Article:

Lewis, S.R., Hallas, K., Keen, B. et al. (3 more authors) (2020) Development of a new shoe/floor slip resistance test rig. Tribology International, 151. 106500. ISSN 0301-679X

https://doi.org/10.1016/j.triboint.2020.106500

Development of a New Shoe/Floor Slip Resistance Test Rig

S. R. Lewis1[1], K. Hallas[3], B. Keen[1], G. Hunwin[3], R. Shaw[3] and M.J. Carré[2]

[1]SyxRail Ltd, 76 – 80 Baddow Road, Chelmsford, Essex, CM2 7PJ, UK
[2]Department of Mechanical Engineering, University of Sheffield, Sheffield, South Yorkshire, S3 7AH, UK
[3]Health & Safety Laboratory Buxton, Derbyshire, SK17 9JN, UK

Stephen.lewis@syxrail.co.uk

Abstract

A critical appraisal of Shoe Slip Tester by The University of Sheffield in collaboration with Health and Safety Laboratories UK is shown in this paper. The Shoe Slip Tester has been designed as a portable and more practical alternative to the Ramp tester which is currently considered the Gold Standard in Shoe/Floor slip resistance testing. Test on identical safety shoe samples were carried out using the Shoe Slip Tester and RAMP in parallel and the data yielded compared between the two test devices. Raw data showed that the Shoe Slip Tester yielded higher coefficients of friction compared to the ramp. However, controlling the data for force applied at shoe impact between the two rigs showed good correlation between the two test devices. A series of recommendations have been made to the design of the Shoe Slip Tester based on tests reported in this paper. These recommendations will improve the correlation between the two test devices. The Shoe Slip Tester can therefore be said to be a suitable alternative to the RAMP tester.

1.0 Introduction

Data from the Health and Safety Executive (UK) indicates that the most common cause of injuries to employees while at work are slips, trips and falls, accounting for 29% of non-fatal injuries and an estimated 1,363,000 lost working days in 2018/19 [1]. A wide variation in the slip resistance of a sample of different safety shoes currently on sale in the UK has been shown. A new portable shoe assessment methodology has been developed which should enable safety shoe manufacturers to assess, develop and deliver better products. The portability of the test rig also allows measurements to be taken at the locations of accidents and in the development and certification of new flooring types. Controlled use of the test rig in the lab can also build on the understanding of how shoes interact with different surfaces, in various environmental conditions.

The Shoe Slip Tester, SST, was first developed by The University of Sheffield, UoS, in collaboration with Health and Safety Laboratories UK, HSL, as a portable and more practical alternative to the Ramp test, shown in Figure 1. The Ramp test is considered the "Gold Standard" in shoe floor friction testing. More information on the operation of the Ramp tester can be found in [2]. For comparative purposes the weight and size of a typical ramp test machine are approximately 300 kgs and 2500 x 1500 x 4000 mm. The SST on the other hand is approximately 35 kgs and 100 x 150 x 150 mm and can be safely lifted and moved by two people.

The SST, shown in Figure 2, is powered by (UK) mains A.C. electrical power (230 V at 50 HZ). The compressed air system can be fed by either a ring main or portable air compressor of 8 Bars. The air pressure feed to the air ram is controlled via a regulator and can be set by the user before testing. The rig consists of a lower horizontal surface intersected by a vertical frame to which the control panel, backing plate and pneumatic system are attached. The vertical frame intersects the area of the lower frame where the operator stands to the test area. The control panel controls the extension and retraction of the air ram and houses safety features such as the emergency stop and dead man's switch, DMS. The DMS ensures the rig cannot be operated without both of the operator's hands on the control panel. Attached to the end of the air ram is a load cell and the mechanical ankle assembly. The mechanical ankle (seen more clearly in Figure 3) allows off-the-shelf shoe samples to be fitted to the air ram with a variable heel angle. Each shoe has a last inserted allowing fitting of the shoe to the ankle. The ankle is constructed of steel and is in two parts bolted together using spring washers to act as pivots with a degree of frictional stiffness.

For all tests reported in this paper the floor surface sample was restricted to a stainless-steel plate, cold rolled and ground and confirming to BS EN 10088-2:2014 [3]. This was to limit the number of tests with a focus on variation of shoe type. The surface roughness of the plate was controlled to between 1.6 µm and 2.5 µm R_z by preparation using silicon carbide abrasive paper (grit size range 100 to 600). Confirmation of the plate roughness was confirmed by measuring with a surface profilometer in 10 different locations.

A similar cart type shoe test device was developed by SHIBATA et. al. [4]. Like the SST this device can also measure various shoe and flooring types and is also portable relative to the Ramp. The cart device has also been shown to be able to measure the friction of various flooring types with correlation between it and Ramp tests [5, 6]. Results from the Ramp test in [4] however, were not converted to a CoF so a direct comparison of the CoF yielded by the cart and the CoF yielded by the Ramp was not made. The cart device is pushed along by an operator at walking speed. The shoe sample is dead weight loaded and lies flat on the test surface i.e. zero heel angle. The heel angle of the SST on the other hand can be varied to more accurately represent the human gait.

This paper presents results of thorough testing of the SST and a critical analysis of the device.

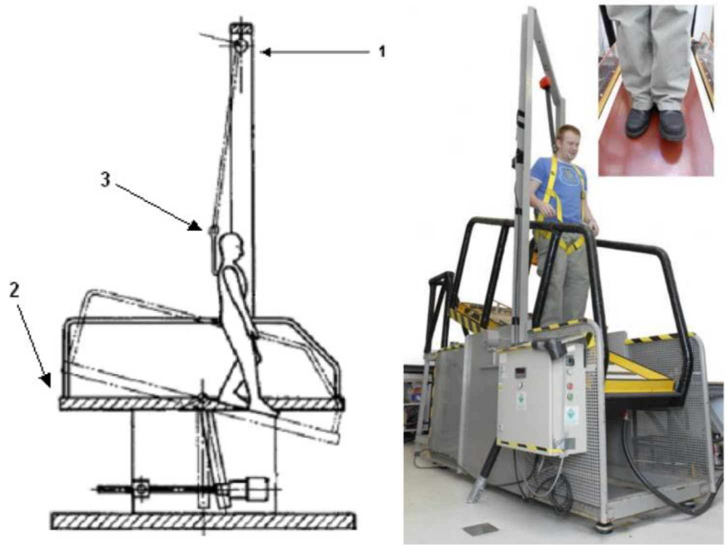

Figure 1. The HSL Ramp Test, Diagram adapted from DIN 51130 [2]

Figure 2 shows the prototype SST in its state at time of writing. The rig uses a pneumatic ram to force a mechanical ankle with attached test shoe into a test surface. A load cell is fitted to the end of the ram to measure forces during shoe-surface contact.

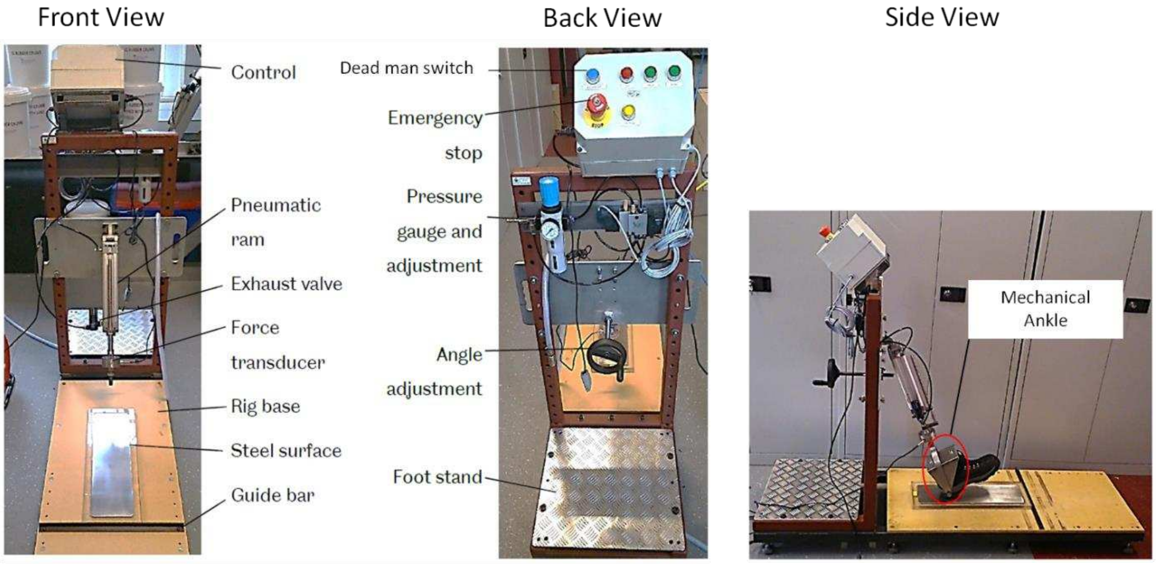

Figure 2. Prototype Shoe Slip Tester

Once the shoe has been prepared by lightly washing and then conditioning the sole with abrasive green lapping paper, it is attached to the mechanical ankle joint, shown in Figure 3a. The mechanical ankle allows the shoe to rotate about a pivot point replicating the human gait. Friction in the ankle pivot is maintained by a bolt and spring washer assembly. This friction is enough to allow the shoe to maintain the set heel angle up to the moment of impact. The deceleration force caused by impact and continual application force by the air ram is enough to overcome the friction in the joint and cause the shoe to rotate flat. The standard method of operation of the rig is first to set the slip angle (θ_S) and then the heel angle (θ_H) according to Figure 3s. In these tests heel angles of 7, 14 and 21° were tested. It has been shown in the literature that the human heel angle on moment of heel impact is between 13 and 25° [7, 8, 9 and 10]. In this first stage the ram is retracted so that there is a gap between the shoe and the test surface (this gap is not shown in Figure 3a). The cleaned test surface will then have contaminant applied according to the test mandate or left if it is a dry test. The operating pressure is then set to between 3 and 5 Bar as in the case of this study. This results in a peak impact force of between 400 and 1100 N (depending on settings such as height of the backing plate and heel angle). Force data is then set to record, if this is required. The test is then ready to begin. The ram is fired and the shoe will impact the test surface either sticking or slipping. Stick and slip events are recognised by eye in the first instance, but also provide a distinct trace that can be observed on the resultant force vs time plot (shown in Figure **3**b). If the result is a stick event then the slip angle is increased by 1 degree and this process is repeated until a slip occurs. The slip and heel angles are set independently of each other (1st slip followed by heel) before each test, meaning that the shoe will always impact the surface at the desired heel angle regardless of the slip angle. The slip angle at which slip occurs is an indirect representation of the ratio of the horizontal to vertical forces at the instance of contact and can be translated into the dynamic friction coefficient using the following formula:

$$\boldsymbol{CoF} = \tan(\boldsymbol{\theta_S}) = \frac{\boldsymbol{F}}{\boldsymbol{R}} \tag{1}$$

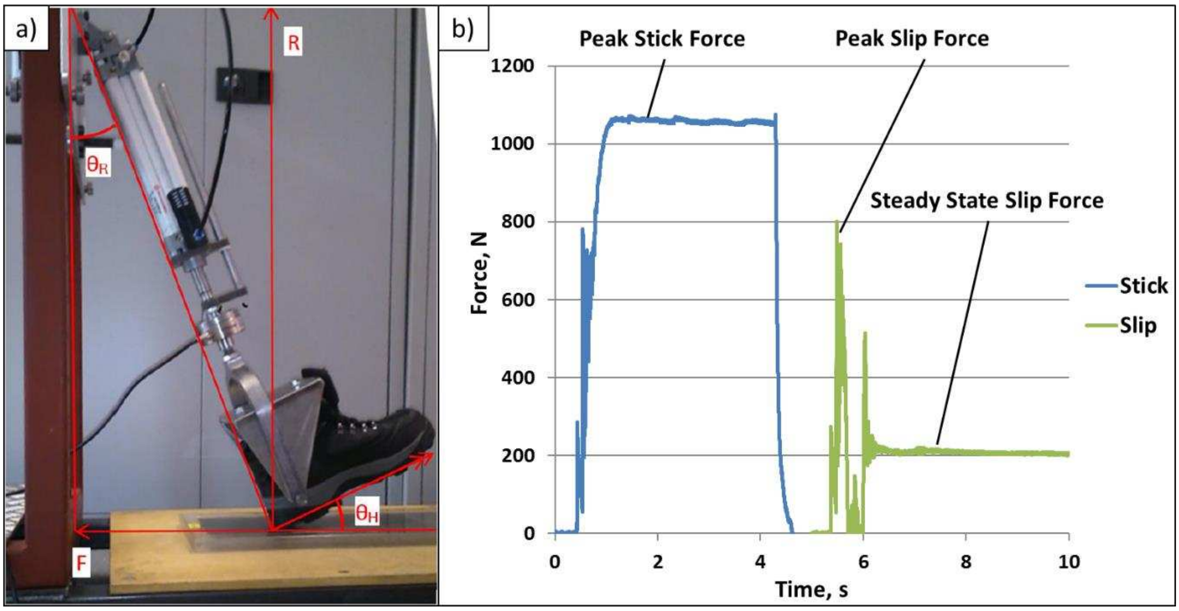

Figure 3. a) Side view of the SST where θ_S is the slip angle, θ_H is the heel angle, R represents the reaction force upon shoe impact and F represents the friction force upon shoe impact b) plots showing typical force vs. time responses for stick and slip events.

A prototype version of the SST was tested at the UoS. At the same time tests were also conducted by HSL on a twin version of the SST, alongside Ramp tests under identical conditions and with identical samples. The aim of this paper is a thorough comparison and analysis of the data generated at the UoS and comparison of this data to that generated at HSL. A critique of the SST in its current guise and suggestion of suitable modification of the test rig is also included in this work. To limit the number of tests which needed to be carried out, four commercially avalible shoe samples were picked for the tests and tested each at UoS and HSL. All shoe samples were the same size, UK size 10 and complied with UK safety regulations at the time of testing. A separate pair of shoes was worn by the operator when tests were conducted using the ramp test.

1.1 Literature Review

The chart in Figure 4 was first shown in [11] and shows typical ground reaction forces for one foot walking on a level surface for one stride. The four sections of the stance phase are shown as: A = heel impact; B = foot flat; C = propulsion; D = toe off [12].

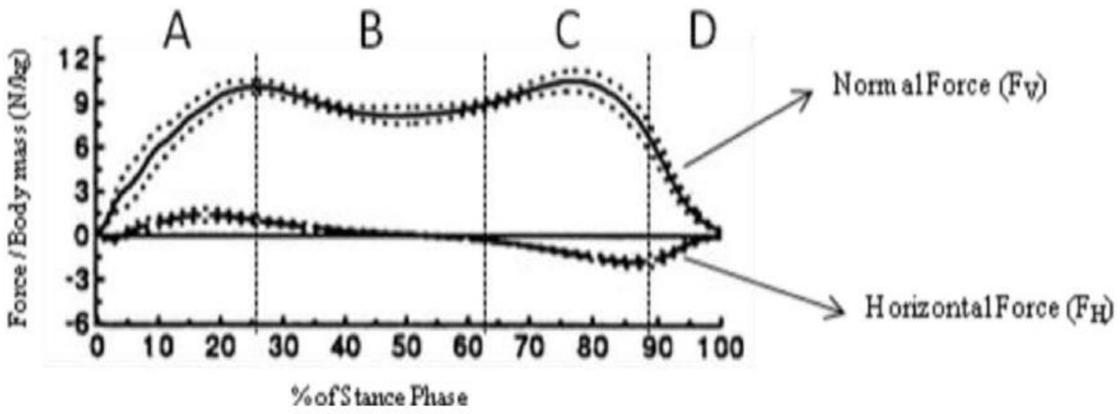

Figure 4. Typical ground reaction forces of human gait [11]. Normal force (Fv), solid line; horizontal force (FH), dashed line; standard deviations, dotted lines. Republished from [11] with permission from Elsevier.

Many authors including [13, 14, 15, 16, 17] have highlighted heel impact is the most likely phase where slips can result in falls. Authors in [7] considered that the first peak in horizontal force (zone A in Figure 4) is the most critical with respect to slips resulting in falls. It occurs roughly 19% into the stance phase, which is 90 to 150 ms after heel contact. At this position of the stance the ratio of F_H to F_V is at a maximum i.e. the friction demand is at its highest. One of the most fundamental factors in determining if slips will happen is the balance between the required coefficient of friction (RCOF), demand and the available COF, supply [7]. This hypothesis can be visualised as a supply and demand model as shown in Figure 5. Any given shoe/floor combination will have a defined dynamic coefficient of friction, CoF. This CoF represents “supply” and essentially means that for a given vertical load the shoe/surface can support a “demanded” horizontal, F_H, load which is equal to, but not greater than F_v multiplied by the CoF. If the Horizontal “demand” exceeds the product of F_v and CoF then slip will occur.

Demand **Supply** **Result**

$$\textbf{If}:\ F_H \ < F_V \times CoF \ \ \textbf{then} \ \ STICK$$

$$\textbf{If}:\ F_H \ > F_V \times CoF \ \ \textbf{then} \ \ SLIP$$

Figure 5. Supply/Demand Model of Heel Strike Friction

Authors in [18] calculated the resultant RCoF values from a typical ground reaction force plot such that shown in Figure 4. It was shown that there was a peak RCOF value of 0.20 which occurred at the same time as the peak shear force. Research conducted in [4] suggested that the minimum CoF needs to be 0.4. A friction between these two values could therefore be seen to be a minimum requirement of any floor/shoe foot interface to meet safety standards although more testing may be required in order to build confidence in this value under a range of conditions and hone in on the relevant factor of safety which may need to be applied i.e. absolute minimum CoF required from any surface/shoe combination.

In [14] it was observed that many sliding motions were observed during the toe-off part of the walking cycle (section C/D Figure 4) however, none of these resulted in falls or even loss of balance, presumably because the walking individual is able to land on the other foot if traction is lost at this end-point of a stride. This raises two points: 1) any test rig design needs to simulate the part of the walking cycle with the highest slip risk i.e. heel-strike; and 2) in most cases, whether or not a slip/slide results in will be dependent on other factors identified in [7]. Some of these are anatomical such as foot geometry, body mass, stride length and height. Others are physiological such as strength, rate of muscle force and the speed of the neurological feedback control i.e. reaction rate. Other factors could also be behavioural such as attentiveness, anticipation of slippery conditions or fear of falling [7]. The motor reactions of the person, timing in the walking cycle and position relative to the person's centre of mass at which slip occurs will largely determine if balance is fully restored or a fall takes place. In [14] it was also observed that the heel always slid upon impact and that in "non-slip" events these sliding motions were too small to be consciously recognised by the test subjects. This sliding was observed even without lubrication contamination.

Brady et al. [8] found that a fall will only generally happen as a result of a slip if the, displacement of the sliding foot exceeds 10 cm and if the peak forward velocity of the sliding foot exceeds 50 cm/s. Thus all slips do not always result in falls.

In [8] it was also found that slip recovery was influenced by the angle of the heel upon heel strike. They found that increasing the heel angle upon impact by one standard deviation (4.7°) increased the odds of recovering from a slip by a factor of 2.91. Andres et al. [9] studied how test subjects changed their gait in response to a slippery surface. Results showed that when negotiating a slippery surface, subjects reduced their stride length resulting in an increased heel-strike angle. This change of gait with a reduced stride length and increased heel angle significantly increased the likelihood of a recovery from a slip event. In [8] it was also concluded that walking velocity was not a key variable for determining of the outcome of a slip event.

Data from the tests carried out on the UoS SST suggest that a higher heel-strike angle decreases the dynamic friction over that of a lower heel-strike angle. This combined with the observations in [8] suggest that increasing the heel-strike angle might not necessarily decrease the likelihood of a slip (evidence suggests it increases it) but instead better prepare an individual to be able to recover biomechanically from a slip i.e. not fall.

For any device which has been designed to measure the friction between a shoe and floor surface the correct representation of the human gait is essential, e.g. heel velocity at impact and the rotational velocity of the heel after impact. Heel impact velocity is reported in the literature to have values between 1.58 m/s [8] and 1.77 m/s [10]. The rotational velocities of the human heel/foot during normal walking and slip events have been measured and reported in [10] to be between 331 and 342 °/s. Data extrapolated from [19] indicates mean values of between 141 and 290 °/s. The reason for differences in these reported angular speed values is unclear as in both studies the participants wore control footwear and walked on level flat surfaces. The main difference seen in the reported methodologies is that in [19] the participants were instructed to "walk as naturally as possible at a comfortable pace throughout the experiment" whereas in [10] the walking speed of the participants was controlled and set at three different levels "1.5 m/s (slow) 1.8 m/s (medium) and 2.1 m/s (fast)".

Another important aspect of any current or potential device is operability and repeatability as highlighted in [20]. In [20] a range of friction testers were ranked in terms of their performance and it was shown that just the operation of some devices modified the surface of the test foot and the test floor [21] depending on the hardness of the rubber used to simulate the test foot. Softer rubbers showed poor abrasion resistance and would be roughened by course test surface, while smooth surfaces tended to polish it. Even with harder rubbers a thin film was deposited on the test surface, thus modifying the shoe/floor interface conditions. A much utilised portable floor friction tester is the Pendulum tester. It was discussed in [20] that when the relatively soft Four S rubber was used in the Pendulum tester, the indicated slip resistance of a smooth product will continue to decrease as the test foot is slowly polished. This is why the UK Slip Resistance Group [21] recommends that the Four S test foot be prepared on a 3 μm pink lapping film. Such an approach may need to be adopted with any new device which is aimed at reliably measuring foot (shoe)/floor friction. Also highlighted in [20] was that the least variation in test results was seen in laboratories with registered testing authority status. This also highlights that robust operator training is also required.

One of the potential uses of the SST device is the measurement of the slip resistance of individual designs of footwear. An point raised in [20] is that it is important for a broad range of walkway surfaces be used when determining the slip resistance of individual types/brands/designs of footwear. This would be of importance to the safety shoe industry where one of the main design criteria of these products is slip resistance which tend to be used on a variety of surface types. As also discussed above the floor shoe interface can evolve over time. This can be counteracted in the laboratory by preparing the surfaces between tests i.e. pink lapping paper in the case of the pendulum tester. This will not happen during the in-situ use of a product however, where a shoe is most likely to be worn until the end or even beyond its design lifetime without any preparation/modification/maintenance of the sole. The European Construction Products Directive states that products must be safe (in this case slip resistant) at the end of their useful life [22]. Therefore one of the steps in determining a nominal figure of the slip resistance of a particular product is to include a value which is representative of a product when it has reached the end of its life. This will thus not only mean testing of new products but also new products which have been artificially worn to a condition which simulates their state at end of life.

2.0 Shoe Slip Tester: Analysis and Review

2.1 Overview/Comparison of UoS - SST, HSL - SST and Ramp Data

All tests were conducted in wet conditions at both the UoS and HSL using the SST and ramp testers. The initial tests done at UoS were also later repeated by another user on the same rig. Two repeat tests of each shoe sample were carried out on the ramp by the same user. A mean of the two ramp test results was then calculated. Figure 6 shows a comparison of the mean values of CoF yielded from each test. Four different safety shoe brands were tested and are referred to as A, B, C, and D throughout the rest of the paper.

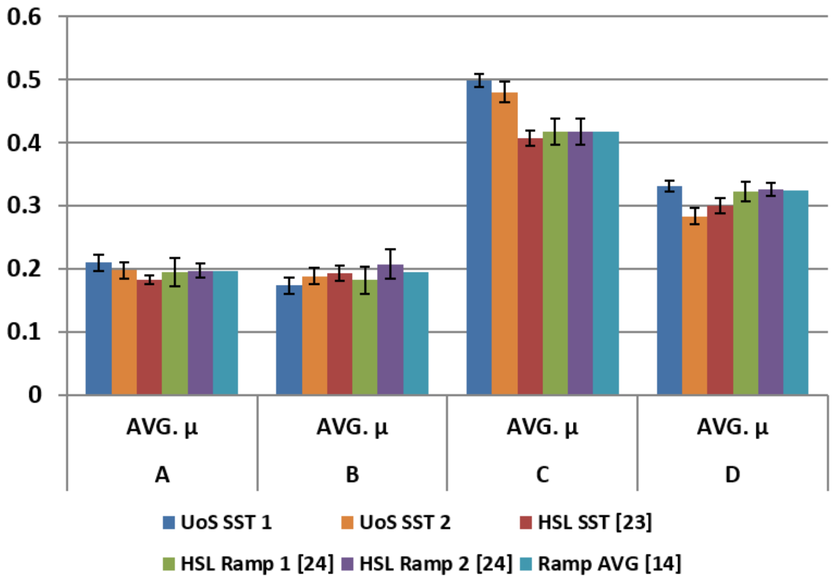

Figure 6. Chart showing mean values of CoF yielded from tests on four different shoe samples using the UoS SST, HSL SST and HSL Ramp Tester. Both UoS and HSL SST's operated at 5 bar, error bars represent 1 standard deviation. Heel angle 5 - 7°, wet conditions, steel surface

As can be seen in Figure 6 there is good agreement for samples A, B and D between all three test rigs (UoS and HSL SST and Ramp). For the two tests on the UoS SST the results for sample C are slightly higher than those given by either of the test methods carried out at HSL.

2.2 Overlay of UoS SST Data with Ramp Data

Wet test data from tests at UoS was compared with data from identical samples tested at HSL using the ramp tester under wet conditions. Figure 7 shows the Ramp data vs. two sets of data from the SST: one at 3 Bar and 7° of heel angle and the other at 5 Bar and 21° of heel angle. A 1:1 line is included to clarify correlation. It can be seen in Figure 7 that at the low pressure and low heel angle the SST gives higher CoF results than the ramp. The linear gradient between the A, C and D shoes suggest that the results from the ramp and SST are in good agreement i.e. the relative differences between the different types of shoes is the same for each rig. However, at the lower heel angles and pressures there seems to be a bias that gives higher CoF readings on the SST. As the pressure and heel angle are increased this differential/factor seems to decrease and the data points move closer to the 1:1 line. At the maximum pressure and a heel angle the data points come to almost sit on the 1:1 line i.e. the SST and ramp data very closely match with little bias. The best correlation between the ramp and SST data is seen at a pressure of 5 Bar and a heel angle of 21°.

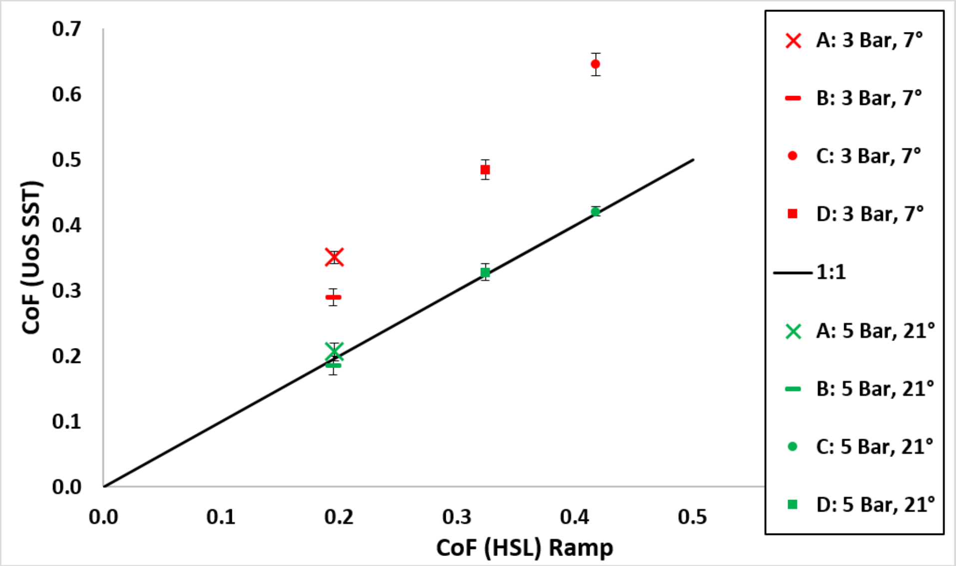

Figure 7. Chart showing ramp data generated at HSL [23, 24] vs. data generated for identical samples on the UoS SST at two different pressure and heel angle settings: 3 Bar, 7° and 5 Bar, 21°.

As the pressure and heel angle are incrementally adjusted from the minimum settings to the maximum the biases between the UoS SST and Ramp data become smaller as illustrated in Table **1**.

Table 1: Data and biases changes between the Ramp and SST for the 9 different settings of used

Settings/Sample		CoF		Bias (SST - Ramp)	
		SST	Ramp	Bias	Mean
7 Deg, 3Bar	A	0.3509	0.1958	79%	58%
	B	0.2899	0.1949	49%	
	C	0.6454	0.4177	55%	
	D	0.4842	0.3240	49%	
7 Deg, 4Bar	A	0.2742	0.1958	40%	25%
	B	0.2004	0.1949	3%	
	C	0.5506	0.4177	32%	
	D	0.4075	0.3240	26%	
7 Deg, 5Bar	A	0.2095	0.1958	7%	10%
	B	0.1734	0.1949	-11%	
	C	0.4986	0.4177	19%	
	D	0.3314	0.3240	2%	
14 Deg, 3Bar	A	0.3153	0.1958	61%	44%
	B	0.2649	0.1949	36%	
	C	0.5970	0.4177	43%	
	D	0.4453	0.3240	37%	
14 Deg, 4Bar	A	0.2401	0.1958	23%	16%
	B	0.1944	0.1949	0%	
	C	0.5096	0.4177	22%	
	D	0.3906	0.3240	21%	
14 Deg, 5Bar	A	0.1824	0.1958	-7%	9%
	B	0.1614	0.1949	-17%	
	C	0.4349	0.4177	4%	
	D	0.3026	0.3240	-7%	
21 Deg, 3Bar	A	0.3090	0.1958	58%	39%
	B	0.2587	0.1949	33%	
	C	0.5392	0.4177	29%	
	D	0.4453	0.3240	37%	
21 Deg, 4Bar	A	0.2432	0.1958	24%	16%
	B	0.2126	0.1949	9%	
	C	0.4699	0.4177	13%	
	D	0.3839	0.3240	19%	
21 Deg, 5Bar	A	0.2065	0.1958	5%	3%
	B	0.1854	0.1949	-5%	
	C	0.4211	0.4177	1%	
	D	0.3282	0.3240	1%	

Table **1** shows the bias between the two rigs (SST CoF minus Ramp CoF) in terms of percentage. An average bias for each setting/sample is shown in the furthest column to the right.

2.5 Constant Resolved Load

The schematic in Figure 8 helps to illustrate how force is applied in each test rig. The operation of each rig is comparable in that the resolved force, F_{res}, is always applied at an angle relative to the floor. In the case of the Ramp it is the floor angle which changes and the direction of F_{res} remains constant and vice versa in the case of the SST.

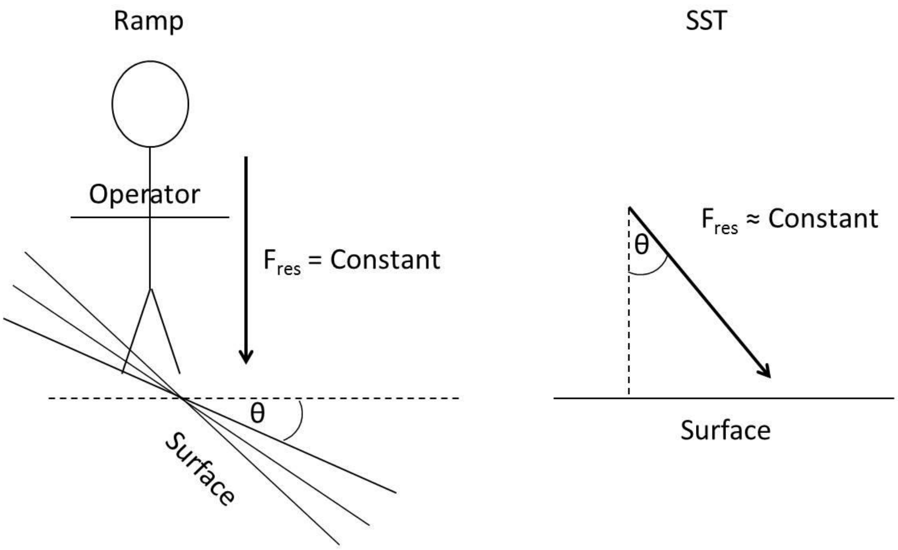

Figure 8. Schematic diagram illustrating the differences between the Ramp and SST test rigs

The UoS SST was operated using three different operating pressures, hence 3 various, F_{res} values. Interpolating between these different F_{res} data points a value of CoF for a theoretically constant applied level F_{res} for each shoe sample could be calculated. These interpolated CoFs could then be plotted on top of a Ramp vs. SST chart as in Figure 7. Figure 9 shows an example of CoF vs. resolved impact force at a heel angles of 21°.

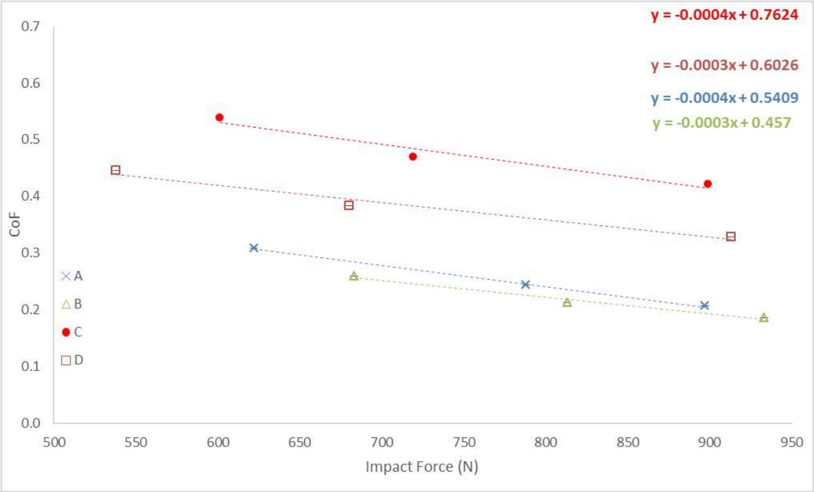

Figure 9. Chart showing CoF vs. resolved impact force of the four shoe samples tested at 3 different pressures: 3 Bar, 4 Bar and 5 Bar and a heel angle of 21° wet conditions steel surface. Pressure increases from left to right. Lines of best fit calculated for each sample and equations displayed in top right corner of chart.

Data was extrapolated from these charts using the equations from the lines of best fit in each chart. As can be seen in Figure 9 the resolved force is not consistent and varies with: operational pressure, shoe type, starting height between shoe and floor (also related to slip angle). However, the operator in the ramp test will apply a near consistent resolved force relative to the floor in each test. Therefore, extrapolating an estimated CoF at a fixed value of F_{res} and overlaying this on a chart of SST vs. Ramp we can find a value of F_{res}, at which, if the SST could apply this consistently, the SST should match data from the ramp test.

Figure 10 and Figure 11 show the trial and error process by which a value of F_{res} and heel angle was obtained to find the theoretically optimum settings for the SST so that it yielded results in line with the ramp test.

CoF values for each of the shoe samples were extrapolated from a chart of CoF vs. Impact force from the SST operated at a heel angle of 14° with varying operating pressure at an F_{res} value of 850N and then overlaid on top of a ramp vs. SST chart as shown in Figure 10.

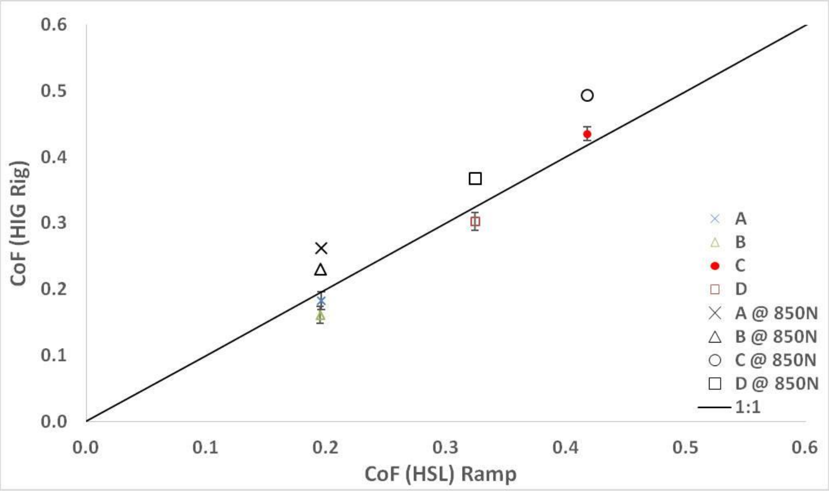

Figure 10. Chart showing ramp data generated at HSL [23, 24] vs. data generated for identical samples on the UoS SST tested at a pressure of 5 Bar and heel angle of 14°. Coloured markers represent data from SST rig. Black markers show data extrapolated from a chart of CoF vs. Impact force from the SST operated at a heel angle of 14° with varying operating pressure at a resolved force of 850N. Black line indicates a 1:1 ratio. Both tests carried out in wet conditions on a steel surface. Error bars indicate 1 standard deviation

It can be seen in Figure 10 that the extrapolated data points (shown in black) sit above the 1:1 ratio line. As the SST shows a trend of CoF decreasing with resolved force applied this suggests that 850N is not enough to match the ramp data. When the resolved force at which the data is extrapolated is increased to 970N then the data points sit much closer to the 1:1 ratio line. The data points do not sit perfectly on the line at any value of F_{res} at which the CoF is extrapolated. The F_{res} value at which the SST and ramp data best match is therefore hypothesised to be somewhere between 950 – 970N for a heel angle of 14°.

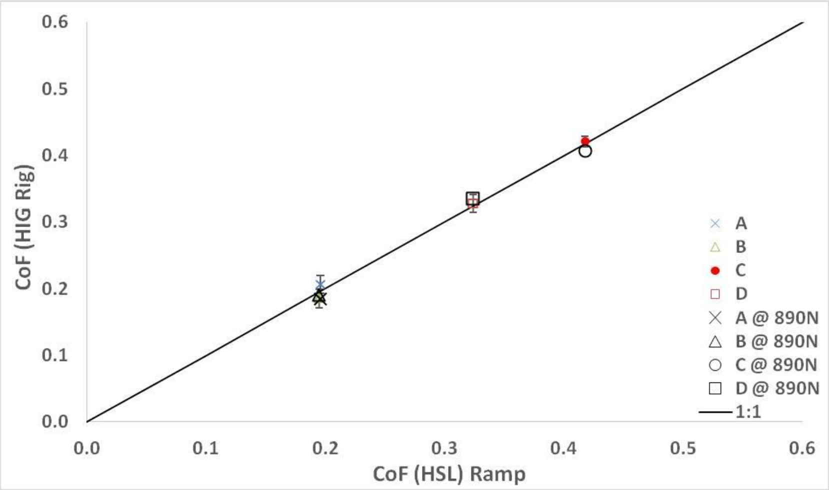

Figure 11. Chart showing ramp data generated at HSL [23, 24] vs. data generated for identical samples on the UoS SST tested at a pressure of 5 Bar and heel angle of 21°. Coloured markers represent data from SST rig. Black markers show data extrapolated from Figure 9 at a resolved force of 890N. Black line indicates a 1:1 ratio. Both tests carried out in wet conditions on a steel surface. Error bars indicate 1 standard deviation

Data was also extrapolated from Figure 9 in the same way as above and plotted on top of a chart showing SST vs. Ramp data with the SST operated at a pressure of 5 Bar and heel angle of 21° as shown in Figure 11. At a heel angle of 21° an extrapolated resolved force of 890N was needed to match the ramp data. Note these are the operating parameters at which SST and Ramp data best matched (see Figure 7i).

3.0 Investigation of Effects of Shoe Starting Height

Each type of shoes tested will have various angles at which they will slip. As the height of the pivot of the air ram is a fixed height above the test surface this in turn means that the test angle influences the starting height of the shoe. In order to investigate the effects of variations in starting height a series of tests were performed where the height of the ram pivot was varied. To limit the number of tests the variable parameters were limited to two heel angles, 7° and 21° and two shoes, A and D. Tests were carried out in wet conditions on a steel surface at 3, 4 and 5 Bar pressure. The height of the backing plate to which the ram pivot is attached on the UoS SST was varied using pre-drilled holes in the frame and holes 3, 4 and 5 were used (the 3rd hole being the highest and 5th being the lowest). It was not possible to test at a hole lower than the 5th as at the smaller slip angles (10° or less) the shoe would contact the floor before test start. It was also not possible to test at a height higher than the 3rd hole as the design of the backing plate and ram mounting points did not allow for this. It should be noted that the slip angles i.e. the CoF's for these tests were much lower compared to the previous tests even though they were carried out under identical conditions. It is thought this may be due to changes in atmospheric conditions compared to earlier tests or changes in the topography of the steel floor and shoe surfaces.

In these tests CoF, impact force and velocity were measured by taking high speed footage and recording the reading from the load cell data for each test.

3.1 Relationship between Shoe Starting Height and CoF

Figure 12a) and b) show CoF vs. backing plate height for shoe A tested at heel angles of 7 and 21° respectively.

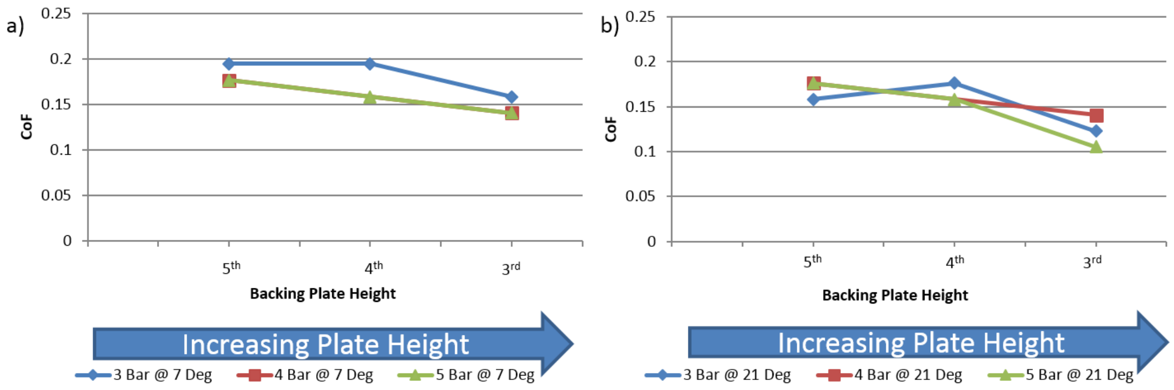

Figure 12. Chart showing CoF vs. backing plate height for sample A with a heel angle of a) 7° and b) 21°. Tests carried out in wet conditions on a steel surface at 3, 4 and 5 bar of pressure.

Figure 13a) and b) show charts of CoF vs. backing plate height for shoe D tested at heel angles of 7 and 21° respectively.

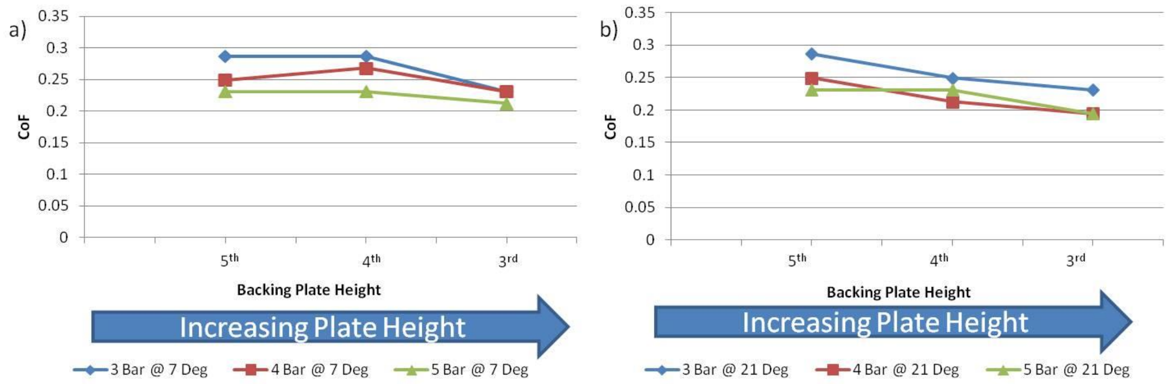

Figure 13. Chart showing CoF vs. backing plate height for sample D with a heel angle of a) 7° and b) 21°. Tests carried out in wet conditions on a steel surface at 3, 4 and 5 bar of pressure.

There is a general pattern seen in Figure 12 and 13 of an inverse relationship between backing plate height and CoF. This relationship was seen between both shoe samples.

3.2 Relationship between Backing Plate Height and Impact Force

Figure 14 and 15 show charts illustrating maximum resolved impact force vs. backing plate height and operating pressure. As in the prior friction tests (UoS SST 2, Figure 6) the operating pressure was varied between 3, 4, and 5 Bar. for shoe A for slip and stick events respectively. Two tests were carried out at each specific pressure and heel angle setting. One test was carried out at a slip angle where the shoe was expected to slip and one where the shoe was expected to stick. In a stick event the shoe would show no observable forward movement upon impact with the ankle rotating to flat after which the shoe would be adhered to the steel surface. In a gross slip event however, upon impact the shoe would immediately slide to a point which the air ram reached its full extension. The shoe would not be adhered to the steel surface. In a few cases however, an event in between stick or slip occurred. These events were labelled as partial slip events. In a partial slip event the shoe would slide upon impact with the steel surface but then come to a rest with the sole of the shoe firmly adhered to the steel surface. The sliding distance of the shoe varied between 10 – 100 mm before coming to a complete rest. It was hard to classify these events as either stick or slip events because the shoe did slip after initial impact but soon after it regained complete adhesion. It is also unclear if such an event would lead to a fall or complete recovery by an individual wearer. It is interesting to note that Brady et al [8] found that "…a fall will occur as a result of a slip if, during the slip the displacement of the slipping foot exceeds 100 mm…". Note that the force data for a pressure of 4 bar for tests conducted from the 4th is not avalible as during these tests the author could not get the shoe to slip. Hence the column for the 4th hole is omitted from Figure **14**b and e.

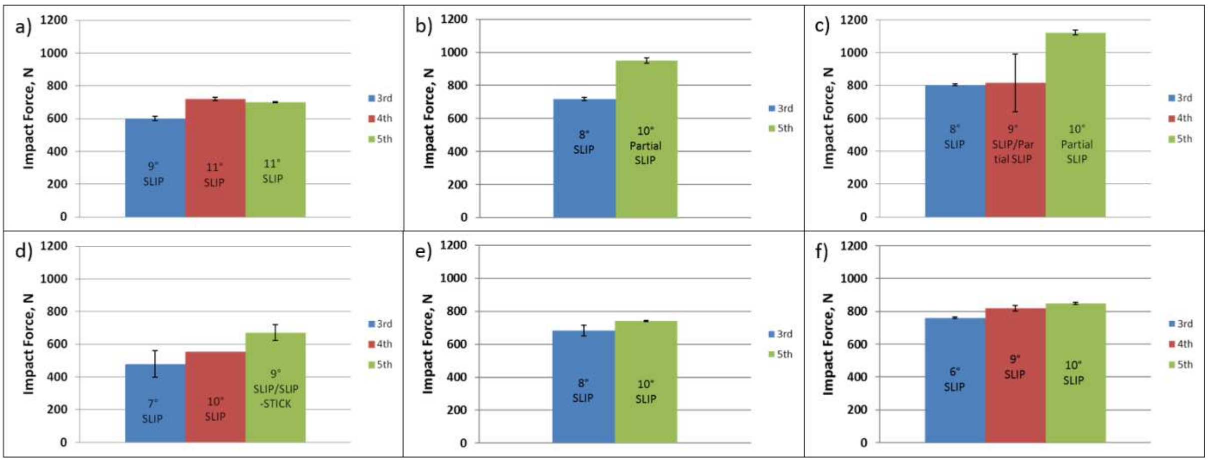

Figure 14. Charts showing maximum resolved impact force vs. backing plate height for shoe A with slip events. a) 3 Bar, heel angle 7° b) 4 Bar, heel angle 7° c) 5 Bar, heel angle 7° d) 3 Bar, heel angle 21° e) 4 Bar, heel angle 21° f) 5 Bar, heel angle 21°. From top to bottom: increasing heel angle. All tests carried out under wet conditions on a steel surface. Error bars indicate 1 standard deviation. Text in the columns describes the slip angle and test outcome i.e. either stick or slip

Figure 14 shows the peak impact force for tests where the shoe slipped or was expected to slip. It seems from Figure 14 that the peak impact force is inversely proportional to the height of the backing plate.

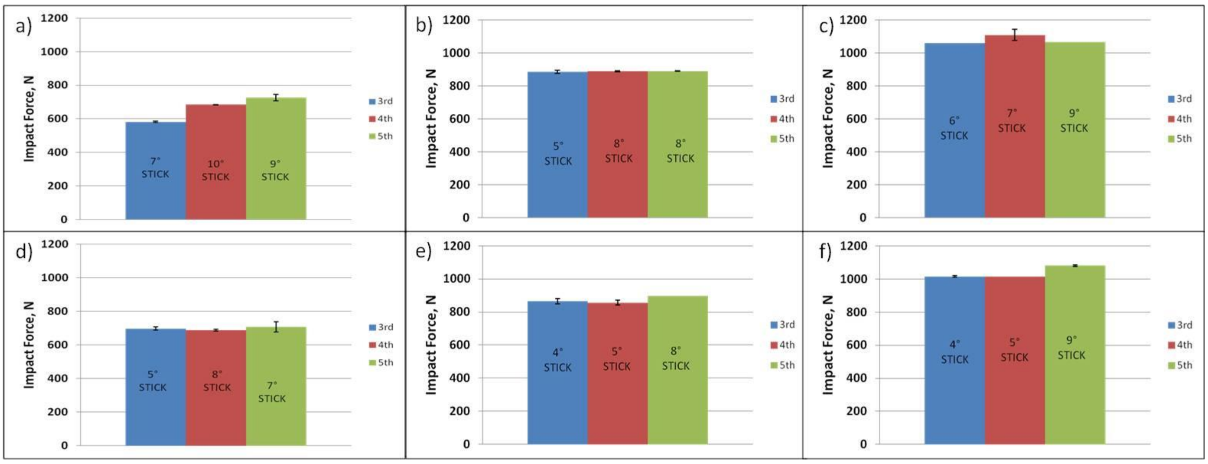

Figure 15. Charts showing maximum resolved impact force vs. backing plate height for shoe A with stick events. a) 3 Bar, heel angle 7° b) 4 Bar, heel angle 7° c) 5 Bar, heel angle 7° d) 3 Bar, heel angle 21° e) 4 Bar, heel angle 21° f) 5 Bar, heel angle 21°. All tests carried out under wet conditions on a steel surface. Error bars indicate 1 standard deviation. Text in the columns describes the slip angle and test outcome i.e. either stick or slip

Figure 15 shows that for stick events the force is relatively unaffected by changes in plate height and is more influenced by pressure. This would be expected as in the event of a shoe stick the force will be able to build up to maximum according to the pressure in the ram. This average force will be less dictated by acceleration of the shoe at impact as the pressure in the ram will build up to maximum regardless.

It can therefore be said that impact force at slip is influenced by shoe height but other factors can also affect it such as heel angle and operating pressure.

3.3 Relationship between Backing Plate Height and Impact Velocity

Impact velocity for a series of tests was measured using high speed footage. Figure 16 shows charts illustrating the measured impact velocity for shoe D for expected slip tests. Impact velocity was measured by tracking a fixed point on the shoe heel and measuring the distance travelled over two frames of footage just before the point of impact. In 3.2 it was seen that plate height has a strong influence upon impact force and as expected there is a direct relationship between plate height and impact velocity. The same relationship is also seen in the stick events as illustrated in Figure 17.

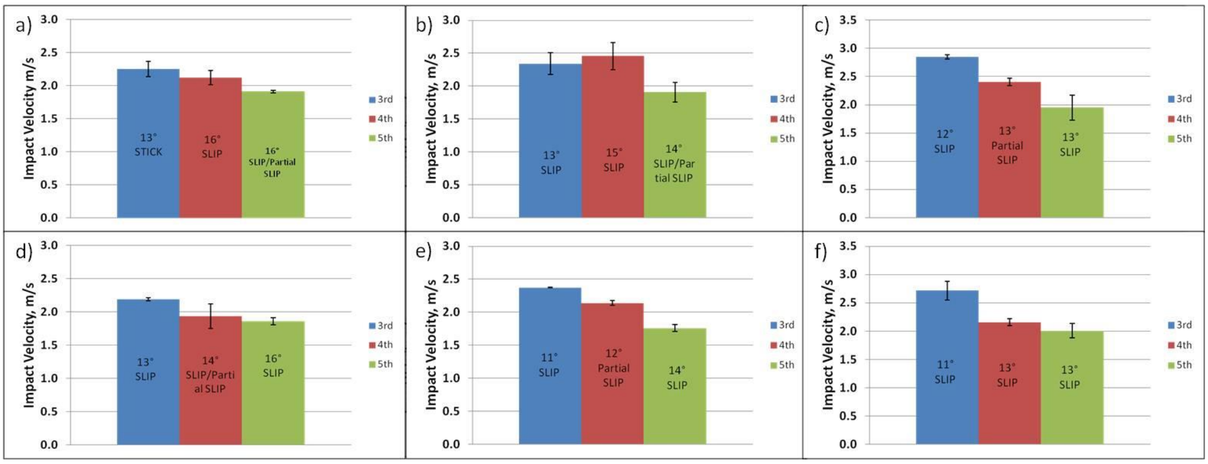

Figure 16. Charts showing resolved impact Velocity vs. backing plate height for shoe D with slip events. a) 3 Bar, heel angle 7° b) 4 Bar, heel angle 7° c) 5 Bar, heel angle 7° d) 3 Bar, heel angle 21° e) 4 Bar, heel angle 21° f) 5 Bar, heel angle 21°. All tests carried out under wet conditions on a steel surface. Error bars indicate 1 standard deviation. Text in the columns describes the slip angle and test outcome i.e. either stick or slip

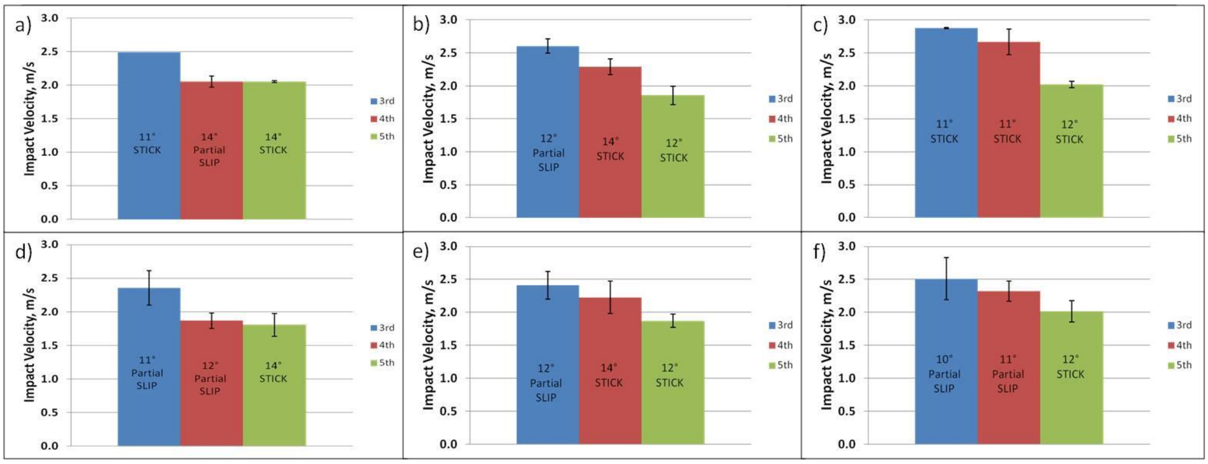

Figure 17. Charts showing resolved impact Velocity vs. backing plate height for shoe D with stick events. a) 3 Bar, heel angle 7° b) 4 Bar, heel angle 7° c) 5 Bar, heel angle 7° d) 3 Bar, heel angle 21° e) 4 Bar, heel angle 21° f) 5 Bar, heel angle 21°. All tests carried out under wet conditions on a steel surface. Error bars indicate 1 standard deviation. Text in the columns describes the slip angle and test outcome i.e. either stick or slip

4.0 Discussion

4.1 Analysis of SST in its Current State of Build

A review and analysis of data generated using the UoS SST was carried out. SST tests were also carried out in parallel with ramp tests at HSL under identical conditions and using identical shoe samples. The HSL Ramp test (see section subsection 1.2, Figure 1) is considered the Gold Standard in footwear friction testing. The SST has been designed as a portable alternative and an attempt to compare the data from these two tests has been made. Initial comparison was made at a specific pressure and heel angle setting of the SST, as seen in Figure 6, and results suggested that the Sheffield SST was giving slightly higher CoF results compared to the Ramp.

However, later tests on the UoS SST were performed over a range of pressures and heel angles. The full range of SST data from both UoS and HSL was then compared to results from the ramp as in Figure 7. (Note the ramp usually has one operator so the weight i.e. pressure is fixed and the operators are encouraged to walk flat footed so ideally there is no incident heel angle in the ramp test). This analysis showed that as the operating pressure and heel angle are increased from 3 – 5 Bar and 7 - 21° respectively the SST data begins to closely match that of the ramp. One reason for this phenomenon is illustrated in Figure 18, which shows that as pressure and heel angle are increased to their maximum values the force applied by the rig becomes more consistent between each shoe sample.

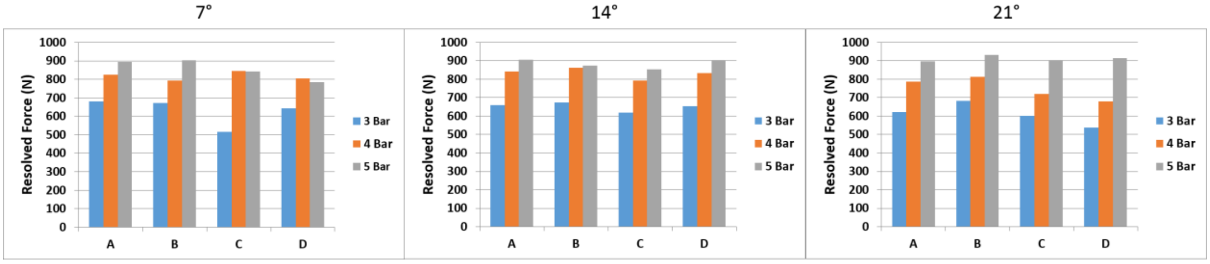

Figure 18. Charts showing peak resolved slip force (force at load cell at impact) at three different heel angles, and 3 different pressures, wet conditions, steel surface

As the SST is operated at higher pressures and heel angles it is representing more closely what is happening on the Ramp. On the ramp the operator applies a near consistent impact force to each shoe sample as their weight will not change during a test.

At the maximum pressure and heel settings the force is almost the same between each shoe. It was thought that maybe at the higher heel angle the pressure in the ram i.e. force at heel contact would have time to build up to maximum while the shoe rotates to be flat with the steel surface. It is also interesting to note that many authors have observed the heel angles at upon floor impact to be between 13 - 25° [7, 8, 9 and 10] which is the range of heel angles at which the SST more closely matched the RAMP test.

It is proposed that at higher operating pressures the impact loads normal to the surface are more reflective of the body weight of the ramp operator in these tests [23, 24]. As CoF is not a constant and will vary with many factors including normal load, attempting to match the applied normal load could be the reason for the matching of CoF between the two rigs.

As the tests on the SST at UoS were performed at 3 various pressures (i.e. 3 various forces per shoe sample) an interpolation could be done between these different pressures to find the friction coefficients for each shoe at a value of force which was theoretically consistently applied to all the shoes on the SST, see Figure 9. These values of CoF were then plotted on a chart of SST vs. Ramp and the theoretical force varied until the SST was a close match to the Ramp data. There was a lack of linearity in the data at a heel angle of 7°. Therefore no data extrapolation could be done at this heel angle. At a heel angle of 14° an extrapolated resolved force of 970N was needed for the CoF's from the SST to match the Ramp. At a heel angle of 21° and extrapolated resolved force of 890N was needed to match the data. These theoretical forces are the forces which need to be applied consistently between each shoe (regardless of slip angle) in order for the SST to match the Ramp (for a given heel angle applied to the SST).

There is a notable decrease in the required level of F_{res} to obtain a tight correlation between SST and Ramp with an increase in the heel angle (from 14 – 21°). I.e 970 N for a heel angle of 14° and 890 N at 21°. It was noticed that the shoe does not slip until the heel is almost flat. Therefore, when a shoe impacts the surface with a higher a heel angle this may give the rig more time for pressure/force to stabilise before slip occurs.

A review of the literature shows that the SST in its current guise represents the real mechanics of human gait. The forces that the rig applies at an operating pressure of 5 Bar are representative of typical human weights plus dynamic forces. However, the impact velocities which the rig operates do seem to lie outside of the observed range, particularly at the higher pressures. Impact velocities have been reported in the literature to be in the region of 1.6 m/s [8] and 1.8 m/s [17]. Even at the lower pressure of 3 Bar the rig applies impact velocities in excess of 1.9 m/s. However, when the pressure is increased to 4 and 5 Bar the impact velocities go to a range of between 2.0 and 3.0 m/s. This seems to far exceed what is seen in the literature. If the intention is for the rig to closer match the dynamics of human gait then the impact velocity of the rig will need to be lowered closer to the 1.6 – 1.8 m/s range. One way of achieving this while still keeping the operating pressure high is to limit the starting height of the shoe as shown in Figure 17 where lowering the starting height of the shoe decreased the impact velocity to an average of 2 m/s.

It was noted from testing on the UoS SST that long term variations in the resultant data for each sample were observed i.e. changes in the angle at which shoes would stick or slip. It is thought that these changes were down to degradation of the shoe treads and the steel surface from wear and corrosion respectively. It is therefore suggested that a future operating manual for the SST suggests that tests are done on batches of each make and model of shoe and that each shoe be replaced with a new one after a certain number of tests. Considerations should be made to the material selection for the floor. Steel is currently used and this material is at risk of corrosion, particularly if constantly wetted. A more suitable alternative floor material may need to be investigated.

4.2 CoF vs. Height

Figure 12 and 13 show the relationship between shoe starting height and CoF for shoe A at 7 and 21° and shoe D at 7 and 21° respectively. The Figures show that there is a negative correlation between plate height (i.e shoe starting height) and CoF. For example a fixed pressure of 5 Bar and a heel angle of 21° there is a drop in CoF of over 40% between the minimum and maximum plate heights for shoe A.

This means that even though shoes may be tested under identical contamination, floor and pressure conditions; because the slip angle varies widely between the shoe samples and thus shoe starting height (assuming all samples are tested at a fixed backing plate height) it does not provide a fair comparison between samples. However, the effect on CoF is likely to only be a secondary effect of changing the shoe height. The true reason why CoF is affected by shoe starting height is due to the fact that the impact forces and velocities will vary with varying shoe height.

4.3 Impact Force vs. Shoe Height

Figure 14 shows the peak impact force for tests where the shoe slipped or was expected to slip. It seems from Figure 14 that the peak impact force is inversely proportional to the height of the backing plate. Figure 15 shows that for stick events the force is relatively unaffected by changes in plate height. This would be expected as in the event of a shoe stick the force will be able to build up to maximum according to the pressure in the ram. This average force will be less dictated by acceleration of the shoe at impact as the pressure in the ram will build up to maximum regardless.

4.4 Impact Velocity vs. Shoe Height

Figure 16 shows charts illustrating the measured impact velocity for shoe D for expected slip tests. It can be seen that plate height has a strong influence upon impact velocity and as expected there is a direct relationship between plate height and impact velocity i.e. for a greater shoe starting height there is a greater velocity. The same relationship is also seen in the stick events as illustrated in Figure 17.

It can therefore be concluded that the starting height of the shoe can vastly effect the: CoF, impact force and velocity at impact. As the SST stands at the time of writing this paper shoe height cannot be controlled to a fine enough degree for specific slip angles. And thus, as it stands, different shoe samples are being tested under differing conditions independent of pressure, heel angle or surface/contamination conditions. It is therefore recommended that a finer method of controlling the shoe starting height be designed into the rig so that it can be kept constant between slip angles. This would allow more consistency in impact forces and velocities between shoe samples and allow for a fairer comparison.

4.5 Future SST Test Suggestions

Further testing on specially designed soles with specific harnesses should be carried out. This would allow a better understanding of the relationship between sole hardness/pattern and CoF. Testing should also be carried out on various flooring materials to gain an understanding of the influence of floor type and topography on shoe friction performance as in [4, 5 and 6].

As there is no way of controlling the resolved force applied by the SST in its current guise; it is suggested that testing be carried out at the three pressure settings as used in the early tests on the UoS SST (3, 4 and 5 Bar) however, heel angles constrained to a range of 13 - 25° as seen in the literature for actual human gait observations [7, 8, 9 and 10]. This has been shown to allow the interpolation of data from the SST at theoretically constantly applied resolved force. The value of resolved force used for the interpolation would depend on the circumstances. For example if replicating a specific RAMP test or investigating an accident etc. a resolved force which matches the ramp operator or the victim’s body weight would be used. Another example may be developing shoes for children. Again would choose a resolved force or range of forces which matches your target consumers spread of weights.

In future testing strict adherence to operating procedures and condition reporting need to be observed. In all tests the atmospheric conditions i.e. temperature and humidity, need to be recorded. Although these such factors cannot be practically controlled they should be recorded so that any operating anomalies can be correlated with significant changes in the atmospheric conditions.

Preparation and maintenance of the shoe and floor topography also needs to be regularly done/checked. This in accordance with the recording of the atmospheric conditions can provide traceability of test results and help reduce inconsistencies in results. Longer term changes in the macro level properties of the shoes, i.e. structural stiffness, hardness of the sole rubber etc., can not necessarily be addressed by regular conditioning of the sole. Such changes will naturally occur as a function of time and also number of tests/impacts. A simple way to address this is to renew shoe samples after a certain time or number of tests. This in itself however, is also an interesting topic for exploration for which the SST would be a useful tool. For example how do these macro changes effect the friction performance of the shoe? Is there a difference between different brands/designs in this rate of change?

5.0 Conclusion

It has been shown in this paper that a good match can be obtained in the outputs of the Ramp and SST by matching the applied resolved forces between the two tests. As the ramp tester is currently considered the most replicable/repeatable laboratory based representation of human gait in relation to slips this shows that the SST is a good alternative. Reviewing the literature it can be said that both rigs do replicate real slip events to a large degree. The relatively compact design of the SST over the ramp however, gives it the added advantage that it can be tested in-situ as well as in the lab.

It is important here though to separate slip events from falls. A slip will increase the likelihood of a fall occurring. However, there are many variables which dictate whether a slip will lead to a fall, some of these human such as reaction time, balance and strength, and some of these mechanical such as friction, heel angle, sliding distance. These two sets of variables will influence one another also for example reaction time could dictate the sliding distance etc. However, it would be much harder to replicate the various reactions that individuals have to foot/shoe slides and hence any test method is more suited to solely measuring the slip resistance of a particular shoe. Factors such as: reaction time, sense of balance, strength etc., will vary widely from individual to individual and are just as likely to determine the outcome of a slip as the slip itself.

Thus the SST is aimed at giving a quantifiable measure of the slip resistance of a particular shoe design. Foreseeable uses of the SST include: measuring the slip resistance and helping prove design changes in sole patterns, measuring particular samples of shoe which may have been involved in accidents, also testing at the scene of accidents where perhaps the flooring or environment is suspect of causing an accident or approval is required for a new flooring type.

Acknowledgments

The authors would like to thank the EPSRC for their grant IIKE fund: Collaborative research into safety shoe-surface interactions, March 2015 for which this research was possible.

References

[1] Health and Safety Executive, 2019. Kinds of accident statistics in Great Britain, 2019. London: Health and Safety Executive

[2] Hunwin, G, Ormerod, K and Darby, A. *A Study of the Effect of Modifying the European Standard Mechanical Slip Resistance Test for Footwear.* London : Health and Safety Executive, 2010

[3] BS EN 10088-2:2014, Stainless steels. Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for general purposes

[4] Shibata, K., Abe, S., Yamaguchi, T., Hokkirigawa, K., 2016. Development of a Cart-type Friction Measurement Device for Evaluation of Slip Resistance of Floor Sheets, Journal of Japan Society for Design Engineering, Vol. 51 (10), pp 721-736

[5] Yamaguchi, T., Yamada, R., Warita, I., Shibata, K., Ohnishi, A., Sugama, A., Hinoshita, M., Sakauchi, K., Matsukawa, S., Hokkirigawa, K., 2018. Relationship Between Slip Angle in a Ramp Test and Coefficient of Friction Values at Shoe-Floor Interface Measured with Cart-type Friction Measurement Device, Bulletin of the JSME: Journal of Biomechanical Science and Engineering, Vol. 13 (1)

[6] Shibata, K., Yamaguchi, T., Hinoshita, M., Sakauchi, K., Matsukawa, S., Hokkirigawa, K., 2019. Effect of Groove Width and Depth and Urethane Coating on Slip Resistance of Vinyl Flooring Sheet in Glycerol Solution, Tribology International. Vol. 135. Pp 89-95

[7] Redfern, M. S., Cham, R., Gielo-Perczak, K., Grönqvist, R., Hirvonen, M., Lanshammar, H., Marpet, M., Yi-Chung Pai, C., Powers, C., 2001. Biomechanics of Slips, ERGONOMICS, 2001, VOL. 44, NO. 13, pp 1138 - 1166

[8] Brady, R. A., Pavol, M. J., Owings, T. M., Grabiner, M. D., 2000. Foot displacement but not velocity predicts the outcome of a slip induced in young subjects while walking, Journal of Biomechanics., Vol. 33, pp 803-808

[9] Andres, R.O., O'Connor, D., Eng, T., 1992. A practical synthesis of biomechanical results to prevent slips and falls in the workplace. In: Kumar, S. (Ed.), Advances in Industrial Ergonomics and Safety IV.Taylor and Francis, London, pp. 1001-1006

[10] McGorry, R. W., DiDomenico, A., Chang, C., 2010, The anatomy of a slip: Kinetic and kinematic characteristics of slip and non-slip matched trials. Applied Ergonomics. Vol. 41, pp 41–46

[11] Redfern, M. S., DiPasquale, J., 1997. Biomechanics of descending ramps, Gait and Posture, Vol. 6, pp 119–125

[12] Clarke, J., Hallas, K., Lewis, R., Thorpe, S., Hunwin, G., Carré, M., 2015. Understanding the Friction Measured by Standardised Test Methodologies Used to Assess Shoe-Surface Slip Risk, Journal of Testing and Evaluation, Vol. 43 (4)

[13] Manning, D.P., Jones, C., 1993. A step towards safe walking, Safety Science, Vol. 16, pp. 207-220

[14] Strandberg, L., Lanshammar, H., 1981. The Dynamics of Slipping Accidents, Journal of Occupational Accidents, Vol. 3, pp 153-162

[15] STRANDBERG, L. 1983, On accident analysis and slip-resistance measurement, Ergonomics, Vol. 26, pp 11 - 32.

[16] LLOYD, D. G. and STEVENSON, M. G. 1992, Investigation of foor surface profle characteristics that will reduce the incidence of slips and falls, Mechanical Engineering Transaction Institution of Engineers (Australia), ME17 (2), pp 99 - 104.

[17] HANSON, J. P., REDFERN, M. S. and MAZUMDAR, M. 1999, Predicting slips and falls considering required and available friction, Ergonomics, 42, pp 1619 - 1633.

[18] MCVAY, E. J. and REDFERN, M. S. 1994, Rampway safety: foot forces as a function of rampway angle, American Industrial Hygiene Association Journal, 55, 626-634.

[19] Cham, R., Redfern, M., 2002. Heel contact dynamics during slip events on level and inclined surfaces, Safety Science. Vol. 40, pp 559–576

[20] 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

[21] Marpet, M.I., and Brungraber, R., The Effect of Contact Pressure and Test-Foot Sliding on Slip Resistance: Experimental Results, J. Forensic Sci., Vol. 41, No. 5, 1996, pp. 770-775.

[22] UK Slip Resistance Group, The Measurement of Floor Slip Resistance. Guidelines Recommended by the UK Slip Resistance Group," Issue 2 June 2000, circulated by Rapra Technology Limited, Shawbury, Shrewsbury, Shropshire, UK.

[23] Hunwin, G. HSL Test Rig Data. [Spreadsheet] s.l. : Health and Safety Laboratory, 2014

[24] Hunwin, G. HSL Ramp Test Data. [Spreadsheet] s.l. : Health and Safety Laboratory, 2014

[25] Gronqvist, R., M. Hirvonen, and A. Tohv, *Evaluation of three portable floor slipperiness testers.* International Journal of Industrial Ergonomics, 1999. 25(1): pp. 85-95.