Jones, 1994; Kim and Smith, 2000, 2003; Chang et al., 2001; Kim et al., 2001; Leclercq and Saulnier, 2002; Kim, 2004b; Li et al., 2004; Kim and Nagata, 2008a,b).

2.2. Functional levels of surface roughness

It is hypothesized that surface roughness affects a DFC in a non-linear fashion and its effect is characterized by three distinctive zones (initial low-growth, steady-growth and plateau). In the initial DFC low-growth zone, multiple friction mechanisms are involved and the interlocking is still not effective; the DFC steady-growth zone reflects a dominance of the interlocking mechanism (where a linear relationship may be valid); while the plateau zone reflects the exhaustion of the interlocking mechanism (“no further benefit”). For practical purposes, it would be useful to find the most effective levels (the “functional range”) of floor surface roughness, which corresponds to the DFC steady-growth zone. The lower bound of the functional range would be determined by the requirement of $DFC > 0.4$, while the upper bound of the functional range would be at surface roughness values that do not provide further benefit to DFC values (or reach values comparable to performance in dry conditions).

3. Materials and methods

3.1. Instrumentation

3.1.1. Measurements of slip resistance performance

A pendulum-type hydraulic dynamic friction tester (Fig. 2) was used to quantify slip resistance performance in this study. This test machine consisted of two hydraulic systems with attached artificial foot, a force component transducer (Kistler 3-Component Dynamometer, Type 9257A), a desktop computer and an angular displacement transducer (Hoang et al., 1985, 1987; Stevenson et al., 1989; Lloyd and Stevenson, 1989, 1992). This tester was designed to simulate the movement and loading of the foot during heel strike

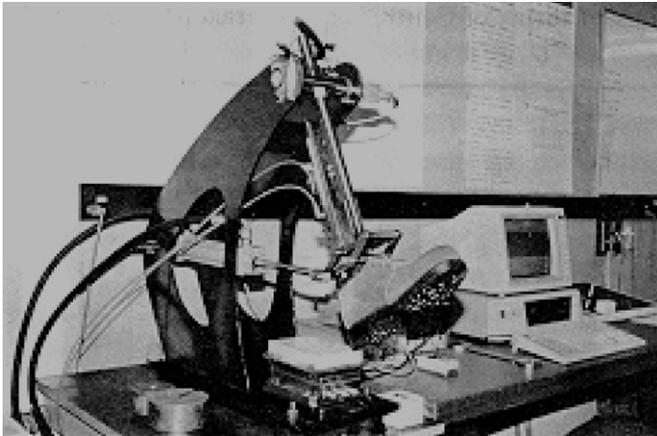


Fig. 2. A photograph for a pendulum-type hydraulic dynamic friction tester.

and initial-slip, and to quantitatively determine the slip requirement as a dynamic friction coefficient (DFC). The tester set up values could be adjusted to cover various parameters taken from human walking trials such as heel contact angle, vertical load and its rate of increase and sliding speed.

To adjust the heel contact angle, tapered shims were inserted between the base of the pendulum and the last on which the shoe was mounted. The vertical load was set by the length of the pendulum adjusted by two nuts. Some fine adjustment to the vertical load was also possible by a pressure control on the oil fed to the vertical hydraulic cylinder. The sliding speed was set by a flow control valve.

In this tester, the test shoe was firmly attached to a last and mounted at the end of the pendulum mechanism. To minimize any movement, the shoe was nailed to the last. The floor surface specimen was glued to a steel plate that was bolted onto the force component transducer. In a test, the shoe was driven forward by the horizontal hydraulic cylinder to contact the floor sample surface at the heel edge. Another hydraulic cylinder was mounted at the end of the pendulum to simulate the body weight portion supported by the leading foot at heel strike. The two hydraulic cylinders were in a common circuit supplied by a pump which was driven by an electric motor.

As the shoe heel passed across the floor sample surface, the frictional (horizontal: H) and normal (vertical: V) components of the resultant force were measured by the force component transducer. The speed of the test was measured by a rotary potentiometer driven by the pendulum shaft. The force component signals and potentiometer voltage were recorded on a personal computer which continually calculated the H/V force ratio. During the tests, the normal force was kept around 350 N and the sliding speed was controlled at 40 cm/s based on gait studies (Strandberg and Lanshammar, 1981; Hoang et al., 1985, 1987; Stevenson et al., 1989; Redfern and Bidanda, 1994; Jones et al., 1995). A heel contact angle of 9° was chosen by the result of previous biomechanical studies (Hoang et al., 1985, 1987; Stevenson et al., 1989; Lloyd and Stevenson, 1989, 1992; Stevenson, 1997).

Each shoe–floor–environment combination was tested ten times and the average was adopted as a DFC. The dynamic friction measurements were taken first on the clean-and-dry surfaces and then on the soapsuds-covered wet surfaces.

3.1.2. Measurements of floor surface roughness

Surface topographies of the floor specimens were measured by a Talysurf 5 profilometer (Taylor–Hobson) that had a conical stylus

with a spherical tip of 12 μm radius. To remove waviness components of the surfaces, a Gaussian filter was used with a 0.8 mm cutoff over a single traverse length of 17.5 mm. Surface profiles of the floor specimens were measured five times each at three different locations. Averages of the individual roughness measures were used for the analysis.

Peak height related roughness parameters such as R_t and R_{tm} were measured together with R_a roughness parameter. Details of the three roughness parameters are found in the literature (British Standards Institution, 1988; International Organization for Standardization, 1998; Kim and Smith, 2000; Chang et al., 2001).

3.2. Test conditions

3.2.1. Floor specimens

Nine commercially available new flooring specimens were used for the study. The floor specimens were carefully chosen to include surfaces within a wide range of different surface roughness. Table 1 shows a summary of the floor specimens with brief descriptions and measurement results of three surface roughness parameters. The floor specimens were thoroughly cleaned with demineralised water to eliminate any dirt and dust, dried and kept in plastic containers during the tests.

3.2.2. Shoe specimens

Three commercially available new shoes were used for the study. The shoes selected included a PVC and two Nitrile Rubber soles and heels. They were named as S1 (Nitrile Rubber: NR 1), S2 (Nitrile Rubber: NR 2) and S3 (PVC), respectively. The shoe specimens were thoroughly cleaned with demineralised water to eliminate any dirt and dust, dried and kept in plastic containers during the tests.

3.2.3. Environmental conditions

The three shoes were rubbed against the nine floor specimens under two different environmental conditions: 1) clean-and-dry surface and 2) soapsuds-covered slippery wet surface. A commercial type detergent (kinematic viscosity: 1.27 cSt at 16°C) was applied to generate the soapsuds-covered slippery wet surface condition. For consistency, a fixed amount of mixture of water and detergent (approximately 15 ml) was spread over the whole floor specimen (surface size: 110×170 mm) before conducting the tests.

Table 1

Summary of the floor specimens with brief descriptions and surface roughness parameters – R_a , R_t and R_{tm} .

Floor surface name	Floor surface brief description	Surface roughness parameter (μm)		
		R_a^a	R_t^b	R_{tm}^c
Terrazzo	Plain smooth terrazzo tile	0.96	8.23	4.85
Smooth vinyl tile	Plain smooth vinyl tile	1.55	13.61	10.26
Smooth metal plate	Smooth metal sheet	2.36	13.38	11.76
Smooth ceramic tile	Very smooth ceramic	3.43	27.50	17.29
Smooth concrete slab	Smooth steel trowelled concrete	6.59	54.00	35.80
Moderate rough ceramic tile	Moderate rough ceramic	14.54	85.51	61.75
Moderate rough concrete slab	Worn wood trowelled concrete	32.97	337.00	224.33
Rough concrete slab	Rough surface finish concrete	44.11	226.75	159.25
Rough ceramic tile	Rough ceramic	70.94	396.80	141.00

^a R_a = Center line average.

^b R_t = Maximum peak-to-valley height.

^c R_{tm} = Maximum mean peak-to-valley height.

3.3. Statistical design and analysis

Three-way analysis of variance (ANOVA) was performed to determine the significant effects of floor, shoe and environment variables and their interactions on the DFC. Polynomial regression models were used to evaluate the relationships between the floor surface roughness and DFC. Independent variables for the ANOVA included: the floor type (“Floor”) with nine different levels defined by the surface roughness magnitudes (measured in Ra , Rt and Rtm), the walking environment (“Environment”) with two conditions – a clean-and-dry surface and a soapsuds-covered wet surface and the shoe type (“Shoe”) classified by the sole/heel materials including two Nitrile Rubber and one PVC type heel/soles. The dependent variable was the dynamic friction coefficient (DFC). A DFC value of 0.4 was used as an acceptable criterion to determine the lower bound of the functional range of floor surface roughness (AS/NZS 4663, 2004). All statistical analyses were performed using SAS (Statistical Analysis System) software.

4. Results

The three-way ANOVA results revealed significant effects and interactions of Floor, Shoe and Environment variables on the DFCs. The regression models supported the theory hypothesis and facilitated to derive and visualize the functional levels of floor surface roughness.

4.1. Floor type and environment interaction

The $9 \times 3 \times 2$ (Floor \times Shoe \times Environment) ANOVA in Table 2 demonstrated a significant interaction between the Floor (surface roughness) and Environment variables on the DFCs. As expected, the DFC values increased significantly on the floor types with higher surface roughness and were drastically reduced on the soapsuds-covered wet surface condition as compared to the clean-and-dry surface one. However, the effect of floor type was only significant in the soapsuds-covered wet condition. Furthermore, DFCs were predicted by cubic functions of three roughness parameters: Ra , Rt and Rtm in Table 3. They indicated fairly good correlations between the roughness parameters of floor surfaces and DFC results for each individual shoe type under the soapsuds-covered wet surface condition.

Tables 4–6 show additional statistical information for the regression function parameters on the soapsuds-covered wet surface condition. They clearly demonstrate the significance of the three roughness parameters on DFCs. The cubic function of each parameter was a close representation of the main hypothesis that surface roughness affected DFCs in a non-linear fashion and its

Table 2
Summary of three-way analysis of variance (ANOVA) results among the shoes, floors and environments under the clean-and-dry and soapsuds-covered wet surface conditions.

Effect on DFC	DF	Sum of squares	Mean square	F value	Pr > F
Intercept	1	23.88414	23.88414	3759.61	<0.0001
Floor type ^a	8	0.76775	0.09597	15.11	<0.0001
Environmental condition	1	3.63326	3.63326	571.91	<0.0001
Shoe type	2	0.12579	0.06290	9.90	0.0016
Floor type*Environmental condition	8	1.12293	0.14037	22.10	<0.0001
Floor type*Shoe type	16	0.06736	0.00421	0.66	0.7902
Environmental condition *Shoe type	2	0.10153	0.05077	7.99	0.0039
Error	16	0.10165	0.00635		

^a Floor type as a categorical variable.

Table 3

SAS regression procedure: DFCs were predicted by cubic functions of Ra , Rt and Rtm parameters in the soapsuds-covered wet condition.

Model	DF	R-square	F value	Pr > F
Ra	3	0.837	39.43	<0.0001
Rt	3	0.874	53.07	<0.0001
Rtm	3	0.867	49.77	<0.0001

effect was characterized by three distinctive zones (initial low-growth, steady-growth and plateau).

4.2. Shoe type and environment interaction

The three-way ANOVA results in Table 2 also demonstrated a significant interaction between the Shoe and Environment variables on the DFCs. Some of the shoe types performed better than others, but this effect was evident only for a specific environmental condition. For example, S1 and S2 were better than S3 on the dry surface condition while S3 was better than S1 and S2 on the lubricated surface condition. However, overall the shoe-type-related effects were relatively small as compared to the surface roughness related ones.

4.3. Functional levels of surface roughness

All the floor types demonstrated high slip resistance properties (DFC > 0.4) when the walking condition was clean-and-dry (Fig. 3). However, under the soapsuds-covered wet condition (Fig. 3), most of the DFC values were largely reduced and recorded dangerously low levels (DFC < 0.4). Acceptable slip resistance performance was demonstrated only by the three floors with surface roughness >30 μm in Ra roughness scale: the moderate rough concrete slab, rough concrete slab and rough ceramic tile, respectively. As shown in Table 1, the Rt and Rtm parameters of these three floors also showed correspondingly high values. However, it also should be noted that the coarser floors, i.e. the rough concrete slab ($Ra = 44.11 \mu\text{m}$) and rough ceramic tile ($Ra = 70.94 \mu\text{m}$) did not provide any further increase of DFC values on the soapsuds-covered wet condition as compared to the moderate rough concrete slab ($Ra = 32.97 \mu\text{m}$).

Fig. 3 also presents the polynomial regression models for Ra , Rt and Rtm roughness parameters with regression lines of the DFCs under the soapsuds-covered wet conditions. The regression equations (cubic functions) demonstrate examples of possible functional relationships between the floor surface roughness parameters and DFC values for the lubricated condition. Using the regression models and the requirement for DFC > 0.4, it is estimated that the lower bound values for floor surface roughness would be at $Ra \cong 17 \mu\text{m}$, $Rt \cong 120 \mu\text{m}$ and $Rtm \cong 85 \mu\text{m}$. The regression curves on Fig. 3 also reveal that with increase of surface roughness the DFC values for the soapsuds-covered wet condition reach a maximum or a plateau after certain surface roughness values. From the regression models, it is estimated that the

Table 4

Detailed SAS regression results. DFCs were predicted by a cubic function of Ra in the soapsuds-covered wet condition.

Variable	DF	Par. estimate	Standard error	t value	Pr > t
Intercept	1	0.21876	0.04130	5.30	<0.0001 ^a
Linear	1	0.00264	0.00951	0.28	0.7838
Quadratic	1	0.00061311	0.00035666	1.72	0.0990
Cubic	1	-0.00000809	0.00000331	-2.45	0.0225 ^a

^a Indicates significant.

Table 5

Detailed SAS regression analysis results. DFCs were predicted by a cubic function of Rf in the soapsuds-covered wet condition.

Variable	DF	Par. estimate	Standard error	<i>t</i> value	Pr > <i>t</i>
Intercept	1	0.23576	0.03970	5.94	<0.0001 ^a
Linear	1	-0.00080780	0.00140	-0.58	0.5684
Quadratic	1	0.00002543	0.00000873	2.91	0.0079
Cubic	1	-5.31839E-8	1.439677E-8	-3.69	0.0012 ^a

^a Indicates significant.

maximum or plateau in DFC values is reached at around surface roughness $Ra \cong 50 \mu\text{m}$, $Rt \cong 300 \mu\text{m}$ and $Rtm \cong 200 \mu\text{m}$. These values could be considered as upper bounds for the functional ranges of surface roughness.

One of the smooth floor surfaces (< 10 μm in Ra roughness scale) showed relatively good slip resistance properties in the soapsuds-covered wet condition. However, the result was demonstrated only for a single floor–shoe combination, i.e., the smooth concrete slab ($Ra = 6.59 \mu\text{m}$) rubbed against the PVC shoe (S3) and thus should not represent an exception from the suggested functional range.

5. Discussion

5.1. Floor type and environment interaction

The interaction between the floor types and environmental conditions indicates that different mechanisms may be involved in slip resistance performance on the dry and contaminated surfaces. The significant correlation between the surface roughness and DFC values under the lubricated condition clearly supports the main theory of the role of floor surface roughness on slip resistance performance in this study. This result is consistent with previous studies reporting functional relationships between the surface roughness and DFC values under contaminated conditions (Chang, 1999, 2001; Manning and Jones, 2001). However, the lack of correlation between the surface roughness and DFC values under the clean-and-dry surface condition indicates involvement of multiple mechanisms of slip resistance properties and possible strong effects of other material characteristics such as wear development during the dynamic friction tests.

5.2. Shoe type and environment interaction

The interaction between the shoe types and environmental conditions demonstrates the importance of shoe selection for improving slip resistance on the contaminated surfaces. The results in this study suggest that the PVC shoe is a better choice for slip resistance in the contaminated condition. However, the overall relatively small effects of shoe type as compared to the floor type effects indicate that modification of the floor surface is a more effective strategy for reducing the risk of slip and fall incidents.

Table 6

Detailed SAS regression analysis results. DFCs were predicted by a cubic function of Rtm in the soapsuds-covered wet condition.

Variable	DF	Par. estimate	Standard error	<i>t</i> value	Pr > <i>t</i>
Intercept	1	0.23813	0.04449	5.35	<0.0001 ^a
Linear	1	-0.00139	0.00256	0.54	0.5940
Quadratic	1	0.00005315	0.00002720	1.95	0.0630
Cubic	1	-1.60083E-7	7.659792E-8	-2.09	0.0479 ^a

^a Indicates significant.

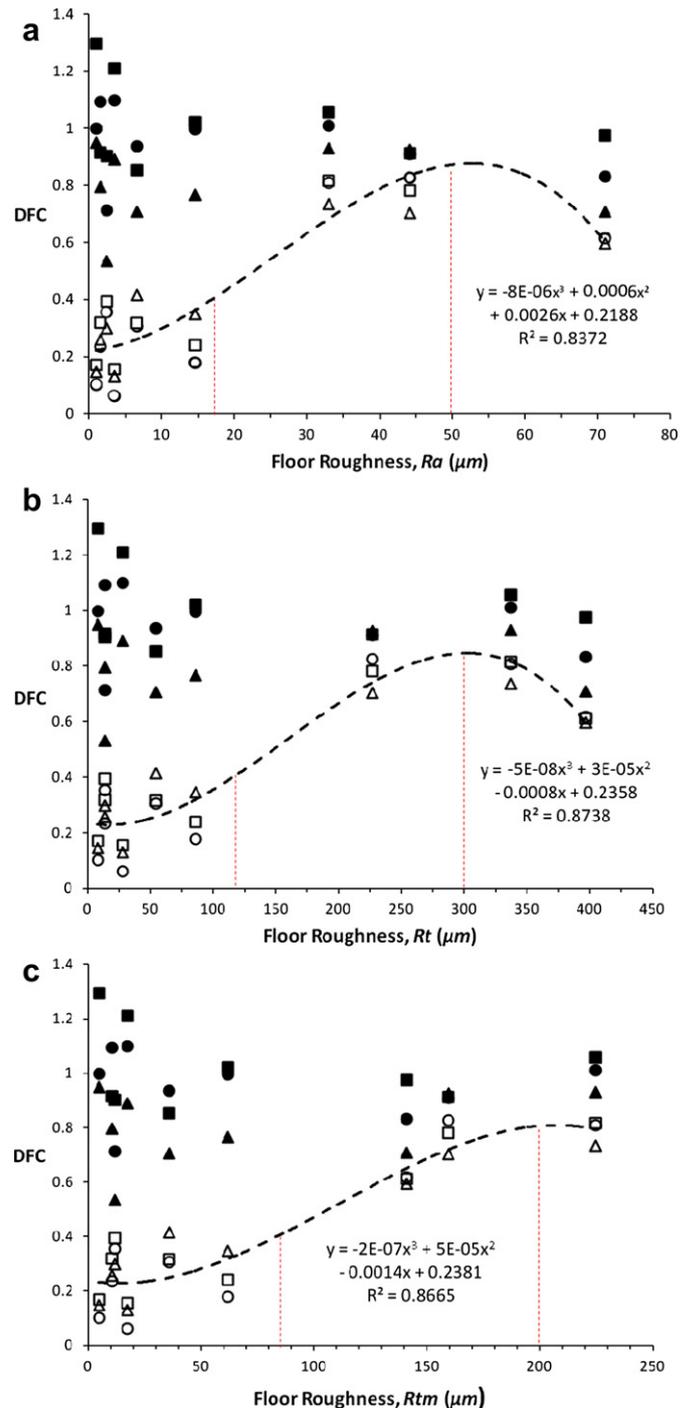


Fig. 3. Scattered plots and regression lines of the DFCs and the floor surface roughness parameters: Ra , Rt and Rtm for the clean-and-dry and soapsuds-covered wet conditions. (a) Floor surface roughness parameter, Ra vs. DFC. (b) Floor surface roughness parameter, Rt vs. DFC. (c) Floor surface roughness parameter, Rtm vs. DFC. ● S1, ■ S2, ▲ S3 (Dry condition). ○ S1, □ S2, △ S3 (Soapsuds condition).— Regression line for soapsuds condition.

5.3. Functional levels of surface roughness

The results of this study provide support for the hypothesis of non-linear relationship between the surface roughness and DFC. Furthermore, the results reveal that increasing the surface roughness beyond certain levels does not provide further benefit for slip resistance (DFC), i.e., there exists a functional range for

optimal slip resistance performance. These findings may have important practical design implications. For example, the estimated results suggest that surface roughness levels in the range of 17–50 μm (in R_a roughness scale) may be sufficient ($\text{DFC} > 0.4$) for slip resistant performance on the soapsuds-covered wet surface condition.

Earlier studies and guidelines have reported and recommended minimum required floor surface roughness values: $R_{tm} > 8\text{--}10\ \mu\text{m}$ for wet floors (Harris and Shaw, 1988); $R_a > 7\text{--}9\ \mu\text{m}$ for glycerol (Grönqvist et al., 1990); R_z (average maximum height of a profile) $> 45\ \mu\text{m}$ for milk and soap solutions (HSE, 2007), as well as have reported “very slip-resistant” surfaces in the range $R_a = 16\text{--}22\ \mu\text{m}$ for glycerol (Grönqvist et al., 1990). Most of these previous reports and recommendations, however, have used different methodologies, experimental conditions and criteria, which do not allow direct comparison with the results of the current study.

The present study suggested using the criteria of “no further benefit” (“not increasing DFC values” or “DFC values approaching dry surface performance”) to determine the upper bound of floor surface roughness (UB-FSR) for slip resistance performance. Other cutoff considerations (criteria) to determine UB-FSR for slip resistance performance could be derived from the requirement of safe and comfortable ambulation, i.e., to avoid tripping (Chaffin et al., 1992). However, the associated critical DFC values that could be used for such criteria have not been established yet.

5.4. Limitations of the study

This pilot study tested only a small selection of flooring materials within a limited number and range of surface roughness scales. Further research on the slip resistance properties of individual materials with different surface characteristics is needed to more precisely determine the specific functional levels of surface roughness. The experimental design of this study involved only one contaminated surface condition – soapsuds-covered wet surface. This limits the applicability of the findings only to this type of surface contaminant. Other surface contaminants with different composition and viscosity may result in different functional levels of surface roughness.

6. Conclusion

This pilot study aimed to understand the effects of floor surface roughness on slip resistance performance under two different test conditions and to identify functional levels of floor surface roughness from a practical design point for the prevention of slip and fall incidents. The results showed that all the tested floor–shoe combinations provided sufficient slip resistance under the clean-and-dry condition. However, there was lack of correlations between the surface roughness and DFC values under the clean-and-dry surface condition. This aspect indicates involvement of multiple mechanisms of slip resistance properties and possible strong effects of other material characteristics such as wear development during the dynamic friction tests.

Slip resistance performance was significantly affected by and well correlated with the floor surface roughness in the soapsuds-covered wet condition. Polynomial regression models of the floor surface roughness and DFC relation allowed estimation of functional range for optimal slip resistance performance. Floor surfaces with 17 and 50 μm in R_a roughness scale most likely represent the lower and upper bound of the functional range of floor surface roughness for slip resistance under the soapsuds-covered wet condition.

Disclaimer

The findings and conclusions in this study are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of any products or inclusion of any reference does not constitute the endorsement by the National Institute for Occupational Safety and Health.

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