SLIP RESISTANCE OF TACTILE GROUND SURFACE INDICATORS

Rodney A. Hunter

Hunarch Consulting,
134 Johnston Street, Fitzroy, Vic., 3065, Australia

Tests of water-wet arrays of tactile ground surface indicators with a new, simulated-foot-slip tribometer identified three key slip distances: very short slip on an indicator top; short slip to the second indicator(s); and full slip. It was concluded that a full slip is more likely to cause overbalancing but that, because the arrays were found to be from "very" to "extremely" slip resistant, the risk of imbalance on arrays appears to be extremely low, except for high-heeled shoes landing between rows of indicators on a smooth substrate, for which the slip resistance was low and therefore the risk of overbalancing high. The SFST provided a wealth of information about foot slips on indicator arrays and revealed the complex interaction of foot rotational behaviour with the interstices of the arrays.

Introduction

The benefit to individuals of reducing the risk of slips and falls on pedestrian surfaces is self-evident, and the socio-economic cost of not doing so is widely acknowledged. There is one type of pedestrian surface that persistently evokes disquiet: arrays of tactile ground surface indicators (TGSIs[1]). This study is an exploratory investigation of the slip resistance of TGSI arrays as measured by a new type of device: a simulated-foot-slip tribometer (SFST)[2]. The TGSIs investigated are 5 mm high, 45°-sided truncated cones with a 25 mm diameter top and 35 mm diameter base, spaced in a square grid of 50 mm pitch as used, for example, in Australia[3].

A variety of tribometers have been used for TGSIs, including the non-portable inclining platform, and portable devices such as the British Pendulum (Pendulum), the English XL, the Brungraber Mark 2 (BM2) and Mark 3 (BM3), and pull-sled devices[4]. Like the BM2 and BM3, the SFST is a mechanically operated portable inclinable articulated strut device. However, it applies the amount and rate of loading of a person at footfall, as established by force platform tests; its heel–ground contact area at heel strike is very small; and it simulates the downward rotation of the forefoot after heel strike in reflexive response to a slip as reported, for example, by Redfern *et.al*. (2001). Weight distribution of the leg and foot, and foot and ankle proportions are realistic, and the foot is articulated in the sagittal plane (like the BM2 and BM3) and partially in the coronal plane. The centre of mass of the foot moves forward with its vertical rotation to simulate adaptive increased forefoot pressure. Amount and rate of loading, and foot rotation and commencement of rotation are adjustable. Slip distance and velocity, and foot

[1] Known also, in various shapes, as "tactile paving", "detectable warnings", and "tenji blocks".
[2] Invented by the author
[3] Intended for hazard warning, as distinct from elongated versions intended for direction indication.
[4] For an example, see Rowe (2010).

rotational velocity are electronically and synchronously recorded, including with video[5]. The SFST was created after doubts about the suitability of the BM3 for this sort of testing, even with modifications to it reported by Hunter (2010) and later more-elaborate ones.

The aim of this study was to investigate the: (1) slip resistance of the super-macro-texture of TGSI arrays; (2) contribution of the different parts of TGSIs arrays to slip resistance; and (3) relationship between slip resistance of TGSIs and foot behaviour.

Method

Tests were in water-wet conditions. Most were with a male heel and outsole, each of Shore-A 84 rubber and 76 mm x 76 mm in size. The heel's posterior edge had a 7.5 mm radius to simulate the effect of wear (see Hunter, 2010). The outsole was convex in the sagittal plane and slightly convex in the coronal plane as typical of many shoes. Some tests were conducted with a women's heel of Shore-A 75 rubber, 14mm x14mm in size. The foot was inclined at 25° to horizontal arrays, similar to the 26° used for worn heels tests by Sigler *et.al*. (1948), and 38.9° to the sloped array (see below). Tests commenced with the heel 10 mm above the TGSI top(s).

TGSIs were of plastic, modified so that some had smooth tops and others had 400-grit textured tops. The rims of most TGSIs were smoothly-sanded to a 1 mm radius, but the sharp prominent rims of some were retained. The array substrates were of hardwood timber, some with a hard shiny finish and some with a 400-grit coating. Most tests were conducted with the array orthogonal to the direction of gait, but some were conducted obliquely to it (at 30°). Some tests were performed with the substrate only, and one test was performed with the array sloped at 13.9°. Still and slow-motion-video photography was used to study the test-foot slip behaviour for many tests. Tests were also conducted with the BM3 and the Pendulum.

Twelve combinations of four independent variables were tested: (1) substrate texture (smooth (Bs), textured (Bt)); (2) top texture (smooth (Cs), textured (Ct)); (3) heel strike position on the first TGSI (6.25 mm, 12.5 mm and 18.75 mm from the rear of the rim (Strt1, Strt2 and Strt3 respectively)); and (4) heel strike location with respect to the array, that is, on the top of a TGSI (Co-So), between them in the sagittal plane (Co-Sb), or between them in the coronal plane (Cb-So).

Four dependent variables were tested: slip resistance coefficient (SRC[6]); duration (Drtn); velocity (Vel); acceleration (Acc); and slip distance.

Three slip distances were used for analysis: (1) up to 18.75 mm (Slip1), being a slip of the heel on but not off the top of the first TGSI (for those tests that were on the axis of TGSI tops); (2) up to 42 mm (Slip2) corresponding with a slip off the first TGSI or from between adjacent TGSIs and across to the next TGSI(s); and (3) a full slip of at least 300 mm (Slip3).

All strut angles for each of thirty-five test sets were recorded: a total of four hundred and thirty-eight strikes (plus eight sets of BM3 and Pendulum tests). Because slips on textured TGSIs tops were difficult to generate, most tests with textured-top arrays were conducted with the first two tops smooth. There were insufficient tests for reliable statistical analyses, but observation of slips partly compensated for this. Not all combinations of variables were tested.

Results

Generally, greater force was required to generate longer slips than shorter slips, and resulted in greater velocities. By far the greatest increase of velocity was between short slips and full slips. The SRC for five of the thirty-five test sets exceeded the tribometer's limit of 1.225.

---

[5] Synchronisation of foot rotational velocity and video recording, and the varied commencement of foot rotation were incorporated after data collection for this study.

[6] "Sip resistance coefficient" is used instead of "coefficient of friction" to convey the complexity of the tribometer foot's slips.

Strike position of male heel on top of first TGSI (smooth)
SRC increased slightly with slip distance from Strt1; remained the same from Strt3 for Slip1 and Slip2; but increased dramatically for Slip3 (see Table 1). SRC from Strt1 was greater than from Strt3 for Slip1 and Slip2, but less for Slip3. This corresponds with Slip1 and Slip2 having greater Drtn and less Vel from Strt1 than from Strt3, but is the opposite for Slip3. In other words, initial slips are facilitated by heel strike on the closest part of tops and full slips by the most distant part.

Heel strike location in array
Generally, SRC was almost the same regardless of whether heel strike occurred on a TGSI top (CoSo), between adjacent TGSIs (CbSo) or between successive TGSIs (CoSb), although SRC for CbSo was marginally the greatest.

Table 1.
Strike position on top

SRC	Cs	
	Strt1	Strt3
Slip1	0.612	0.471
Slip2	0.642	0.471
Slip3	0.692	1.0187

Male heel, start on TGSI (Co-So); horiz. orthog. array; rounded rim.

Table 2.
Texture; heel strike location

SRC	Co-So			Cb-So			Co-Sb	Cb-So*	No TGSI
	BsCs	BtCs	BsCt	BsCs	BtCs	BsCt	BsCs	BsCs	
Slip1	0.541	0.541	0.610	-	-	-	-	-	-
Slip2	0.556	0.572	1.099	0.471	0.735	0.806	0.642	0.557	-
Slip3	0.856	0.796!	1.221	0.950	1.049	0.930!	0.891	0.664	0.519

Male heel; horiz. orthog. array; Slip1 SRC is for top only (of first TGSI); BtCt array not tested; first two tops of BsCt and Ct array were smooth; BtCs and BsCt not tested with Co-Sb; rounded rims. = Sloped array.*

Texture of TGSI tops (male heel)
Except as indicated by the two exclamation marks in Table 2, SRC for textured tops and substrates was greater than for smooth tops and substrates, although not significantly (the exceptions might be attributable to the small number of tests). There were no consistent or significant SRC differences between each of the texture conditions and slip distances for male heel strikes, that is: on TGSIs (Co-So); between adjacent TGSIs (Cb-So); and between successive TGSIs (Co-Sb). However, for the texture conditions generally, including for sharp-rimmed TGSIs, SRC for Co-So was less than for Cb-So and Co-Sb for Slip2 and Slip3. That is, male heel slip resistance along rows was approximately the same as between them.

Sloped array (male heel)
For smooth substrate and tops (BsCs), SRC between TGSI rows (Cb-So) of the sloped array was greater than for the horizontal array for Slip2, but less for Slip3 (see Table 2). This is reflected in the negligible difference of Vel for Slip2 but the larger difference for Slip3 (see Table 6).

Array alignment (male heel)
Generally, the male heel SRC on the oblique alignment was slightly greater than on the orthogonal alignment for smooth-topped TGSIs, but the opposite for textured-topped TGSIs. The result for Slip2 is anomalous because the first two TGSI tops in the textured-top array were smooth. Discrepancy was also evidenced by slip Drtn and Vel. There was weak correspondence between AccRsq and SRC variances, with slips tending to be “rougher” on the orthogonal than on the oblique smooth-topped TGSI array, but rougher on the oblique than on the orthogonal textured-topped TGSI array, but this was opposite to expectation. It is concluded that for slips along TGSI rows, there is no difference between orthogonal and oblique arrays.

Rim shape of TGSI top (male heel)
Sharp rims produced greater SRC than rounded rims for Slip2, but less for Slip3 (see Table 4). SRC increased substantially from Slip2 to Slip3 for the rounded rims, but negligibly for the sharp rims. For sharp-rimmed TGSIs, textured collars provided slightly greater SRC than smooth collars.

Heel type

SRC of the high-heel was less than the male heel, except as indicated by the three exclamation marks in Table 5. SRC differences were not significant.

Table 3. Array alignment

SRC	BsCs		BsCt	
	Orth	Oblq	Orth	Oblq
Slip1	-	-	-	-
Slip2	0.556	0.868	1.099	1.061
Slip3	0.856	0.883	1.221	1.080

Male heel; on TGSI top (Co-So); smooth substrate; 1st two tops of BsCt array smooth; rounded rims; Slip1 not applic.. Orth = orthogonal; Oblq = oblique

Table 4. Rim profile

SRC	Rim profile	
	Rnd	Shrp
Slip1	-	-
Slip2	0.556	0.653
Slip3	0.856	0.675

Male heel; horiz. orthog. array; Co-So, BsCs only; Slip1 not applic.. Rnd = rounded; Shrp = sharp

Table 5. Collar texture

SRC	Texture	
	Smooth	Textured
Slip1	-	-
Slip2	0.636	0.686
Slip3	0.667	0.692

Sharp rims; male heel; horiz. orthog. array; Co-So, BsCs only; Slip1 not applic..

Temporal variables

High-heel Vel for all slips was greater than male heel Vel, with three exceptions indicated by exclamation marks in Table 6. The difference of Vel between the high-heel and male heel was not significant for Slip1 and Slip2 generally, but it was significant for Slip3 for heel strike between TGSIs (Cb-So) and borderline significant for heel strikes on TGSIs (Co-So).

Table 5. High heel compared with male heel

SRC	Co-So				Cb-So				No TGSIs	
	BsCs		BtCs		BsCs		BtCs		Bs	
	MH	HH	MH	HH	MH	HH	MH	HH	MH	HH
Slip1	0.612	0.413	0.612	0.413	-	-	-	-	-	-
Slip2	0.642	0.471	0.673	0.972!	0.471	0.348	0.606	0.582	-	-
Slip3	0.692	0.808!	0.690	0.981!	0.986	0.368	0.823	0.787	0.519	0.388

Horiz. orthog. array; all tops smooth; Slip1 SRC is for TGSI top only; Strt1 only; rounded rims.

Table 6. Mean velocity

Vel (m/s)	Co-So				Cb-So				No TGSIs; Bs		Cb-So*
	BsCs		BtCs		BsCs		BtCs				BsCs
	MH	HH	MH	HH	MH	HH	MH	HH	MH	HH	MH
Slip1	0.015	0.051	0.015	0.051	-	-	-	-	-	-	-
Slip2	0.093	0.475	0.022	0.351	0.132	0.094!	0.352	0.269!	-	-	0.136
Slip3	0.711	0.836	0.648	0.582!	0.651	1.026	0.790	0.980	0.922	1.097	0.851

Orthog. array; TGSI tops smooth; Slip1 Vel is for top only; Strt1 only; rounded rims. = Sloped array.*

For all array conditions, slip Drtn increased with slip distance: 0.201 s, 0.241 s and 0.506 s for Slip1, Slip2 and Slip3 respectively. The increments were not proportional with variations of slip distance. The mean Vel for Slip1, Slip2 and Slip3 was 0.080, 0.190 and 0.661 m/s respectively. In other words, Slip3 was over eight-times faster than Slip1 and three-and-a-half-times faster than Slip2. Mean Acc for Slip1, Slip2 and Slip3 was 0.138, 0.591 and 2.321 m/s^2 respectively. AccRsq decreased from 0.132, 0.067 to 0.017. That is, slips became marginally "rougher" with increasing distance. Greatest Vel was on the smooth substrate without TGSIs.

Comparison with BM3 and Pendulum results

As indicated in Table 7, tests of sharp-rimmed, smooth-topped TGSIs yielded an extremely low coefficient of friction (CoF) when measured with the BM3 (0.03), and a low CoF with the Pendulum (0.26). This contrasts with 0.653 and 0.675 respectively with the SFST. The smooth substrate without TGSIs had an extremely low CoF when measured with the BM3 (0.05); a very low CoF with the Pendulum (0.25); a low CoF as reported by the manufacturer for sharp rims and textured tops (0.49); a low SRC with the SFST and the high heel (0.388), and moderately high SRC with the male heel (0.519). There was close correspondence for the texture-topped array between the BM3 (0.98) and the SFST for Slip3 (0.930), but the Pendulum results of 0.33 and 0.45 are approximately one third and one half respectively of the SRC with the SFST (0.856 and 0.883). The BM3 CoF for smooth top and substrate arrays was 0.43 compared with 0.572 for Slip2 and 0.796 for Slip3 with the SFST.

Table 7. BM3 and Pendulum test results

	BM3[1]				Pendulum[2]				
	Co-So	Cb-So		No TGSIs	Co-Sb			Co-Sb[3]	No TGSIs
	BsCs[4]	BsCs	BsCt	Bs	BsCs	BsCs[4]	BsCt[5]	BsCs	Bs
CoF	0.03	0.43	0.98	0.05	0.33	0.26	0.49	0.45	0.25

[1] *With Neolite test pad.* [2] *With Four-S rubber slider; CoF=3*BPN/(330-BPN).* [3] *Oblique array.* [4] *Sharp rims.* [5] *Sharp rims; texture comprised of fine concentric rings; result given by Supplier*

Discussion

The effect of the male heel strike position on the first TGSI top (Co-So) highlights the critical interaction of foot rotation with heel strike on TGSI arrays. The greater distance of Strt1 allows the foot to rotate more than for the shorter distance of Strt3 before launching off the TGSI. With greater rotation, the heel posterior becomes more elevated and the foot more co-planar with the tops of the TGSIs. Not only does the heel posterior tend to avoid the substrate but the whole heel tends to avoid the collar and rim of the next TGSI, landing instead on the top of it with consequently less slip impediment to continued slipping than for Strt3. There would tend to be less avoidance of the substrate if the heel was new and its posterior edge therefore sharp.

The slightly greater SRC for heel strike between the first and second TGSI (CoSb) than for the other two locations might be due to the very short distance to the second TGSI and the consequent limitation of the foot's rotation before it engages the second TGSI. As a separate comment, whereas for heel strike on a TGSI or between successive TGSIs the heel engages the next TGSI at the heel's mid-width, for heel strikes between adjacent TGSIs, the heel engagement is at each of its sides and it tends to become wedged.

The greater Slip2 SRC for the sloped array than for the equivalent horizontal array corresponds with the perching of the heel on the tops of the second and third TGSIs, not on the rim of the second as for the horizontal array. This might be due to the greater angle through which the foot rotated to engage the TGSIs, exerting greater pressure immediately upon completion of rotation, greater compression of the heel, and greater SRC. Consistent with this was the observed compression of the anterior corners of the heel by the TGSIs at each side of it.

The similarity of results for the orthogonal and oblique arrays might be partly attributable to the small number of tests, to the use of only one heel strike location within the array, and to the first two TGSIs in the textured-topped array being smooth. If tests were also conducted with the high-heels, SRC differences would result because there would be no opportunity for full slips between adjacent rows of TGSIs.

The greater SRC of sharp rims compared with rounded rims for Slip2 is attributable to the aggressive indentation of the plane of the heel in its inclined pose by the sharp rim of the second TGSI(s). The greater SRC of rounded rims for Slip3 is attributable to decreased contact area of the prominent sharp rims compared with the rounded rims (consistent with results with the Pendulum). Only one test was conducted for collar texture (heel strike on a sharp rimmed TGSI array). Compared with smooth collars, SRC differences between smooth and textured collars would be greater for rounded rimmed TGSIs, and for heel strikes between TGSIs.

The lesser SRC for the high-heel strike than for the male heel between adjacent TGSIs (Cb-So), for Slip2 and initially Slip3, is attributed to the high-heel's sides not engaging adjacent TGSIs as do those of the male heel. An explanation of the exceptions noted for heel strikes on TGSI tops (Co-So) is frustrated by the absence of video recording of high heel tests and by the very small number of the tests; nor do temporal results assist in clarification. However, for Slip1, the lesser SRC of the high-heel might be attributable to its more-compressible rubber and its sharp posterior edge—allowing it to creep forward. The lesser SRC of the high-heel might also be due to the slight increase in contact area of the male heel as it rotates downward.

With respect to Slip2 and Slip3, the SRC differences (but not necessarily the order of them) between the high-heel and male heel are attributable to the following: (1) the male heel rotates on its posterior at heel strike on the TGSI top and then launches across to the rim of the second TGSI, which it strikes with its underside and whereupon it perches (see also above); progression to Slip3 entails the heel rotating about the fulcrum constituted by the rim, and the sole therefore becoming co-planar with the array tops; (2) the high-heel also rotates on its posterior at heel strike but, because of its smallness, after launching it lands on the substrate, completes its vertical rotation, on its posterior edge, and strikes the collar of the second TGSI with its anterior tapered face (the angle to the vertical of the TGSI collar and the high-heel's anterior face were unintentionally similar); progression to Slip3 therefore entails the heel's anterior face sliding up the TGSI collar, with the sole already co-planar with the array tops.

A conspicuous characteristic observed during some tests on oblique and orthogonal arrays was zigzagging of the foot during full slips, especially for the high-heel. For orthogonal arrays, this is attributed to the foot being slightly offset from the centre of successive TGSIs in the same row or from the centre between adjacent rows, or to slight angular misalignment of the array. This behaviour has implications for maintenance of balance following a slip, particularly for wearers of high-heel shoes.

Of the three slip distance categories: (1) slip confined to the top of a first TGSI, (2) slip extending to the second TGSI(s), and (3) full slip, it is predicted that the first one is very unlikely, the second unlikely, and the third likely to cause loss of balance. Loss of balance from full slips is predicted because of their speed, and possibly also their "roughness" in the horizontal and vertical planes. The predicted improbability of loss of balance from the other two slips is based on their very short distances.

A goal of the SFST was to determine whether slips were arrested or retarded by the reflexive downward rotation of the foot. In this study, this occurred in less than 2% of all tests, with stopping distances ranging from 13 mm to 82mm beyond the start of the second TGSI; as reported above, full slips were accompanied by substantial acceleration. If the SFST accurately simulates reflexive foot rotation, slip arrest and balance recovery prior to completion of full slips would depend upon other reflexive responses, such as with the other leg.

Based on the results here, it is predicted that the slip resistance of TGSI arrays would be greater for treaded and compressible soles than for the smooth firm soles used in this study. TGSI arrays of different grid pitch and TGSI shapes are also predicted to yield different results to the arrays tested here.

The substantial difference in results between the SFST and the BM3 and Pendulum is attributable to the following: (1) the interaction of the BM3 test foot with the TGSI array is limited to the TGSI tops; (2) the Pendulum's test foot interacts with the substrate and collar of TGSIs, but does not replicate the vertical rotation of the foot; (3) the Pendulum tends to bounce on macro-textured surfaces (Fwa et.al., 2005) and even on smooth surfaces, as found by Sigler (*1948*) and observed by the author.

Hallas and Hunwin (2009) recommended the use of a 76 mm rather than a 38 mm slider for the Pendulum when testing macro-textured surfaces to minimise interaction with interstices of protrusions, the same reason that Australian slip resistance test standards[7] now stipulate that

[7] AS 4586-2013: Slip resistance classification of new pedestrian surface material; AS 4663-2013: Slip resistance measurement of new pedestrian surfaces. Standards Australia, Sydney, Australia.

TGSI arrays be tested obliquely (at 30°). The present study considers that interaction of the heel with interstices is inherent to foot slip behaviour for "heel-down" gait and that measurement of it is necessary. It seems evident that this also applies to other macro textured surfaces.

Conclusion

When water-wet arrays of truncated-conical TGSIs were tested with a new, simulated-foot-slip tribometer, three key types of slips were identified: very short slip on a TGSI top of up to 18.75 mm; short slip to the second TGSI(s) of up to 42 mm; and full slip of 300 mm. The full slip is concluded to be the most likely to cause imbalance. However, results suggest that TGSIs are "very" to "extremely" slip resistant (and even "non-slip"), and much more so than indicated by tests with the Brungraber Mark 3 and the British Pendulum tribometers. In other words, the risk of imbalance on TGSIs appears to be extremely low, except for high-heeled shoes landing between rows of TGSIs on a smooth substrate, for which the slip resistance was low and therefore the risk of overbalancing high.

It is tentatively concluded that for the male heel:

- Greater force was required to generate longer slips than the short slips, and resulted in greater velocities and acceleration, by far the greatest of which was for full slips.
- For heel strike on the top of a first TGSI, a short slip is more likely for strikes on the closest part of TGSI top, and a full slip is more likely on the most distant part.
- Slip resistance along the tops of rows was approximately the same as between rows; and slightly greater for obliquely than for orthogonally aligned arrays for smooth-topped TGSIs, but the opposite for textured-topped TGSIs. In other words, the direction of gait and location of heel strike on the array substrate seems to be irrelevant.
- A sloped array, for heel strike between TGSI rows of an array with smooth substrate, was greater than for the equivalent horizontal array for the short slip but less for the full slip.
- Sharp rims produced greater SRC than rounded rims for Slip2, but less for Slip3. SRC increased substantially from Slip2 to Slip3 for the rounded rims, but negligibly for the sharp rims.
- Textured collars of sharp rim TGSIs provided slightly greater SRC than smooth collars.
- Slip resistance was greater than for the high-heel

The new tribometer provided a wealth of information about foot slips on TGSI arrays and revealed the complex interaction of foot rotational behaviour with the interstices of the arrays; this enabled the explanation of seemingly inconsistent test results.

References

Hallas, K. and Hunwin, G. (2009) A study of Pendulum slider dimensions for use on profiled surfaces. Research Report RR726, HSL, Harpur Hill, Buxton, Derbyshire.

Hunter, R.A. (2010). Spheroidal heel posterior: implications for slips and falls. Proceedings of 2010 International Conference on Fall Prevention and Protection. Dept. Health and Human Services, CDCP, NIOSH, Morgantown, WV, USA.

Lee, Y.P.K., Fwa, T.F. and Choo, Y.S. (2005). Effect of pavement surface texture on British Pendulum test. *J.of the Eastern Asia Society for Transportation Studies*, 6, pp. 1247–1257

Redfern, R.S., Cham, R., Gielo-Perczak, K., Gronquist, R.G., Hirvonen, H., Lanshammar, H. Ê K., Marpet, M., Pai, Y-C., and Powers, C. (2001). Biomechanics of slips. *Ergonomics*, 44, 13, pp. 1138–1166.

Rowe, T.J. (2010) Recommended procedures for testing ard evaluating detectable warning systems. Report 670. Transportation Research Board. Nat. Cooperative Highway Research Program (NCHRP).

Sigler, P. A., Geib, M. N. and Boone, T. H. (1948). Measurement of the slipperiness of walkway surfaces. *J. of Research*, Research Paper RP1879, 40, pp. 339 – 346. Nat. Bureau of Standards, U.S. Dept. of Commerce, Washington, D.C.