Gait & Posture 42 (2015) 105–109

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

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

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ARTICLE INFO

Article history:
Received 29 October 2014
Received in revised form 10 February 2015
Accepted 20 April 2015

Keywords:
Biomechanics
Gait
Falls
Trips
Footwear

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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http://dx.doi.org/10.1016/j.gaitpost.2015.04.011

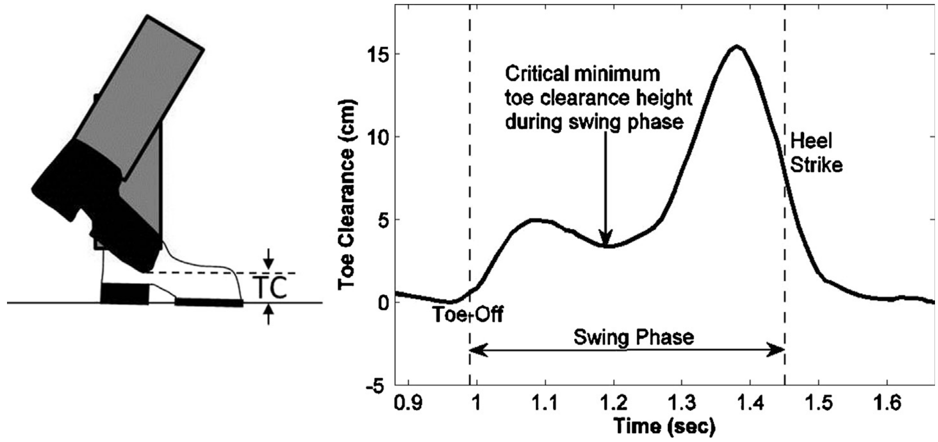

Fig. 1. Illustration of toe clearance (TC) during the swing phase (left) and corresponding toe clearance trajectory (right), as calculated from data obtained with a 3D optoelectronic camera system. Heel strike and toe-off were determined from the foot kinematics employing a previously established method [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 $\pm$ SD (range): 73 ± 5 (14) years, body mass mean $\pm$ SD (range): 79 ± 14 (52) kg, height mean $\pm$ 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

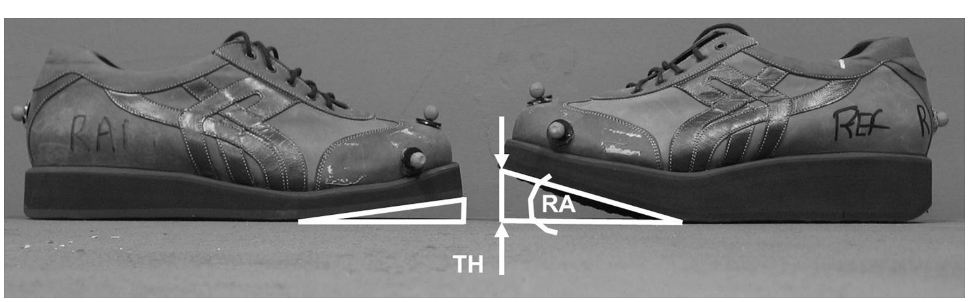

Fig. 2. Shoes with different toe height (TH) with respect to the ground: standard sole 'S' (left) and "rocker" sole 'R' (right) as reported in [8]. These two pairs only differ in their toe height (due to differences in rocker angle RA) and sole thickness, but not in other properties such as bending stiffness, 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).