Proposed surface modeling for slip resistance of the shoe-floor interface

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ABSTRACT

Slips and falls are the major causes of the pedestrian injuries in the industry and the general community throughout the world. With the awareness of these problems, the friction coefficients of the interface between floorings and footwear have been measured for the evaluation of slip resistant properties.

During this measurement process, the surface texture has been shown to be substantially effective to the friction mechanism between shoe heels and floor surfaces under various types of walking environment. Roughness, either of the floor surface or shoe heels, provides the necessary drainage spaces. This roughness can be designed into the shoe heel but this is inadequate in some cases, especially after wear. Therefore, it is essential that the proper roughness for the floor surface coverings should be provided.

The phenomena that observed at the interface between a sliding elastomer and a rigid contaminated floor surface are very diverse and combined mechanisms. Besides, the real surface geometry is quite complicate and the characteristics of both mating surfaces are continuously changing in the process of running-in so that a finite number of surface parameters can not provide a proper description of the complex and peculiar shoe - floor contact sliding mechanism.

It is hypothesised that the interface topography changes are mainly occurred in the shoe heel surfaces, because the general property of the shoe is soft in the face of hardness compared with the floor materials This point can be idealised as sliding of a soft shoe heel over an array of wedge-shaped hard asperities of floor surface. Therefore, it is considered that a modelling for shoe - floor contact sliding mechanism is mainly depended upon the surface topography of the floor counterface.

With the model development, several surface parameters were measured and tested to choose the best describing surface parameters. As the result, the asperity peak density (APD) of the floor surface was developed as one of the best describing parameters to explain the ambiguous shoe - floor interface friction mechanism.

It is concluded that the floor surface should be continuously monitored with the suitable surface parameters and kept the proper level of roughness to maintain the footwear slip resistance. This result can be applied to the initial stage of design for the floor coverings.

1. Introduction

Today slips and falls are the leading categories of non-traffic accidents in terms of serious injuries and fatalities. There is no doubt that slipping incidents are the cause of a very substantial proportion of industry and the general community injuries. (Hoang et. al., 1987) In Australia, the latest statistical findings show that the deaths by accidental falls are about 0.7% of total male deaths during the periods 1990 - 1992. Rather higher rates, 1.0% in 1990 and 0.9% in both 1991 and 1992, were found for females during the same periods. (Australian Bureau of Statistics, 1993)

With the awareness of these problems, the coefficients of friction (COF) of the contact interface between floorings and footwear have been measured for the evaluation of the slip resistant properties. (Redfern and Bidanda, 1994; Jung and Fischer, 1993; Chaffin et. al., 1992) During the friction measurement process, the surface texture has been shown to be substantially effective to the friction mechanism between shoe heels and floor surfaces under various types of walking environment. Roughness, either of the floor surface or shoe heel, provides the necessary drainage space. This roughness can be designed into the shoe heel but this is inadequate in some cases, especially after wear. (Harris and Shaw, 1988) Therefore, it is essential that the proper level of roughness for the floor coverings should be provided and maintained.

The frictional phenomena which are observed at the contact interface between a sliding elastomer and a rigid contaminated floor surface are diverse and combined mechanisms. (Grönqvist, 1991; Leclercq et. al., 1991b) Besides, the real surface geometry is quite complicate and the characteristics of both mating surfaces are continuously changing in the process of running-in so that a finite number of surface parameters can not provide a full description of the complex and peculiar shoe-floor contact sliding mechanism. And the conditions surrounding an individual asperity and its interaction with the opposing asperity are crucial to understanding of the shoe-floor friction process.

Because the general property of the shoe is soft in the face of hardness compared with the floor materials, however, it is simply hypothesised that the interface topography changes mainly occur in the shoe heel surfaces. That is, hard floor asperities can plough into the softer shoe heel surfaces and produce wear particles as results of continuous friction actions. This point can be idealised as sliding of a soft shoe heel over an array of wedge-shaped hard asperities of a floor surface.

Since 1988, the importance of floor surface roughness was emphasised but this aspect is rarely considered. (Proctor, 1993) Especially, the studies about characteristic changes in the surface topographies of either or both of the shoe-floor sliding members as a result of sliding actions do not seem to have been studied quantitatively so far. This study, therefore, is primary concerned with understanding the friction mechanism of the shoe-floor contact interface and searching for surface roughness parameters to characterise the sliding mechanism of shoe-floor contact interface which is mainly depended upon the surface topography of the floor counterface on the dry floor surface conditions.

2. Friction test arrangement and results

2 -1. Friction measurement system

The pendulum type Dynamic Friction Testing Machine which was developed by the Department of Safety Science (Stevenson et. al., 1989) was used to evaluate dynamic slip resistance of the interface between the shoe heel and floor surface. (see, Fig. 1) This machine was designed to simulate the movement and loading of the foot at a moment of heel strike and initial sliding. During the shoe-floor contact sliding, it measures the normal and frictional forces. In this sense, a ratio of the shoe heel's frictional force divided by the heel's normal force represents the dynamic friction coefficient (DFC). A mean DFC is then estimated for each trial.

The normal force was kept around 350 newtons and its sliding speed was controlled at a speed of 0.4 m/sec through the entire process. The whole process and data acquisition were operated by a computer. A full description of the dynamic friction testing machine is given in the report of Hoang et. al. (1987).

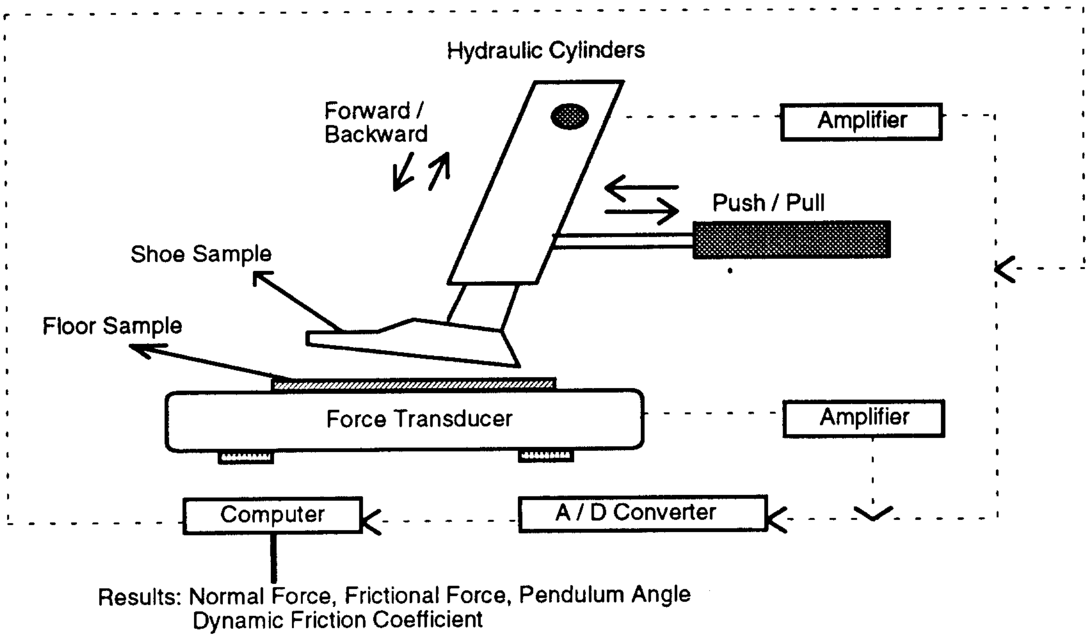


Figure 1. Diagram for the Dynamic Friction Machine

2 - 2. The friction tests

The friction tests were conducted with three shoes and nine floor surfaces subject to four floor contaminant conditions - dry, wet, soapy and oily. The tested floors are described in Table 1 with their roughness measurements. All floor surfaces tested were never used new ones. It is considered that this is a quite important point because the floor surface geometry play an vital role in the friction mechanism of the shoe-floor interface so that faces of all floor surfaces should be kept undamaged as much as possible. The shoes tested were three typical industrial work shoes which were two of them with a Nitrile Rubber heel and one with a PVC heel.

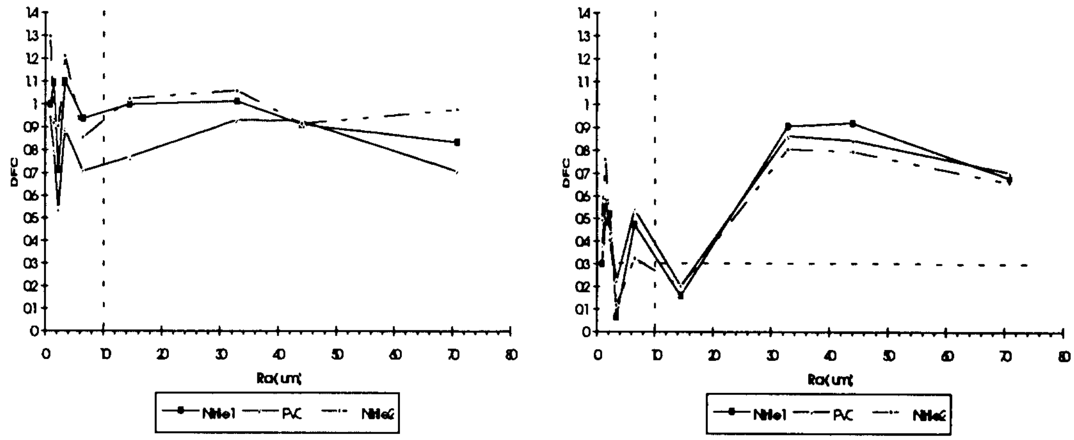
The Talysurf 5 surface roughness measurement system which has a spherical tip of 12 μm radius was used for the measurement of the floor surface roughness (Ra). Each floor surface was measured 5 times at different positions and averaged. The measurement results of each floor surface, in rank order, are shown in Table 1.

Table 1. The floors that were used for friction test

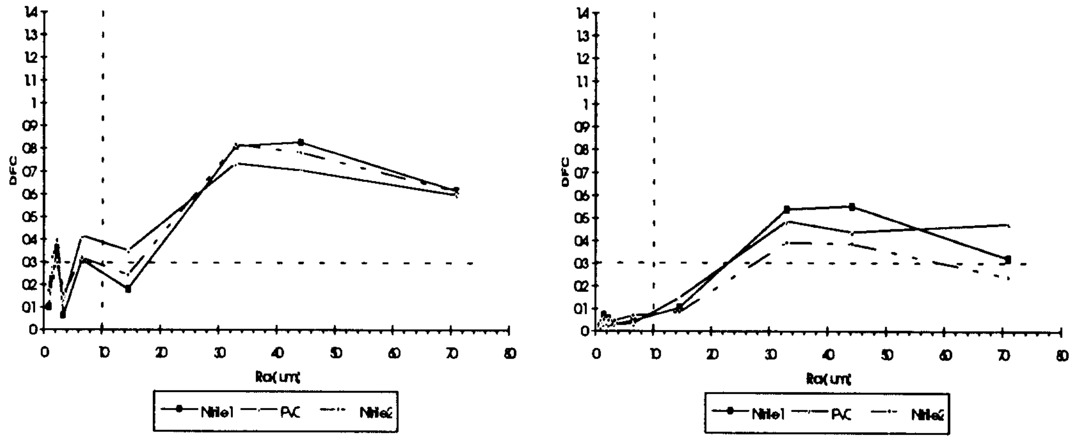
Test No.	Floor Type	Ra (μm)	Rtm (um)
1	Terrazzo	0.961	4.853
2	Smooth vinyl tile	1.551	10.260
3	Smooth metal	2.360	11.757
4	Smooth ceramic tile	3.434	17.293
5	Smooth concrete	6.590	35.800
6	Moderate rough ceramic tile	14.543	61.750
7	Moderate rough concrete	32.970	224.333
8	Rough concrete	44.107	159.250
9	Rough ceramic tile	70.936	141.000

The friction results of these shoe-floor combinations with 4 different surface contaminants are shown in Figure 2. From Fig. 2, it can be observed that the friction available at the contact interface of the shoe heel and floor surface is dependent on the floor surface roughness (Ra), shoe heel material, and pollutant used for simulating different industrial situations encountered. Especially, the roughness of floor surface has strong effect on the dynamic friction coefficient when the floor surfaces are contaminated. This trend seems to be generally accepted to the rather rough surfaces which have over 10 μm roughness (Ra).

However, the linear relationship between the DFC and floor surface roughness is not generally observed at some smooth floor surfaces which have below 10 μm roughness values on the dry floor surface conditions. (see, Fig. 2 (a)) The DFC plots for the dry and clean surface condition show substantial scatter in the friction results. That is, in spite of low levels of surface roughness, some floor surfaces such as terrazzo, smooth vinyl tile, and smooth ceramic tiles have high level of DFCs. Besides, there is an another interesting finding from the Fig. 2. Although the rough ceramic tile is the roughest floor surface (70.94 μm) amongst all floor surfaces tested, it does not show its corresponding highest DFC results through all floor surface conditions.



(a) Dry conditions (b) Wet conditions



(c) Soapy conditions (d) Oily conditions

Figure 2. The plot of dynamic friction coefficients for 3 shoes against the Ra roughness of the 9 different surfaces on the 4 different pollutant conditions.

From above findings, it can be summarised that the friction available at the shoe-floor interface is mainly dependent on the shoe property, floor surface geometry and polluted status. The fact the smooth floor surfaces such as terrazzo, smooth vinyl and smooth ceramic tile against all three shoes gave significantly high values of DFC indicates that there is an evidence of geometrical interaction between a shoe heel and floor surface.

These facts make more difficult to understand the sliding mechanism of the shoe-floor contact interface. It is clear that a simple comparison with a single roughness parameter such as the centre line average, Ra, for a floor surface is not suitable any more to explain the complex friction mechanism between the shoe heel and floor surface. More detailed study, therefore, is needed to establish a firm reference basis for the friction mechanism of the shoe-floor contact interface.

3. Tribological observation of the shoe-floor contact interface

3 - 1. Description of shoe-floor contact sliding mechanism

Almost all real surfaces are rough on a microscopic scales, and when two such surfaces are in contact they touch only at tiny discrete areas where their highest asperities are in contact. (Bowden and Tabor, 1950) Thus, in general, the real area of contact is only a small percentage of the nominal contact area. The local pressure at the contact regions is then high enough to cause plastic deformation of the asperities even at the lightest load. Initial contact occurs at the highest asperities but an increase in normal load and slide in a direction result in both the deformation of these asperities and an increase in the number of asperities. As a result, the highest asperities are smoothed out, the initial asperities are partially or completely destroyed, and new asperities are established which differ in shape and dimensions from the first.

With the awareness of contact sliding events between two mating surfaces mentioned above, there are two commonly recognised basic friction mechanisms, that is, abrasion and adhesion. The abrasive friction is a result of the ploughing of hard body asperities into a soft body surface. The adhesion friction is the result of the sequential creation and rupture of molecular bonds between both mating bodies.

The changing phenomena in the surface topography between two mating members as a result of sliding action could be applied to the sliding process of shoe-floor interface. The interaction between a floor surface and a shoe polymer can be considered to be almost plastic deformation.

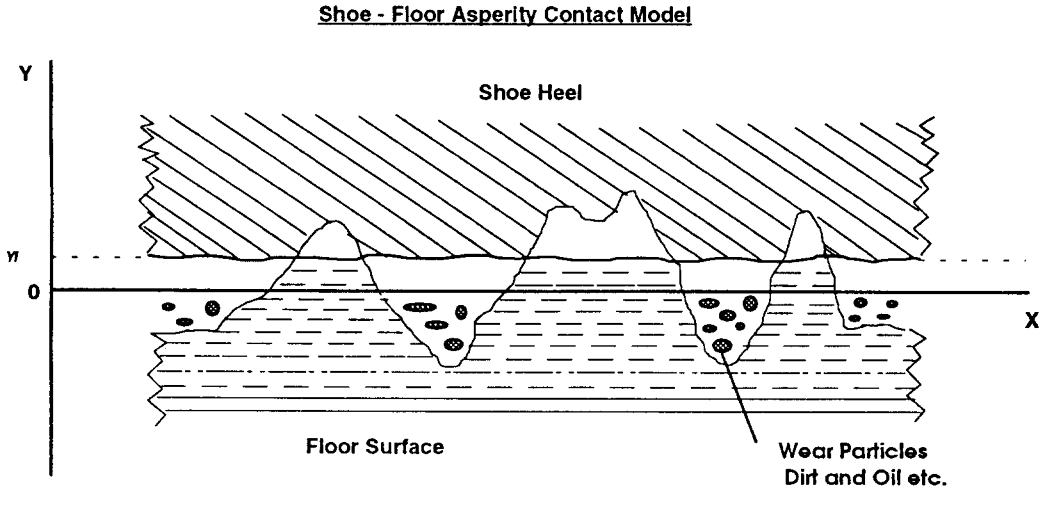


Figure 3. The geometrical model for shoe-floor contact interface.

The deformations are assumed to be concentrated on the shoe heel, whose elasto-plastic modulus is ten times or more less than that of the floor surface. It is also assumed that the tribological behaviour of a shoe-floor pair is influenced by the surface microtopography of the floor counterface alone. Therefore, it can be considered that a contact area of a shoe heel is indented by a rigid floor surface. That is, this point can be idealised as sliding of a soft shoe heel over an array of wedge-shaped hard asperities of a floor surface. Figure 3 suggests a rather exaggerated but reasonable model for the contact interface between a shoe heel and a floor surface based on above assumptions.

From the figure 3, it can be observed that the high asperities of the floor surface penetrate into the shoe heel areas and make real areas of contact. If the shoe heel slides on the floor surface, the surface of shoe heel will be ruptured and deformed by the wedge-shaped asperities of the floor surface. It is therefore considered that the some highest asperities and density of peak height (denseness of peak asperity within the assessment length) of the floor surface's profile are seemed to be important factors to affecting the shoe heel wearing.

When a shoe heel slides across the asperity wedges of a floor surface, the angle (θ) of attack of the wedge will play an important role in the configuration of shoe heel deformation. Therefore, the average angle of each floor surface is also considered as the root mean square (RMS) form.

During a number of running-in friction process, the topography of a floor surface itself also could be affected by several reasons. Amongst various possible causes, one consideration is that the deposition of abraded polymer particles from a shoe heel into the cervices of asperities on the floor surface could be one of the reasonable points. This means that the asperity valley of a floor surface also is one of the important surface parameters so that it should be examined separately. These factors will consequently influence on the friction test results. Therefore, it is believed that frictional event of the shoe-floor interface is mainly depended on the surface topography of the floor counterface.

3 - 2. Surface Parameters

The surface roughness parameters considered are the asperity surface density, height distribution and asperity slope. The effect of various surface parameters on the coefficient of friction has been studied in an attempt to determine the parameters that are relevant to the interface COF. (Myers, 1962; Moore, 1972; Nowicki, 1985) The surface parameters considered for shoe-floor interface contact model are as follows.

1) The following parameters represent the height of the asperities:
   Ra : the arithmetical average roughness
   Rtm : the maximum peak-to-valley height
   Rpm : the maximum height of the profile above the mean line

2) The angle θ of the inclination of the asperities is also used to characterise the floor surface as its rms slope (Δq).

A surface profile can be considered as a height y which is a function of distance *x* from a reference point on the surface. The profile is digitally sampled and recorded as a data set of N points acquired at discrete intervals as shown in Fig. 4.

Description of the Surface Parameters

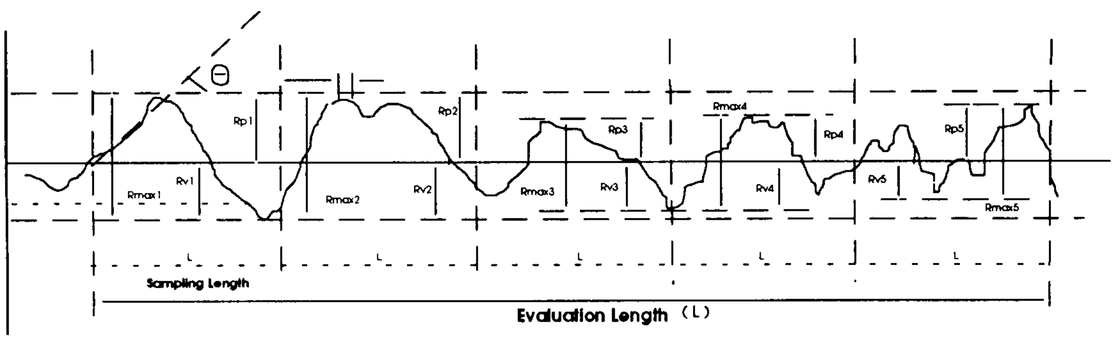


Figure 4. Illustration showing the surface profile digitally sampled.

The arithmetical average roughness (Ra), which is average deviation of a surface profile about its mean line, has been referred for quantifying surface roughness to slip resistance. (Stevenson et. al., 1989; Grönqvist et. al., 1990)

It is defined by

$$Ra = 1/N \times \sum |Y_i| \qquad (1)$$

It is useful to have a measure of the extremes of departure of a profile. The most commonly used of these are: the mean of maximum peak-to-valley height (Rtm) and the mean of maximum departures of the profile above and below the mean line, referred to as Rpm and Rvm respectively. (see, Fig. 4)

The maximum peak-to-valley surface parameter (Rtm) has been used to assessing the roughness of both floor surfaces and shoes. (Harris and Shaw, 1988; Proctor, 1993; Manning and Jones, 1994) However, they simply used this parameter so that it should be noticed that there are some relationships amongst each roughness parameters. Both parameters of the Rtm and Rt indicate the maximum height of profile, but there is a difference between them.

The Rtm is the average of the maximum peak-to-valley height (Rmax)of five consecutive sampling lengths (L). But the Rt is the maximum peak-to-valley height of the profile within the assessment length.

$$\mathbf{Rtm = (Rmax1 + Rmax2 + \bullet \bullet \bullet + Rmax5) / 5} \qquad (2)$$

The Rpm is the mean value of the maximum height of the profile above the mean line (Rp) determined over several consecutive sampling lengths (L).

$$\mathbf{Rpm = (Rp1 + Rp2 + \bullet\bullet\bullet + Rp5) / 5} \qquad (3)$$

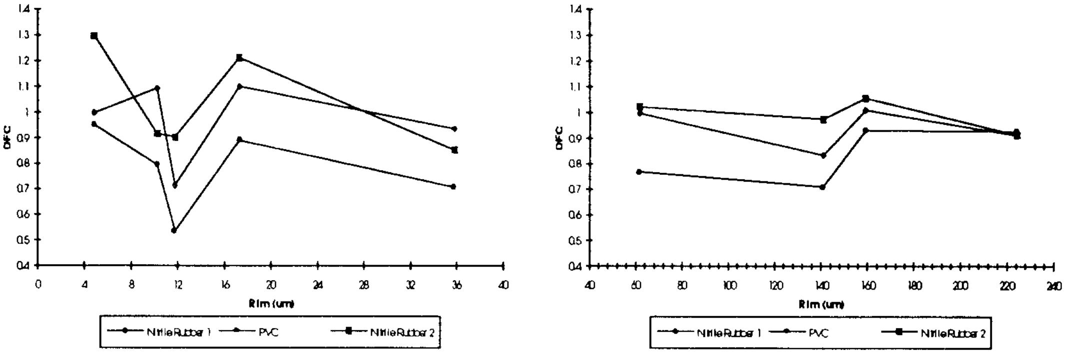
Another parameter which can be observed from the shoe-floor interface model is the average slope of asperities (Δa). As mentioned in the shoe-floor friction mechanism, the friction interface can be regarded as a tangential force required to overcome the adhesion at regions of intimate contact plus the tangential force required to lift the asperities over each other. During this process, the angle of each asperity will affect the extent of tangential forces applied in the sliding direction. Therefore, the average slope of asperities should be involved to investigate its role to the friction results. It is defined by

$$\Delta q = \left(\frac{1}{L} \times \int_{0}^{L} \left(\frac{dy}{dx} \right) dx \right)^{1/2} \qquad (4)$$

4. Results and discussion

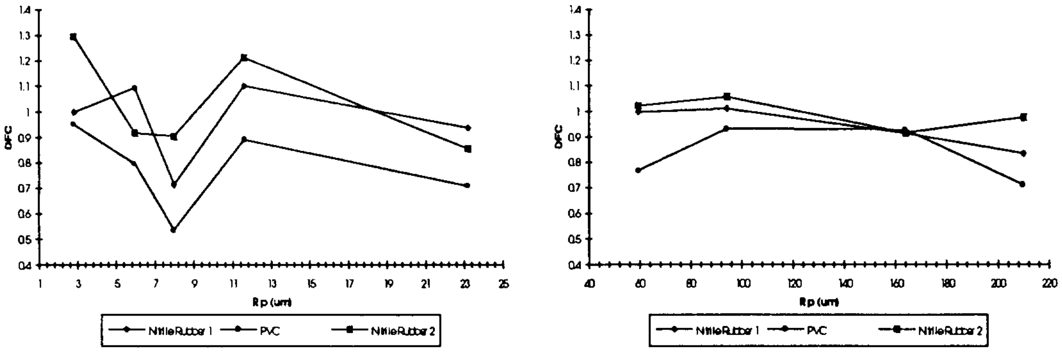
(1) Overview

The relationships between dynamic friction coefficients and surface roughness parameters are showing from Figure 5 to 7. Each figure shows variation in the coefficient of dynamic friction with the maximum peak-to-valley height (Rtm), the maximum height (Rpm) of the profile above the mean line and the rms slope of the profile (Δq) respectively. Similar behaviour was found with each parameter. This result is feasible because the floor surfaces were prepared by the same blasting technique.



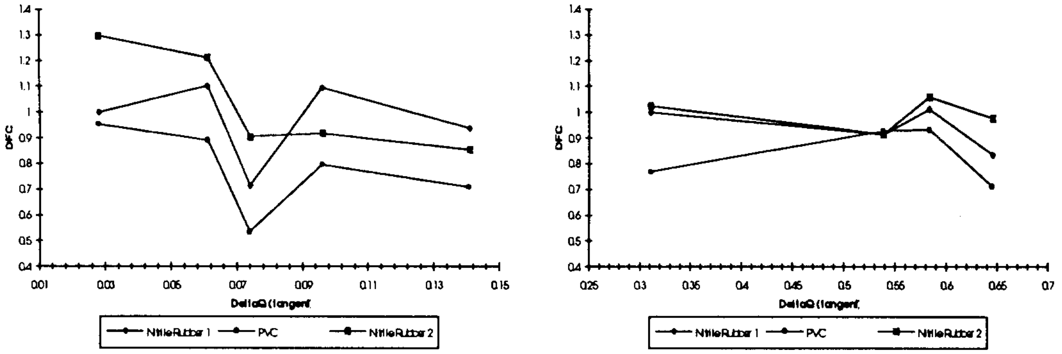
(a) below 10 μm floor surfaces (b) over 10 μm floor surfaces

Figure 5. Experimental variation in the dynamic friction coefficient with the Rtm on the dry floor surface conditions.



(a) below 10 μm floor surfaces (b) over 10 μm floor surfaces

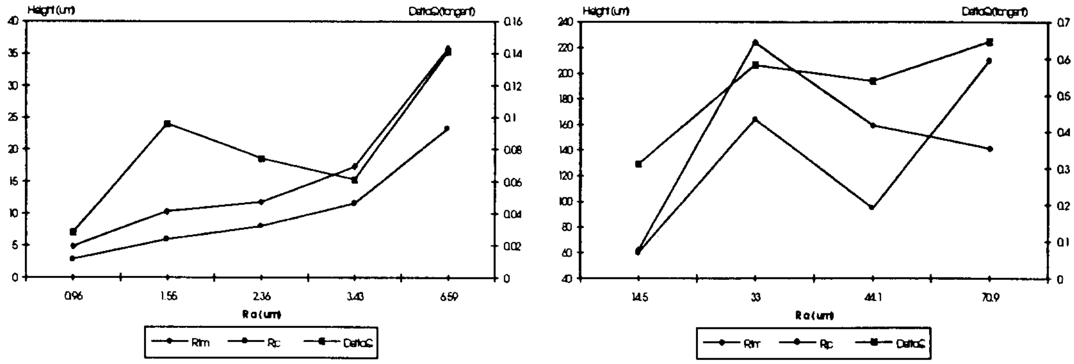
Figure 6. Experimental variation in the dynamic friction coefficient with the Rpm on the dry floor surface conditions.



(a) below 10 μm floor surfaces (b) over 10 μm floor surfaces

Figure 7. Experimental variation in the dynamic friction coefficient with the DeltaQ on the dry floor surface conditions.

Each surface parameter was compared with each other to examine its relationship and contribution to the DFCs in Figure 8.



(a) below 10 μm floor surfaces (b) over 10 μm floor surfaces

Figure 8. Relationship amongst each surface parameter with the increase of the arithmetical average roughness (Ra).

From the figure 8, it can be noticed that variation in the maximum height of the profile (Rtm) in the both floor types rise with the increase of the floor surface roughness (Ra). Besides, the rms slope angles (Δq) of each floor surface are also increase with the growth of their surface roughness. Thus, the increase in the surface roughness (Ra) results in the increase of the maximum roughness height (Rtm) and the rms slope angle of each floor surface. It generally follows an increase in the DFC result between a shoe heel and a floor surface.

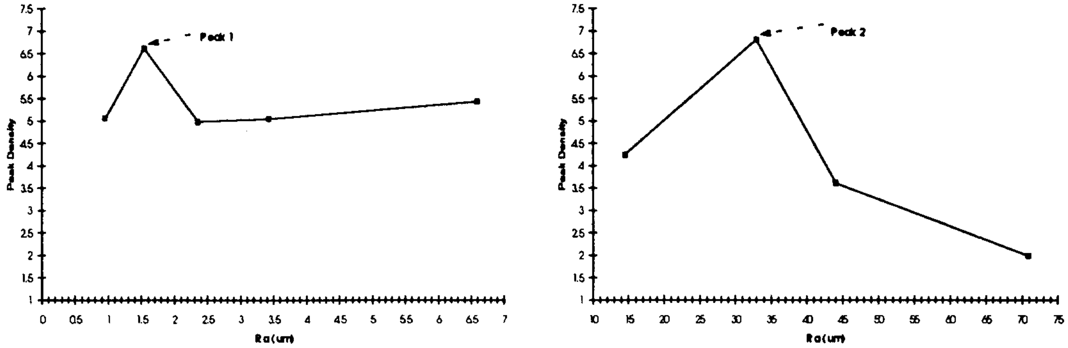
(2) Peak density

However, the general frictional configuration between the floor surface roughness and DFC is not always corresponding linearly as pointed in the initial stage of this study. Observation of the maximum height of the profile above the mean line (Rpm) is seemed to suggest a reasonable answer to the frictional trend of the Perspex based floors. The fact obtained for this parameter provides that the highest peak asperities on each floor surface is crucial factor to determine the frictional character between the shoe-floor interface. It is clear that the highest peak asperities of the floor surface plough into the contact area of shoe heel so that they will consequently influence to the DFC results.

For the configuration of the denseness of highest peak asperities, a new factor " Peak Density (PD) " is introduced to represent the denseness of highest peak asperities on the mean line. This is defined as the ratio of the Rtm to Ra and as a dimensionless indicator.

$$\mathbf{PD = Rtm / Ra} \qquad (5)$$

The results of this factor on each floor surface are plotted in Figure 9 which is divided into two categories according to their roughness scale of floor surfaces.



(a) below 10 μm floor surfaces (b) over 10 μm floor surfaces

Figure 9. Relationship between the peak density (PD) and the arithmetical average roughness (Ra) from the first stage of friction tests.

It can be observed that the plot trend of the peak density of two categories of floor surfaces are showing the exact shape of DFC results (P1 and P2). This fact seems to give an answer for the scattering of the dynamic friction test results. This means that the highest asperities and their density of the surface profile are one of the major factors to break the contact interface adhesion between a shoe heel and floor surface. This phenomenon will eventually influence to the result of DFC.

5. Conclusions

The friction mechanism is the combined result of adhesion, deformation and ploughing. The relative contribution of these components depends on the environmental conditions of the sliding interface and materials mating. Especially, the shoe-floor friction mechanism has quite peculiar and complex characteristics because of their mating material properties and moving patterns - contact and sliding. Besides, because of different frictional characteristics between the clean and contaminated surfaces, this study is mainly focused on the understanding the friction mechanism of the shoe-floor interface in the case of dry floor surface conditions only as a first step.

One of the most important fact is that the characters of the both mating surfaces are continuously changing in the process of running-in so that the surface topography of both materials also will be changed. Therefore, it is necessary to monitor the surface finishing continuously with the suitable surface parameters. Because the modulus of the shoe is much less harder than the floor surface, however, it was simply hypothesised that the changes of the shoe-heel topography mainly occur in the shoe heel areas. This point was modelled by the geometrical configuration of the floor surface.

Two surface parameters, Ra and Rtm, were suggested as evaluation parameters in slip resistance tests by few researchers. From the friction tests of this study, the minimum measured value of the Rtm on the wet floors to avoid the slipping hazard was 10.26 μm and its corresponding Ra reading was 1.55 μ m. (see, Table 1 and Fig. 2) These figures are exactly in the range of Harris and Shaw's finding.

With the above two parameters of surface roughness, Ra and Rtm, other surface parameters were suggested to characterise the friction phenomena between a shoe heel and floor surface. The maximum height of the profile above the mean line (Rpm), the rms slope (Δq) of the profile and the density (PD) of the highest peak asperities of each floor surface were compared with the results of DFC.

The results have shown that the peak asperity height and its density of the floor surface profile were best describing surface parameters to explain the frictional events between the shoe-floor interface on the dry floor conditions. Therefore, it became clear that why rougher floor surfaces do not always have corresponding high values of DFC. It is intended to carry out further studies particularly in contaminated floor conditions where slipping problems are more frequently happened.

References

Australian Bureau of Statistics, 1993, 1993 DEATHS AUSTRALIAN, Catalogue No. 3302.0, Australian Bureau of Statistics.

Bowden, F.P. and Tabor, D., 1950, The friction and lubrication of solids, Partl, Clarendon Press, Oxford, 5-32.

Chaffin, D.B., Woldstad, J.C. and Trujillo, A., 1992, Floor/shoe slip resistance measurement, Am. Ind. Hyg. Assoc. J., 53(5), 283-289.

Grönqvist, R., Roine, J., Korhonen E. and Rahikainen, A., 1990, Slip resistance versus surface roughness of deck and other underfoot surfaces in ships, J. of Occupational Accidents, 13, 291-302.

Grönqvist, R., 1991, Mechanisms of friction and assessment of slip resistance of new and used footwear soles on contaminated floors, Fourth International Conference on Slipping, Tripping and Falling Accidents, London.

Harris, G.W. and Shaw, S.R., 1988, Slip resistance of floors: Users' opinions, Tortus instrument readings and roughness measurement, J. of Occupational Accidents, 9, 287-298.

Hoang, K., Stevenson, M.G., Nhieu, J. and Bunterngchit, Y., 1987, Dynamic friction at heel strike between a range of protective footwear and non-slip floor surfaces, Report CSS/1/87, The Centre for Safety Science, University of New South Wales, Australia.

Jung, K. and Fischer, A., 1993, An ISO test method for determining slip resistance of footwear. Determination of its precision, Safety Science, 16, 115-127.

Leclercq, S., Tisserand, M. and Saulnier, H., 1991b, Tribological concepts involved in slipping accident analysis, Fourth International Conference on Slipping, Tripping and Falling Accidents, London.

Manning, D.P. and Jones, C., 1994, The superior slip-resistance of footwear soling compound T66/103, Safety Science, 18, 45-60.

Moore, D.F., 1972, Friction and lubrication of elastomers, Pergamon, Oxford, 41-45.

Myers, N.O., 1962, Characterisation of surface roughness, Wear, 5, 182.

Nowicki, B., 1985, Multiparameter representation of surface roughness, Wear, 102, 161-176.

Proctor, T.D., 1993, Slipping accidents in Great Britain - an update, Safety Science, 16, 367-377.

Redfern, M.S. and Bidanda, B., 1994, Slip resistance of the shoe-floor interface under biomechanically-relevant conditions, Ergonomics, 37, 511-524.

Stevenson, M..G., Hoang, K., Bunterngchit, Y. and Lloyd, D.G., 1989, Measurement of slip resistance of shoes on floor surfaces, Part 1: Methods, J. of Occupational Health and Safety - Aust NZ, 5(2), 11-32.

Stevenson, M.G., 1992, Proposed standard testing methods for slip resistance, J. of Occupational Health and Safety - Aust NZ, 8(6), 497-503.