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Effects of shoe sole geometry on toe clearance and walking stability in older adults

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ABSTRACT

Thirty-five percent of people above age 65 fall each year, and half of their falls are associated with tripping: tripping, an apparently 'mundane' everyday problem, therefore, significantly impacts on older people's health and associated medical costs. To avoid tripping and subsequent falling, sufficient toe clearance during the swing phase is crucial. We previously found that a rocker-shaped shoe sole enhances toe clearance in young adults, thereby decreasing their trip-risk. This study investigates whether such sole design also enhances older adults' toe clearance, without inadvertently affecting their walking stability.

Toe clearance and its variability are reported together with measures of walking stability for twelve older adults, walking in shoes with rocker angles of 10°, 15°, and 20°. Surface inclinations (flat, incline, decline) were chosen to reflect a potential real-world environment.

Toe clearance increased substantially from the 10° to the 15° rocker angle ($p = 0.003$) without compromising measures of walking stability ($p > 0.05$). A further increase in rocker angle to 20° resulted in less substantial enhancement of toe clearance and came at the cost of a decrease in gait speed on the decline.

The novelty of this investigation lies in the exploration of the trade-off between reduction of trip-risk through footwear design and adverse effects on walking stability on real-life relevant surfaces. Our two studies suggest that the current focus on slip-resistance in footwear design may need to be generalised to include other factors that affect trip-risk.

1. Background

In 1999, fall-related injuries sustained by older people in the UK cost £981 million (647,721 A&E attendances, 204,424 hospital admissions) [1]. Indeed, 35% of people above age 65 fall each year, and fall frequency as well as severity of the consequences increase with an increase in age [1–3]. More than 50% of older adults' falls are associated with tripping [4]. Tripping, an apparently 'mundane' everyday problem, therefore significantly impacts on older people's health and associated medical costs.

During walking, trips result from involuntary contact of the foot in motion with the ground, with an obstacle, or with the other leg. To avoid tripping and subsequent falling, adequate lifting of the foot during the swing phase is crucial, and toe clearance (Fig. 1), and its variability have been linked to risk of tripping [5,6]. Specifically, toe clearance and its variability inform on the risk of tripping over undetected obstacles of various heights, as would be relevant when negotiating raised concrete, for example, due to a tree root in poor lighting conditions.

Inspired by an inquiry from the UK Health and Safety Laboratory, we previously published on young adults' toe clearance when walking in a "rocker" shoe (Fig. 2). Whilst previous research focused on the effects of a rocker shoe design on plantar pressure [7], our study was the first to document its effect on toe clearance and its variability for both, level and ramp walking. Specifically, we found that the geometry of the shoe sole affected toe clearance in young adults: the rounded "rocker profile" (Fig. 2), as compared to a flat shoe sole, consistently increased toe clearance during the swing phase of the foot, regardless of ground inclination or paving type, thereby reducing their risk of tripping over unseen obstacles or surface irregularities [8]. Since older adult gait is known to be different to that of young adults, for example with regard to gait symmetry and regularity [9], variability in step width, stride time

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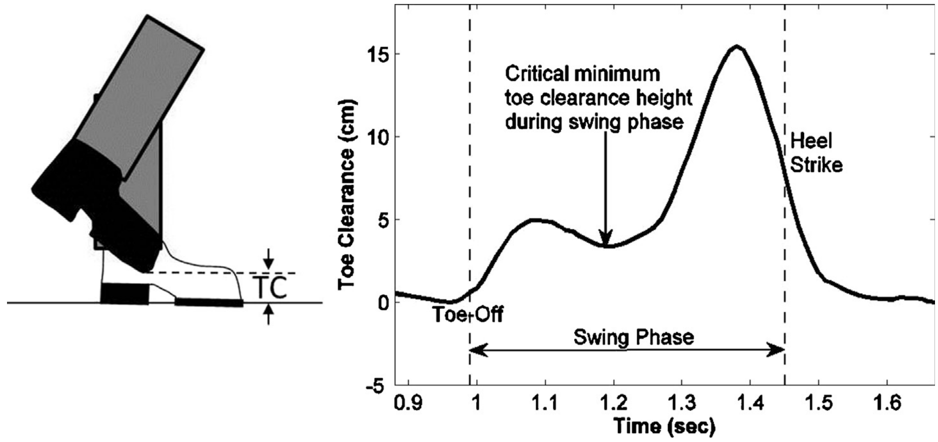

Fig. 1. Illustration of toe clearance (TC) during the swing phase (left) and corresponding toe clearance trajectory (right), as calculated from data obtained with a 3D optoelectronic camera system. Heel strike and toe-off were determined from the foot kinematics employing a previously established method [17].

and velocity [10]; and also toe clearance variability [11], the question of whether such rocker sole geometry may be of benefit to older adults' toe clearance has yet to be answered.

Notably, it is known that the geometry of the shoe sole also affects other aspects of walking. For example, whilst an elevated heel increases toe clearance it simultaneously results in a slower and hence more cautious gait [12]. Therefore it is critical that effects of the rocker sole on older adults' toe clearance and toe clearance variability are investigated in conjunction with measures of their stable gait, to explore whether a trade-off exits between the two.

Finally, previous work highlighted the importance of environmental factors when investigating modulation of toe clearance and gait in older adults. For example, studies have reported changes in toe clearance in response to inclines and declines [13–15]; especially modulation of toe clearance when walking up an incline is important due to the increased likelihood of foot–ground contact during the ascent. Hence experimental surface conditions that reflect a potential real-world environment are important for an enhanced understanding of toe clearance modulation and other relevant gait adaptation in response to footwear design.

It was therefore the objective of this study to assess the effects of rocker profile on older adults' toe clearance and walking stability on different surface inclinations. Specifically, this study investigates older adults' toe clearance, toe clearance variability, and parameters indicative of walking stability for walking on flat ground as well as for walking up an incline and down a decline. Effects of sole geometry, i.e. rocker angle, and effects of ground inclination on all outcome measures are reported. We hypothesize that an increase in rocker angle increases toe clearance regardless of ground inclination, however, measures indicative of walking stability may also be affected.

2. Methods

2.1. Experiment

The experimental protocol was approved by the institutional ethics committee. Inclusion criteria were (1) age ≥ 65; (2) able to walk community distances without walking aid. Exclusion criteria were (1) history of head injury or concussion; (2) visual disorders not correctable by glasses; (3) diagnosed peripheral or central nerve dysfunction. Fourteen community-living healthy subjects were recruited to the study and gave informed consent, two of which informed the design of the experimental protocol with regard to its feasibility in terms of repeated trials, slope of the ramp, and selection of footwear. Since these two pilot subjects showed severe imbalance when walking in shoes with a 25° up-tilt, those shoes were excluded from further analysis. Hence, only three different pairs of shoes with up-tilt angles of 10°, 15°, and 20° (10° representing a normal, commercial shoe) were tested in the remaining cohort of 12 participants (4 males, 8 females, age mean ± SD (range): 73 ± 5 (14) years, body mass mean ± SD (range): 79 ± 14 (52) kg, height mean ± SD (range): 1.7 ± 0.08 (0.25) m).

Subjects walked 10 trials in each direction of a walkway that started on a 4 m long flat surface, followed by a 1.5 m long ramp (slope: 1:12), followed by a 1.5 m long flat surface. The ramp was custom-built with a slope informed by the guidelines of the Department for Transport, hence reflecting a potential real-world

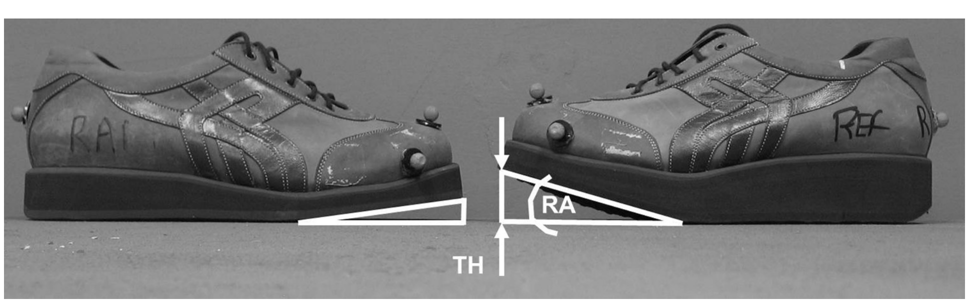

Fig. 2. Shoes with different toe height (TH) with respect to the ground: standard sole 'S' (left) and "rocker" sole 'R' (right) as reported in [8]. These two pairs only differ in their toe height (due to differences in rocker angle RA) and sole thickness, but not in other properties such as bending stiffness, mass, length, grip, or the shoes' upper fit. Note that increased sole thickness is required for an increased rocker angle to supply the same bending stiffness (but this was achieved without increasing mass, by utilizing different materials).

environment. Movement data during walking on level and sloped ground were collected with a 3D motion tracking camera system.

Each subject was provided with three pairs of custom-made shoes that differed in their sole geometry with regard to toe height ("rocker angle") (Fig. 2). Specifically, the three pairs under investigation had rocker angles of 10°, 15° and 20°, but did not differ in mass, length, grip, bending stiffness, or the shoes' upper fit. Presentation of footwear was randomized and for each shoe pair data were collected for walking on flat ground, walking up the incline of the ramp, and (on the reverse trials) walking down the decline of the ramp.

2.2. Data collection and processing

Kinematic data of reflective markers were sampled at 100 Hz with a 3D motion capture system (Qualisys Proreflex, Gothenburg, Sweden). Data recorded during the first and last 1.5 m of the test platform were excluded from the analysis to minimize possible acceleration/deceleration effects on outcome measures.

To track the footwear in 3D space, those markers were placed on each heel cap at the approximate location of the calcaneus, and clusters of three markers were also mounted onto the rigid toe cap of each shoe. In order to allow for mathematical reconstruction of the shoe sole in relation to the ground post data collection [16], the positions of the toe markers with respect to seven corresponding markers on the shoe sole were recorded in a static calibration trial prior to testing subjects in the lab. The sole markers were then removed prior to the recording of dynamic walking trials. A static trial of the ramp's geometry was also recorded with markers defining the boundaries and orientation of the ramp in 3D space, thereby allowing for calculation of toe clearance height as the perpendicular distance to the underlying slope of the ramp (see Fig. 3 in Thies et al. [15]). All kinematic data were filtered with a fourth-order Butterworth filter (MATLAB®) using a cutoff frequency of 7 Hz.

Post data collection, the critical minimum toe clearance height during the foot's swing phase (Fig. 1) was calculated for each reconstructed sole marker position. Minimum toe clearance ('MTC_L') was defined as described in [8], i.e. as the lowest of seven sole positions in a given swing phase. Since it has been previously established that toe clearance distributions are generally skewed [11], the median and inter-quartile-range (IQR) for MTC_L were calculated subsequently to describe each subject's toe clearance and toe clearance variability, respectively, and this was done for each pair of shoes on level and sloped ground.

This study also determined walking stability via assessment of step time variability (STV) and COM-ankle inclination angle. STV was assessed because rhythmic gait has been shown to become more variable when balance is challenged, for example [18–20] and has furthermore been shown to predict future falls where other measures could not [19,20]. STV was defined as the standard deviation of step time, which, for each step, was defined as the time elapsed from one heel strike to the next. COM-ankle inclination angle, defined as the centre of mass position relative to the ankle in the frontal plane, was assessed because it has previously shown to detect gait imbalance [21]. In this study the COM position was approximated by placing a reflective marker on the L3 vertebra. Subsequently, the medio-lateral COM-ankle inclination angle during single support was calculated as the angle between the line formed by the L3 vertebra and a lateral malleous marker, and the vertical line passing through the marker in the frontal plane [21]. Finally, the first derivative of the L3 vertebra's position data, recorded along the direction of forward progression, was used to obtain gait speed, defined as the average walking velocity of the trial. Gait speed was determined to, for example, assess whether a more cautious (i.e. slower) gait was adopted for walking in shoes with a larger rocker angle.

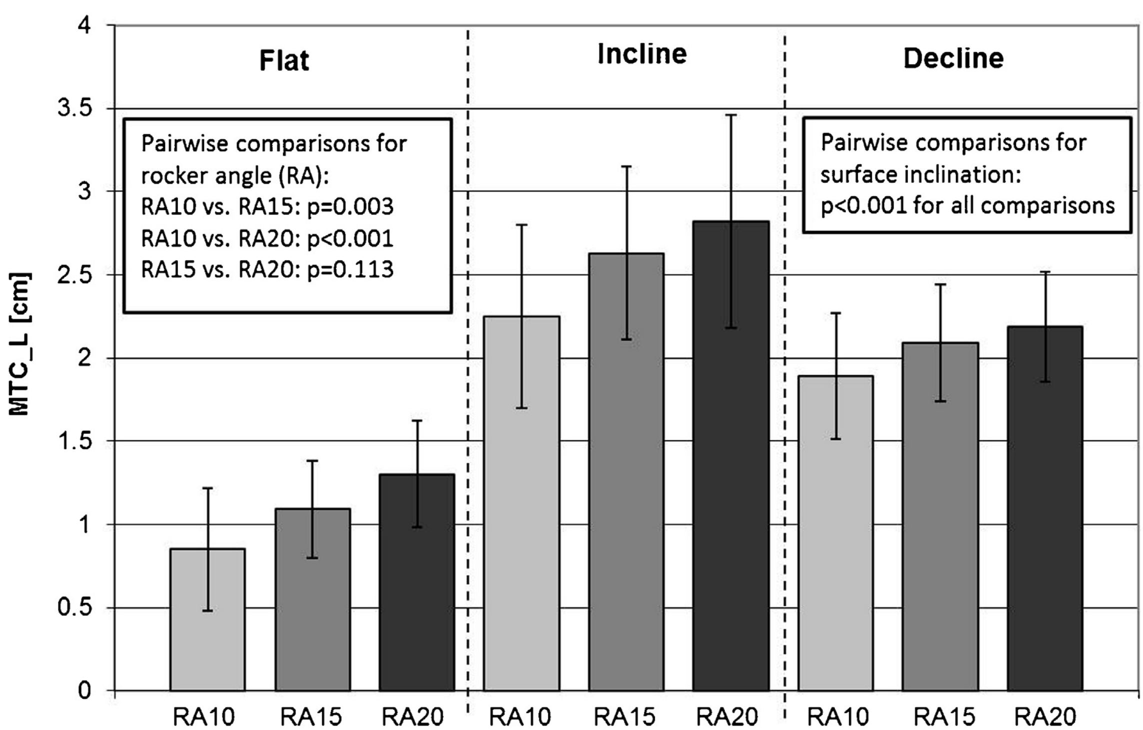

Fig. 3. Older adults' toe clearance (MTC_L) for all test conditions: regardless of ground inclination, an increase in rocker angle 'RA' increased toe clearance during the swing phase of walking (and thereby decreased risk of tripping over unseen obstacles or ground irregularities). Bars denote group means, error bars denote group standard deviations of median toe clearance values. RA = rocker angle (i.e. 10°, 15°, 20°). Ground inclinations: flat ground, incline (i.e. 4.5° ascending ramp), decline (i.e. 4.5° descending ramp).

2.3. Statistical analysis

A general linear mixed effects model (SPSS®) was used to analyze toe clearance parameter 'MTC_L' as well as the corresponding variability measure (IQR). Sole geometry (10°, 15°, and 20° rocker angle) and ground inclination (flat ground, inclining ramp, declining ramp), as well as the interaction term "sole geometry × ground inclination", were modelled as fixed effects, and the individual was modelled as a random effect since subjects physical abilities (and hence toe clearance) may be different due to, for example, their everyday activity levels. In a second analysis, the same statistical method was used for analysis of the measures of STV and COM-ankle inclination angle, as well as gait speed.

3. Results

The interaction term "sole geometry × ground inclination" was insignificant with $p > 0.1$ in all statistical analyses.

3.1. Toe clearance and toe clearance variability

Fig. 3 illustrates changes in toe clearance for all 9 test conditions (3 rocker angles × 3 surface inclinations). Statistical analysis of lowest minimum toe clearance (MTC_L) showed that estimates of fixed effects were associated with *p*-values of less than 0.05 for both factors (rocker angle, surface inclination). Specifically, with regard to differences in rocker angle, a substantial increase in toe clearance was observed as the rocker angle of the shoe increased, however, significance at the $p < 0.05$ level was only obtained for comparing the 10° rocker sole to the 15° and 20° rocker sole – but not for comparing the 15°–20° rocker sole. With regard to toe clearance modulation in response to surface inclination, toe clearance was notably larger for walking down a decline as compared to walking on flat ground, and larger still for walking up an incline. Results of these pairwise comparisons are shown in Table 1 and corresponding group means and group standard deviations are shown in Table 2.

In contrast, statistical analysis of toe clearance variability (the associated IQR of each individual's MTC_L values) showed that estimates of fixed effects were associated with *p*-values of greater than 0.05 for both factors, i.e. neither rocker angle nor surface inclination impacted notably on toe clearance variability.

3.2. Walking stability

3.2.1. Step time variability

Statistical analysis of this surrogate measure of controlled gait rhythm showed that estimates of fixed effects were associated with *p*-values of less than 0.05 for surface inclination only, but not for the rocker angle, i.e. the rocker angle did not impact notably on step time variability. With regard to surface inclination, pairwise comparisons showed that the marked difference was for comparing the flat surface to the incline and decline ($p = 0.008$ and $p = 0.001$, respectively): gait rhythm was more irregular for walking up the incline and down the decline as compared to walking on flat, level ground.

Table 1
Statistics for pairwise comparisons of effects of shoe sole geometry (RA = rocker angle of 10°, 15° and 20°) and surface inclination on the lowest minimum toe clearance 'MTC_L'. Confidence intervals refer to median toe clearance values in units of cm.

	p-value	95% Confidence interval	
		Lower bound	Upper bound
Sole geometry			
RA10 vs. RA15	0.003	−0.5	−0.1
RA10 vs. RA20	<0.001	−0.6	−0.2
RA15 vs. RA20	0.113	0.4	0.0
Surface inclination			
Flat vs. incline	<0.001	−1.7	−1.3
Flat vs. decline	<0.001	−1.2	−0.8
Incline vs. decline	<0.001	0.3	0.7

3.2.2. Centre of mass position relative to the ankle in the frontal plane (angle in degrees)

Statistical analysis of this surrogate measure of frontal plane imbalance showed that estimates of fixed effects were associated with *p*-values of less than 0.05 for surface inclination only, but not for the rocker angle, i.e. the rocker angle did not have a notable effect on this measure. With regard to surface inclination, pairwise comparisons showed that the marked difference was for comparing the incline to the decline ($p = 0.017$): the angle defining the centre of mass position relative to the ankle was greater for walking down the decline.

3.2.3. Gait speed

Statistical analysis of this surrogate measure of fear of falling [22] showed that estimates of fixed effects were associated with *p*-values of less than 0.05 for both, rocker angle and surface inclination. With regard to rocker angle, pairwise comparisons showed that the marked difference was for comparing both, the 10° rocker angle and the 15° rocker angle to the 20° rocker angle (both $p < 0.001$): subjects walked markedly slower with the 20° rocker sole. With regard to surface inclination, again, pairwise comparisons showed that the marked difference was for comparing both,

Table 2
Parameters (group mean ± group standard deviation) for all test conditions. RA: rocker angle; MTC_L: lowest minimum toe clearance as defined in Methods; IQR: inter quartile range; STV: step time variability*; angle: COM-ankle inclination angle.

	MTC_L (cm)[a,b]	IQR MTC_L (cm)	STV* (s)[b]	Angle (°)[b]	Speed (m/s)[a,b]
Flat					
RA10°	0.85 ± 0.37	0.70 ± 0.15	0.02 ± 0.01	4.26 ± 0.71	0.99 ± 0.16
RA15°	1.09 ± 0.29	0.86 ± 0.29	0.02 ± 0.01	4.14 ± 0.65	1.00 ± 0.15
RA20°	1.30 ± 0.32	0.79 ± 0.25	0.03 ± 0.02	4.19 ± 0.61	0.96 ± 0.19
Incline					
RA10°	2.25 ± 0.55	1.01 ± 0.59	0.03 ± 0.01	3.99 ± 0.60	0.99 ± 0.16
RA15°	2.63 ± 0.52	0.79 ± 0.33	0.03 ± 0.01	3.98 ± 0.48	1.00 ± 0.15
RA20°	2.82 ± 0.64	0.99 ± 0.39	0.03 ± 0.03	4.09 ± 0.65	1.00 ± 0.19
Decline					
RA10°	1.89 ± 0.38	0.81 ± 0.38	0.03 ± 0.02	4.22 ± 0.66	0.96 ± 0.15
RA15°	2.09 ± 0.35	0.82 ± 0.43	0.03 ± 0.02	4.26 ± 0.82	0.95 ± 0.15
RA20°	2.19 ± 0.33	0.71 ± 0.25	0.03 ± 0.01	4.46 ± 1.07	0.90 ± 0.04

* Standard deviation of step time.
[a] $p < 0.05$ for sole geometry.
[b] $p < 0.05$ for surface condition.

the flat surface and the incline to the decline (both $p = 0.004$): subjects walked slowest when walking down the decline.

4. Discussion

This study is the first to investigate the effects of various degrees of rocker angle of the shoe sole on older adults' toe clearance in conjunction with measures of their walking stability, and does so for multiple surface inclinations. The novelty of this investigation lies in the exploration of the trade-off between reduction of trip-risk through footwear design and adverse effects on walking stability under real-life relevant surface conditions.

The key finding of this study was that toe clearance increased most substantially from the 10° rocker angle to the 15° rocker angle without compromising surrogate measures reflective of walking stability. A further increase in rocker angle to 20° degrees resulted in a less substantial enhancement of toe clearance and came at the cost of a decrease in gait speed when negotiating the decline, i.e. resulting in a more cautious gait [22]. This highlights that there is a limit to the benefits of increasing the rocker angle. Furthermore, since an increased rocker angle requires a thicker shoe sole to provide the same bending stiffness, we acknowledge that we cannot separate out the individual contribution of the two design features on toe clearance modulation. However, we note that the % increase in toe-height of the shoe due to the rocker angle was substantially larger than the % increase in heel height.

A further insight gained from this study was that surface inclination did impact on measures of walking stability. Gait rhythm was more irregular for walking up the incline and down the decline as compared to walking on level ground, moreover, the angle defining the centre of mass position relative to the ankle was markedly greater for walking down the decline. The former has been reported to indicate that balance is challenged [18–20], and the latter has been specifically associated with greater imbalance in the frontal plane [21].

That toe clearance was lowest for walking on a flat, level surface was in agreement with our recent investigation of young adults [8], however, that these older adults showed greater toe clearance when walking up the incline as compared to walking down the decline did not reflect our previous observation in young adults. It is possible that these older adults were more cautious when walking up the incline; they may have exhibited increased toe clearance to adapt to the increased risk of foot–ground contact as they were gaining ground on each step when walking up the ramp.

Finally, that effects of rocker angle and surface inclination on toe clearance variability were negligible may reflect the ability of these older adults to walk with modulated toe clearance whilst maintaining a steady, low variability gait pattern.

In conclusion, whilst a large amount of slip-resistant footwear is already available in the market, the UK Health & Safety Laboratory has identified a need to investigate effects of footwear design features on toe clearance and trip-risk. In this study of older adults, and our previous study of young adults [8], we have shown that as rocker angle is increased, toe clearance is increased. Here we further demonstrate that a trade-off exists between increasing older adults' toe clearance and decreasing their gait speed. Nevertheless, we found that there is a value for the rocker angle of the shoe sole which appears to reduce trip-risk whilst not adversely affecting gait speed and other measures of stability. Therefore suitably designed footwear has the potential to positively impact on trip prevention and may contribute to reduced incident rates of falls, thereby supporting active ageing. The laboratory-based findings presented here now need to be substantiated in a larger community-based study, allowing for investigation of additional questions including user-compliance, comfort and falls incidence. Furthermore, future studies need to look at toe clearance modulation when climbing stairs or negotiating steps and obstacles with rocker shoes.

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Conflict of interest

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

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