Clinical Biomechanics 26 (2011) 962–968

Contents lists available at ScienceDirect

Clinical Biomechanics

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

Ageing and limb dominance effects on foot-ground clearance during treadmill and overground walking

Hanatsu Nagano, Rezaul K. Begg, William A. Sparrow *, Simon Taylor

Institute of Sport, Exercise and Active Living (ISEAL), School of Sport and Exercise Science (SES), Victoria University, Melbourne, Australia

ARTICLE INFO

Article history:
Received 23 December 2010
Accepted 23 May 2011

Keywords:
Foot-ground clearance
Ageing
Treadmill walking
Gait asymmetry
Foot trajectory

ABSTRACT

Background: Foot-ground clearance during the gait cycle swing phase is a critical locomotor adaptation to uneven terrain and non-optimal lower limb control has been linked to tripping and falling. The aim of this research was to determine ageing effects on bilateral foot-ground clearance during overground and treadmill walking.

Methods: Ageing and walking surface effects on bilateral foot trajectory control were investigated in 11 older (mean age 73.8 years) and 11 young (mean age 22.5 years) participants. First maximum clearance after toe-off, minimum foot-ground clearance and second maximum clearance prior to heel contact were determined from sampled 3-dimensional marker coordinates during preferred-speed treadmill walking and walking overground.

Findings: Preferred walking speed was lower in treadmill walking for both groups. In both groups non-dominant minimum foot-ground clearance and first maximum clearance were greater than for the dominant foot. A high positive correlation was found between these two swing foot clearances when older adults walked on the treadmill. Second maximum clearance was reduced in the older group but this was the only overall age effect. Treadmill walking reduced minimum foot-ground clearance relative to overground locomotion except in the older adults' non-dominant limb that revealed greater vertical clearance height in the non-dominant foot.

Interpretation: Decreased second maximum clearance in the older group may be linked to reduced dorsiflexion. Greater minimum foot-ground clearance in the older adults' non-dominant foot may reflect functional asymmetry, in which the non-dominant limb primarily secures or stabilizes gait. The high positive correlation between first maximum and minimum foot-ground clearances suggests that intervention designed to increase first maximum clearance may also increase minimum foot-ground clearance. A direction for future research is to further understand ageing effects on lower limb trajectory variables in response to a range of walking surface characteristics.

1. Introduction

Each year approximately 33% of Australians aged over 65 years experience a fall and half this number fall more than once (Hill et al., 1999; Keskin et al., 2008; Stalenhoef et al., 2002). In addition to the physical and psychological trauma, there is an annual financial cost of falls-related injuries exceeding A$3 billion (Australian Bureau of Statistics, 2006). Rapid growth in the proportion of the population over 65 years will accelerate falls-related healthcare costs (Moller, 2005) and, as a consequence, there is a considerable worldwide research effort to understand the primary causes of falls and devise measures to prevent them.

Falls sustained by older adults when walking have been categorised according to their direct cause, such as tripping, slipping, unexpected stepping down, and fainting (Smeesters et al., 2001) and of these tripping has been identified as the leading cause of falls, accounting for approximately 50% of all falls-related incidents (Blake et al., 1988; Zhou et al., 2002). Tripping can be defined as an event in which the most distal feature of the swing limb, usually the lowest part of the shoe or foot, makes unanticipated contact with either the supporting surface or objects on it with sufficient force to destabilize the walker. When stability cannot be recovered the individual sustains a fall. In the experiment reported here we investigated how age-related changes to lower limb trajectory control could increase the risk of tripping due to unintended foot-ground contact.

In previous work tripping risk has been examined when negotiating substantial obstacles in the approximate range 7 cm to 20 cm. Such obstacles are relatively easily detected and, as a consequence, elicit an intentional, prepared response in the form of significant modifications to limb trajectory (e.g., Begg and Sparrow, 2000; Di Fabio et al., 2004; Sparrow et al., 1996). Our aim in this project was, however, to investigate a less well researched human gait phenomenon that is

* Corresponding author at: Institute of Sport, Exercise and Active Living (ISEAL), Victoria University, 300 Flinders Street, Melbourne, Victoria 3000, Australia.
E-mail address: tony.sparrow@vu.edu.au (W.A. Sparrow).

0268-0033/$ – see front matter. Crown Copyright © 2011 Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.clinbiomech.2011.05.013

clinically important when evaluating the effects of ageing and other disturbances to gait function. Considerable risk is associated with traversing the constantly changing "rough" or uneven surfaces of the everyday environment due to relatively small but, given the low amplitude of swing phase ground clearance, functionally significant obstructions. Toe trajectory during the swing phase of the gait cycle is typically as illustrated in Fig. 1 and for analytical purposes three key events associated with safe ground clearance can be defined. Following toe-off the swing foot exhibits a first maximum clearance (Mx1) after which, approximately halfway through the swing phase, the lowest clearance point subsequent to Mx1 is seen – minimum foot-ground clearance (MFC). At approximately 90% of the swing phase second maximum clearance is achieved (Mx2). The magnitude and precise timing of these events are individual-specific but in normal gait they appear in this order.

Early work by Winter (1991) described the link between MFC and tripping risk by demonstrating that at MFC the foot is very close to the walking surface, approximately one centimetre, and horizontal velocity reaches maximum. Any contact-related destabilization at MFC occurs, furthermore, during the vulnerable single limb support phase of the stance foot. More recent work has extended the investigation of tripping risk during the swing phase. Using simulated obstacle heights between 0.2 cm and 1.0 cm Best and Begg (2008) developed computational methods for calculating the probability of such 'unanticipated' tripping based on central tendency, variability, and distribution patterns of minimum foot clearance (MFC). Furthermore, MFC distributions of young and older adults have been compared to understand why ageing may increase the risk of tripping. While older adults consistently showed greater variability in minimum foot clearance (Begg et al., 2007; Karst et al., 1999; Mills et al., 2008; Sparrow et al., 2008; and Winter, 1991) none of these studies found age-related differences in MFC.

Begg et al. (2007) also demonstrated that tripping risk can be reduced by either increasing MFC height or reducing MFC variability. MFC is, however, observed during mid-swing and a complex interaction of biomechanical variables influence this highly dynamic event. Other foot-ground clearance events such as Mx1 and Mx2 may, therefore, affect swing foot amplitude at MFC. In this experiment Mx1 and MFC were correlated to illuminate any interdependence of these swing phase variables. At Mx2, for example, the swing foot is most highly dorsiflexed (Winter, 1991) and older adults have been reported to have weaker dorsiflexor muscles (Perry et al., 2007); reduced dorsiflexion could therefore critically decrease ground clearance of the fore foot (Begg and Sparrow, 2006; Moosabhoy and Gard, 2006). In this experiment we undertook a comprehensive study of ageing, surface, and limb dominance effects on Mx2 to more fully understand the event's importance in lower limb swing phase control.

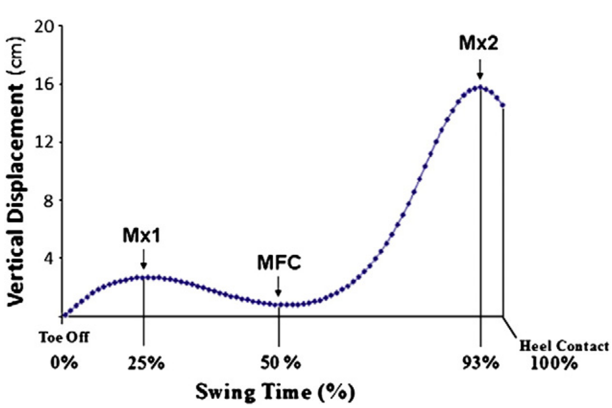

Fig. 1. Schematic to illustrate three measured events (Mx1, MFC and Mx2) of the foot trajectory during the swing phase of the gait cycle; data for one young subject's dominant foot in the overground walking condition: Mx1, the first peak vertical displacement after toe off (25%); MFC, the lowest vertical displacement between Mx1 and Mx2 (50%); Mx2, the maximum vertical displacement during the swing phase (90%).

Most previous MFC modelling relied on extended data samples from treadmill-walking but there is debate as to whether treadmill gait validly represents the biomechanics of overground locomotion (Goldberg et al., 2008; Riley et al., 2007). Despite the reported differences in some kinetic and kinematic parameters, Goldberg et al. (2008) and Riley et al. (2007) both concluded that the treadmill does provide a valid measure of overground walking but previous treadmill validation experiments have usually employed young participants (Goldberg et al., 2008; Riley et al., 2007). In the only validation test involving older adults, most participants did not familiarise to treadmill walking within 15 min of practice and could not walk at the same speed as overground without holding the treadmill's handrail (Wass et al., 2005). Treadmill walking may, therefore, have age-specific effects on lower limb trajectory control and, specifically, foot ground clearance was hypothesised to be lower in treadmill walking due to previously demonstrated reductions in joint range of motion and kinetic components in treadmill walking (Goldberg et al., 2008; Riley et al., 2007).

With one exception (Sparrow et al., 2008) previous research into the statistical characteristics of MFC employed single-limb analysis but there is increasing evidence that adaptive locomotor control is dependent on complex interactions *between* the lower limbs, as reflected in kinetic and kinematic variables that are unequal or "asymmetrical". Sadeghi, 2003; Sadeghi et al. (1997, 2000) suggested, furthermore, that asymmetry in spatio-temporal parameters has not only been observed in pathological gait but also seen in non-impaired individuals. Experimental findings of gait asymmetry have been used to address the "functional asymmetry" hypothesis, which proposes that the dominant limb adopts a primary role of forward progression while the non-dominant limb serves to secure gait stability (Sadeghi et al., 2000; Seeley et al., 2008). Lower limb muscle strength and power become more asymmetrical with age (Perry et al., 2007; Sadeghi et al., 2000; Skelton et al., 2002) and, importantly, asymmetry in older individuals has been linked to falls risk (Di Fabio et al., 2004; Hill et al., 1999; Perry et al., 2007). Accordingly, it was hypothesised here that older adults would show greater asymmetry in swing foot kinematics.

In summary, the overall aim was to determine ageing effects on foot-ground clearance at three swing phase events; Mx1, MFC and Mx2 (Fig. 1). Two further questions were how older adults' foot-ground clearance parameters would be affected by the walking surface (overground vs. treadmill) and limb dominance (dominant vs. non-dominant).

2. Methods

2.1. Participants

Eleven young adults (7 males and 4 females aged 22.5, SD 2.9 years) and eleven older adults (7 males and 4 females aged 73.8, SD 7.22 years) participated in this study. Anthropometric characteristics were: height (young: 1.70, SD 0.07 m, older 1.69 ± 0.11 m) and weight (young: 68.3, SD 11.72 kg, older 72.7, SD 8.64 kg). All older participants lived independently, were able to perform routine daily activities, free of any known cognitive, orthopaedic or neurological abnormalities and able to walk for at least 20 min continuously. Both young and older volunteers were excluded if they met one or more of the following conditions: exceeding 12 s on a 'timed up and go test', scoring less than 20 on a visual contrast sensitivity test ('Melbourne Edge Test') and reporting at least one fall within the previous two years. The Human Research Ethics Committee, Victoria University,