Gait adaptations to awareness and experience of a slip when walking on a cross-slope

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***4. Title Page (with authors and addresses)**

Gait adaptations to awareness and experience of a slip when walking on a cross-slope

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Abstract

Falls that occur as a result of a slip are one of the leading causes of injuries, particularly in the elderly population. Previous studies have focused on slips that occur on a flat surface. Slips on a laterally sloping surface are important and may be related to different mechanisms of balance recovery. This type of slip might result in different gait adaptations to those previously described on a flat surface, but these adaptations have not been investigated. The aim of this study was to assess whether, when walking on a cross-slope, young adults adapted their gait when made aware of a potential slip, and having experienced a slip. Gait parameters were compared for three conditions – 1) Normal walking; 2) Walking after being made aware of a potential slip (participants were told that a slip may occur); 3) Walking after experiencing a slip (Participants had already experienced at least one slip induced using a soapy contaminant). Gait parameters were only analyzed for trials in which there was no slippery contaminant present on the walkway. Stride length and walking velocity were significantly reduced, and stance duration was significantly greater in the awareness and experience conditions compared to normal walking, with no significant differences in any gait parameters between the awareness and experience conditions. In addition, 46.7% of the slip trials resulted in a fall. This is higher than reported for slips induced on a flat surface, suggesting slips on a cross-slope are more hazardous. This would help explain the more cautious gait patterns observed in both the awareness and experience conditions.

Keywords: Slips; Falls; Ageing; Balance; Cross-slope.

1. Introduction

Humans have an inherently unstable posture during gait and are often faced with challenging perturbations due to various environmental factors. Therefore, they are susceptible to falls with potentially serious and sometimes life-threatening consequences [1]. Ageing results in an increased susceptibility, potentially leading to functional disability. Even in the absence of injury, a tendency to lose balance can result in reduced physical activity and reduced ability to function suitably in social roles [2]. Several papers have recognised that falls occurring in the community are variable and happen under a variety of situations and circumstances. These can include trips, slips, or a change in the support surface, for example [3]. Slip-related falls are particularly prevalent, with slips comprising up to 40% of outdoor falls in community dwelling older adults [4]. Moreover, up to 25% of fall-related hip fractures result from slips [5].

Maki et al. suggested that medio-lateral balance ability is an important predictor of successful fall avoidance [6]. Lateral perturbations during quiet stance have been analysed [2, 6, 7], but understanding of a predominantly lateral slip during gait is limited. Several laboratory-based studies have focused on slips induced during gait on a flat walkway [8, 9, 10]. Slips have been induced using a sliding platform [10], steel rollers [8, 9] or a slippery contaminant [11, 12, 13, 14]. When a slip is induced using a slippery contaminant, a medio-lateral component to the slip has been identified even on a flat surface. In particular, Troy et al. reported that lateral placement of the recovery foot was an important factor in avoiding a fall when stepping onto a flat slippery surface [11]. This supports the notion that maintaining lateral balance is an important contributor to avoiding a slip-induced fall. A slip induced on a cross-slope is likely to have an increased medio-lateral component, but little is known about the kinematics of walking on a potentially slippery cross-slope.

Humans alter their gait patterns when walking on a known slippery surface [15]. For example, when walking in simulated slippery conditions on a flat surface, humans often adopt a more “cautious” gait - characterized by a shorter step and a flatter foot upon foot strike [16]. Adaptations in gait occur when participants are made aware that the surface they are walking on may be slippery. Experience of a slip is not required for adaptations to occur, although prior experience of a slip does cause more pronounced changes in gait than awareness alone [17].

Several investigations of gait adaptations have been performed on a flat walking surface. To our knowledge, gait adaptations on a laterally sloping surface have not been studied. Therefore, the aim of this study was to assess the effect of awareness of potential slips and prior experience of a slip on cross slope walking. It was hypothesized that individuals would adapt their gait with both awareness and experience of a slip, and that adaptations would be more pronounced after experience of a slip.

2. Methods

2.1. Participants

Fifteen men volunteered to participate in the study (age 25.3 ± 2.9 years, height 1.79 ± 0.1 m, mass 72.5 ± 5.6 kg). Participants were healthy with no history of balance or musculoskeletal disorders. All participants read and signed an informed consent form, and all procedures were approved by the Sheffield Hallam University Ethics Committee.

2.2. Experimental setup

Participants wore non-obstructive clothing, and were asked to walk along a purpose built 4.8 m wooden walkway with a cross-slope, inclined by 7° to the horizontal. The incline sloped from the participants' left to right and was covered with a 2.3 m long section of non-slip rubber, followed by a 1.5 m section of vinyl (removable, fixed with Velcro) and, finally, 1 m of non-slip rubber. The full walkway contained both a sloped section and a flat section (Figure 1). This meant that a participant experiencing a large perturbation slipped onto the flat section, rather than off an edge of the walkway, minimizing the risk of injury. Before any walking trials, each participant was fitted into a full body harness, running on an overhead rail - fitted so that each participant had close to full mobility, whilst ensuring their legs would not make contact with the walkway if a fall occurred. Fourteen Polhemus Liberty sensors (Polhemus, Colchester, VT, USA) mounted on moulded thermoplastic bases, were then attached to body segments using a self-adhesive wrap (Figure 2). Sensors were attached at positions that minimized soft tissue artefact, whilst ensuring motion was not restricted by the sensor wires. The upper trunk sensor was placed on the chest to minimize magnetic interference caused by the metal attachment point on the harness. Subsequently, 35 anatomical landmarks were palpated and digitized using a stylus, with the participant standing in the anatomical position. These landmarks were used to define the proximal and distal end-points of each body segment, and to define segment anatomical coordinate systems.

2.3.Procedure

All participants completed walking trials, for three different conditions:

1) Normal walking (trials 1-5)
2) Awareness of a potential slip (trials 6-10)
3) Experience of a slip (trials 11-20)

The conditions were presented in the same order for all participants. In condition one, participants completed five walking trials, during which there was no risk of a slip. For conditions two and three, participants were told that there was a possibility of a soapy contaminant being placed on the vinyl section of the walkway. In condition two, no contaminant was actually placed on the walkway, and participants completed five walking trials. In condition three, participants completed 10 trials. During the first trial of condition three (trial 11), the dry vinyl section of the walkway was removed and replaced with an identical vinyl section that was covered with an odourless, transparent and colourless soapy solution (both the sloped and the flat parts of the vinyl section were covered). Following the initial slip trial for condition three, participants completed a further nine trials (trials 12-20) – four with a slippery, and five with a dry, vinyl section. In conditions two and three, participants were distracted between trials (they sat facing away from the walkway, listening to music via headphones), so that they were unaware of whether the walkway was contaminated. The time between each walking trial was kept as consistent as possible (approximately 2 minutes). During all trials, in all conditions, participants were asked to walk on the sloped part of the walkway as naturally as possible, and to look straight ahead while walking. Room lighting was arranged to ensure that the different reflectivity of the wet surface was not apparent to the participant.

2.4. Data Collection and Analysis

The data for some of the trials were affected by technical problems. However, at least three usable walking trials were available for all participants in each of the conditions. Where more than three usable trials were available, three were randomly selected for analysis. Full body kinematic data were collected using a Polhemus Liberty wired system, sampling data at 240Hz. The data were filtered using a low-pass Butterworth filter (6 Hz cutoff frequency) and further analyzed using Visual 3D (C-motion, Germantown, MD, USA). Foot strike (FS) and Toe Off (TO) events were identified using a kinematic method based on the anterior-posterior velocity of the foot segment relative to the pelvis [18]; FS was defined as the instant of relative positive-to-negative zero crossing of the foot segment velocity, and similarly TO was the negative-to-positive zero crossing. One full gait cycle was analyzed for each trial – foot strike to foot strike of the same foot. The following dependent variables were calculated: a) Stride Length (the anterior-posterior displacement between foot strike of one foot, to foot strike of the same foot; b) Stance Duration (time from foot strike to toe off of the same foot, represented as a percentage of the full gait cycle duration); c) Velocity (stride length * stride frequency); d) Ankle angle at foot strike; e) Step Width (medio-lateral displacement between contralateral footstrikes, along the frontal axis of the laboratory coordinate system). These variables were chosen to ascertain whether participants demonstrate more cautious gait in conditions two and three, as compared to normal walking. A more cautious gait is characterized by slower walking velocity, increased stance duration, and a flatter foot upon foot strike [17].

The stride length and stance duration variables were measured from the first foot strike that occurred on the vinyl section of the walkway. Therefore, the gait cycle that occurred as participants stepped onto the potentially slippery surface was analyzed. The foot that made intitial contact with the vinyl surface (i.e. Right or left) was not controlled as participants were asked to walk as naturally as possible. The foot that made initial contact with the vinyl section of the walkway was recorded.

A plantar-dorsiflexion, invesion-eversion, ab-adduction cardan sequence was used to calculate ankle angle. The plantar-dorsiflexion angle was used for analysis, which was normalised to the position of the foot and shank during the static trial (the ankle angle was zero when participants were in a neutral position).

In all the trials analyzed, there was no slippery contaminant on the surface of the walkway. No kinematic data was analyzed for the slips trials described in the previous section, but the frequency of falls were recorded to provide some context for the gait adaptations. A fall was defined as when both the participants' feet left the ground, and the body was fully suspended in the harness.

2.5. Statistics

Within-subjects repeated measures ANOVA was used to ascertain whether there was a statistical difference for all kinematic parameters across the three conditions. For the gait parameters that were significantly different across the three conditions, a two-tailed paired-samples *t*-test was performed to establish where the differences occurred (Condition 1 vs 2, 1 vs 3, and 2 vs 3). No corrections were made to the data to reduce the likelihood of Type II errors, and to ensure that potentially important differences were not masked [19].

To determine whether there were any differences in the foot which landed first on the vinyl section of the walkway between each condition, a two-tailed binomial test comparing the proportions was used. Statistical significance was set at 0.05 for all analyses.

3. Results

Five of the seven gait variables were significantly different across the three conditions ($P < 0.05$). Only the two step width variables (left FS to right FS and right FS to left FS) showed no significant difference ($P > 0.05$) (Table 1).

The paired-samples *t*-test identified that all pairwise comparisons were significantly different between conditions 1 and 2, and conditions 1 and 3 (Table 2). For condition 2 vs. 3, there were no significant differences for all dependent variables (Table 3).

Stride length decreased by 0.16m and 0.19m respectively in conditions 2 and 3, relative to condition 1. Walking velocity also decreased in conditions 2 and 3, relative to condition 1. The duration of stance phase increased by over 2% in both conditions 2 and 3, compared to condition 1. The ankle angle for both left and right feet was significantly more plantar flexed by 4 - 5° for conditions 2 and 3, relative to condition 1.

The frequency with which the right foot landed on the vinyl section of the walkway increased by 22.1% in both conditions 2 and 3, as compared to condition 1. The binomial test revealed that this increase was significant ($P = 0.034$).

During the slip trials, seven of the participants fell at least once. Of those seven participants, five of them fell more than once.

4. Discussion

The aim of this study was to assess whether young, healthy adults adapt their gait when made aware of a slip, or having experienced a slip when walking on a cross-slope. The analysis revealed that participants adopt a 'cautious' gait, similar to that described by Heiden et al. [17]. When made aware of the risk of a slip, participants adopted a significantly shorter stride, and flatter foot upon foot contact. The same adaptations were observed when participants had experienced a slip, and there were no differences between awareness and experience of a slip. This might suggest that, when given the additional task of negotiating a cross-slope, participants do not need to experience a slip to recognise the threat to their balance.

The stride length results could have been influenced by participants taking a short step immediately before stepping onto the vinyl section. More specifically, several participants lowered their left foot to the ground just before stepping onto the potentially slippery section of the walkway. Therefore, the right foot, which was closest to the flat section of the walkway, would be the first foot to strike the potentially slippery section of the walkway. This strategy would explain the changes observed in the contact foot for the 'awareness' and 'experience' conditions. This behaviour might be explained by balance recovery strategies observed in postural control studies during stance. Research based on lateral perturbations during stance suggest it is more difficult to recover balance, and there is an increased chance of the limbs colliding, when cross-over of the legs is required [20]. In the present study, stepping onto the slippery surface with the right foot may have minimized the possibility of the left foot sliding down the slope, and contacting the right foot when the slip occurred.

The duration of the stance phase (%) increased significantly, and the walking velocity decreased significantly for both the awareness condition and experience condition, compared to normal walking.

This again suggests that the perceived risk of falling is high when walking on a potentially slippery cross-slope, regardless of whether or not a slip has been experienced.

There was no significant effect of walking condition on step width, but for step width from left FS to right FS, the difference was close to significant (P = 0.053) - it is possible that a statistical difference may have been identified with a larger sample size.

The notion that the perceived risk of falling is high when walking on a potentially slippery cross-slope is further supported by the frequency of falls observed. The number of participants that experienced a fall (46.7%) is greater than reported in other studies of slips in young adults [11, 21]. Of the seven participants that fell, five of them experienced more than one fall across the five slip trials. This might be because a slip on cross-slope is less predictable than slips induced using steel rollers or a sliding platform, on a flat surface. The high frequency of falls observed in this in this study is likely explained by the magnitude of the normal force acting on the foot, which is reduced on a slope compared to a flat surface. The reduced normal force requires a higher coefficient of friction to avoid a slip, which makes a slip on a cross-slope more likely than on a flat surface.

The slips that occur on a contaminant (such as oil or soap) produce a more unpredictable slip compared with those induced using a sliding platform [11, 12, 13, 14, 21]. This type of slip produces some medio-lateral motion of the foot even on a flat surface. This medio-lateral motion is almost completely absent in studies using steel rollers or sliding platforms. Some of these studies using sliding platforms or steel rollers have reported no falls occurring in young adults [9]. It is postulated that the adaptive responses observed in these studies, where there is minimal loss of balance by the fifth slip trial [1], may be because the slips are more predictable, and do not contain a medio-lateral aspect. However, this type of induced balance loss has the advantage of being easier to control.

There were several limitations of the present study that are worth noting. Firstly, a longer walkway may have resulted in a more steady-state walking speed, although work conducted by Muir et al. suggests that gait is effectively stable within three steps in young adults [22]. Secondly, the use of a harness could influence the way that participants walked, in that they knew that the harness would arrest their fall. Additionally, one participant grasped the harness during one of the slip trials, which is clearly a reaction that cannot be applied to a loss of balance that occurs in the community. Finally, the highly variable nature of the slip could be considered a limitation. This could have been somewhat reduced by asking participants to contact the potentially slippery section of the walkway with the left or right foot, but this 'targeting' method could have implications. Studies that have asked participants to contact a force platform suggest that, although 'targeting' had no effect on ground reaction forces, temperospatial alterations were evident in the steps leading up to the target [23]. Therefore, it was decided to avoid asking participants to target the vinyl section of the walkway with either the left or right foot.

In summary, participants altered their gait both when aware of a potential slip and having experienced a slip, when walking on a cross-slope. A shorter stride length, flatter foot at foot strike, and a slower walking velocity are all characteristics of a more cautious gait. There were no significant differences between the slip awareness and slip experience conditions. This suggests that, unlike on a flat surface [14], there may be an increased perceived risk of falling when walking along a potentially slippery cross-slope. This encourages participants to adopt a more cautious gait even without having experienced a slip. The higher incidence of falls reported in this study, as compared to previous slips studies, supports the notion that perceived risk of falling may explain the more cautious gait patterns observed before a slip has occurred. In addition, the high incidence of falls suggests that slips on a cross-slope can be particularly hazardous, and potentially present a high risk of injury. Future analysis should focus on how young adults recover balance when a slip is induced on a cross-slope, and what differences exist between 'fallers' and 'non-fallers'.

Acknowledgements

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6. Table(s)

Table 1 – Summary of results from the Repeated Measures ANOVA analysis. Results are presented as

Dependent Variables	Normal Walking	Slip Awareness	Slip Experience	P Value
Stride length (m)	1.42 ± 0.11	1.26 ± 0.16	1.23 ± 0.16	0.000*
Stance duration (%)	61.2 ± 1.4	63.9 ± 2.9	63.9 ± 2.3	0.000*
Velocity (m/s)	1.25 ± 0.13	1.07 ± 0.25	1.05 ± 0.18	0.006*
Left ankle angle (°)	1.1 ± 6.2	5.3 ± 5.2	6.1 ± 6.9	0.004*
Right ankle angle (°)	-1.7 ± 4.3	2.8 ± 6.6	3.2 ± 10.8	0.031*
Step width - right FS to left FS (m)	0.15 ± 0.5	0.16 ± 0.5	0.16 ± 0.5	0.162
Step width - left FS to right FS (m)	0.8 ± 0.4	0.10 ± 0.3	0.10 ± 0.3	0.053

mean ± standard deviation

* Indicates a Significant difference at P ≤ 0.05 level

Table 2. Paired Sample T-test comparisons of gait parameters for normal walking vs awareness and experience of a slip

Variable	**Condition**	**Mean Difference**	**Sig (vs. Normal)**
Stride Length (m)	Normal Walking		
	Awareness	-0.16	0.001*
	Experience	-0.19	0.001*
Duration of Stance (%)	Normal Walking		
	Awareness	2.7	0.003*
	Experience	2.7	0.000*
Velocity (m/s)	Normal Walking		
	Awareness	-0.18	0.023*
	Experience	-0.20	0.002*
Right ankle angle at foot strike (°)	Normal Walking		
	Awareness	4.5	0.002*
	Experience	4.9	0.047*
Left ankle angle at foot strike (°)	Normal Walking		
	Awareness	4.2	0.001*
	Experience	5.0	0.010*

*Indicates a Significant difference at $P \leq 0.05$ level

Table 3. Paired Sample t-test comparisons of gait parameters for awareness vs experience of a slip

Variable	Condition	Mean Difference	Sig.
Stride Length (m)	Awareness		
	Experience	0.03	0.194
Duration of Stance (%)	Awareness		
	Experience	0.0	0.919
Velocity (m/s)	Awareness		
	Experience	0.02	0.561
Right ankle angle at foot strike (°)	Awareness		
	Experience	-0.4	0.779
Left ankle angle at foot strike (°)	Awareness		
	Experience	-0.8	0.592

*Indicates a Significant difference at $P \leq 0.05$ level

7.Figure 2
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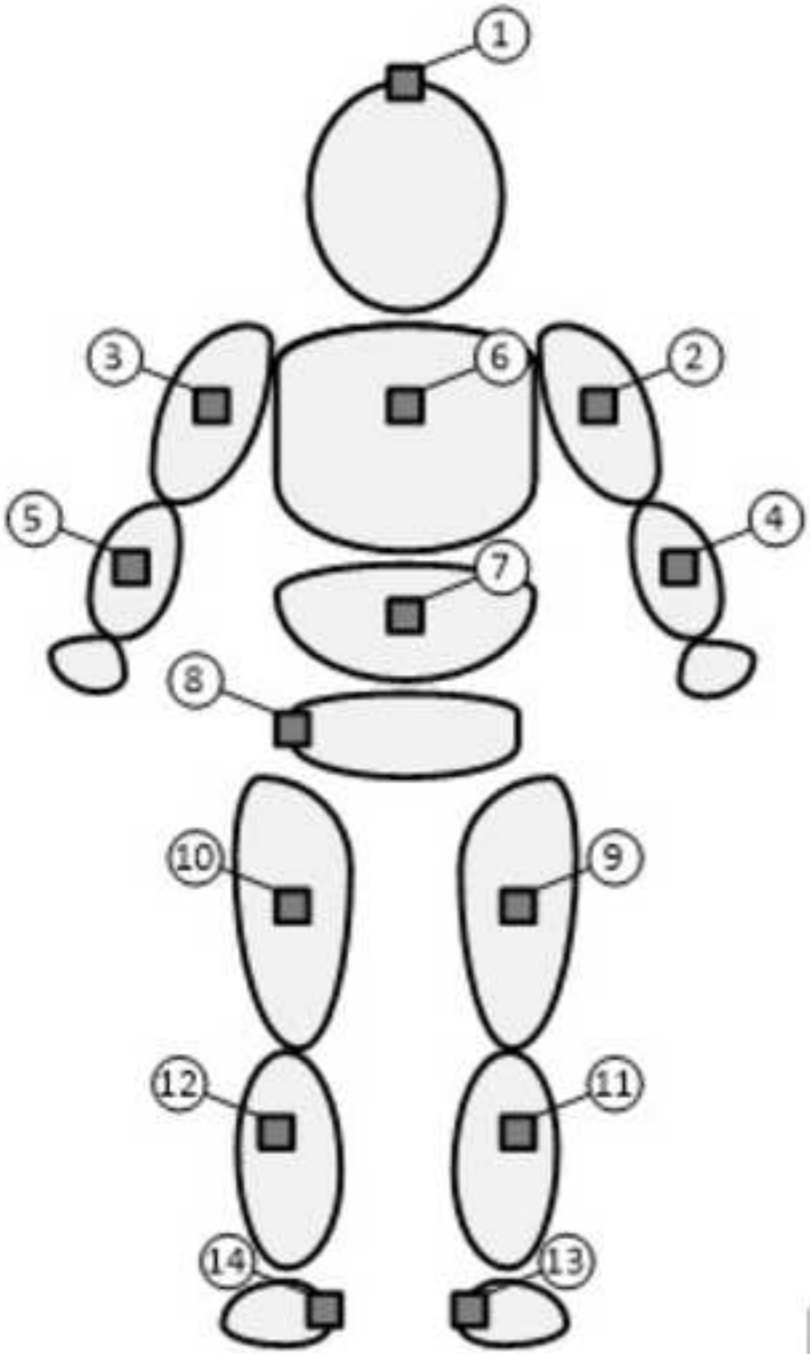

Sensor No.	Segment
1	Head
2	Left upper arm
3	Right upper arm
4	Left forearm
5	Right forearm
6	Upper trunk
7	Lower trunk
8	Pelvis
9	Left thigh
10	Right thigh
11	Left shank
12	Right shank
13	Left foot
14	Right foot

7. Figure 1 and 2 captions

Figure 1 - Cross slope set up, a) wooden frame of the cross slope illustrating flat section and angled section, b) walkway covered in non-slip rubber and a 1.5m section of vinyl

Figure 2 - Schematic of position of Polhemus sensors on individual body segments

7. Figure 1

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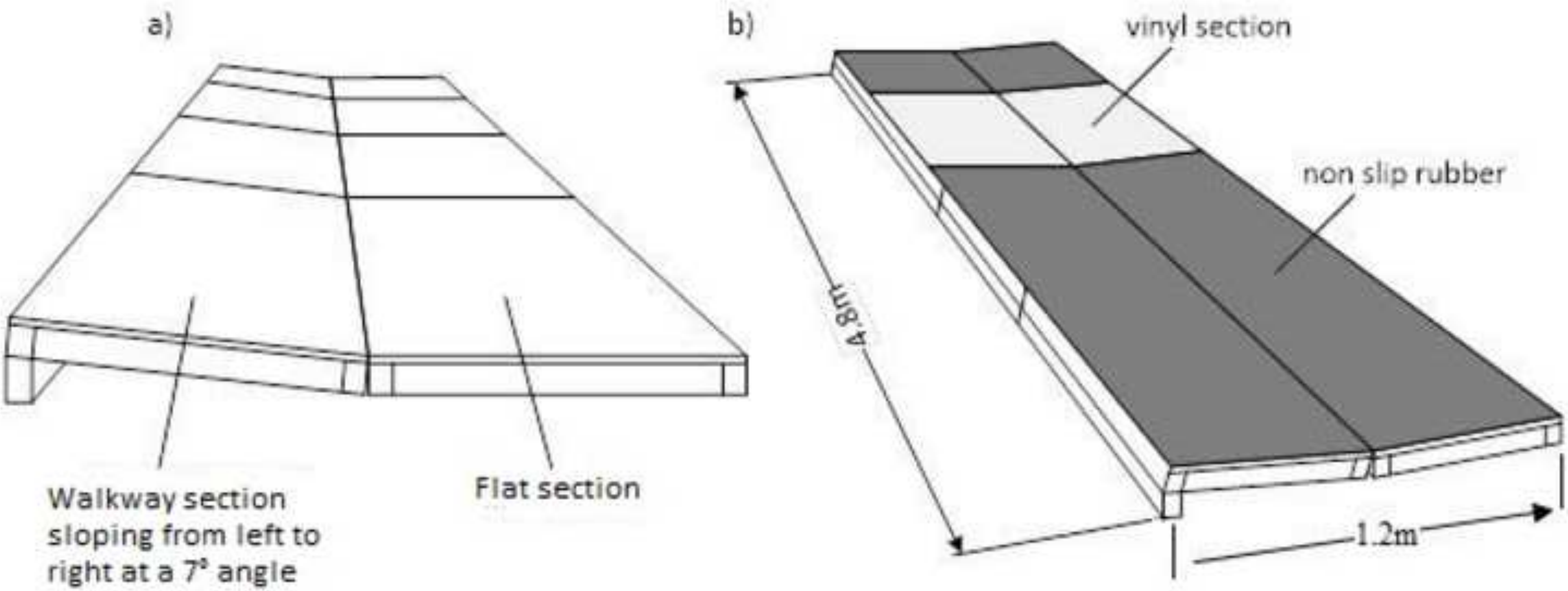

*Research Highlights

Research Highlights

- First slips study to conduct analysis on a cross-slope
- Cautious gait patterns observed when aware that a slip might occur on a cross-slope
- Cautious gait patterns also observed after experiencing a slip on a cross-slope
- No differences between potential awareness and experience of a slip
- High incidence of falls when participants slip on a cross-slope