Article:

Clarke, J.D., Hallas, K., Lewis, R. et al. (3 more authors) (2015) Understanding the friction measured by standardised test methodologies used to assess shoe-surface slip risk. Journal of Testing and Evaluation, 43 (4). 723 - 734. ISSN 0090-3973

https://doi.org/10.1520/JTE20120334

Title: Understanding the friction measured by standardised test methodologies used to assess shoe-surface slip risk.

J.D. Clarke[1], K Hallas[2], R Lewis[1], S Thorpe[2], G Hunwin[2], *M.J. Carré[1]

[1] Dept. Of Mechanical Engineering, The University of Sheffield, Sheffield, S1 3JD, UK
[2] Health & Safety Laboratory, Harpur Hill, Buxton, Derbyshire SK17 9JN, UK

*Corresponding author:

M.J. Carré, m.j.carre@shef.ac.uk, Tel: +44(0)114 2227839

Abstract

This paper discusses standardised mechanical test methodologies that measure dynamic coefficient of friction in order to assess the risk of a pedestrian slip. Currently two shoe-surface contact test methods are specified in British Standards to assess the risk of pedestrian slips during the heel strike phase. A pendulum test device as specified in BS 7976-2:2002 is used to determine the slip resistance of surfaces. Another standard, BS EN ISO 13287:2007 specifies the test method to assess the slip resistance of conventionally soled safety, protective and occupational footwear. Experiments were conducted on six common household surfaces in water contaminated conditions in compliance with the aforementioned standard procedures. The roughness and stiffness of each surface was also found. The results show no statistically significant linear correlation between the dynamic coefficient of friction found via the two standardised test methods. At low levels of roughness, no statistically significant linear correlations were found between the coefficient of friction found via the two standardised test methods and roughness. For flooring with a compliant layer the contact conditions of the pendulum test device were found to cause friction losses associated with energy dissipated as the surface deforms and recovers during sliding. Differences in sliding velocity and area of contact were found to influence the measurements given by the two test procedures. The higher velocity pendulum is a more appropriate test device to replicate slip in wet conditions as it predicts the worst case scenario. However, it is likely to give misleading results on deformable surfaces as, on such surfaces, as it is not replicating the loading conditions during a real-life heel strike.

Keywords: footwear, friction mechanisms, slip resistance, surface roughness, surface stiffness

1. Introduction

Nomenclature

COF	Coefficient of friction
PTV	Pendulum Test Value
STM	Slip Testing Machine
A_0	Surface area in contact with a test surface
δ	Vertical Deformation
F_H	Horizontal force
F_V	Vertical force

h	Squeeze film thickness
K_E	Correction factor (1)
K_p	Pressure variation correction factor (0.025)
l	Average contact length
m	Arbitrary constant
n	Arbitrary exponent
R	Effective radius of contact area
t	Time
u	Velocity
μ	Fluid viscosity

1.1 Defining the problem

The Health and Safety Executive (HSE) in the UK reported nearly 11,000 workers were seriously injured from slips or trips in 2007 [1]. This has a significant economic impact in terms of employee sickness pay, time off work and increased burden on the National Health Service. A slip can be defined as unwanted horizontal movement at the shoe-surface interface due to insufficient friction being present. The severity of a slip can be determined by the distance the shoe moves relative to the surface [2]. A severe slip can lead to a fall and injury to an individual.

The tribological interaction between footwear and surfaces is a complex problem . Standardised mechanical test devices have been developed to simulate dynamic footwear-surface interaction to provide a repeatable measure of floor slipperiness. The HSE have reported concerns regarding the relevance of such test devices [3] and better understanding of the footwear-surface interactions as simulated by test methodologies is required. Understanding the mechanics of the dynamic interaction between footwear and surfaces can aid the development of such test devices. Once friction mechanisms are understood surface properties and/or footwear can be more effectively designed to minimise risk. This paper presents experimental test data in order to understand the current standardised test methodologies used to assess the risk of a slip.

1.2 Forces at the shoe-surface interface

A mechanical test device should best predict the friction that will be experienced by a pedestrian [4]. Typical ground reaction forces during a walking step on a level surface are presented in Figure 1 [5]. The ground reaction forces can be split into four sections (see Figure 1) during which a braking phase and a push-off phase occur [6]: A = *heel impact*; B= *foot flat*; C = *propulsion*; D = *toe-off*.

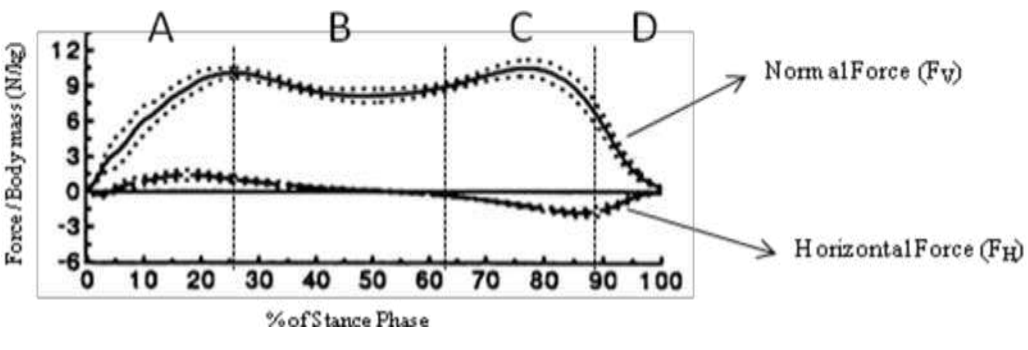


Figure 1: Typical ground reaction forces modified from Redfern and DiPasquale (1997) [5] with permission from Elsevier. Normal force, solid line; Horizontal force, dashed line; standard deviations, dotted lines.

Figure 2 shows the ratio of F_H and F_V. It is argued that during a step the critical phases are when the ratio of F_H and F_V peaks and the highest coefficient of friction are required. Figure 2 shows these peaks occur during the impact phase and the propulsion phase of a step on a level surface and is therefore at most risk of slipping. The initial heel impact is considered the phase with the highest risk of falling from a slip as a person is less able to recover balance at this stage compared to the forefoot propulsion phase [7].

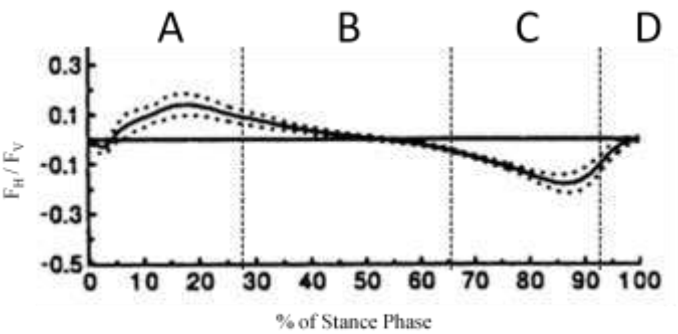


Figure 2: Ratio of Horizontal and Vertical ground reaction forces modified from Redfern and DiPasquale (1997) [5] with permission from Elsevier. Standard deviations across subjects, dotted lines.

1.3 Friction mechanisms developed at the shoe-surface interface

Viscoelastic materials, such as rubbers or the elastomer TPU (thermoplastic polyurethane), are generally used on the outsoles of shoes. In these contacts adhesion and hysteresis friction mechanisms are present during sliding [8]. The presence of water at the shoe-surface interface has been found to reduce friction due to lubricating effects and hence increase the risk of a slip [9]. In wet conditions the friction mechanisms are therefore developed differently than in dry conditions.

During a horizontal sliding event the asperities of viscoelastic materials deform elastically. The asperities recover during unloading; assuming the load applied locally does not exceed its elastic limit. The loading/unloading phase results in a net loss of energy [10-12] and hysteresis friction arises..

Adhesion is the process of junctions forming, due to van der Waals interaction between the contacting surfaces [10-16] and the arising friction force is the force required for the junctions to shear. Adhesion friction is more prevalent when rubber slides over a smooth surface and depends significantly on the real contact area and therefore the roughness characteristics of the surface the rubber is sliding on. As asperity contact increases, the real contact area, and hence friction, increases. The compressibility of typical shoe outsole material leads to its real contact area increasing under higher loading (the extent of which will also depend on the surface).

Interactions between asperities change when moisture is present and the interface becomes lubricated. If one surface slides along another at a sufficiently high speed and if the shape of the leading edge of the moving surface enables liquid to be gathered under the sliding surface, the two surfaces can be separated and slide easily. If the lubricant has a sufficiently high viscosity then the surfaces can be completely separated causing no asperity contact and friction will arise solely from shearing the viscous lubricant film. If the viscosity of the fluid and/or the sliding velocity is sufficiently low the fluid will be squeezed out allowing asperity contact. Also, if the height of the asperities is sufficient to penetrate the fluid film this will cause partial contact. Consequently, surfaces should be selected to be compatible with expected contaminants.

1.4 Mechanical testing of shoe-surface slip risk

Mechanical test devices often measure slip resistance as a form of dynamic coefficient of friction [17]. Currently two test methods are specified in British Standards to assess slip-risk. A pendulum test device (Figure 3), as specified in BS 7976-2:2002 + A1:2013, is used to determine the slip resistance of surfaces. Another standard, BS EN ISO 13287:2007 specifies the test conditions to assess the slip resistance of conventionally soled safety, protective and occupational footwear. Although studies have been conducted to compare and understand the results of mechanical test methods [18-27] there remains debate regarding whether such devices predict the slip-risk a person is likely to experience [28, 29]. However, it has been found that the slip resistance predicted by the pendulum device, and the thresholds used, have a good correlation with slip accidents [30].

Figure 3: Photograph of a pendulum test device as detailed in BS 7976-2:2002.

The pendulum device is designed to simulate contact conditions during a slip due to a footwear heel strike. When released, a rectangular spring-loaded rubber slider/heel (termed Slider 96) comes into contact with the surface. The rebound height (termed Pendulum Test Value (PTV)) is measured on the scale. PTV values are in practice found to be approximately equal to COF x 100, however due to dynamic effects of the spring-loaded arrangement of the slider there is a small but significant deviation. The empirical relationship between PTV and COF is therefore described by Eq. (1):

$$\mathrm{COF}_{\mathrm{pendulum}} = \left(\frac{110}{PTV} - \frac{1}{3}\right)^{-1} \tag{1}$$

Table 1 shows classifications of slip potential (based on PTV values) that were developed by the United Kingdom Slip Resistance Group (UKSRG) [31] and adopted by the Health and Safety Executive (HSE) [1].. The thresholds in Table 1 were extrapolated from force plate studies conducted by Harper *et al*. (1961) [32].

Table 1: Slip potential classification based on PTV, COF and R_z (R_z based on wet conditions) [1].

PTV	$COF_{pendulum}$	Surface roughness (R_z)	Slip Potential
0-24	0-0.235	Below 10 µm	High
25-35	0.246-0.356	10-20 µm	Moderate
36+	0.367+	20+ µm	Low

Table 1 also shows classifications of slip potential (in wet conditions) based on surface roughness as published by the HSE [1]. Studies have shown that floor surface topography and roughness can greatly influence slip resistance measurements [9, 33-36]. Chang found, for wet tiled surfaces, higher asperity peaks decreased slip-risk as direct contact between the test foot and surface asperities is possible, but noted the effect of surface roughness on friction was also dependent on the mechanical test device used [9]. Hunwin *et al.* compared the SATRA slip resistance test (STM 603) with a human ramp-based slip test and found some agreement but this was limited by the relatively small range of parameters that could be tested due to the control of the equipment at that time [36]. Bowman *et al.* found that different slip resistance measurement devices produced different levels of reliability and that the softness of the rubber test foot used in some tribometers had a significant effect on the results produced. In this study, ten different ceramic tiles were used with R_z values ranging from 7.7 to 44.9 µm [37]. This paper focuses on comparing the two methods used most often in the UK to test shoes and surfaces, respectively.

Roughness, measured as the mean peak-to-valley height of asperities, (R_z) is used by HSE as a guide to floor slipperiness because it takes into account any large scale variation in surface height (e.g. waviness) and is accepted as a useful measure of roughness that is local to the area of interest. .

2. Material and methods

Experiments were conducted on six commercially available household surfaces (summarised in Table 2) in wet conditions. For each surface, slip resistance was measured under the two standard methods discussed, and measures of stiffness and roughness were also taken.

Table 2: Summary of the surfaces tested (*commonly referred to as "lino").

Reference	Description	R_z, µm	R_a, µm	R_q, µm
PVC	Stiff polyvinyl chloride (PVC) floor tile.	1.86	0.26	0.31
Ceramic	Stiff ceramic tile.	4.84	1.39	1.71
Vinyl 1*	Deformable polyvinyl chloride (PVC).	8.17	0.91	1.10
Vinyl 2*	Deformable polyvinyl chloride (PVC).	3.72	0.75	0.87
Nylon	Stiff nylon flooring tile.	2.39	0.16	0.22
Laminate	Stiff synthetic surface.	9.36	1.39	1.65

2.1 Surface Roughness

A Surtronic Duo profilometer was used to measure the roughness parameter R_z, the mean peak-to-valley height of asperities, of each surface sample. First the profilometer was calibrated by taking three values of R_z on a verification surface of known profile. A total of ten R_z values were taken at 4 locations on the surface being tested; three along the direction of travel at regular intervals, three perpendicular to these, and three at a 45° angle to these and finally one over an area and orientation chosen randomly. No obvious directionality was observed and all the surfaces were judged as being isotropic in terms of roughness. These values were recorded to find a mean value, as shown in Table 2. Also reported in Table 2 for comparison are the measured values of R_a, the arithmetic average roughness and R_q, the root mean squared roughness. Note: all six surfaces' R_z values were below 10 μm, suggesting "High" slip potential according to the HSE study [1] (see Table 1).

2.2 Surface Stiffness

The average stiffness of each surface was found by measuring the force and surface deformation as a rigid steel cylinder of 12 mm diameter was quasi-statically loaded from 0 N – 600 N normally to each surface, this is shown schematically in Figure 4. The procedure was repeated five times for each surface to find a mean value. As the cylinder contacted the surface the vertical force (F_v) and displacement (δ) was recorded via a load cell and a linear variable differential transformer (LVDT) respectively at a sampling frequency of 2500 Hertz. The average stiffness was taken as the mean linear ratio between vertical force and displacement during loading. The results shown in Figure 5 highlight how the two vinyl surfaces are significantly less stiff than the other four surfaces.

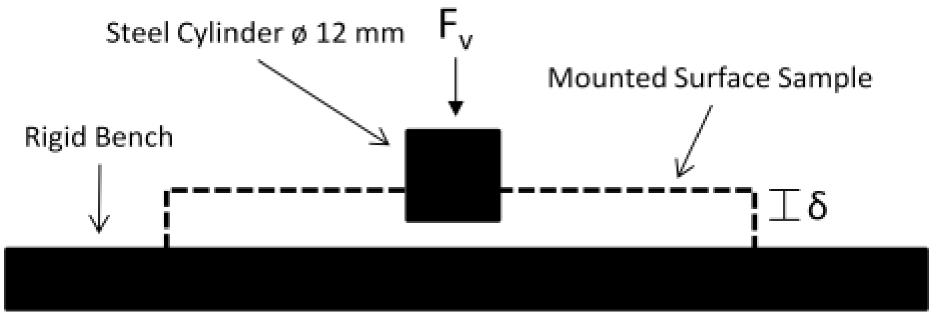


Figure 4: Schematic of the procedure used to measure average surface stiffness.

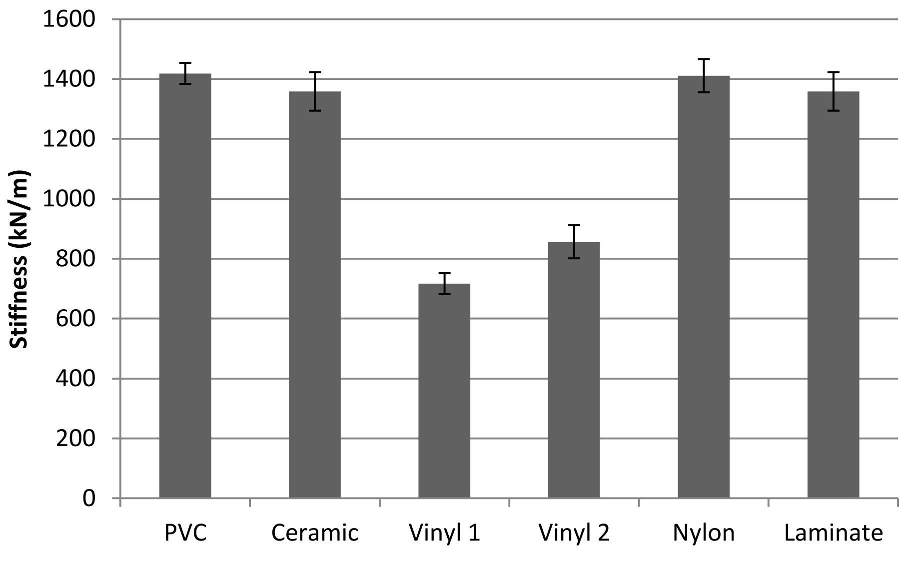


Figure 5: Plot of the mean average stiffness of each surface (± 1 standard deviation).

2.3 Slip Resistance

A SATRA slip resistance testing machine (STM 603) was used in order to comply with BS EN ISO 13287:2007 standards. However, whereas the standard relates to the testing of footwear on two standard surfaces (polished stainless steel and a *Pavigres* ceramic tile) with glycerol and soap solution as contaminants, the tests in this study were modified to assess the slip resistance of the different floor surfaces with standardised footwear. Firstly the STM 603 machine (Figure 6) was calibrated according to BS EN ISO 13287:2007. Tests were conducted with the heel segment of a test shoe (EU size 42). The test shoe had a standard smooth outsole of the same rubber used in the pendulum slider. For testing the shoe was aligned parallel to the direction of movement with a preloaded contact angle between the outsole and each surface sample set at 7°. The standard specifies a normal force of 500 N is applied to the heel segment of the shoe. In this study tests were also conducted at a normal force of 150, 200, 300, 400, and 600 N. For each condition, tests were repeated five times for analysis, this resulted in thirty individual tests per surface sample. This was to investigate the effect normal force has on the friction measured. For each test a motor drives the surface at a horizontal velocity of 0.3 m/s to replicate a dynamic slip event.

Figure 6: (Left) SATRA STM 603 device. (Middle) The test shoe used for testing. (Right) Schematic of test shoe as positioned in the test rig extracted from BS EN ISO 13287:2007 .

Before testing began the outsole was cleaned with an ethanol solution and allowed to dry at ambient temperature. Tests were repeated five times on each surface for statistical analysis. Before testing each surface or loading parameter, the outsole rubber was prepared by applying P400 silicon carbide paper under minimal pressure and any debris was removed using a clean, soft, dry brush. Before each test the test surface was sprayed with water so that a continuous layer of minimum 1 mm thickness was formed. This corresponded to at minimum 10 ml/100 cm^2. All the procedures described are in line with BS EN ISO 13287:2007 Section 9. Also, in accordance with the standard, the mean dynamic coefficient of friction (termed COF_{13287} in this study) was measured between 0.30 s and 0.60 s after the start of sliding movement. Plots of force against time and distance are produced by the test devices bespoke software 'Slipmaster'. These plots (see example in Figure 7) were analysed to find the mean dynamic COF_{13287} over a period of 0.3 seconds. This example shows the coefficient of friction remaining relatively constant over the 0.3 second period.

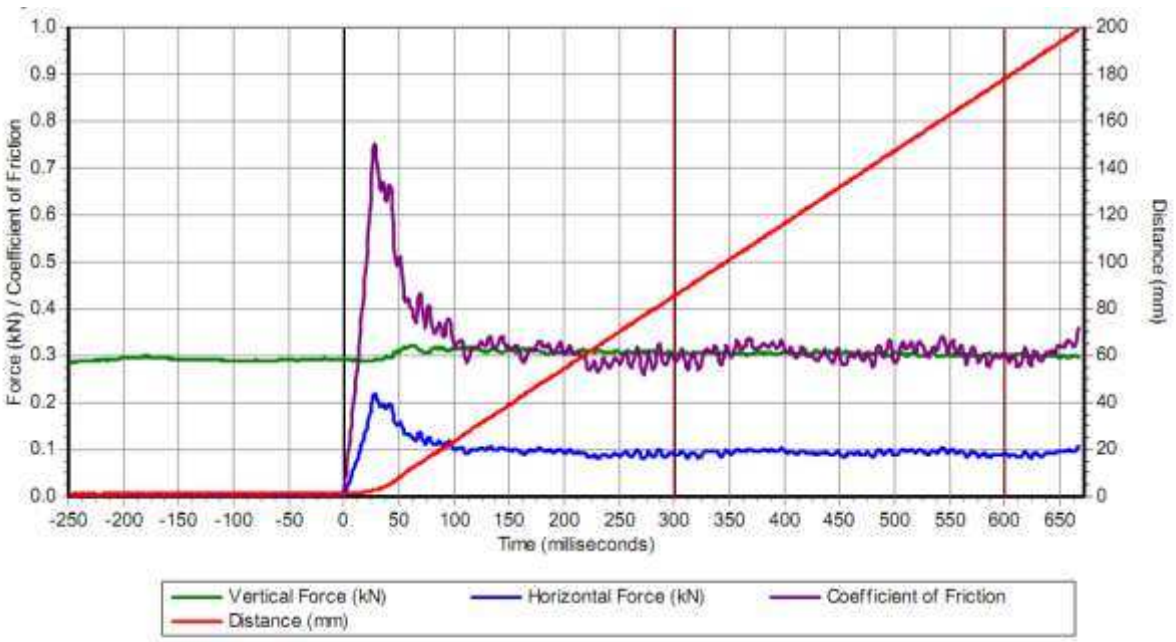


Figure 7: Typical plot given by SATRA slip resistance testing machine (STM 603) for 'Vinyl 2' surface.

Pendulum tests were conducted according to BS 7976-2:2002+A1:2013 and the explicit guidelines set out by the UK Slip Resistance Group [31]. The pendulum tester was set up on a rigid laboratory bench onto which the surface samples could be affixed using high-strength adhesive tape, preventing movement in any direction. In order to negate the effects of temperature on the rubber slider the temperature of the laboratory where calibration is conducted must be 20±5 ° C and the apparatus conditioned for at least 2 hours at laboratory temperature. This was monitored using a thermometer and the apparatus was left to equilibrate for two hours, before testing began. The pendulum was then calibrated in accordance with BS 7976-2:2002.

The slider conformed to the properties of Slider 96 rubber specified in BS 7976-2:2002. The rubber slider was prepared using P400 grade silicon carbide resin bonded paper, conforming to BS 7976-2:2002. A sheet of the paper measuring at least 127 mm in the direction of travel and 76 mm across was rigidly affixed to a work bench. Since the slider pad was new, firstly, ten repeats on the paper were carried out in dry conditions. Furthermore, in order to complete the slider preparation, twenty repeats were carried out in wet conditions over 3M 261X Imperial TM Lapping Film Grade 3MIC, on its matt side.

As wet conditions were tested in this study, before releasing the pendulum, the test surfaces were thoroughly wetted so that a continuous layer of minimum thickness 1 mm was formed over the whole area which is to be in contact with the slider. For each test the pendulum arm is released, the slider contacts the surface, and the pointer gives a PTV value to be recorded. The pendulum arm is caught on the return swing before the slider strikes the test surface on its down swing. The procedure was repeated eight times for each surface. The first three readings were disregarded, since they can be assumed to be unreliable as the tester equilibrates to its surroundings. The mean PTV value is calculated as the mean of the last five recordings, to the nearest whole number. This PTV value is then converted to a coefficient of friction (termed $COF_{pendulum}$) using Eq. 1.

2.4 Contact Area

Understanding the influence of contact area is important when comparing test methods [38]. The surface area in contact between the smooth rubber outsole and surface (A_0) was estimated by forming ink prints. This technique was also used by Valiant in order to compare the contact area between a flat shoe outsole and a patterned shoe outsole [39]. A film of ink was applied to cover the outsole of the shoe. The shoe was then positioned with a preloaded contact angle between the outsole and each surface sample set at 7° within the test rig. Graph paper was rigidly attached onto a smooth Perspex sheet under the shoes before they were loaded vertically at the 500 N normal force condition. The procedure was repeated 3 times and the area left by each ink print was calculated. The average area (± 1 standard deviation) was found to be 1373 ± 20 mm^2. The rectangular contact area of the pendulum's rubber slider in contact with the surface was calculated by multiplying the average length by the average width that is in contact with the surface during sliding. The average slider length in contact was found to be 4 mm and the average slider width in contact was found to be 76 mm giving a contact area of 304 mm^2.

3. Results

3.1 Comparison of standard slip resistance methodologies

Figure 8 shows the lack of a significant relationship between the friction measurements found from each test device. Linear regression analysis found that for this correlation $p = 0.383$. This shows the disagreement between the results of two standard test methodologies and highlights the requirement to understand how each rest affects the friction mechanisms occurring during simulated heel/slider-surface contact. Figure 8 also shows the stiff surfaces recorded low $COF_{pendulum}$ but high COF_{13287}. On the stiff surfaces the BS EN ISO 13287:2007 standard appears to overestimate friction compared with the pendulum test.

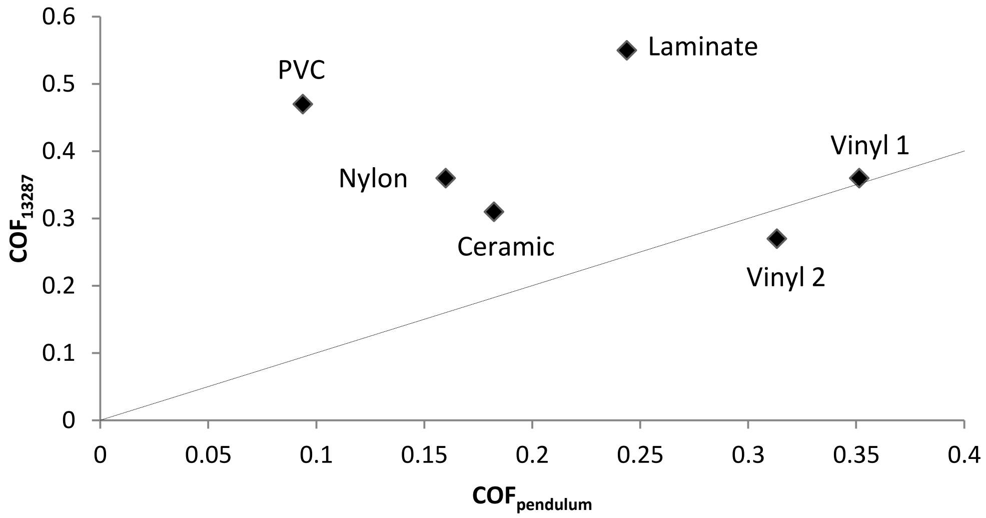


Figure 8: Plot of the measured mean coefficient of friction with the pendulum device against the measured mean coefficient of friction with the SATRA STM 603 device. Dotted line: $COF_{pendulum} = COF_{13287}$.

3.2 The effect of roughness on measured COF values

Figure 9 shows a plot of mean surface roughness (R_z) and the mean coefficient of friction measured by the pendulum device. According to the mean roughness (R_z) and mean $COF_{pendulum}$ each surface has high slip potential (Table 1 and Table 2 respectively). The linear relationship between R_z and $COF_{pendulum}$ was not found to be statistically significant ($p = 0.171$). The vinyl surfaces are deformable and have relatively high $COF_{pendulum}$. However, the other surfaces are hard and stiff surfaces, for which the $COF_{pendulum}$ increases with surface roughness. The high friction measurements found for the deformable Vinyl surfaces may be caused by internal energy losses as the surface deforms and recovers during the loading and unloading phases of the pendulum impact.

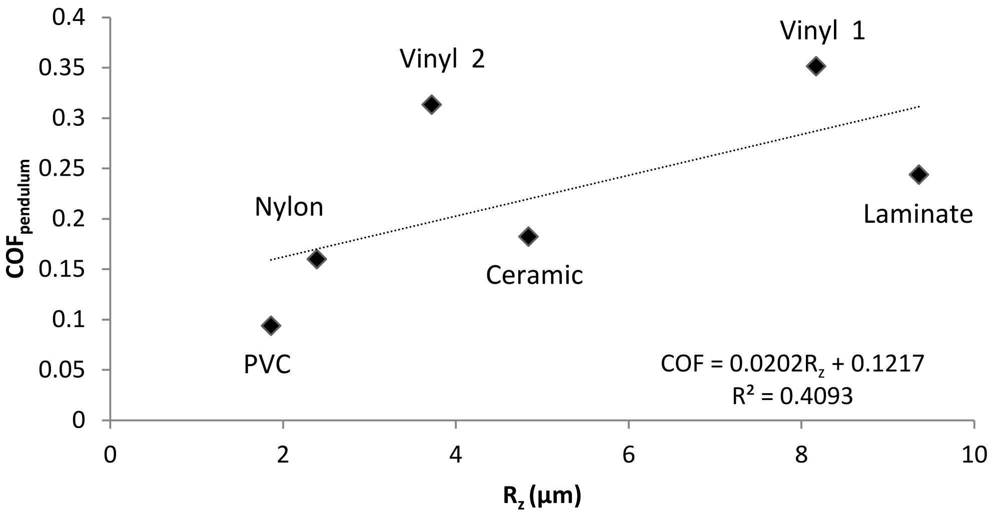


Figure 9: Plot of mean roughness (R_z) against the measured mean coefficient of friction with the pendulum device.

Figure 10 shows a plot of mean surface roughness (R_z) against the mean coefficient of friction measured according to BS EN ISO 13287:2007 standards. According to the mean COF_{13287} the Vinyl 2 and ceramic surfaces have moderate slip potential whereas the other surfaces have low slip potential (Table 1). This finding is in disagreement with the mean roughness and mean $COF_{pendulum}$ which rank each surface to have high slip potential. The relationship between R_z and COF_{13287} was not found to be significant ($p = 0.704$). The smoother surfaces (Nylon and PVC) show relatively high COF_{13287}, whereas the other surfaces show an increase in COF_{13287} with increasing roughness.

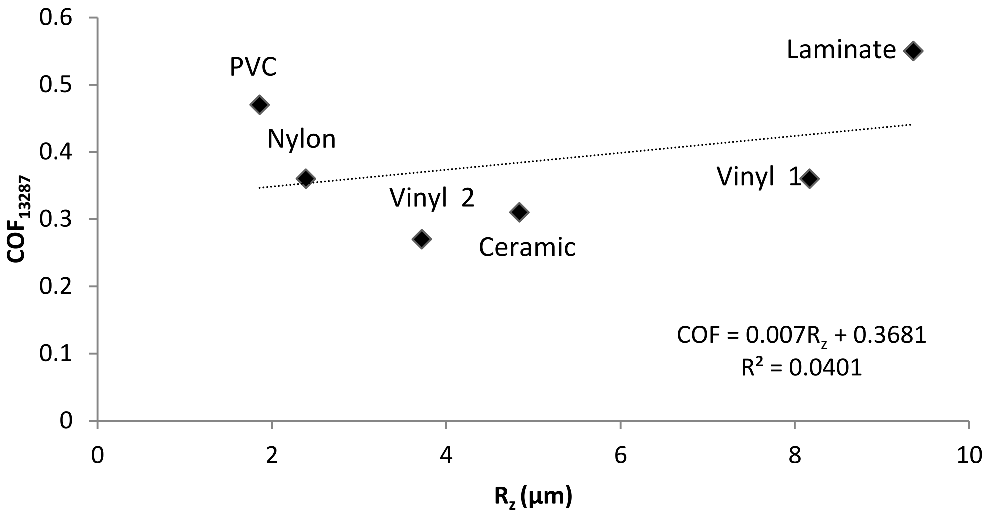


Figure 10: Plot of mean roughness (R_z) against the measured mean coefficient of friction measured according to BS EN ISO 13287:2007 standards.

3.3 The effect of normal force on COF_{13287}

Table 3 presents the mean COF_{13287} from the further tests conducted according to BS EN ISO 13287:2007 standards but under the six normal loading conditions. Table 3 highlights the repeatability achieved by the experienced operator during testing, reflected by the low standard deviations (where n = 5). Figure 11 shows a plot of mean COF_{13287} for each surface tested under increased normal load. Figure 11 highlights the low spread of results for the stiff surfaces (PVC, Ceramic, Nylon, and Laminate). For these surfaces no trend between normal force and COF_{13287} was found. However, the deformable vinyl surfaces showed a larger range of COF_{13287}. The plots of normal force against COF_{13287} for the two vinyl surfaces are shown in Figure 12. Strong power relationships were found between COF_{13287} and normal force for these surfaces and can be described by Eq. (2):

$$COF_{13287} = m(F_V)^n \quad (2)$$

Where F_V is the normal force and m is an arbitrary constant and n is an arbitrary exponent. The results show how friction mechanisms change with normal force as the deformation of the vinyl surfaces change. Under increasing load the surface deformation increases, increasing the friction force at a higher rate as energy is dissipated during the deforming and recovery of the surface.

Table 3: Mean COF_{13287} (standard deviation) under the different of normal force conditions (n =5).

Normal Force (N)	Surface					
	PVC	Ceramic	Vinyl 1	Vinyl 2	Nylon	Laminate
150	0.43 (0.0084)	0.24 (0.0130)	0.60 (0.0292)	0.40 (0.0045)	0.31 (0.0134)	0.53 (0.0089)
200	0.42 (0.0207)	0.25 (0.0084)	0.56 (0.0167)	0.34 (0.0055)	0.32 (0.0055)	0.53 (0.0045)
300	0.50 (0.0182)	0.27 (0.0207)	0.46 (0.0055)	0.31 (0.0045)	0.36 (0.0130)	0.55 (0.0071)

400	0.42 (0.0098)	0.26 (0.0055)	0.39 (0.0032)	0.26 (0.0020)	0.36 (0.0060)	0.53 (0.0040)
500	0.47 (0.0105)	0.31 (0.0154)	0.36 (0.0037)	0.28 (0.0024)	0.36 (0.0136)	0.55 (0.0024)
600	0.42 (0.0081)	0.25 (0.0068)	0.33 (0.0032)	0.27 (0.0024)	0.32 (0.0055)	0.49 (0.0032)

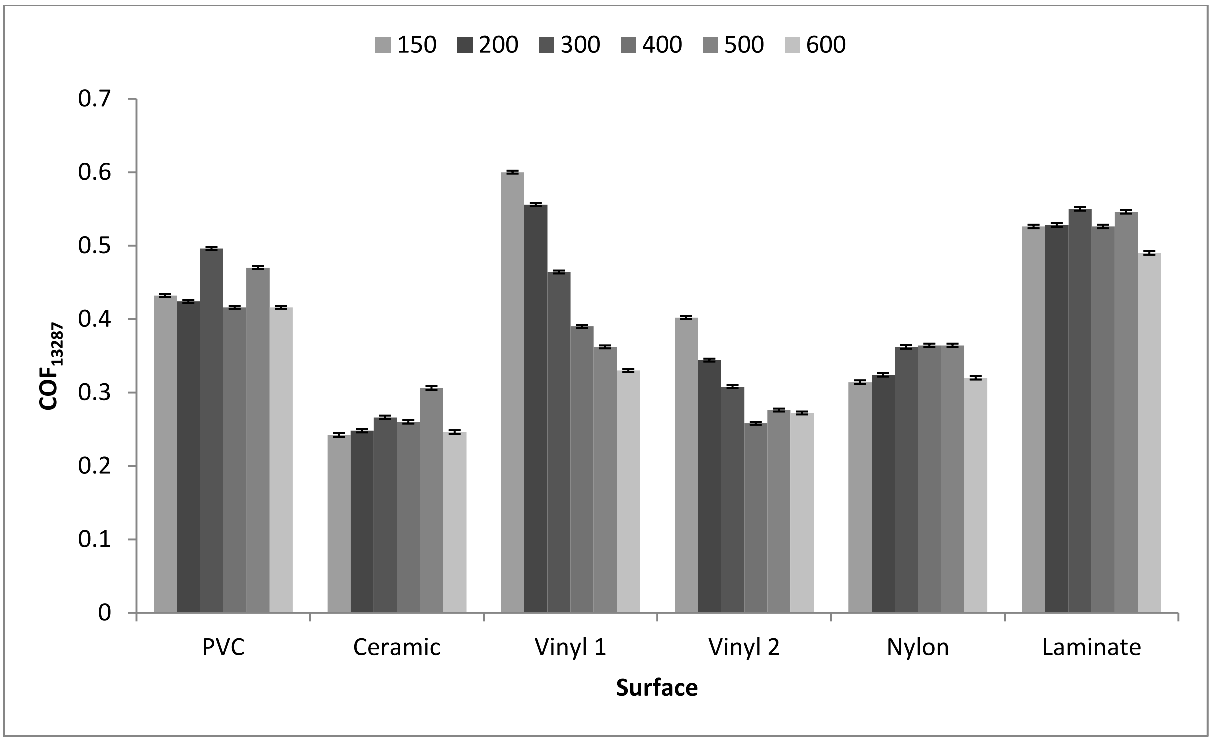


Figure 11: Plot of the mean COF_{13287} of the 6 surfaces under the 6 different normal force conditions (increasing from left to right). Error bars denote ± 1SD.

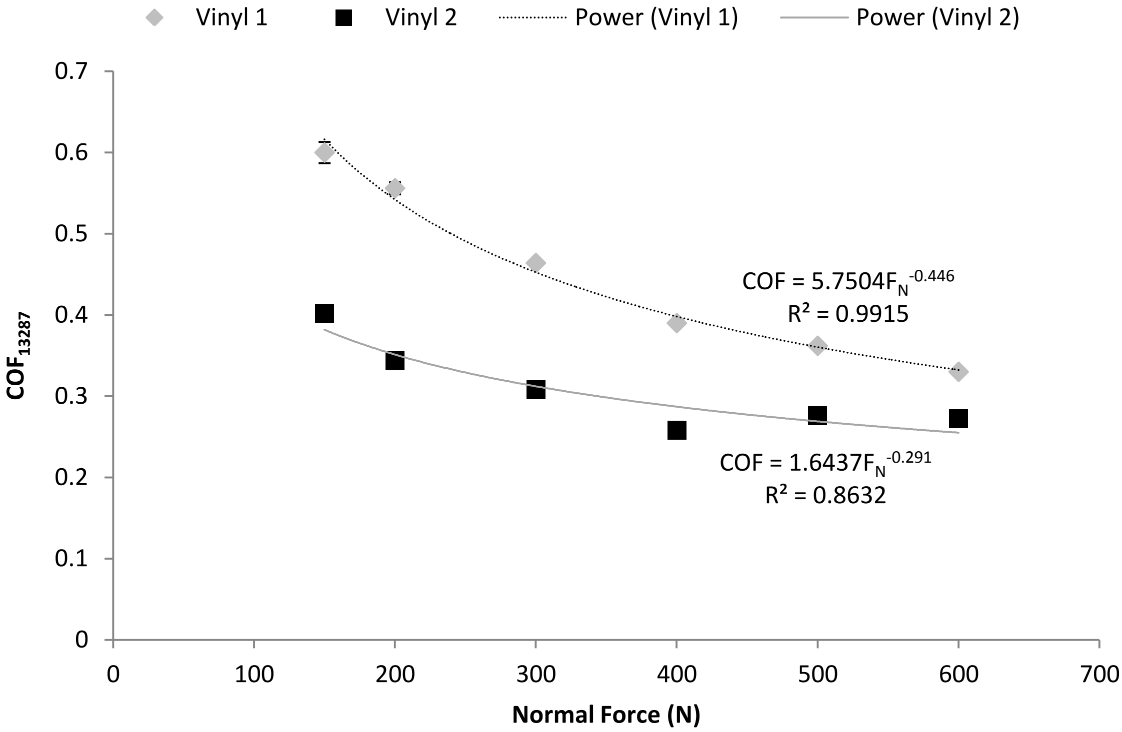


Figure 12: Plot of the mean COF_{13287} against normal force, and line of best power fit, for the 2 vinyl surfaces. Error bars denote ± 1SD.

4. Discussion

The results show no correlation between the two standardised mechanical test methods used to assess the risk of slip. This can be attributed to the effect the different testing methodologies have on the friction mechanisms developed at heel-surface contact. The static normal force applied by the pendulum slider assembly is reported to be 24.5 N, however, the pendulum device has been found to apply a relatively low normal force of 12 N during sliding contact with a surface [40]. Also, in comparison to the BS EN ISO 13287:2007 standard the pendulum produces a higher contact velocity which results in a lower contact time, and has a lower contact area. Gronqvist *et al*. (1999) reported a pendulum device of identical specification to have a mean sliding velocity of 2.8 m/s [19].

The results suggest that a linear relationship between roughness (R_z) and slip resistance, as measured by the pendulum, may exist for stiff surfaces. However, the relationship does not include deformable surfaces due to energy losses at impact caused by the surfaces viscoelastic hysteresis. With stiff surfaces the friction caused by asperity contact is dominant, and controlled by surface roughness. However, the energy dissipated during loading and unloading throughout impact contributes to a significantly increased friction measurement for deformable surfaces.

Surface deformability also affected the COF_{13287} measured on the deformable surfaces (Vinyl 1 and Vinyl 2). As the load increases the effect of surface deformation becomes less dominant and the rate at which the friction force increases with normal load decreases and eventually plateaus. This results in the power relationships shown in Figure 12. This finding questions the suitability of only testing at the current fixed normal load. In order to extract a suitable normal loading condition, it is recommended that further work is conducted to understand the differences in normal loading conditions during real-life walking between compliant, deformable surfaces and stiff surfaces. Figure 12 suggests the power relationship on the stiffer Vinyl 2 surface plateaus between 300 and 400 N normal load. Therefore the energy losses observed as the Vinyl 2 surface deforms will not be as dominant during the standard 500 N test. The comparatively high loading (500 N) may have resulted in the surfaces maximum deformation. The energy losses associated with the surface deforming and recovering may have a negligible effect on the overall friction compared with the other friction mechanisms associated with footwear-surface contact. The power relationship found between COF_{13287} and normal force on deformable surfaces will be dependent on the particular deformation recovery cycle of the surface system. As surface stiffness affected both sets of standardised results it is recommended that surface stiffness is considered when assessing the slip resistance of flooring.

During heel-surface contact when testing under the BS EN ISO 13287:2007 standard, it can be hypothesised that different friction mechanisms are dominant in comparison to the pendulum. Of the stiff surfaces, the PVC and Nylon surface samples were found to be the smoothest surfaces. Therefore, moisture is more likely to be squeezed out of asperity contact, firstly as the heel is loaded on the surface and secondly as the surface slides.

Fuller describes the thickness the hydrostatic squeeze film produced when a load is applied by [41]:

$$t = \frac{3\pi\mu R^4}{4F_v}\left[\frac{1}{h_2^2} - \frac{1}{h_1^2}\right] \tag{3}$$

Which can be rearranged to give:

$$h_2 = \sqrt{\frac{1}{\left[\frac{4tF_v}{3\pi\mu R^4} + \frac{1}{{h_1}^2}\right]}} \tag{4}$$

And the hydrodynamic squeeze film produced during a sliding event can be found using [41]:

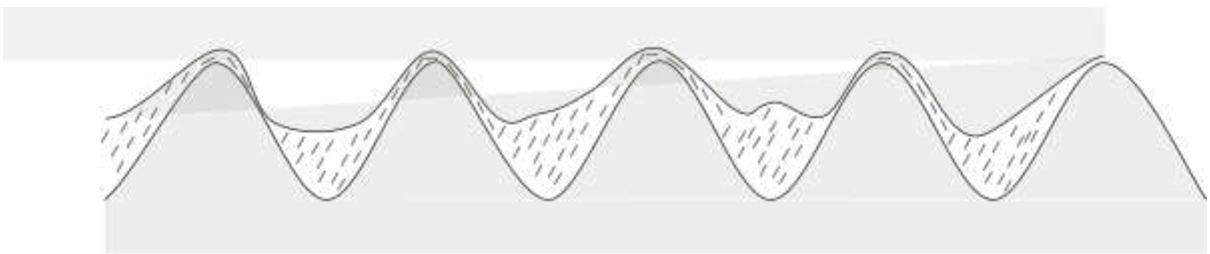
$$h = \sqrt{\frac{6\mu u l A_0 K_E}{F_v} \times K_p} \tag{5}$$

From observing Figure 7 it can be assumed the surface is preloaded for a minimum time (t) of 0.25 seconds and the initial thickness of water (h_1) standing on the surface has a minimum thickness of 1 mm, as stated in the standard. Equation 3 shows that as t increases the squeeze film decreases as fluid is squeezed out of contact. During the initial contact time the squeeze film will be significantly reduced prior to contact. During sliding the lubrication of the contact will be depend significantly on the roughness characteristics of the surface profile. As the pendulum foot contacts the surfaces with an initial velocity (approx. 2.8 m/s) a thicker squeeze film is developed (Table 4) and one hypothesis is that a continuous squeeze film is present throughout the contact, as is illustrated in Figure 13. Therefore, the relatively high COF_{13287} observed on the PVC and Nylon surfaces could be due to an insufficient lubrication film.

Table 4: Hydrodynamic squeeze film, *h*, calculated for the different test methods using Equation 5.

Test Method	μ, Nm^{-2}	u, ms^{-1}	*l*, mm	A_0, mm^2	K_E	K_P	F_v, N	*h*, μm
BS 7976 1-3:2002 (Pendulum low load)	1×10^{-3}	2.8	4	304	1	0.025	12	6.52
BS 7976 1-3:2002 (Pendulum high load)	1×10^{-3}	2.8	4	304	1	0.025	24.5	4.57
BS EN ISO 13287:2007 (STM 603 device)	1×10^{-3}	0.3	19	1373	1	0.025	500	1.54

(a)



(b)

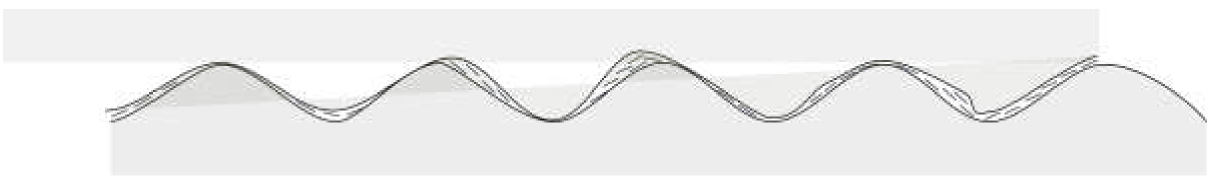


Figure 13: Hypothesis of rubber-surface contact with identical applied pressure. (a) The rough surface profile prevents the water lubricant from being squeezed out of the contact area. (b) Reduced surface roughness allows increased lubricant being squeezed out of contact and results in regions of direct contact between the two surfaces.

Differences in contact time have been shown to significantly affect slip resistance [42]. The BS EN ISO 13287:2007 standard is conducted at a lower velocity (0.3 m/s) than the pendulum (2.8 m/s). At a higher velocity, as with the pendulum test, there will be insufficient time for the fluid to be squeezed out resulting in a continual film of fluid between the surfaces. This explains why the stiff surfaces recorded low $COF_{pendulum}$ but high COF_{13287}. These findings are in agreement with Beschorner *et al*. who found friction decreased with sliding speed during experiments simulating wet dynamic shoe-floor contact [43, 44]. Both studies attributed this relationship to the transferring of load from asperities to the fluid with increased sliding speed.

An examination of the force traces given by the PVC and Nylon surfaces shows the development of this fluid squeeze effect and the possible contribution of different friction mechanisms. A study by Strobel *et al.* also concluded that adhesion and hysteresis both contribute to shoe-floor friction [45]. A typical trace taken on the PVC surface is shown in Figure 14, the friction mechanisms developed during contact can be described in 5 phases, with hypotheses for the friction mechanisms at play:

1. The surface is loaded to 500 N. Water is squeezed out of the contact and adhesive bonds form.
2. The devices motor reaches constant velocity (0.3 m/s) and a period of slip occurs with an approximate coefficient of friction of 0.39. During this time water is continuously pushed out of contact increasing the real contact area which leads to increased adhesion.
3. The friction increases as the rubber heel deforms laterally due to high adhesive attraction. A peak is reached when maximum heel deformation and contact area has been achieved. Increased friction occurs as water is pushed out of the contact and the lubricating effect is reduced.
4. A high period of peak constant friction as the heel has reached its peak deformation and contact area. The friction force required to overcome adhesion is therefore constant.
5. The friction has a sudden drop. The adhesive friction between the heel and surface is reduced but energy is dissipated as the rubber heel experiences slight recovery.

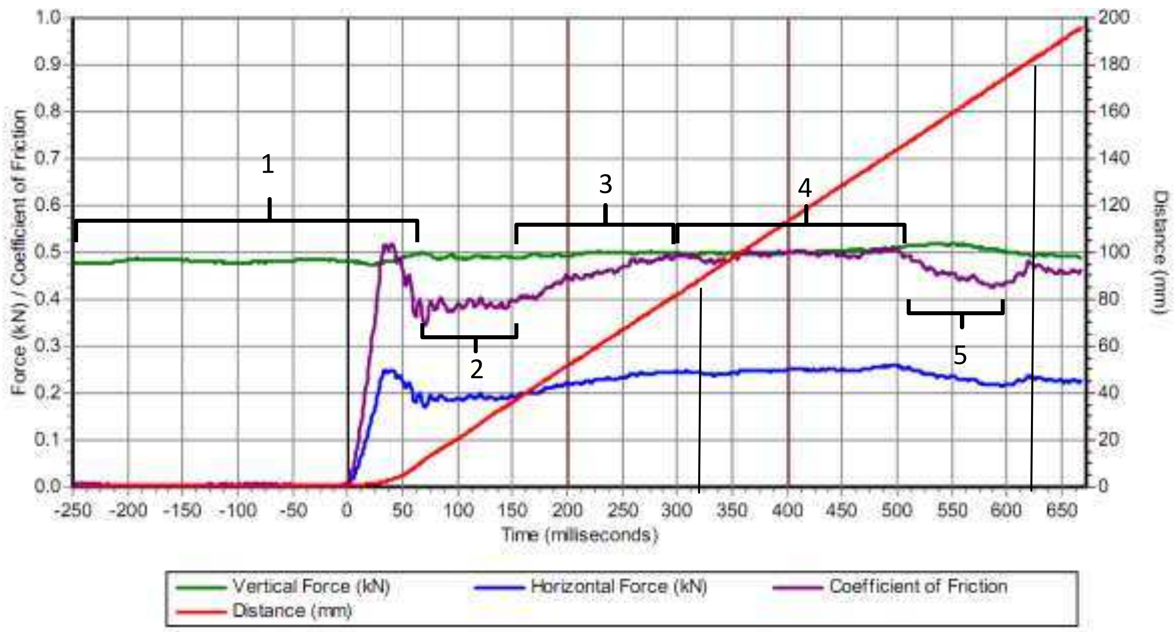


Figure 14: Typical plot given by SATRA slip resistance testing machine (STM 603) for 'PVC' surface.

The findings show care needs to be taken when assessing results from the STM 603 test rig in wet conditions. The trace shown in Figure 14 shows how the periods of peak friction (phase 4) and slip/recovery (phase 5) would have been used to measure the mean COF between 0.3 and 0.6 seconds – as specified in the standard. Although such phenomena might be present during a real slip event, the result given will be dependent on the localised moisture. As the severity of a slip can be described by its length, on the smooth surfaces tested in this study, continual surface moisture to contaminant and lubricate contact would be required to replicate severe slip conditions.

5. Conclusions

The pendulum test described in BS 7976-2:2002 attempts to characterise flooring slip-risk , whereas the test described in BS EN ISO 13287:2007 attempts to characterise footwear slip-risk, both for a given contaminant. The measured values of COF collected using both methods do not compare well due to different contact and friction mechanisms associated with each test method. Surface roughness and surface stiffness controlled the $COF_{pendulum}$ in wet conditions. The contact conditions of the pendulum device specified in BS 7976-2:2002 and the contact conditions specified in BS EN ISO 13287:2007 on deformable flooring cause friction losses associated with energy dissipated during loading and unloading. On stiff surfaces no trend between normal force and COF_{13287} was found. A power relationship was found to exist between normal force and COF_{13287} on deformable surfaces. Surface roughness controls COF_{13287} in wet conditions on stiff surfaces. Under the high loading scenario of a real slip event, as replicated by the BS EN ISO 13287:2007 standard, surface friction from adhesion is the dominant component. The key difference between the test methods is the lubricating layer developed. If a slip is to lead to a fall on a smooth wet surface then a continual film of fluid is required to be maintained between the footwear and the flooring. These findings suggest that specifying a fluid layer of at least 1 mm thickness (as stated in BS EN ISO 13287:2007) is not suitable to replicate actual slip conditions between 0.3 and 0.6 seconds for a heel slip occurring at 0.3 m/s. To accurately predict the risk of slipping the test method has to characterise the shoe-surface system when a person slips. Despite its lower normal loading conditions the high velocity pendulum is a more appropriate test device to replicate such severe slip conditions. No significant linear relationship was found between either $COF_{pendulum}$ or COF_{13287} with surface roughness (R_z). However, these findings suggest R_z is suitable to assess the risk of slip on stiff surfaces if it is assumed a continual film of fluid will remain within the heel-surface contact. Although the pendulum is suitable to assess such a risk, it may give misleading results on deformable surfaces as it is not replicating the loading conditions during actual slip conditions. Further work is required to define the degree of flooring compliance at which the pendulum test is affected by this mechanism.

References

1. HSE. *Assessing the slip resistance of flooring - A technical information sheet.* . 2007 [cited 2012 March 14th]; Available from: http://www.hse.gov.uk/pubns/web/slips01.pdf.
2. Perkins, P.J., *Measurement of slip between the shoe and ground during walking*. 1978, Philadelphia, PA, ETATS-UNIS: American Society for Testing and Materials. 17.
3. HSE. *A study of the effect of modifying the European Standard mechanical slip resistance test for footwear.* 2010 [cited 2012 March 14th]; Available from: http://www.hse.gov.uk/research/rrpdf/rr801.pdf
4. Marpet, M., *On threshold values that separate pedestrian walkways that are slip resistant from those that are not.* Journal of Forensic Sciences, 1996. **41**(5).
5. Redfern, M.S. and J. DiPasquale, *Biomechanics of descending ramps.* Gait & Posture, 1997. **6**(2): p. 119-125.
6. Whittle, M.W., *Generation and attenuation of transient impulsive forces beneath the foot: a review.* Gait & Posture, 1999. **10**(3): p. 264-275.
7. Strandberg, L. and H. Lanshammar, *The dynamics of slipping accidents.* Journal of Occupational Accidents, 1981. **3**(3): p. 153-162.

8. Williams, J., *Engineering Tribology*. 1994: Oxford University Press.
9. Chang, W.-R., *The effect of surface roughness on the measurement of slip resistance.* International Journal of Industrial Ergonomics, 1999. **24**(3): p. 299-313.
10. Persson, B.N.J., *Theory of rubber friction and contact mechanics.* Journal of Chemical Physics, 2001. **115**(8): p. 3840-3861.
11. Palasantzas, G., *Influence of self-affine roughness on the adhesive friction coefficient of a rubber body sliding on a solid substrate.* Surface Science, 2004. **565**(2-3): p. 191-196.
12. Persson, B.N.J., F. Bucher, and B. Chiaia, *Elastic contact between randomly rough surfaces: Comparison of theory with numerical results.* Physical Review B, 2002. **65**(18): p. 184106.
13. Persson, B.N.J., *On the theory of rubber friction.* Surface Science, 1998. **401**(3): p. 445-454.
14. Palasantzas, G., *Comparison of hysteric and adhesive coefficient of friction for rubbers sliding onto self-affine rough surfaces.* Journal of Applied Physics, 2005. **97**(3): p. 4.
15. Persson, B.N.J., *Elastoplastic Contact between Randomly Rough Surfaces.* Physical Review Letters, 2001. **87**(11): p. 116101.
16. Persson, B.N.J., *Rubber friction: role of the flash temperature.* Journal of Physics: Condensed Matter, 2006. **18**(32): p. 7789.
17. Clarke, J.D., *Improving the relevance of portable mechanical test methodologies used to prevent slips at the footwear-surface interface.*, in *International Conference on slips, trips and falls*, H.a.S. Laboratory, Editor. 2011: Buxton, UK.
18. Chang, W.-R., J.P. Cotnam, and S. Matz, *Field evaluation of two commonly used slipmeters.* Applied Ergonomics, 2003. **34**(1): p. 51-60.
19. Gronqvist, R., M. Hirvonen, and A. Tohv, *Evaluation of three portable floor slipperiness testers.* International Journal of Industrial Ergonomics, 1999. **25**(1): p. 85-95.
20. Gronqvist, R., et al., *The validity and reliability of a portable slip meter for determining floor slipperiness during simulated heel strike.* Accident Analysis and Prevention, 2003. **35**(2): p. 211-225.
21. Marpet, M., *Comparison of walkway-safety tribometers.* Journal of Testing and Evaluation, 1996. **24**(4): p. 245-254.
22. Ricotti, R., M. Delucchi, and G. Cerisola, *A comparison of results from portable and laboratory floor slipperiness testers.* International Journal of Industrial Ergonomics, 2009. **39**(2): p. 353-357.
23. Hallas, K. and R. Shaw, *Evaluation of the Kirchberg rolling slider and slipalert slip resistance meters*. 2006, Health and Safety Laboratory.
24. Smith, R., *Assessing testing bias in two walkway-safety tribometers.* Journal of Testing and Evaluation, 2003. **31**(3).
25. Powers, C., et al., *Repeatability and bias of two walkway safety tribometers.* Journal of Testing and Evaluation, 1999. **27**(6).
26. Marpet, M. and D. Fleischer, *Comparison of walkway safety tribometers: part two.* Journal of Testing and Evaluation, 1997. **25**(1).
27. Kulakowski, B., et al., *Evaluation of performance of three slip resistance testers.* Journal of Testing and Evaluation, 1989. **17**(4).
28. Powers, C.M., et al., *Assessment of walkway tribometer readings in evaluating slip resistance: A gait-based approach.* Journal of Forensic Sciences, 2007. **52**(2): p. 400-405.
29. Siegmund, G.P., et al., *The effect of subject awareness and prior slip experience on tribometer-based predictions of slip probability.* Gait & Posture, 2006. **24**(1): p. 110-119.
30. Hallas, K., et al. *Comparison of site-based friction measurements and slip potential*. in *Contemporary Ergonomics 2008: Proceedings of the International Conference on Contemporary Ergonomics (CE2008)*. 2008. Loughborough University, UK: Taylor and Francis.
31. *The assessment of floor slip resistance: The UK slip resistance group guidlines (version 4)*. 2011: UK slip resistance group.

32. Harper, F.C., W.J. Warlow, and B.L. Clarke, *The Forces Applied to the Floor by the Foot in Walking: 1. Walking on a Level Surface*. 1961, National Building Studies, Building Research Station.: London.
33. Kim, I.J. and R. Smith, *Observation of the floor surface topography changes in pedestrian slip resistance measurements.* International Journal of Industrial Ergonomics, 2000. **26**(6): p. 581-601.
34. Kim, I.J., R. Smith, and H. Nagata, *Microscopic observations of the progressive wear on shoe surfaces that affect the slip resistance characteristics.* International Journal of Industrial Ergonomics, 2001. **28**(1): p. 17-29.
35. Tsai, H.J., et al., *A Microscopic Model for Pedestrian Slips Caused by Particle Contamination*, in *Advanced Tribology*, J.B. Luo, et al., Editors. 2009, Tsinghua University Press: Beijing. p. 831-832.
36. Hunwin G., Thorpe S. and Hallas K., *Improvements to the EN Slip Resistance Test for Footwear*, Contemporary Ergonomics and Human Factors 2010, Proceedings of the Annual Conference of the Institute of Ergonomics and Human Factors, M. Anderson, Editor. 2010, Taylor & Francis: UK. p. 471-479.
37. Bowman, R., Strautins, C.J., Westgate, P., and Quick, G.W., *Implications for the Development of Slip Resistance Standards Arising from Rank Comparisons of Friction-Test Results Obtained Using Different Walkway-Safety Tribometers Under Various Conditions*, in *Metrology of Pedestrian Locomotion and Slip Resistance, STP 1424,* M. Marpet and M.A. Sapienza, Editors. 2002: American Society for Testing and Materials, West Conshohocken, PA.
38. Smith, R., *Test foot contact time effects in pedestrian slip-resistance metrology.* Journal of Testing and Evaluation, 2005. **33**(1).
39. Valiant, G.A. *The effect of outsole pattern on basketball shoe traction.* in *4th International Symposium on Biomechanics in Sports*. 1986: DelMar, CA, Academic Publishers.
40. Lewis, R., et al., *A comparison of pendulum heel slip simulation with actual foot friction measurements.*, in *International Conference on slips, trips and falls*, H.a.S. Laboratory, Editor. 2011: Buxton, UK.
41. Fuller, D.D., *Theory and practice of lubrication for engineers*, ed. W. J. 1956, New York.
42. Irvine, C., *Evaluation of the effect of contact-time when measuring floor slip resistance.* Journal of Testing and Evaluation, 1986. **14**(1).
43. Beschorner, K.E., et al., *Modeling Shoe-Floor-Contaminant Friction Applied to a Pin-on-Disk Apparatus*, in *Contemporary Ergonomics 2008*, P.D. Bust, Editor. 2008, Taylor & Francis Ltd: London. p. 717-722.
44. Beschorner, K., et al., *Modeling mixed-lubrication of a shoe-floor interface applied to a pin-on-disk apparatus.* Tribology Transactions, 2009. **52**(4): p. 560-568.
45 Strobel, C.M., et al. *Analysis of the contribution of adhesion and hysteresis to shoe-floor lubricated friction in the boundary layer lubrication regime*. Tribology Letters, 2012. **47**(3): p. 341-347.