Journal of Biomechanics 60 (2017) 142–149

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

The effect of uphill and downhill walking on gait parameters: A self-paced treadmill study

Shani Kimel-Naor [a], Amihai Gottlieb [a], Meir Plotnik [a,b,c,*]

[a] Center of Advanced Technologies in Rehabilitation, Sheba Medical Center, Ramat Gan, Israel
[b] Department of Physiology and Pharmacology, Sackler Faculty of Medicine, Tel-Aviv University, Tel Aviv, Israel
[c] Sagol School of Neuroscience, Tel Aviv University, Tel Aviv, Israel

ARTICLE INFO

Article history:
Accepted 16 June 2017

Keywords:
Biomechanics
Virtual reality
Gait parameters
Inclined walking
Motor function
Self-paced walking

ABSTRACT

It has been shown that gait parameters vary systematically with the slope of the surface when walking uphill (UH) or downhill (DH) (Andriacchi et al., 1977; Crowe et al., 1996; Kawamura et al., 1991; Kirtley et al., 1985; McIntosh et al., 2006; Sun et al., 1996). However, gait trials performed on inclined surfaces have been subject to certain technical limitations including using fixed speed treadmills (TMs) or, alternatively, sampling only a few gait cycles on inclined ramps. Further, prior work has not analyzed upper body kinematics. This study aims to investigate effects of slope on gait parameters using a self-paced TM (SPTM) which facilitates more natural walking, including measuring upper body kinematics and gait coordination parameters.

Gait of 11 young healthy participants was sampled during walking in steady state speed. Measurements were made at slopes of +10°, 0° and −10°. Force plates and a motion capture system were used to reconstruct twenty spatiotemporal gait parameters. For validation, previously described parameters were compared with the literature, and novel parameters measuring upper body kinematics and bilateral gait coordination were also analyzed.

Results showed that most lower and upper body gait parameters were affected by walking slope angle. Specifically, UH walking had a higher impact on gait kinematics than DH walking. However, gait coordination parameters were not affected by walking slope, suggesting that gait asymmetry, left-right coordination and gait variability are robust characteristics of walking. The findings of the study are discussed in reference to a potential combined effect of slope and gait speed. Follow-up studies are needed to explore the relative effects of each of these factors.

1. Introduction

Daily walking often involves changes in elevation which requires body adjustments. For example, uphill walking consumes more energy than level walking (Margaria, 1938; Minetti et al., 2002), and downhill walking requires coping with inertial forces acting upon the body (Gottschall and Kram, 2005). The biomechanics of walking adapt to an inclined surfaces and conform to the specific accompanying constraints (Andriacchi et al., 1977; Crowe et al., 1996; Gottschall et al., 2011; Item-Glatthorn et al., 2016; Kawamura et al., 1991; Kirtley et al., 1985; Leroux et al., 2002; McIntosh et al., 2006; Plotnik et al., 2013; Redfern and DiPasquale, 1997; Sun et al., 1996; Whittle, 1996). While horizontal gait has been thoroughly examined, studies of inclined gait have been subject to certain technical limitations. For example, most studies were performed in a restricted walking space that allows sampling of a limited number of continuous gait cycles (Gottschall et al., 2011; McIntosh et al., 2006; Prentice et al., 2004; Redfern and DiPasquale, 1997). Another limitation of prior studies of inclined gait is that they used treadmills (TMs) that can be tilted, with predetermined fixed belt speed (Item-Glatthorn et al., 2016; Werner et al., 2007), which may not accurately reflect over ground walking (Dingwell et al., 2001; Lee and Hidler, 2008). Indeed the relevance of this limitation is evident from work showing that gait parameters depend on the participant's speed (Andriacchi et al., 1977; Crowe et al., 1996; Gottschall et al., 2011; Item-Glatthorn et al., 2016; Kawamura et al., 1991; Kirtley et al., 1985; Leroux et al., 2002; McIntosh et al., 2006; Plotnik et al., 2013; Redfern and DiPasquale, 1997; Sun et al., 1996; Whittle, 1996). Thus, gait parameters during

* Corresponding author at: Rehabilitation Hospital, Chaim Sheba Medical Center, Ramat Gan 5265601, Israel.
E-mail address: meir.plotnik@sheba.health.gov.il (M. Plotnik).

http://dx.doi.org/10.1016/j.jbiomech.2017.06.030
0021-9290/© 2017 Published by Elsevier Ltd.

natural walking conditions on an inclined surface have yet to be adequately characterized.

Technological advancements have resulted in TMs that can be operated in self-paced (SP) mode, whereby treadmill speed is set dynamically based upon the participant's performance (Plotnik et al., 2015; Sloot et al., 2014a,b). Data gathered thus far support the contention that self-paced treadmill (SPTM) walking resembles natural over ground walking (Plotnik et al., 2015; Sloot et al., 2015, 2014b; van der Krogt et al., 2014). Facilitation of a natural walking experience is further enhanced if the SPTM is incorporated within a virtual reality (VR) system that provides visual flow (Fung et al., 2004; Plotnik et al., 2015; Sinitski et al., 2015; Sveistrup, 2004). It therefore appears likely that the study of uphill and downhill walking may benefit from SPTMs implemented within a VR facility. Indeed the limitations associated with the fixed speed of a standard TM and restricted sampling of gait cycles on the inclined surface can both be addressed with this approach.

Several gait parameters during walking on inclined surfaces have not yet been studied. Specifically, upper body parameters including shoulder and elbow angles, as well as coordination parameters including phase coordination index (PCI), gait asymmetry (GA) and gait variability have not been described. To the best of our knowledge, only one study utilized SPTM during inclined walking and measured only few gait parameters (Sinitski et al., 2015).

The objective of the present study was to investigate adaptation of gait parameters when walking up or down on inclined surfaces in a naturalistic SPTM VR setting. In particular, we aimed to measure key gait parameters that had never been measured in this type of settings, including parameters related to upper body joint angels. Additionally, we aimed to report on gait parameters that had been previously described, but data were collected only in restricted conditions. As walking on inclined surfaces is entering the gait rehabilitant training repertoire (e.g., Al-Jarrah et al., 2014; Sinclair et al., 2014), we find it important that the subtleties related to this type of walking will be available for the clinical and the research communities.

2. Methods

2.1. Participants

Eleven young healthy adults participated in this study (mean age 31.8 ± 4.3 y, 7 women). All participants reported that they were in good health and free of any conditions likely to affect gait. The experimental protocol was approved by the Ethical Committee of Human Studies at the Sheba Medical Center. A written informed consent was provided by all participants prior to entering the study.

2.2. Apparatus

A fully immersive VR system (CAREN High End, Motek Medical, The Netherlands) projected a virtual environment on a full-room dome-shaped screen (Fig. 1a). This system comprises a moveable platform with six degrees of freedom and an embedded TM, and is synchronized to a motion capture system (Vicon, Oxford, UK). Kinematic data from the walking participants were collected from the three-dimensional position of 41 passive markers attached to the participant's body. Spatial resolution is 1 mm and sampling rate is 120 Hz.

TM speed was determined in a self-paced (SP) mode that enabled each participant to walk at his/her preferred speed (Plotnik et al., 2015; Sloot et al., 2014a,b).

Uphill, downhill and level walking was simulated when the platform was pitched at +10°, −10° and 0°, respectively, along with synchronous corresponding elevation of a projected scene of a one-lane road on a bright day (Fig. 1b–d).

2.3. Procedure

2.3.1. Structured walking training

The experiments began with static standing ('sway' recordings) for 30 s at each of the three inclinations. Then participants were trained to walk in SP mode in three consecutive trials. Each trial began with 15–35 s of level walking followed by a one minute of walking at one of the three inclinations: (T1) 0° inclination (i.e., no change); (T2) +10° inclination; and (T3) −10° inclination.

2.3.2. Experimental trials

Nine 2-min walking trials, in random order, covering all possible combinations of platform and visual flow inclinations (3 × 3) were performed (Plotnik et al., 2013). Here we report only on the three congruent conditions: level (LV); uphill (UH); and downhill (DH). In cases of missing data due to technical issues, we substituted with data from the corresponding training trial (occurred in 2 out of 33 trials).

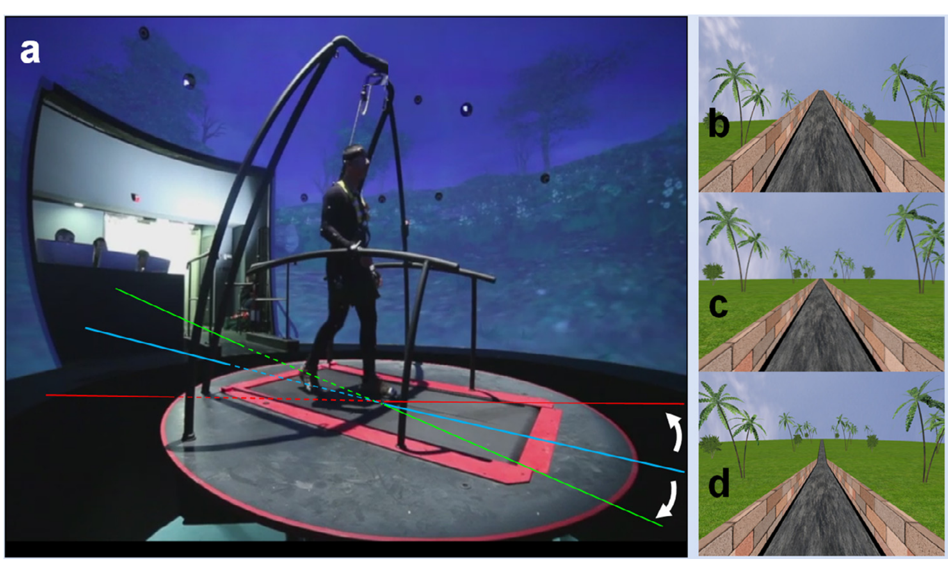

Fig. 1. The experimental setup. The CAREN high end system (Motek Medical, The Netherlands). A moveable platform with 6 degrees of freedom is synchronized with visual scenery projected on a 360° dome-shaped screen. A self-paced treadmill (SPTM) is embedded in the platform and controlled by biofeedback from four hip markers that are part of a VICON motion capture system. Three platform inclinations were used: level (blue line), 10° downhill (green line), and 10° uphill (red line). The scenery projected for each inclination is shown in panels (b), (c) and (d), respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)