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http://dx.doi.org/10.1016/j.jbiomech.2010.12.016

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Publication title	Journal of Biomechanics
Publisher	Elsevier
Type	Article
USIR URL	This version is available at: http://usir.salford.ac.uk/id/eprint/12651/
Published Date	2011

Biomechanics for inclusive urban design: effects of tactile paving on older adults' gait when crossing the street.

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Type of manuscript: original article
4042 words, 2 tables, 5 figures

Keywords: urban design, inclusive design, biomechanics, gait, falls

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Abstract

In light of our ageing population it is important that the urban environment is easily accessible and hence supports older adults’ independence. Tactile ‘blister’ paving was originally designed to provide guidance for visually impaired people at pedestrian crossings. However, as research links irregular surfaces to falls in older adults, such paving may have an adverse effect on older people. We investigated the effects of tactile paving on older adults’ gait in a scenario closely resembling “crossing the street”. Gait analysis of 32 healthy older adults showed that tactile, as compared to smooth, paving increases the variability in timing of foot placement by 20%, thereby indicating a disturbance of the rhythmic gait pattern. Moreover, toe-clearance during the swing phase increased by 7% on tactile paving, and the ability to stop upon cue from the traffic light was compromised. These results need to be viewed under consideration of the limitations associated with laboratory studies and real world analysis is needed to fully understand their implications for urban design.

1. Introduction

In light of our ageing population and rapid expansion of the oldest-old group (age >85) (Christensen et al., 2009), it is important that the urban environment is easily accessible. As part of ‘inclusive design’ policies, tactile ‘blister’ paving was designed to provide guidance for visually impaired and blind people at sites such as pedestrian crossings. However, a report by the UK Health & Safety Laboratory (HSL2005/07) questioned whether tactile blister paving may lead to trips in older adults due to the height of the blisters. Tactile paving may be considered manmade uneven ground and we know that walking on uneven ground is associated with falls (Berg et al., 1997). Only one study has investigated gait on tactile paving (Kobayashi et al., 2005): increased toe height during swing and increased hip flexion moment were the major gait changes attributed to tactile paving. While useful, the conclusions were limited by the healthy young test population.

To date, no study has investigated the gait of older adults on tactile paving nor the effect of tactile paving on measures of gait that are associated with stability and falls-risk in older adults. Our objective was to develop a laboratory platform closely resembling a pedestrian crossing, and to investigate suitable gait parameters in older adults on smooth and tactile paving.

A number of studies have identified relationships between biomechanical variables, measured during walking on smooth or irregular surfaces, and fear of falling, gait stability, and falls risk. For example, reduced gait speed has been associated with fear of falling in older adults, while walking with a wider stride appeared to be linked to falling and fear of falling (Maki, 1997). Similarly, investigations of surface effects in healthy young and older adults showed that for walking on uneven, as compared to even, ground, step width and toe-clearance increased and speed decreased (Menant et al., 2008; Menant et al., 2009). These gait adaptations in response to uneven ground were interpreted as a more cautious gait allowing for stabilization of the torso and visual field and avoidance of tripping hazards. Hence we tested the primary hypothesis that older adults exhibit a more conservative gait on tactile blister paving compared to smooth paving, i.e. when negotiating the 5mm-high protruding blister domes they would decrease their speed, increase their step width, and increase their toe-clearance in mid-swing.

Walking stability requires continuous control of the whole-body centre of mass in response to the changing boundaries of the base of support. This can be achieved via adjustments of foot placement and also via changes in timing of foot placement. With regard to the former, a study of young adults found that step width became more variable when walking with eyes closed, suggesting that variations in step width are indicative of control of frontal plane balance (Bauby and Kuo, 2000).

With regard to the latter, increased variability of step/stride time has been associated with increased falls-risk (Hausdorff et al., 2001) and is elevated in balance impaired adults, in particular on uneven ground (Richardson et al., 2004; DeMott et al., 2007). These studies highlight that subjects respond with increased temporal and spatial adjustments in foot placement when balance is challenged. Tactile blister paving with its protruding blister domes may similarly pose a challenge to balance control, hence we tested the secondary hypothesis that tactile pavement, compared to smooth pavement, would increase spatial (step width) and temporal (step time) gait variability.

Finally, we investigated step length, step length variability, and the timing of minimum toe clearance during the swing phase, and we explored whether tactile paving would decrease an older person's ability to successfully stop within the boundary of the curb.

2. Methods

2.1. Test platform

The platform was built according to the UK's Department for Transport (DoT) guidelines for an in-line controlled crossing (Figure 1). This allowed for an investigation of the effects of tactile paving on gait when the paving is sited and laid as prescribed in the guidelines. Consequently, the platform consisted of two flat sections, followed by a ramp and dropped curb that leads onto a simulated street. Sections of the platform could be moved to enable either a smooth or tactile paving scenario. Each section had a stiff underlying plywood skeleton that supported the weight of the paving slabs. In further correspondence with the UK DoT guidelines, the blisters on the tactile paving slabs were 25mm in diameter and 0.5mm in height, and were distributed uniformly with a distance of 66.8mm from one blister's midpoint to the next. A pedestrian traffic light was controlled by two pairs of infrared light beams that, if inadvertently broken by the feet of the walking participant, switched the light to red. The first infrared beam was at the start of the ramp section and the other 40cm down the ramp. The two different positions allowed for an ‘early’ or ‘late’ instruction for the participant to stop before stepping onto the ‘street’ (i.e. with a remaining distance to the curb of 1.2m and 0.8m, for early and late trigger, respectively). A safety harness system was installed over the length of the test platform.

2.2. Experiment

2.2.1. Participants

The study was approved by the institutional ethics committee. Thirty-two healthy, independently-living older adults (Table 1) gave informed consent and participated. Inclusion criteria were 1) age>60 years; 2) able to walk household distances without an assistive device; 3) walking in the community at least once per week; 4) no history of head injury, concussion, stroke, or diabetes; 5) no visual disorders not correctable by glasses; 6) no history of central or peripheral nerve dysfunction.

2.2.2. Clinical assessment

Participants were screened for peripheral nerve dysfunction using the Michigan Diabetes Neuropathy Score (Feldman et al., 1994) and for central nerve dysfunction using tests of rapid alternating movements such as finger and toe tapping and heel-to-shin and finger-to-nose manoeuvres. Participants were also asked to perform the alternate step test, sit-to-stand test, and 6m-walk and their self-reported fall history was recorded (Tiedemann et al., 2008).

2.2.3. Protocol

Participants were randomly allocated into group A or B and provided with standard shoes representative of older adult’s footwear (Hotter Comfort Concept shoes). Group A began with 15 walking trials on tactile paving, followed by 15 on smooth paving; group B proceeded in the reverse order. Prior to data collection participants received two practice trials (one continuous walking trial and one stop trial). They were then instructed to walk at their comfortable speed and observe the light, and to stop without stepping onto the "street" if the light turned red. Three different scenarios were each presented five times in a random order, for each paving condition (smooth and tactile):

i) continuous walking: the participant proceeds along the walkway uninterrupted;
ii) walking & stopping with an "early" trigger of the light (at the start of the ramp, 1.2 m before the curb);
iii) walking & stopping with a "late" trigger of the light (40cm into the ramp, 0.8 m before the curb).

2.3. Data collection & processing

Kinematic data were collected at 100 Hz with a 3D motion analysis system (Qualisys, Gothenburg, Sweden) and state changes of the green/red light recorded via the same system. Marker data were passed forward and backward through a fourth-order Butterworth filter (MATLAB®) with a 7 Hz cutoff frequency. During dynamic motion capture (recording of walking trials) one reflective marker was placed on the waist (over the L3 vertebra), one on each heel at the most posterior point of each shoe approximately 2cm below the level of the maleoli, and a cluster of 3 markers was located on the rigid toecap of each shoe, distal to the shoe crease line. To allow reconstruction of the shoes' underside in these walking trials, a 'static' recording of the shoes alone provided data to locate additional markers placed on the sole of each shoe in relation to the toecap markers; the former were removed for the walking trials. A further 'static' recording captured the geometry of the test platform to allow for identification of foot positioning relative to the flat, ramp, curb and street areas.

2.4. Gait parameter analysis – continuous walking trials

During continuous walking trials data were collected over the paving area only (flat and ramp section). Data were therefore analysed at comfortable walking speed, excluding periods of acceleration and deceleration over the 2m approach and 4m street section.

2.4.1. Comfortable speed

The first derivative of the waist marker's position data, recorded along the direction of forward progression, was used to obtain gait speed, defined as the average walking velocity while the participant had both feet fully on the pavement area of the platform.

2.4.2. Step time, width and length

Heel and toe markers were used to identify heel strike and toe-off (O'Connor et al., 2007) and subsequently to obtain step time ('ST'). Step width ('SW') and length ('SL') during dual support were calculated from the position data of the heel markers. Parameter variability ('STVar', 'SWVar', 'SLVar') was characterized by the coefficient of variation. There are 11 possibilities of foot positioning with at least one foot on the paving area for which ST, SW and SL can be calculated (Figure 2). To investigate the effects of tactile paving on step parameters the following approach was taken:

Analysis 1: According to the UK DoT guidelines, tactile paving at controlled crossing points should be laid over a 1.2m x 1.2m long flat section followed by a 1.2m x 1.2m long ramp section that leads down to the curb. Therefore, to assess the gross effect of tactile paving on gait when laid according to guidelines, parameters were calculated, for both tactile and smooth paving conditions, for steps where both feet were at least partially on this area as defined by heel and/or toe-markers being on sections 2 and/or 3 (steps of type C, D, E, F, G, H, I – see Figure 2).

Analysis 2: To assess whether the effects of tactile paving on gait parameters are more apparent on the flat or the ramp section, a second analysis was undertaken: parameters were calculated separately for steps with both feet entirely on the flat paving area (D), for steps cleanly transitioning from the flat to the ramp (F) and for steps with both feet entirely on the ramp (H). Participants had to provide a minimum of 4 steps (i.e. exhibit a step of a given type in at least 4 out of 5 trials) to be included in any step type's assessment. Hence only a subset of participants contributed to each part of 'Analysis 2'.

2.4.3. Toe-clearance

Minimum-toe-clearance distributions are typically skewed (Begg et al., 2007), hence the median and inter-quartile-range (IQR) for each participant served as measures of toe-clearance ('TC') and toe-clearance variability ('TCVar'). Using the static data locating the sole markers with respect to the toe-marker-clusters (Best and Begg, 2008), the positions of the sole markers were reconstructed for the dynamic walking trials (Cappozzo et al., 1995). Minimum-toe-clearance during swing (see Figures 3 & 4) was defined as the minimum distance between the reconstructed sole marker position, plus the marker's radius, and the top of the test platform (for blister paving: the top of the 5mm-high protruding blisters). The timing of minimum-toe-clearance (TCT) was determined as % swing phase. Two different analyses were performed:

Analysis 1: toe-clearance values obtained within the boundaries of the entire pavement area.

Analysis 2: toe-clearance values obtained within the boundaries of the flat pavement area and, separately, for values obtained within the boundaries of the ramp pavement area.

2.5. Gait parameter analysis – stop trials

Since it was possible that triggering of a red light ('stop') occurred at a different time in the gait cycle for one paving condition versus the other, the time elapsed between the light turning red and the preceding heel strike was obtained as a covariate. Similarly, participants' gait speed was monitored before the light was triggered. Hence, the ability to stop successfully within the curb boundary could be interpreted in conjunction with initial gait speed and timing of the light-trigger with respect to the gait cycle. The final foot positioning was investigated once the waist marker velocity was<0.05m/s (Cao et al., 1997) and a successful stop was defined by all toe marker x-positions lying within the curb boundary.

2.6. Statistical analyses

2.6.1. Continuous walking

Each participant walked on smooth and tactile paving and did so for 5 trials, resulting in multiple data points being obtained for each of the variables "V". To characterize the average performance of each participant, the median (toe-clearance; Begg at al., 2007) OR the mean (all other variables) were obtained for each participant. Similarly, to characterize the variability in performance of each participant, the inter-quartile-range (toe-clearance; Begg at al., 2007) OR the coefficient of variation (all other variables) were obtained. All values were checked for normality and where the normality condition was not met, the variable was transformed using the natural log and normality of the data was established. Any difference between the smooth and tactile paving conditions was defined as:

$$\Delta V = V_{Tactile} - V_{Smooth}$$

Using Δ variables for statistical analysis of all gait parameters allowed for each participant serving as their own control and retained the advantage of a paired sample. A univariate general linear model (GLM) was chosen to analyse each Δ variable as the dependent variable.

Walking speed was considered to have a potential interaction effect on the influence of paving type. To investigate this, all other gait parameters were assessed a second time with the GLM, this time in conjunction with two speed covariates: 1) a measure of each subject's "baseline speed", and 2) a measure of their "speed adaptation" from smooth to tactile paving. With regard to the former covariate, their self-selected walking speed on smooth paving was adjusted by subtracting the groups' mean speed on smooth paving from each individual's speed. With regard to the latter covariate, the ratio of the speed obtained on tactile to the speed obtained on smooth paving was calculated for each individual. Again, the groups' mean ratio was subtracted from each individual's ratio. With this centring, when the covariates take their average values, the intercept becomes the estimate of the Δ dependent variable. The effect of "centring" the covariates in this way is thus to give the regression intercept (constant term) a physical meaning.

2.6.2. Stop trials

If the participants executed the stop successfully a value of 1 was scored (0 if unsuccessful). For the 32 participants a total of 320 observations were made (32 participants x 5 trials x 2 paving types). These data were analysed with a mixed-effects logistic regression to model the probability of a successful stop as a function of paving type. Each person provided 5 observations for each paving type. However, because each individual has an 'intrinsic frailty', causing them to fail to stop more or less often than others, these repeated observations must not be considered independent measurements. Hence the individual person was modelled as a random effect in the mixed-effects logistic regression.

Moreover, walking speed prior to the light trigger and the time elapsed since the last heel strike up to the moment the light turned red can be considered initial conditions in this part of the experiment. Hence, each individual's mean prior walking speed and mean time elapsed were obtained, for each type of paving; and for both variables the ratio of tactile paving to smooth paving was derived, reflecting the change from smooth to tactile paving for each individual. As described before, the data were "centred" and the effect of paving type on successful stopping was determined once more, this time with the adjusted ratios serving as covariates in the mixed-effects logistic regression.

3. Results

3.1. Continuous walking

In 'Analysis 1' (flat & ramp data combined) an average of 14 steps on each type of paving were obtained for every participant. STVar, SWVar and SLVar as well as TCT during the swing phase did not pass checks for normality and were hence transformed using the natural log scale prior to statistical analyses. On both paving types the group walked at a similar speed (Δspeed = -0.02m/s, p=0.20, Table 2) The TCT during the swing phase remained also comparable on smooth and tactile paving as did ST, SW, SWVar, SLVar, and TCVar (p>0.1, Table 2). In contrast, STVar and TC were increased on tactile as compared to smooth paving (by 20% and 7%, respectively, Table 2) while SL was decreased by 1.2% (Table 2). Whilst speed was similar on both paving types, the two speed-based covariates affected the statistical analyses as can be seen in the changes in p-values in Table 2. More specifically, a faster baseline speed was associated with reduced STVar (p=0.01) and higher TC (p=0.03). Similarly, adapting a faster speed on tactile as compared to smooth paving (as defined by the speed ratio) was likewise associated with reduced STVar (p=0.04) and also with longer steps (p<0.001).

Between 11 and 32 participants provided the required minimum of 4 steps to be included in 'Analysis 2', and the exact number varied for assessment of different platform sections and for different gait parameters. Analysis 2 showed that paving type had a significant effect on STVar on the ramp (p=0.034, 12 participants), and on TC height on the flat section (p=0.006, 32 participants). Participants were more variable in the timing of foot placement on the ramp section before reaching the curb, and they lifted their feet higher on the flat section, i.e. when beginning to walk on tactile paving. Moreover, in response to tactile paving, SL was found to be increased for steps taken entirely on the flat (p=0.007, 19 participants) or ramp (p=0.026, 13 participants) section, but not for steps transitioning from the flat paving onto the ramp (p=0.186, 12 participants). Interestingly, when analysing data obtained on the flat and ramp section separately, we found that the TCT was after all affected by paving type: on tactile as compared to smooth paving TCT occurred earlier in the swing phase on the flat platform section (p=0.032, 32 participants) but later in the swing phase on the ramp section (p=0.003, 32 participants).

3.2. Stop trials

For the “early” light trigger, only two unsuccessful stops (of 320 observed) were recorded, one on each type of paving. Hence the data were not processed further. For the “late” light trigger the mixed-effect logistic regression showed that paving type had a significant effect on successful stopping (p=0.003): participants stopped less successfully on tactile paving with the number of unsuccessful stops increasing from 7% on smooth paving to 15% on tactile paving. The p-value did not change when entering the two covariates “speed ratio” and “trigger timing ratio” into the mixed-effects logistic regression as neither showed an effect on successful stopping (p=0.87 and p=0.59, respectively). However, it needs to be noted that the standard deviation of the regression constant term was large (Estimate = 3.59, p=0.002), indicating that some participants contributed more to this outcome than others due to differences in their ‘intrinsic frailty’ (Figure 5).

4. Discussion

This is the first study to report on gait during a scenario that closely resembles street-crossing in the presence of tactile paving. Low variability in timing of foot placement is characteristic of automated, rhythmic walking and considered an indicator of safe gait in absence of perturbations.

One of the key outcomes of this study is that on tactile paving rhythmic gait becomes more variable, indicating that balance is challenged (Hausdorff et al., 2001; Richardson et al., 2004; DeMott et al., 2007). Moreover, a subset of 12 subjects that provided steps of type D, F and H demonstrated that the increased variability in timing of foot placement on tactile paving is most evident on the ramp section right before the curb, i.e. at a point where movement control is most crucial. Simultaneously, we found that for the late trigger of the traffic light the ability to stop without stepping onto the "street" was reduced on tactile paving. Furthermore, in accordance with previous work (Kobayashi et al., 2005), we found that participants lifted their feet higher on tactile as compared to smooth paving when walking on the flat platform section. Such strategy can be viewed a successful functional adaption that reduces the risk of tripping. It is noteworthy that the participants in this study indeed overcompensated as they increased their TC approximately 2mm beyond the 2.5mm blister height, which may indicate that tactile paving is perceived to increase risk of tripping. Finally, an interesting effect of tactile paving on gait was that minimum toe-clearance occurred earlier in the swing phase for steps taken on the flat platform section but later in the swing phase for steps taken on the ramp. This implies that mechanisms for increasing TC on tactile paving are different for level and ramp walking, and this merits further study.

SW and SWVar were not affected by paving type, suggesting that participants remained stable in the frontal plane and did not have to increase their base of support. Furthermore, participants did not adopt a slower gait speed on tactile paving, an outcome that would have indicated fear of falling (Maki, 1997). However, this finding may be compromised by our use of a harness: participants were aware they had protection in the event of a fall. Interestingly, a post-hoc analysis revealed that SW adaptation differed between fallers and non-fallers: fallers decreased their SW on tactile paving (p=0.014; CI: -1.6 to -0.2) while non-fallers did not show significant SW adaptation (p=0.177; CI: -0.3 to 1.3) and this group difference was associated with a p-value of 0.015. No other group differences were found.

As others report (Beauchet et al., 2009), a faster walking speed was associated with reduced STVar. Moreover, a faster speed was associated with higher TC. It is noteworthy that the decrease in SL on tactile paving was associated with a p-value of 0.005, ST and comfortable gait speed, however, had p-values greater than 0.1 (though as expected step time showed a corresponding increase and speed a decrease). These larger p-values can be explained by greater variability (i.e. standard errors) for ST and speed.

It is important to note that we did not see a gross effect of tactile paving across all parameters investigated, and none of our participants fell. However, this study represents the ideal world: the paving was in perfect condition, laid according to the Department for Transport guidelines, was dry and well lit. Our participants were healthy older adults without impairments that may have compromised their mobility. The conservative nature of this experimental design allowed us to establish a baseline with regard to the Department for Transport guidelines on tactile paving and its effect on healthy older adult gait. That we found some effects of tactile paving on gait parameters in this perfect scenario leads us to speculate that larger effects may be observed in the real world where paving is often laid contrary to guidelines, is subject to wear and tear, and may be wet or icy. Additional work in the real world is hence required and an observational study on how tactile paving is actually sited is underway. Moreover, future work needs to investigate the effects of tactile paving on more vulnerable parts of the population that have balance impairments, for example, due to stroke, diabetes and/or neuropathy. Finally, the underlying mechanisms (Thies et al. 2006) by which tactile paving affects gait during the stance phase merit further investigation.

Safe ambulation in the community is crucial to older adults’ independence & quality of life, and gait analysis can support good urban design. The research team is part of a larger consortium that aims to identify aspects of design that may help or hinder older people in using the outdoors. Hence only older adults were tested and conclusions are consequently limited to this population. The results of our analysis provide insights into the effects of tactile paving on gait in older people crossing the street and the experimental setup developed for this baseline study could be further utilized to assess alternative paving slab designs. Moreover, we believe that a similar approach could also be applied to other urban design problems. Further analysis in the real world (with inertial sensors) is pending to substantiate these findings.

5. Acknowledgements

We thank the UK Engineering & Physical Science Research Council for funding this study.

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7. Conflict of interest statement

The authors declare no financial or personal relationship with any organization or people that would influence the outcomes of this study.

8. Tables

Table 1. Subjects - descriptive data. SD: standard deviation.

Gender	
Male	11 participants
Female	21 participants
Age	
Mean	72 years
SD	6 years
Range	63:85 years
Walking Outdoors	
Every day	20 participants
Several days per week	12 participants
Falls in last 12 months	
None	21 participants
One	9 participants
Two	2 participants
Sit-to-Stand*	
≤ 12 sec	19 participants
≥ 12 sec	13 participants
Alternate-step-test*	
≤ 10 sec	21 participants
≥ 10 sec	11 participants
Six-metre-walk*	
≤ 6 sec	31 participants
≥ 6sec	1 participant

* Tiedemann A et al. 2008

Table 2. Parameters (group mean ± group std) and p-values for Analysis 1 (data for flat and ramp section combined). A univariate general linear model was used for analysis of the dependent Δ variables. Note: p-values remain unchanged for use of standard deviation as the variability measure.

	Smooth Paving	Tactile Paving	P	P (with speed covariates)
Speed (m/s)	1.13 ± 0.17	1.11 ± 0.19	0.204	---
ST (sec)	0.55 ± 0.05	0.56 ± 0.06	0.275	0.272
STVar†	0.035 ± 0.010	0.042 ± 0.015	0.005*	0.002*
SW (cm)	16.86 ± 2.65	16.95 ± 2.73	0.763	0.766
SWVar†	0.17 ± 0.06	0.17 ± 0.07	0.825	0.818
SL (cm)	55.47±5.32	54.82±5.41	0.025*	0.005*
SLVar (cm)	0.063±0.02	0.068±0.04	0.741	0.697
TC (cm)	2.34 ± 1.22	2.50 ± 0.97	0.053	0.042*
TCVar$^{\gamma}$ (cm)	1.27 ± 0.81	1.20 ± 0.96	0.313	0.306
TCT (% swing)	49.56±3.04	50.20±3.94	0.249	0.264

† Coefficient of variation; $^{\gamma}$ Inter-quartile-range; * $P < 0.05$ considered significant for Δ variable.

9. Figure captions

Figure 1. In-line controlled crossing as set up in the Human Performance Laboratory. Dimensions are in units of metres. Notice the cut-outs on each platform section designed for manoeuvring with a pallet truck. Locations of two sets of infrared light beams, used for changing the light from green to red, are also shown.

Figure 2. Illustration of the different platform sections (1: flat even approach; 2: flat paving; 3: ramp; 4: street) and possible foot positioning during dual support (A to K). Participants may exhibit different combinations of foot positions, i.e. combinations where one foot is on the border of two platform sections (top) and combinations where each foot is fully on one section (bottom).

Figure 3. Side view: minimum-toe-clearance (“TC”) shown for both the flat and ramp sections of the test platform. TC is defined as the perpendicular distance between the platform surface and a reconstructed “virtual” sole marker plus the sole marker’s radius ‘r’. Note: d is the distance between the camera system’s origin and the start of the ramp, known from the static trial that defines the platform geometry; α is determined by the slope 1:12; and X_{TCM} and Z_{TCM} are coordinates of the reconstructed sole marker at any given frame of a walking trial, derived via the CAST technique that utilizes a static calibration trial of that marker’s position with respect to three markers on the toe cap.

Figure 4. Illustration of the reconstructed sole marker trajectory and values of minimum-toe-clearance (o).

Figure 5. Illustration of the effect of ‘intrinsic frailty’ on number of successful stops performed on smooth and tactile paving for the late light trigger. Given that subject performed five stop trials on each paving type a perfect score (no failed stops on either paving) is reflected by data points on the 45° line at the coordinate [5, 5]. Data points above the 45° line reflect a greater number of failed stops on tactile paving while data points below the 45° line reflect a greater number of failed stops on smooth paving.

10. Figures

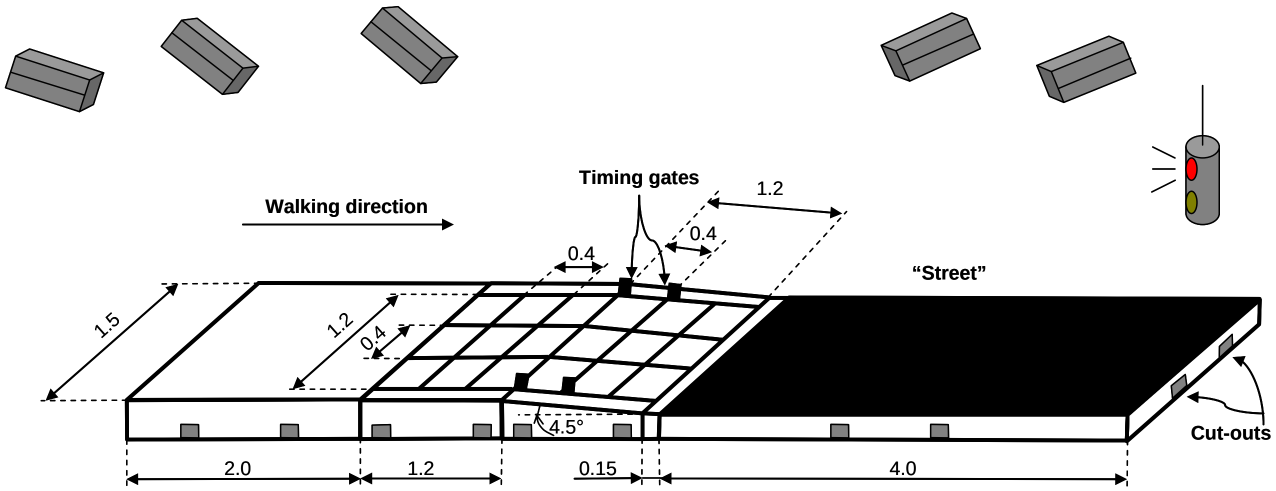


Figure 1.

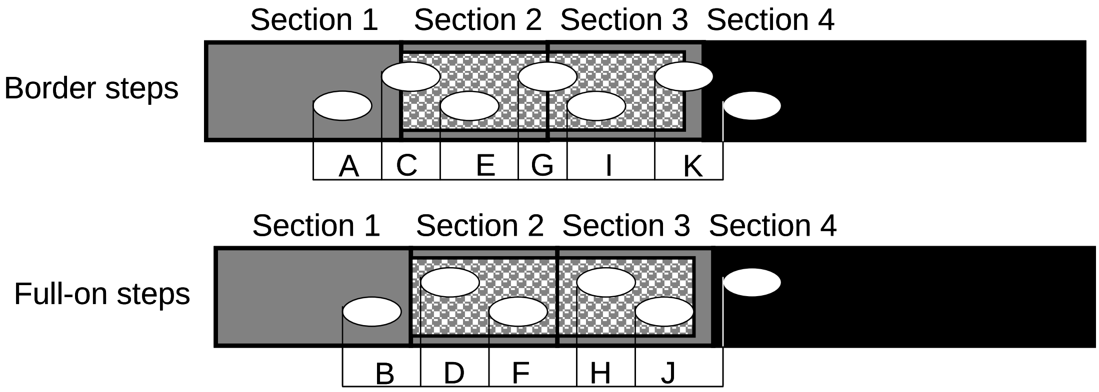
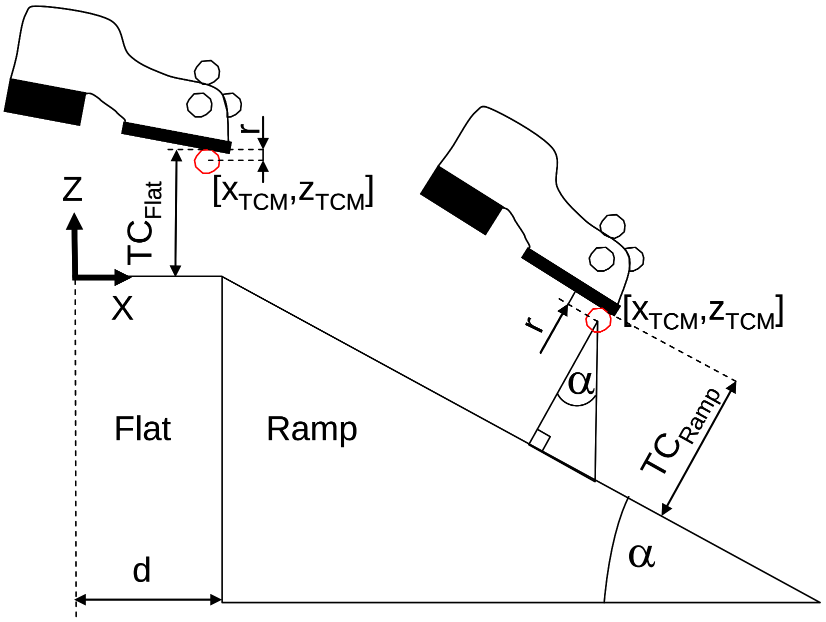


Figure 2.



$$TC_{Flat} = r + Z_{TCM}$$
$$TC_{Ramp} = r + \cos(\alpha) * \mathrm{abs}(-(X_{TCM}-d)/12 - Z_{TCM})$$

Figure 3.

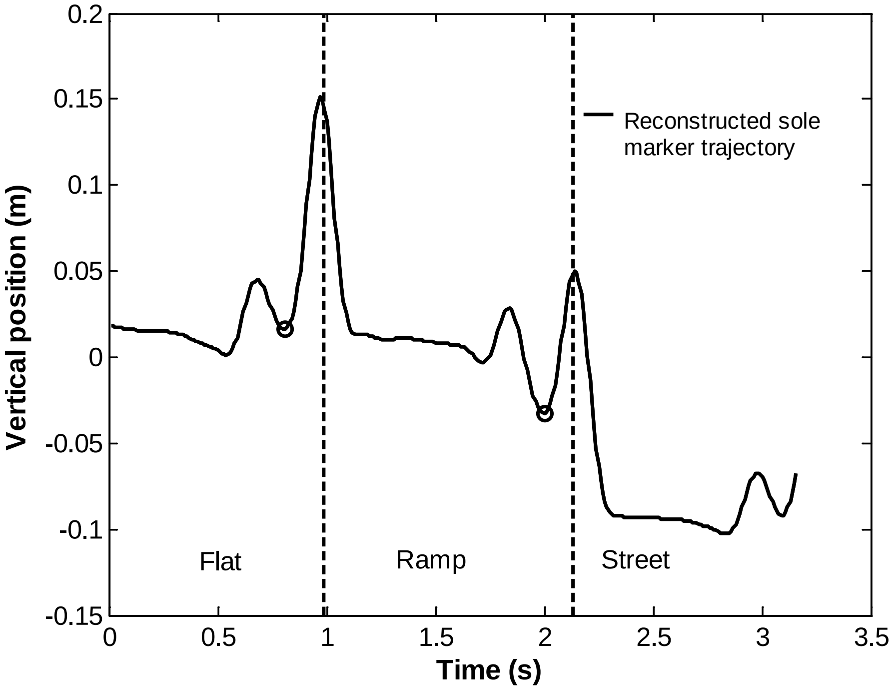
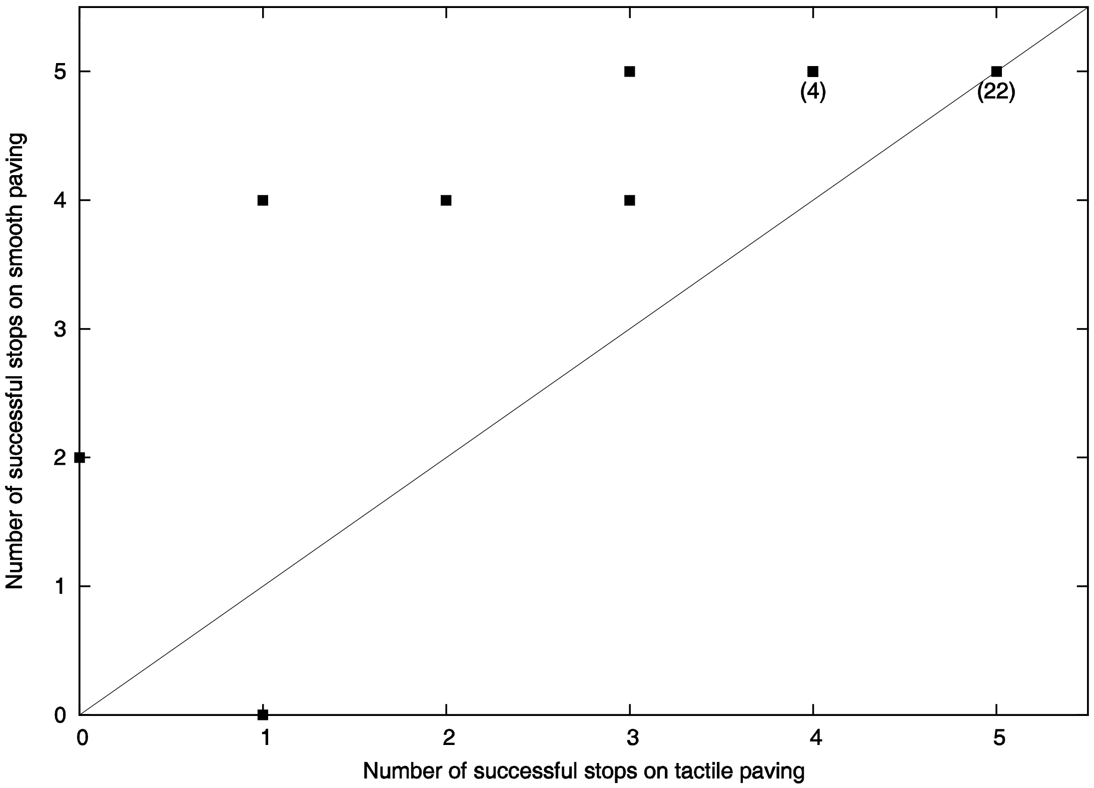


Figure 4.



Number of successful stops on smooth paving
0
1
2
3
4
5
Number of successful stops on tactile paving
0
1
2
3
4
5
(4)
(22)

Figure 5.