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Adaptive gait responses to awareness of an impending slip during treadmill walking

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ABSTRACT

The awareness of potential slip risk has been shown to cause protective changes to human gait during overground walking. It remains unknown if such adaptations to walking pattern also exist when ambulating on a treadmill. This study sought to determine whether and to what extent individuals, when being aware of a potential slip risk during treadmill walking, could adjust their gait pattern to improve their dynamic stability against backward balance loss in response to the impending slip hazard. Fifty-four healthy young subjects (age: 23.9 ± 4.7 years) participated in this study. Subjects' gait pattern was measured under two conditions: walking on a treadmill without (or normal walking) and with (or aware walking) the awareness of the potential slip perturbation. During both walking conditions, subjects' full body kinematics were gathered by using a motion capture system. Spatial gait parameters and the dynamic gait stability against backward balance were compared between the two walking conditions. The results revealed that subjects proactively adopted a "cautious gait" during aware walking compared with the normal walking. The cautious gait, which was achieved by taking a shorter step and a more flatfoot landing, positioned the body center of mass closer to the base of support, improving participants' dynamic stability and increasing their resistance against a possible slip-related fall. The finding from this study could provide insights into the dynamic stability control when individuals anticipate potential slip risk during treadmill walking.

1. Introduction

Falls are a significant health problem in elderly, a fast increasing population worldwide [1], with a serious economic burden to the healthcare system [2,3]. Falls precipitated by slips account for 40% of outdoor falls among community-living older adults [4]. Considerable efforts have been dedicated towards understanding the mechanisms of slip-related falls [5].

An essential component of investigating the underlying mechanisms of slip-related falls is to reproduce the real-life slip accidents [6]. Several techniques have been used to create real-life like slips in a laboratory environment, such as the contaminated surfaces [7–9], steel rollers [10], moved force plates [11], movable platforms [12,13], and treadmills [14,15]. Although the approaches of generating slips were various, the experimental protocols were similar among studies. Generally, subjects were instructed that they would initially walk normally without perturbation and later slip perturbations could happen [7–9]. Only a few studies examined the effects of the awareness or anticipation of the possible slip perturbation on gait pattern. Although some studies reported that awareness alone may not result in changes in temporal gait parameters, such as stance time [8,16] and swing time [8], other studies did find that adults would make significant gait changes when there is a potential risk of slipping during overground walking [7]. The preventive changes include a shortened step length and a reduced foot landing angle [7–9]. These alterations are considered features of "cautious gait", and have the potential to reducing the severity of slip or improving subjects' resistance to slips [7,10].

In previous studies concerning the effect of awareness of potential slip on gait pattern, subjects walked over ground [7,9]. Given the influence of the awareness of possible slip on gait pattern, the gait speed might vary between walking conditions, becoming a potential confounding factor. For example, subjects tend to walk more slowly when they anticipate the possible slip hazard than when they do not have such an anticipation while walking on a cross-slope slippery surface [9]. Therefore, the observed adaptive changes in gait pattern between normal and aware walking conditions could be attributed to at least two

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factors: the awareness of possible slip and the varied walking speed. It is nearly impossible to separate the contributions between these two factors to the observed adaptive gait changes during overground walking. The change in gait pattern could also be a by-product of the changed gait speed. Therefore, it remains unclear how the awareness alone affects gait pattern. A standard platform in which the gait speed can be precisely controlled across walking conditions is thus highly desired.

Treadmill has been broadly used in biomechanical research primarily due to its inherent advantages [14,17,18]. One of these advantageous features is the control of gait speed. Treadmill could thus be an ideal platform to pinpoint the influence of the awareness of a potential slip on the gait pattern. Additionally, treadmills with the capability of inducing slip perturbations are increasingly used in the field of fall prevention [14,18–21]. It however remains unknown if individuals, when made aware of the impending slip during treadmill walking, would also adapt their gait pattern in response to the potential slip risk. Thus, an in-depth understanding of how awareness of potential slip influences the gait pattern is needed to better interpret slip and fall experiments conducted on treadmills.

Dynamic gait stability has been identified as a key factor resulting in slip-related falls [13]. Technically, dynamic stability is characterized by the relative motion state (i.e. the position and velocity) between one's center of mass (COM) and the base of support (BOS) [22,23]. By using mathematical modeling, the feasible stability region (FSR) in the COM-BOS phase space was derived (Fig. 1) [22,23]. When one's COM motion is below the lower boundary of the FSR, the person would experience a backward balance loss – a precursor of a backward falls. The stability against backward balance loss is calculated by comparing the COM motion state to the lower boundary of the FSR [22]. No study has examined the effect of the awareness of potential slip hazards in dynamic gait stability while ambulating on a treadmill.

The primary goal of this study was to determine whether individuals, when being aware of a potential slip risk during treadmill walking, could adjust their gait pattern to improve their dynamic stability against backward balance loss in response to the impending slip. We hypothesized that adults would adopt a cautious gait pattern when anticipating the potential slip risk, by taking a shorter step and a flatter foot landing to improve their dynamic stability, compared with walking without the anticipation on a treadmill. Given the controlled gait speed, the design of this study allows us to determine that the gait adaptations, if any, which occur when aware of a potential slip, are not just a by-product of a slower walking speed.

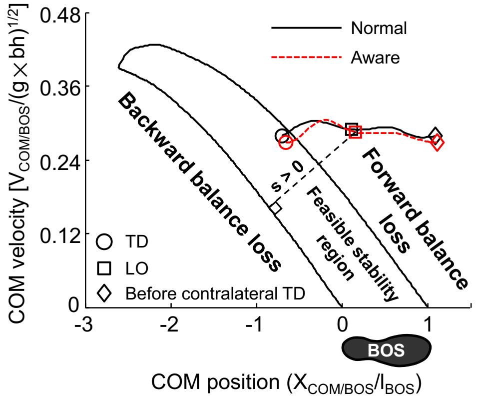

Fig. 1. Schematic illustration of the feasible stability region, which is enclosed by two boundaries: the one against backward balance loss (the lower boundary) and the one against forward balance loss (the upper boundary). The stability measurement (*s*, the length of the thin dashed line) indicates the magnitude of the instantaneous stability of the center of mass (COM) against backward balance loss, and is computed as the shortest distance from the COM motion state (i.e., the combination of position represented by the abscissa and velocity denoted by the ordinate) to the threshold against backward balance loss. Also shown are the representative COM motion state trajectories of a normal walking (the solid thin line) and an aware walking (the dotted thin line) progressing from the touchdown (TD, circle), through the contralateral foot liftoff (LO, square), and immediately prior to the contralateral foot TD (diamond). 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.

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 and 27 males) participated in this experiment. They were free of any known neurological, musculoskeletal, or other systemic disorders that would have affected their postural control. All participants gave written informed consent approved by the Institutional Review Board before the experiment.

2.2. Experimental protocol

Two walking conditions: without (or normal) and with (or aware) the awareness of an impending slip hazard, were measured and compared. After 5 overground walking trials upon a 14-m walkway, all subjects stepped onto a regular treadmill over which each subject's comfortable treadmill walking speed was determined. They also walked approximately 5 min to habituate to treadmill walking. They were then moved to an ActiveStep treadmill (Simbex, NH) and donned a full body safety harness attached to an overhead arch. Subjects were instructed that "the following trials will be normal walking ones without any perturbation." After walking 3–5 times at their self-selected gait speed as determined above, they walked three times at the speed of 1.2 m/s. They were then told that "from the next trial on, you may or may not experience a simulated slip in each trial. If a slip happens, try to recover your balance and then continue walking." Following the instructions, subjects walked two trials at the speed of 1.2 m/s without perturbation on the treadmill. Full body kinematics data from 26 retro-reflective markers placed on the subjects' body were gathered using an 8-camera motion capture system (Vicon, UK) at 120 Hz. The positions of the 26 markers include: vertex, ears, rear neck (C7), shoulders, right scapular, elbows, wrists, sacrum, greater trochanters, mid-thighs, knees, tibias, ankles, heels, and toes. The actual belt speed and displacement were also registered by the ActiveStep treadmill controller. Trials immediately before and after the verbal instruction regarding the upcoming slip were selected as the representative trials for the two walking conditions. The only difference between these two trials was the awareness of the impending slip while all other factors were controlled. Each trial on ActiveStep treadmill lasted approximately 30 s. To eliminate the effects of acceleration and deceleration of belt speed on our results, only the middle 15-s duration was considered. Approximately, 27.8 ± 2.2 and 28.5 ± 1.8 steps were analyzed for the normal and aware walking condition, respectively.

2.3. Data reduction

Marker paths were low-pass filtered at marker-specific cut-off frequencies (ranging from 4.5 to 9 Hz determined by the residual analyses [24]) using fourth-order, zero-lag Butterworth filters. Locations of joint centers, heels, and toes were computed from the filtered marker positions. Only the kinematic data on the sagittal