NOSING SHAPE, NOSING TEXTURE, TREAD TEXTURE AND STAIRWAY SLIP RESISTANCE

Rodney A. Hunter

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

Slip resistance tests of stair treads with a new, simulated-foot-slip tribometer found that: (1) three parts of the foot contribute to slips on stairs treads; (2) three distinct slip distances need to be considered in assessing fall risk during stair descent, of which one is critical; (3) slip resistance differs substantially over the slip distances; and (4) the contribution of nosing shape, nosing texture and tread texture to slip resistance varies with slip distance, as does slip duration, velocity and acceleration. Results suggest that nosing shape and texture contribute to tread slip resistance. Temporal correlates of slips help explain the behaviour of the slipping foot and have implications for balance maintenance and recovery. Vertical rotation of the foot at stair tread contact, and the effects of this, suggests that a rotational model is more useful than the conventional linear model of slip resistance.

Introduction

The benefit to individuals of reducing the risk of slips on stairs is self-evident and the socio-economic justification for doing-so is widely acknowledged.

A previous study by Hunter (2011) of slip resistance of stair tread nosings, tested with a modified Brungraber Mark 3 tribometer (BM3), indicated that tread nosing shape and texture influence slip risk during stair descent, although not substantially nor as much as tread texture. This paper is the continuation of that research, except that it uses a new, simulated foot slip tribometer[1]. The study has the same motivations as the earlier one, with an additional context that, in Australia, it is proposed that building regulations stipulate slip resistance ratings for stairs as determined by the British Pendulum, notwithstanding its limitations in testing stair nosing–tread configurations, and that the requirement will only be for the plane of the treads. An additional motivation arose from reservation about results with the BM3, as modified by Hunter (2011) and as later more-elaborately modified by him, for this sort of testing.

Like the BM3 and its predecessor, the new tribometer 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, and simulates the downward rotation of the heel after forefoot contact on treads during stair descent. Weight distribution of the leg and foot, and foot and ankle proportions are realistic, and the foot is realistically articulated in the sagittal plane (like the BM3) and partially in the coronal plane. The amount and rate of loading, foot rotation and commencement of rotation are adjustable. Slip distance and velocity, and angular velocity of foot rotation are electronically and synchronously recorded for analysis, including with video.

[1] Invented by the author.

Like its precursor, this study explores the contribution of nosing shape, nosing texture and tread texture to slip resistance and, secondarily, explores the suitability of the new tribometer for testing stair tread and nosing configurations, including when in-situ. The study also explores the effect of delayed foot rotation on slip resistance, duration, velocity and acceleration.

Method

Tests were conducted with the sole of a new, adult male shoe (with sole arch) having a length of 295 mm. The heel had a length of 95 mm, and a concave anterior edge. The heel was comprised of Shore-A 84 rubber, and the outsole and sole arch were of Shore-A 75 rubber, all smoothed with 400-grit abrasive. The outsole was slightly convex in the sagittal plane, as is common, but not in the coronal plane. The foot was aligned so that it protruded 55 mm forward of the tread nosing, corresponding with the ball of the foot being located just behind it. The foot was set so that the outsole was 10 mm above the nosing.

The sole was set at 25° to the tread, on the basis of measurements taken from a video recording of a randomly selected (and unaware) person, instead of 20° as reported by Redfern *et al.* (2001) or 20.5° as in Riener *et al.* (2002). Slow-motion-video photography was used to study the tribometer's foot-slips[2].

Treads and nosings were natural finish aluminium. For the textured treads and nosings, 400-grit wet-and-dry abrasive paper was adhered to the aluminium. The radii of the round and "square" nosings were 6 mm and 1.5 mm respectively. For smooth nosings, the tread texture was placed 6 mm from their front; the texture of textured nosings was continuous with that on the treads. All tests were in water-wet conditions.

Measurements were recorded for all strut angles for each of the twenty-five test conditions: a total of one hundred and seventy-four measurements. Three sets of slip distances were used for analysis: (1) over 240 mm, corresponding with slip of the whole foot from the tread; (2) up to 150 mm, corresponding with slips for which the heel and the sole arch interlocked with the nosing; and (3) 40 mm for which the heel and part of the outsole remained on the tread[3]. Velocity of foot rotation was not recorded, and variation in commencement of foot rotation was recorded only to a limited extent[2]2 above.

The 40 mm slip distance was derived by subtracting the 55 mm of the sole overhang from the 95 mm distance between the front of the sole to the ball of the human foot upon which the sole was modelled. It was assumed that loss of balance might occur from shorter slips but that there would be greater opportunity for recovery than for longer slips. The critical supported length of the sole was 200 mm, or 68% of the sole length— equivalent to the 70% reported by Loo-Morrey *et al*. (2004) as being required for foot support on treads.

Twelve combinations of four independent variables were tested: nosing profile (rounded, squared); nosing texture (smooth, textured); tread texture width (0 mm, 50 mm, 250 mm); and delay of foot rotation. For regression analysis, the tread texture was categorised as front texture (the 50mm band at the nosing) and back texture (the 250 mm behind the band). Four dependent variables for the study were slip resistance coefficient (SRC[4]); slip distance (Dst); slip duration (Drtn); slip velocity (Vel); and slip acceleration (Acc).

Results

Slip resistance coefficients

Generally, SRC increased with increased Dst; increased with tread texture width; and increased in the order of square-smooth, round-smooth, round-textured and square-textured nosings, see

[2] Synchronisation of foot rotational velocity and video recording, and the method of controlling commencement of foot rotation were modified after data collection for this study.

3 The next slip distance beyond 150 mm was a full slip of 240 mm. The slip resistance coefficients for the 40 mm distances were obtained from linear interpolation.

[4] "Sip resistance coefficient" is used instead of "coefficient of friction" to convey the complexity of the tribometer's foot-slip dynamics.

Table 1. Overall, correlations were moderate-to-strong, and significant, for SRC with nosing and tread texture, but not for SRC with nosing shape, nor between the nosing and tread variables.

SRC was better-explained by separate analyses of the three slip distances: (1) the theoretical Dst1, for which there is no conspicuous change in foot behaviour; (2) Dst2 when slips ceased with the sole interlocked with the nosing (such that the sole arch was in contact with the nosing and the leading edge of the heel was in contact with the tread just behind the nosing); and (3) Dst3 for which sufficient load was applied to overcome the interlocking of the foot at the nosing and causing the foot to leave the tread.

As indicated in Table 1, SRC increased with slip distance for partly and fully textured treads but, although this was the general trend for smooth treads, the least SRC for smooth treads was for Dst2. The strength, direction and significance of correlations with SRC of the nosing–tread variables differed between the three slip distances.

Table 1. SRC for slip distances and tread and nosing characteristics

		Tread texture width (mm)							
Distance	Nosing	0		50		300		All	
Dst3 = 240 mm	Round-smooth	0.281		0.613		0.937		0.528	
	Round- textured	- *	μ:	0.664	μ:	- *	μ:	0.664	μ:
	Square-smooth	0.345	0.308	0.707	0.673	0.829	0.883	0.587	0.583
	Square- textured	- *		0.711		- *		0.711	
Dst2 <= 150 mm	Round-smooth	0.069	μ:	0.499		0.740		0.344	
	Round- textured	- *	0.068	0.554	μ:	- *	μ:	0.554	μ:
	Square-smooth	0.065		0.500	0.535	0.344	0.542	0.269	0.364
	Square- textured	- *		0.587		- *		0.587	
Dst1 = 40 mm	Round-smooth	0.127		0.274		0.583		0.278	
	Round- textured	- *	μ:	0.449	μ:	- *	μ:	0.449	μ:
	Square-smooth	0.131	0.129	0.115	0.377	0.366	0.488	0.206	0.323
	Square- textured	- *		0.456		0.513		0.494	
All	Round-smooth	0.159		0.494		0.753		0.36	
	Round- textured	- *	μ:	0.529	μ:	- *	μ:	0.49	μ:
	Square-smooth	0.180	0.168	0.505	0.535	0.513	0.616	0.33	0.422
	Square- textured	- *		0.610		0.513		0.55	

* Textured nosings were not tested with smooth and fully textured treads[5]

The four variables: nosing shape, nosing texture, tread front-texture and tread rear-texture were regressed on SRC for each of Dst1, Dst2 and Dst3 (the model for Dst generally was much less predictive than separate models). The models were highly significant and, as indicated in Table 2, explained 85%, 88% and 94% of the variability of SRC, but became less reliable with increasing slip distance category.

The models indicate that with increasing slip distance, SRC increases for nosing shape (the square nosing contributes more to SRC than the round), and decreases for nosing texture. However, whilst SRC increases with slip distance generally for front tread texture, the greatest SRC was for Dst2. In contrast, for tread rear texture, SRC was the least for Dst2 and approximately the same for Dst1 and Dst3.

The models also indicate that smooth treads and nosings provide the least slip resistance; that fully-textured treads with textured nosings provide the greatest slip resistance; and that partly textured treads with textured nosings provide greater slip resistance than fully textured treads with smooth nosings. For the critical Dst1, nosing texture contributed more to SRC than the partly textured

5 The textured nosings were omitted because their contribution to slip resistance was thought to be self-evident. In retrospect, their inclusion would have been better.

treads, and half of the SRC of fully textured treads; for the next most critical distance, Dst2, tread front texture contributed substantially more than tread rear texture regardless of nosing texture.

Table 2. Contributions of tread and nosing characteristics to SRC

	P>|t|				SRC				SRC		
	Dst1	Dst2	Dst3		Dst1	Dst2	Dst3		Dst1	Dst2	Dst3
Constant	0.00	0.10	0.00		0.168	0.101	0.295		0.168	0.101	0.295
Nosing shape	0.03	0.12	0.34	Sqr	-0.091	-0.079	0.000	Rnd	0.000	0.000	0.030
Nosing texture	0.01	0.33	0.57	Smth	0.000	0.000	0.000	Txtrd	0.159	0.072	0.028
Tread front texture	0.04	0.00	0.00	Smth	0.000	0.000	0.000	Txtrd	0.122	0.436	0.349
Tread rear texture	0.00	0.55	0.00	Smth	0.000	0.000	0.000	Txtrd	0.205	0.044	0.224
R-sq: Dst1 85.1%; Dst2 87.6%; Dst3 93.8%				∑	0.077	0.022	0.295	∑	0.654	0.653	0.926

Sq = "square"; Smth = "smooth"; Rnd = "rounded"; Txtrd = "textured".

Temporal variables

Mean Drtn for Dst1, Dst2 and Dst3 were 0.110 s (Drtn1), 0.227 (Drtn2) and 0.359 s (Drtn3). The correlations with SRC were very strong and significant for Drtn1 and strong and significant for Drtn2 and Drtn3. The results indicate a second opportunity of a quarter of a second for balance recovery during Drtn3 after Drtn1; and of an eighth of a second during Drtn2 after Drtn1, and during Drtn3 after Drtn2.

The features that correlated reliably with Drtn were nosing texture and tread front texture for Slip1; tread front and tread rear texture for Slip2; and, for Slip3, in decreasing strength and reliability of correlation, tread front texture, tread rear texture, and nosing shape (nosing shape correlated negatively). In other words, the features that most prolonged slips were textured nosings and tread front textures for Slip1, full tread texture for Slip2, and tread front texture and, to a lesser extent, round nosing and, to a slightly even lesser extent, tread rear texture.

The fact that Drtn1, Drt2 and Drtn3 were not in the same ratio as Dst1, Dst2 and Dst3 is consistent with mean Vel being 0.363 m/s for Dst1 (Vel1), 0.472 m/s for Dst2 (Vel2) and 0.667 m/s. for Dst3 (Vel3). In other words, slips over increasing distance occurred with increasing velocity.

Reliable correlations indicated that Vel1 and Vel3 decreased with increasing slip resistance; and a less reliable correlation indicated that Vel2 also increased slightly. Direct observation and preliminary analysis of distance, velocity and acceleration graphs suggest that Vel2 is more-greatly affected by the sole arch. This is because, under the momentum of the foot, even though the heel maintained contact with the tread, the contact of the outsole with the nosing was momentarily lost until contact was made with the nosing by the sole arch. The Dst1 slip (Slip1) decelerated with textured nosing and tread front texture; the Dst3 slip (Slip3) decelerated with tread front and rear texture; but the Dst2 slip (Slip2) accelerated—with nosing shape, nosing texture and tread front texture contributing almost equally.

R-sq of acceleration with time (AccRsq) was used as an approximate indicator of the smoothness of slip motion. AccRsq correlated strongly, negatively and significantly with SCR for Slip1; moderately, negatively but insignificantly for Slip2; and very weakly, negatively and insignificantly for Slip3. That is, increased SRC corresponded with greater slip distance and with variability of acceleration. The greatest contributor to variability of acceleration for all slips was tread front texture. The rate of deceleration to cessation of Slip1 and Slip2 contributed substantially to variability of acceleration.

Delayed foot rotation contributed an extra 0.013 s for Slip1, 0.002 s for Slip2, and 0.032 s for Slip3. Delayed foot rotation corresponded with a SRC reduction of 0.034 for Slip1 and an increase of 0.049 and 0.057 for Dst2 are Dst3 respectively. This was reflected (very weakly and insignificantly) in the positive correlation of DFR with SRC for Slip1, and in the negative correlation with Slip2 and Slip3. The results very tentatively suggest that delayed commencement of foot rotation slightly increased SRC for Slip1, whereas undelayed foot rotation slightly increased SRC for Slip2 and Slip3. The discrepant Slip1 is reflected in the fact that nosing–tread features correlated negligibly with delayed foot rotation whereas tread front texture correlated weakly (but insignificantly) with delayed rotation for Slip1. The discrepancy of Slip1 is probably due to the interaction of the sole's topography with the nosing–tread features.

Discussion

The fact that round smooth nosings contributed more to slip resistance and duration than square smooth nosings for Slip1 and Slip2 but less for Slip3 is believed to be due to two factors: (1) for Slip1 and Slip2, the nosing curvature allowed the first contact of the sole to be with the front edge of the tread texture as well as with the smooth nosing, whereas for square nosings, the first contact was with the smooth nosing only; and (2) the contribution of fully textured treads (tread front texture plus tread rear texture) increases with slip distance and the contribution of nosing shape decreases. Decreased foot angle at initial foot contact would exaggerate this.

The substantial difference of SRC for tread rear texture for Slip1 compared with Slip2 and Slip3 is believed, for Slip2, to be due to the interlocking of the heel and sole-arch with the nosing occurring with less foot rotation and therefore with less engagement of the heel with the tread rear texture. For Slip1 and Slip3, the foot more fully rotates so that there is more engagement of the heel with the rear texture.

Three parts of the sole observably contributed to slip arrest: the outsole at forefoot contact, the heel (in conjunction with the outsole) after downward foot rotation, and the heel's anterior edge (in conjunction with the sole-arch) beyond Dst1. It was the interlocking between the nosing, the heel's front edge and the sole arch that had to be overcome before a full slip occurred. The corners of the heel's anterior edge also contributed to the interlocking as evident in the compressive distortion of the corners.

A focus of this study was 40 mm slips because this seems to be an appropriate safety criterion. With increasing slip distance, there is not only increased probability of loss of balance, but also less opportunity for balance recovery, and increased probability of more serious injury.

Comparison with other studies and tests

Several studies have reported slip velocities (e.g. Brady *et al.*, 2000; Chambers *et al.*, 2001; Cham and Redfern, 2002; Strandberg and Lanshammar, 1981). However, the velocities were not for slips during stair descent, and the lubricant was not plain water. They are therefore not directly comparable with results found here. Variability in this study of acceleration was investigated to establish whether it contributes, even if scarcely, to loss of balance. However, the results gave no answer.

Jones and Watt (1971) reported that the minimum times for reflexive reaction and effective voluntary response to a sudden fall were 0.102 s and 0.190 s respectively. The three slip durations of 0.110 s (Drtn1), 0.227 (Drtn2) and 0.359 s (Drtn3) found here therefore indicate that there is an opportunity for balance recovery, even though it diminishes with the key slip distances (Dst1, Dst2, Dst3). Slip duration also has implications for tread width. Wider treads facilitate lesser protrusion of the foot which therefore increases slip distances, slip durations, and opportunity for balance retention or recovery. However, Jones's and Watt's fall event was instantaneous and total, in contrast with slip events

The temporal variables are useful descriptors of slip dynamics, as well as indicators of the interaction between nosing–tread configuration and the topography of the sole and rotational motion of the foot. However, with the exception of tread width, it has not been possible to draw usable inferences for optimal nosing–tread characteristics.

The precursor to this study (Hunter, 2011) found that nosing shape contributed to SRC very marginally. The same was found here but, for shorter slips, square nosings were found to contribute less than round nosings, not more as in the earlier study. Nosing texture was found to contribute to SRC in both studies. However, the earlier study indicated a negligible contribution whereas the present study found a substantial contribution. Although textured treads were found to substantially and significantly contribute to SRC in both studies, results for tread characteristics are not reliably comparable between the two studies because the former did not test for partly textured treads or slip distances, nor employ a full sole, and the present study did not test for different test foot overhangs.

For the 40 mm slip distance used here, the required friction values of 0.15 to 0.27 for stair treads found by Loo-Morry *et al.*(2004) are satisfied by all textured tread and nosing configurations except by the partly textured treads with square smooth nosing, and the smooth treads with smooth nosings.

Proposed Australian building regulations require a slip resistance of 45 to 54 BPN for water-wet stair treads when tested with the Pendulum [6]. This represents a SRC range of 0.473 to 0.587[7]. For the critical Slip1, the only nosing–tread configuration that satisfies the requirement is the fully textured tread with the round textured nosing. For Slip2 and Slip3, all nosing–tread configurations satisfy the requirement. However, Pendulum testing, and therefore the regulatory requirement, is restricted to the plane of the tread. The comparable surfaces in this study are the partial and full tread texture. The predictive model indicates that the partially textured tread alone would not satisfy the requirement, and that the fully textured treads would satisfy the requirement only for Slip2 and Slip3. However, it is suggested here that Slip2, and especially Slip3, are inappropriate criteria for stairway fall risk avoidance.

Pendulum tests by the author of fully textured tread samples, with the slider path wholly on the tread, produced a mean BPN of 88. Tests of the 50mm band, with the end of the slider's path 5 mm beyond the front edge of the band, produced a mean BPN of 56. The tread samples therefore comply with the proposed regulations. After conversion to SRC, the results are 1.09 and 0.61 respectively. A test of a fully textured tread with the Hunter tribometer set at its maximum strut inclination to the vertical, and without foot overhang, failed to induce a slip at an SRC of 1.054. This is similar to the Pendulum result. The predicted SRC with the Hunter tribometer for the 50 mm textured band was 0.122 for Slip1, 0.44 for Slip2 and 0.349 for Slip3. If the contribution of textured nosing is added, the values become 0.381, 0.508 and 0.377—still well below the 0.61 produced by the Pendulum.

Rotational model of slips

Observation of the forefoot upon landing on treads and throughout slips suggests that the conventional linear model of flat-planar motion during slips is not as valid as a rotational model.

For the linear model, the contact area on the foot is stationary as the contact area on the tread moves, whereas for the rotational model, the contact area on the foot also moves. The rotational model has implications for surface modification and adhesion effects during slips; for variation of contact area and pressure, as noted by Hunter (2010); and for foot slip behaviour.

The rotational model helps explain why round smooth nosings with textured treads are more slip resistant than square smooth nosings: because of the foot's angle at foot-fall, it first contacts, tangentially, the curve of the nosing but then almost immediately rotates downward so that the fulcrum moves from the nosing to the front edge of the tread texture with which the foot increasingly engages as it rotates. This also occurs with square nosings but there is greater duration before engagement with the tread texture edge and therefore greater slipping and acceleration of the foot before engagement.

Because the rotation of the foot about its ankle is incremental, and for a constant leg inclination and intersection of its longitudinal axis with the tread–nosing, the foot's tangential force component on the tread–nosing increases exponentially with rotation, and the friction required to prevent a slip also increases exponentially. This contrasts with the BM3, including as modified by Hunter (2011), but is similar to the tangential force component of the Pendulum's slider during the second half of its path.

Future investigations

Better understanding of foot slip behaviour would be gained by testing for various foot protrusions; sole sizes, types and materials; and textures, widths and vertical profile of bands at nosings.Testing of various textured band widths would indicate whether they can sufficiently

[6] http://www.abcb.gov.au. Retrieved 20th June 2013. The requirement is for the whole tread or a strip at the nosing.

[7] Using COF = 3*BPN/(330-BPN) e.g. Bowman, R., Australian CSIRO Building Construction and Engineering (1999). An introductory guide to the slip resistance of pedestrian surface materials, HB 197-1999, Standards Australia. SAI Global.

provide tread slip resistance of treads regardless of the rest of the tread. For the present study, the estimated minimum band width required was 150 mm, calculated as the length of the sole less its tread overhang and length of heel. If the risk threshold is increased (undesirably) by deducting the 40 mm of Dst1, the width is 110 mm. Testing the protrusiveness of bands at nosings would indicate their effect upon slips by the forefoot and interlocking with the bands by the sole arch. Various amounts and rates of loading; various foot angles; and various rates of rotation and delays of commencement of foot rotation also require testing.

The results found here are not applicable to landings and their nosings at the tops of stair flights because the foot rotates about the outsole during stair descent whereas it typically rotates about the posterior of the heel on landings. Moreover, foot angles prior to stair descent are likely to be shallower as people adjust their gait in preparation for descent (if the presence of the stair is detectable).

Conclusion

The interaction between the various parts of the stair tread with three parts of the shoe sole—the outsole; the sole-arch and the heel, especially the anterior edge of the heel—was central to the results found here.

Three slip distances were identified: full slip off the tread; partial slip that stopped with the sole arch on the nosing; and a shorter partial slip beyond which for a person there would be inadequate foot support The shorter slip appears to be critical for assessing tread slip resistance.

The study found that nosing shape, nosing texture, and extent of tread texture contribute, to varying extents, to the slip resistance of stair treads and therefore to avoidance of falls on stairs. It also found that contributions to slip resistance varied with the three key slip distances.

Analysis of slip duration, velocity and acceleration provided insight into the behaviour of the slipping foot, and has implications for balance retention and recovery and therefore fall avoidance.

The new tribometer yielded a wealth of information about simulated foot slip behavior, and allowed for useful comparisons of its results with those of other tribometers. It also highlighted the role of foot rotation in slips, and the merits of a rotational model of foot slips rather than a linear model.

References

Brady, R.A., Pavol, M.J., Owings, T.M. and, Grabiner, M.D. (2000). Foot displacement but not velocity predicts the outcome of a slip induced in young subjects while walking. *J. of Biomech,* 33, 803-808.

Cham, R. (2003). Kinematics of the foot during slips, *Occupational Ergonomics,* 3, 225–234, IOS Press

Chambers, A.J., Margerum, S., Redfern, M.S. and Cham, R. (2003) Kinematics of the foot during slips, *Occupational Ergonomics,* 3, pp. 225–234, IOS Press.

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.

Hunter, R.A. (2011). Friction at tangential contact: in-situ slip testing of stair nosings. *Proceedings of 2011 International Conference on slips, trips and falls*. Health and Safety Laboratory, Buxton, Derbyshire, UK.

Jones, G.M, and Watt, D.G.D. (1971), Muscular control of landing from unexpected falls in man. *J. of Physiology*, 219, pp. 729-737.

Loo-Morrey, M., Hallas, K.A. and Thorpe, S.C. (2004). Minimum going requirements and friction demands during stair descent, *Contemporary Ergonomics*, CRC Press.

Riener, R., Rabuffetti, M. and Frigo, C. (2002). Stair ascent and descent at different inclinations, *Gait and posture*, 15, 34.

Strandberg, L. and Lanshammar, H., (1981). The dynamics of slipping accidents, *J. of Occupational Accidents*, 3, pp. 153−162.