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Dynamic gait stability of treadmill versus overground walking in young adults

Feng Yang *, George A. King

Department of Kinesiology, University of Texas at El Paso, El Paso, TX 79968, USA

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ABSTRACT

Treadmill has been broadly used in laboratory and rehabilitation settings for the purpose of facilitating human locomotion analysis and gait training. The objective of this study was to determine whether dynamic gait stability differs or resembles between the two walking conditions (overground vs. treadmill) among young adults. Fifty-four healthy young adults (age: 23.9 ± 4.7 years) participated in this study. Each participant completed five trials of overground walking followed by five trials of treadmill walking at a self-selected speed while their full body kinematics were gathered by a motion capture system. The spatiotemporal gait parameters and dynamic gait stability were compared between the two walking conditions. The results revealed that participants adopted a "cautious gait" on the treadmill compared with over ground in response to the possible inherent challenges to balance imposed by treadmill walking. The cautious gait, which was achieved by walking slower with a shorter step length, less backward leaning trunk, shortened single stance phase, prolonged double stance phase, and more flatfoot landing, ensures the comparable dynamic stability between the two walking conditions. This study could provide insightful information about dynamic gait stability control during treadmill ambulation in young adults.

1. Introduction

Treadmill has been broadly used in biomechanical research primarily due to its inherent advantages over conventional overground walking, including less space requirements, precise control of walking speed, and the ability to use fewer cameras and gather sufficiently long consecutive gait cycles for biomechanical parameters (Padulo et al., 2014). Because overground locomotion is the ultimate goal of all treadmill-based studies or training, a fundamental question when using a treadmill for gait analysis is whether treadmill gait is equivalent to overground gait (Wass et al., 2005).

Considerable efforts have been dedicated to comparing spatiotemporal gait parameters (Lee and Hidler, 2007; Watt et al., 2010), joint kinematics (Alton et al., 1998; Watt et al., 2010) and kinetics (Lee and Hidler, 2007; Watt et al., 2010), and muscle activation (Lee and Hidler, 2007) between overground and treadmill walking. Various similarities and differences between the two walking conditions have been suggested. For example, studies indicated that during treadmill walking, people tend to self-select a slower speed, utilize a shorter step length and greater step frequency, and spend less time in the swing phase and more time in the double-support phase compared to overground walking (Alton et al., 1998; Murray et al., 1985).

Stability during human locomotion is defined as the ability to restore or maintain the upright posture without altering the existing base of support (BOS) when confronting with an internal or external disturbance. A theoretical framework (the feasible stability region theory, or FSR) that extends the concept of static stability (Borelli, 1680) to dynamic conditions (Hof et al., 2005; Yang et al., 2007) suggests that dynamic stability can be characterized by the kinematic relationship between the body's center of mass (COM) motion state (i.e., the combination of COM position and velocity related to the BOS) and the analytically-derived stability limits (Fig. 1). Dynamic gait stability, measured based on this theoretical framework, has been identified as a key factor leading to falls (Yang et al., 2009). It has also been broadly used to quantify gait stability among various populations, such as amputation (Beltran et al., 2014) and stroke (Hak et al., 2013). Since dynamic gait stability contains two domains: the COM position and velocity, it is a more comprehensive index to quantify human movement stability than simple kinematic measurements. Details about the FSR and

* Corresponding author at: Department of Kinesiology, University of Texas at El Paso, 1851 Wiggins Way, Rm-452, El Paso, TX 79968, USA.
E-mail address: fyang@utep.edu (F. Yang).

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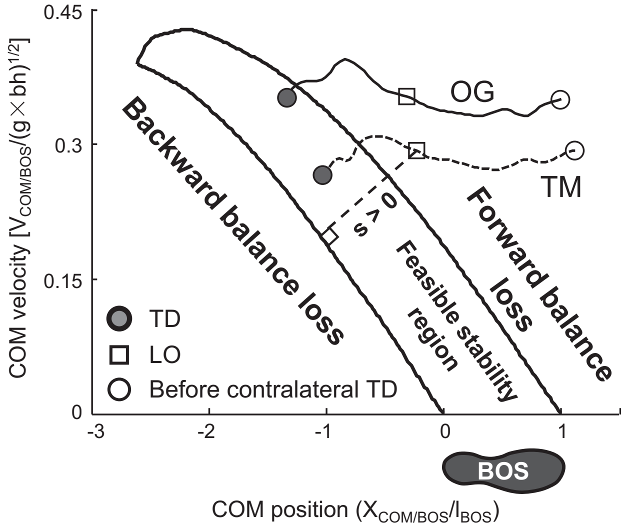

Fig. 1. Schematic illustration of the feasible stability region, which is enclosed by two boundaries: the threshold against backward balance loss (the lower boundary) and the one against forward balance loss (the upper boundary). The stability measurement (*s*, the length of the thin solid line) indicates the magnitude of the instantaneous stability of the center of mass (COM) against backward balance loss, and is defined as the shortest distance from the instantaneous COM motion state (i.e., the *x*- and *y*-coordinates represent the COM anteroposterior position velocity, respectively) to the threshold against backward balance loss. Also shown are the representative COM motion state trajectories of an overground (OG) walking (the thin solid line) and a treadmill (TM) walking (the thin dashed line) progressing from the touchdown (TD, filled circle), through the contralateral foot liftoff (LO, square), and immediately prior to the contralateral foot TD (open circle). Position and velocity of the COM relative to the base of support (BOS) are *dimensionless* as a fraction of l_{BOS} and $\sqrt{g \times bh}$, respectively, where l_{BOS} represents the foot length, *g* is gravitational acceleration, and *bh* the body height. Dynamic stability is also a *unitless* quantity.

calculations of dynamic stability were provided in the Online Supplement.

To our knowledge, no study has examined dynamic gait stability in terms of the FSR theory during treadmill walking. It remains unknown if dynamic gait stability on a treadmill approximates that measured during overground walking. This highlights the importance of comparing dynamic stability control between treadmill and overground ambulation. Given other facts that balance and stability control is a critical component of gait rehabilitation (Shen and Mak, 2014) and that treadmill has been increasingly used to improve stability in various populations (Herman et al., 2009; Shimada et al., 2004; Yang et al., 2013), it is paramount to understand the stability control during treadmill gait.

The nature of the relative movement between a person's COM and the BOS differs between overground and treadmill walking. Specifically, one's COM demonstrates a small movement in the inertial frame when walking on a treadmill with the stance foot traveling backward to produce the forward progression of the COM relative to the BOS during the stance phase. However, in overground walking, the COM has a significant forward movement while the foot keeps in a relatively steady position during the stance phase. Such differences could consequently result in discrepancies in dynamic stability control as COM dynamic stability reflects the relative motion of the COM to the BOS (Yang et al., 2007). It was reported that adults tend to walk slower (Chiu et al., 2015; Dal et al., 2010) with a shorter step length (Nagano et al., 2013) when walking on the treadmill than over ground if self-selecting the comfortable gait speed under the two walking conditions. Based on the FSR theory, a shortened step length would bring the COM closer to the BOS (Espy et al., 2010) and in turn improve the dynamic stability against backward balance loss while a reduced gait speed would have the potential to deteriorate the dynamic stability (Yang et al., 2007). The opposing effects from these two factors on the dynamic stability could nullify the influence of each other likely resulting in comparable stability between the two walking conditions. Nevertheless, the impact of treadmill walking on the dynamic stability remains to be determined.

The primary purpose of this study was to determine the extent of influence on dynamic stability between overground and treadmill walking among healthy young adults. We hypothesized that the dynamic gait stability would be comparable between the two walking conditions.

2. Methods

2.1. Participants

Fifty-four healthy young adults (mean ± standard deviation age: 23.9 ± 4.7 years; body mass: 80.1 ± 24.5 kg; body height: 167.1 ± 9.6 cm; 27 females) participated in the experiment. They were free of any known neurological, musculoskeletal, or other systemic disorders that would have affected their postural control. Prior to any data collection, each participant gave written consent to participate using an informed consent form approved by the University of Texas at El Paso Institutional Review Board.

2.2. Experimental protocol

All participants were told that they would initially walk on a walkway and later on a treadmill. For both walking conditions, each participant chose the preferred gait speed. They were also instructed to walk as they would normally walk on a street. All participants first walked five times across a 14-m walkway at their self-selected comfortable speed. They then stepped onto a regular treadmill over which participants' comfortable walking speed was determined (Jordan et al., 2007) and then they walked approximately 5 min to habituate to the treadmill walking. Afterwards, they were moved to an ActiveStep treadmill (Simbex, NH). The belt speed for all following treadmill walking trials was set at each participant's pre-determined value. The actual belt speed and displacement were also registered by the ActiveStep treadmill controller. Each participant completed five treadmill walking trials, each approximately 30 s in duration. Full body kinematics data from 26 retro-reflective markers placed on the participants' body were gathered using an 8-camera motion capture system (Vicon, Oxford, UK) at 120 Hz. The fifth overground trial and the fifth treadmill trial were selected as the best representation of the two walking conditions for the comparison of dynamic gait stability control between them.

2.3. Data reduction

The timing for two characteristic and transient events in each gait cycle: touchdown (TD) and liftoff (LO), was identified from the foot and sacrum kinematics (Zeni et al., 2008). Temporal measures included the double (from TD to subsequent LO of the contralateral limb) and single (from LO to the following TD at the ipsilateral foot) stance phase times and the duration of the entire gait cycle (from TD to the following TD of the ipsilateral side).

Marker paths were low-pass filtered at marker-specific cut-off frequencies (ranging from 4.5 to 9 Hz) using fourth-order, zero-lag Butterworth filters (Winter, 2005). The locations of joint centers were computed from the filtered marker path by using transformations derived from anthropometric measurements (Vaughan et al., 1992). Spatial measurements included the step length, and