A BIOMECHANICAL MODEL OF THE SPACING AND WIDTH EFFECTS OF ANTI-SLIP STRIPS

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The current research tested an 'anti-slip' strip product at two spacings (20cm and 26cm) on a very low friction, vegetable oil-contaminated surface (CoF = 0.07-0.10). Kinematic data were collected from 80 walking trials using an Optotrak 3D motion capture system to sample shoe-mounted infra-red light emitting diodes (IREDS) at 100Hz. No slipping was observed when the foot directly landed on the strip, accounting for 43% of trials at 20cm-spacing and 28% at 26cm-spacing. While maximum potential slipping distance could be hypothesised to equal the strip spacing, results indicated maximum slipping distances up to foot contact with the strip of only 1.71cm and 3.15cm for 20cm- and 26cm-spacing, respectively. Following strip contact the foot travelled a further 4.2cm (20cm-spacing) and 5.25cm (26cm-spacing) until it decelerated. In summary, 20cm spacing was superior to 26cm spacing in minimising the frequency and severity of slipping.

Introduction

Minimization of slip-related injuries is an important consideration in both occupational and residential settings, as 20% of cases lead to absence from work for more than one month (Chiou et al., 2003; Leclercq, 1999; Yoon and Lockhart, 2006). For the older population (over 65 years) slipping is a major contributor to hip fracture, with negative effects on morbidity and mortality, especially in developed countries where a demographically ageing population is exacerbating ageing and health concerns (Cassell and Clapperton, 2008; Hung et al., 2012; Sherrington and Menz 2003).

One approach to reducing slipping risk is to retrospectively apply 'anti-slip' strips to the floor to increase slip-resistance. In applying these products one critical decision for the client and supplier is determining adequate and cost-effective spacing to provide a high degree of safety with minimum labor and materials. Previous studies of slipping biomechanics (e.g. Leclercq, 1999) suggested that the strip-spacing should be less than 10cm. This recommendation is reasonable on the assumption that the heel slips up to 10cm without any reflexive foot-flattening response. Spacing greater than 10cm was, however, considered viable when taking into account the frequency of either direct foot contact with the strip, more anterior part of the foot first contacting the strip or immediate foot-flattening that would reduce slipping distance to less than the strip spacing.

The aim of this project was to test the spacing effect (20 cm and 26 cm) of an abrasive slip-resistant strip on the biomechanical characteristics of foot-ground contact when walking on an oil contaminated smooth Perspex surface wearing a soft soled walking shoe and a hard soled dress shoe, see Figure 1.

Methods

Testing Protocol
Two physically active, healthy male participants (30 years and 38 years) performed 10 walking trials at each strip spacing (20 cm and 26 cm). Start position was adjusted such that the third step would allow right foot contact with the forceplate. Vegetable-based cooking oil was used to contaminate the Perspex plate to provide a coefficient of friction (CoF) of 0.07-0.10 as measured using Four S rubber (400 P abrasive power: AS/NZS 4586, 2004), Four S rubber (400 P abrasive paper: BS 7976-2, 2002) and TRL rubber (400 P abrasive paper: AS/NZS 4586, 2004), defined as an extremely slippery walking surface (Nagano et aql., 2013). The plate was retouched following each trial. The above procedure was undertaken with both shoes. Following 10 trials with 20 cm spacing, the plate was rotated to provide a 26 cm margin from the front edge of the plate to the strip (Figure 1 C).

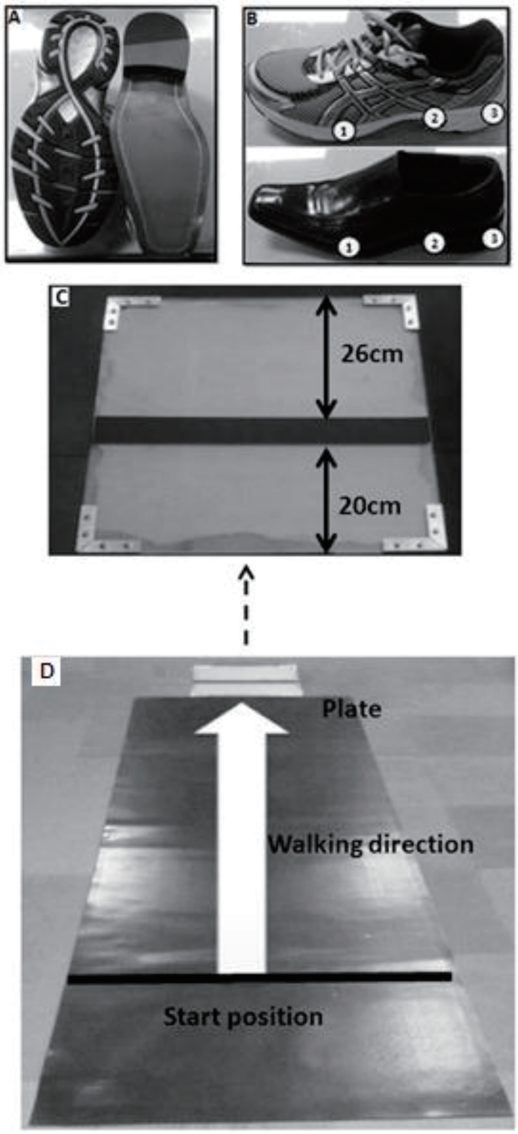

Figure 1. (A) Bottom sole: walking shoe (left) and dress shoe (right). (B) Marker locations, a walking shoe (top) and dress shoe (bottom) both 27cm in length. Marker ①= forefoot (10cm anterior to mid-foot); marker ②= mid-foot (8.8cm anterior to heel); and marker③= heel. (C) Strip attachment on Perspex. (D) Experimental setup.

To capture foot kinematics an Optotrak® optoelectic motion capture system (Northern Digital Inc., Canada) with 3 camera towers tracked the 3D position (100Hz) of 3 light-emitting diodes placed on the proximal inferior surface of the outer sole of the shoe (Figure 1). Raw position-time data were low-pass filtered using a 4th order zero-lag Butterworth Filter with a cutoff frequency of 15 Hz.

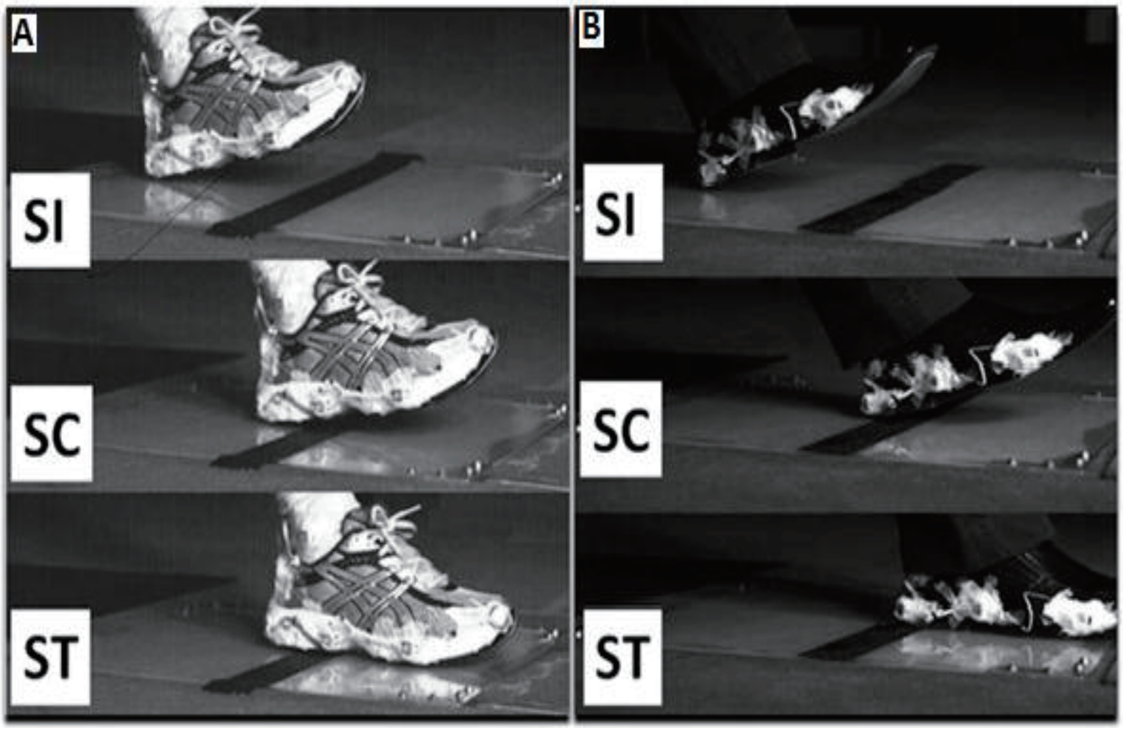

Figure 2. SI (Slip Initiation), SC (Strip Contact), and ST (Slip Termination) taken by high speed camera (A): for the rubber soled walking shoe and (B): dress shoe.

Parameterisation

Slipping distances between the following four events were measured to assess the effectiveness of anti-slip strips on falls prevention due to slipping. Figure 2 visualized the four events monitored by high-speed camera (Photoron SA3) at 500Hz.

As illustrated in Figure 3, Slip Initiation (SI) was defined kinematically as the first positive acceleration following heel contact (Lockhart et al., 2003); Strip Contact (SC) occurred when any part of the shoe contacted the strip, confirmed by the three markers' 3D coordinates on Perspex relative to the anterior-posterior location of the strip. The Strip Effect (SE) was when the strip first took effect as reflected in negative acceleration (i.e. slowing) and peak horizontal velocity following strip contact. At Slip Termination (ST) horizontal acceleration and velocity approximated zero (i.e. the foot had stopped).

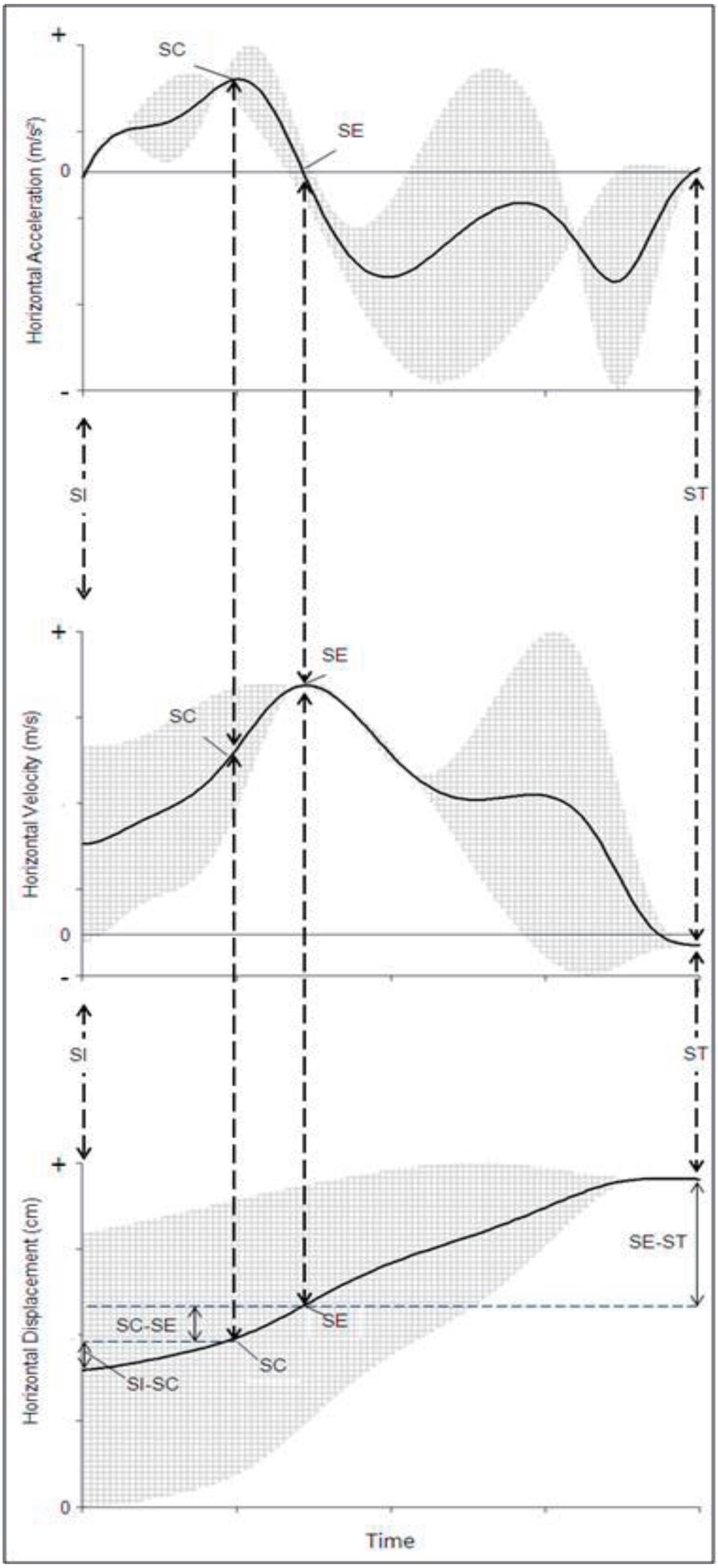

Figure 3. Kinematic definitions of SI-SC, SC-SE, SE-ST.

Results

Strip effectiveness was based on overall slipping frequency (slip or no-slip, Table 1) combined with the three slipping distances based on the above kinematic events (Table 2). Responses with a total slipping distance of less than 3 cm were not included as they are considered "micro-slips" (Liberty Mutual Group, 2004).

Slipping Frequency

With 20 cm spacing there was no recorded slip on 43% of trials whereas at 26 cm 28% of trials were no-slip (Table 1). All non-slip trials were due to subjects stepping directly onto the strip. As described in Table 1 strip contact with the heel was 10/ 80 (13%) of trials and of these 10 trials only two trials with an SC-SE distance exceeding 5 cm did not attain foot flattening.

Table 1. Frequency of slipping associated with three contact locations. Data presented as frequency of slips/n of contacts (%). *(e.g. In 20 cm spacing with walking shoe, mid-foot contacted strip 11 times and in 55% of cases (n= 6) the shoe slipped)*

	Walking Shoe			Dress Shoe		
	Contact Location			Contact Location		
Strip Spacing	Heel	Mid-foot	Forefoot	Heel	Mid-foot	Forefoot
20cm	0/0 (0)	6/11 (55)	7/9 (78)	0/5 (0)	5/5 (100)	5/10 (50)
26cm	0/3 (0)	5/5 (100)	9/12 (75)	2/2 (100)	3/6 (50)	10/12 (83)
Total	0/3 (0)	11/16 (69)	16/21 (76)	2/7 (29)	8/11 (72)	15/22 (68)

Slipping Distance

Slipping distances are summarized in Table 2. Despite the 26 cm condition eliciting greater SI-SC slipping distance than the 20 cm condition, in both spacings SI-SC was considerably less than the maximum distance available (i.e. 20 cm and 26 cm). SC-SE indicates the slipping distance from contact with the strip to when the strip took effect. There was no clear shoe-type effect on this variable, with the dress shoe showing a short strip effect distance at 20cm but a considerably longer distance at 26cm while for the walking shoe SC-SE were more comparable for the two spacings.

The distance required to completely stop the slip from when the strip began to take effect was indicated by SE-ST. The 20 cm spacing demonstrated shorter SE-ST distance (by 1.6 cm) for the walking shoe. Considerably shorter SE-ST distance was found for the dress shoe than the walking shoe (3.3cm). In summary, for the walking shoe a reduction in strip spacing from 26 cm to 20 cm achieved approximately 20% less distance travelled from when the strip took effect to stopping while for the dress shoe the 20 cm spacing decreased the distance by approximately 50%.

Table 2. Slipping Distances (cm)

	Walking shoe		Dress shoe	
	20cm	26cm	20cm	26cm
SI-SC	2.00 ± 1.56	3.54 ± 2.42	1.43 ± 0.54	2.76 ± 4.33
SC-SE	5.91 ± 4.97	4.31 ± 2.51	2.49 ± 1.47	6.18 ± 4.63
SE-ST	6.20 ± 1.88	7.82 ± 3.00	3.19 ± 1.01	6.50 ± 2.64

Discussion

Narrower spacing remarkably increased the frequency of direct foot contact with the strips;

when reducing the spacing from 26 cm to 20 cm, slip frequency was 15% lower. As all ‘no slip’ trials were confirmed as due to stepping directly onto the strip, reduced spacing between multiple strips would be assumed to be effective in increasing the probability of direct contact.

Previously, a slipping distance of 10cm has been documented as the threshold for recovery from posterior balance loss due to heel anterior slipping (Leclercq, 1999; Moyer et al., 2006; Parijat & Lockhart, 2008; Strandbert & Lanshammar, 1981). In this project, however, slip initiation to strip contact (SI-SC) averaged *less* than 10cm with strips spaced at 20 cm and 26 cm. This suggests that in everyday applications considerably wider spacing may be effective in significantly reducing slipping distance.

In the above slipping model SC-SE distance is a potentially very useful variable for determining anti-slip strip *width* effects. If a strip is contacted at the most posterior point of the heel, and continues without foot flattening, SC-SE distance is required to be less than strip width to effectively decelerate the foot. SE is when foot acceleration first becomes negative. As Figure 1 indicates the mid-foot marker was located 8.8 cm anterior to the heel marker. When, therefore, strip contact occurred at mid-foot (34% of trials) the SC-SE distance threshold can be extended to 13.8 cm (5 cm + 8.8 cm). On 54% of trials strip contact occurred at the forefoot marker, providing a 23.8 cm SC-SE threshold. At 20 cm spacing, strip effect to slip termination (SE-ST) distance was reduced compared to 26 cm spacing. Narrower spacing is, therefore, effective in reducing slipping distance.

In summary, narrower spacing increased direct foot contact with the strip and reduced slipping distance. In future work, using our slipping model, it would be informative to further investigate strip width effects in addition to spacing. Biomechanical testing can be usefully used in developing strategies for real-world falls prevention by determining the security achieved for a given application cost.

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