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Voluntary changes in step width and step length during human walking affect dynamic margins of stability

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ABSTRACT

"Cautious" gait is generally characterized by wider and shorter steps. However, we do not clearly understand the relationship between step characteristics and individuals' stability. Here, we examined the effects of voluntarily altering step width (SW) and step length (SL) on individuals' margins of stability. Fourteen participants completed three 3-min treadmill walking trials during three SL (short, normal with metronome, and long) and three SW (narrow, normal and wide) manipulation conditions. SL manipulations yielded significant changes in mean anterior–posterior (AP) margins of stability (MOS_{ap}) ($p < 0.0005$) but not mediolateral (ML) margins of stability (MOS_{ml}) ($p \geq 0.0579$). Taking wider steps increased mean MOS_{ml} while decreasing MOS_{ap} ($p < 0.0005$). Walking with either wider or long steps, each of which increases the base of support, yielded increased AP and ML MOS variability ($p \leq 0.0468$). Step-to-step analysis of MOS_{ml} indicated that subjects took stable steps followed immediately by stable steps. Overall, short-term, voluntary adoption of wider steps may help increase instantaneous lateral stability but shorter steps did not change lateral stability during unperturbed walking. We suggest that the observed changes in stability margins be considered in gait training programs which recommend short-term changes in step characteristics to improve stability.

1. Introduction

Stability is the capacity of a system to respond to perturbations [1,2]. During human walking, stability quantifies how we respond to perturbations from our environment or from within our own bodies that influence our ability to move. Clinical measures like step characteristics and step variability may predict fall risk [3–6], which is likely related to stability, and nonlinear techniques have been used to directly quantify stability during human walking [7–9]. We previously directly addressed how voluntary changes in step width (SW) and step length (SL) influenced local and orbital stability [10]. While this approach was useful in determining the overall stability of an individual, the techniques rely on averages over many steps or strides. Thus, information about the stability of individual steps or from one step to the next could not be determined.

To obtain information about instantaneous stability and step-to-step control we used the "extrapolated center of mass" (XcoM) approach proposed by Hof et al. [11]. This technique is based on the inverted pendulum model of walking, which estimates stability by considering the position of an individual's center of mass (COM) relative to his or her base of support (BOS). The XcoM, however, accounts for COM position *and* velocity and, when compared to the edge of the BOS, can be used to calculate an individual's dynamic margin of stability (MOS). If the XcoM is within the boundaries of the BOS (i.e. positive MOS), an individual is considered stable. This approach suggests a simple control of stability by using foot placement, particularly through SW, to control the MOS magnitude [12]. An individual can adjust the size, or boundary, of his BOS by making his steps wider, narrower, longer or shorter depending on the motion of his COM.

Previous studies have demonstrated that individuals maintain an approximately constant mean lateral MOS despite changes in walking surface type. Surface types examined have included overground (OG) [13–15], foam [13,14,16], treadmill [15]. However, these studies focused only on mean MOS over multiple steps, rather than MOS variability or step-to-step changes in MOS. We also found previously that mean MOS at heel strike changed minimally, though significantly, when people were subjected to different continuous, pseudo-random perturbations [17]. This was consistent with the earlier studies on surface type [13,15,16]. However, we observed significant increases in MOS variability and

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frequency of unstable steps (negative lateral MOS) when we applied perturbations medio-laterally [17].

The present study determined whether voluntarily adopting various SWs and SLs could alter instantaneous stability during walking. Wider and more variable step characteristics may predict increased risk of falling [3]. However, we do not know how adoption of these step characteristics independently influences stability of a single step or between steps. We hypothesized that participants would be more stable, i.e. have larger MOS, when walking with wider or shorter steps and that they would demonstrate increased MOS variability when adopting any walking strategy different from their preferred gait. We also hypothesized that examining step-to-step changes in stability would yield unique insights into how subjects controlled their stability from each step to the next that were not apparent in means and standard deviations of MOS.

2. Methods

Thirteen young healthy adults (seven males, six female; age, 18–35) participated. Participants were screened for history of lower extremity injuries, surgery or neurological conditions which could affect their gait. All participants provided written, informed consent prior to participation, and the study was approved by the Institutional Review Board at the University of Texas at Austin.

Participants walked on a motorized treadmill (ProXL Model, Woodway USA, Waukesha, WI), which had the control panel and railing removed. The treadmill belt was quite large: 68.58 cm (27″) wide by 223.52 cm (88″) long. This allowed individuals to walk with the required gait characteristics without risk of stepping off of the treadmill belt in any direction.

Participants completed a ~10 min warm-up by walking on the treadmill. The first 5 min were used to determine the participant's preferred walking speed (PWS) using an established protocol [18]. During the second 5 min each participant walked at his or her PWS to become familiarized with walking on the treadmill. Participants then completed three 3-min walking trials for each of six experimental conditions. During the normal (NO) condition, participants walked normally at PWS. During the normal metronome (NM) condition, they walked in time with a metronome adjusted to match their cadence during NO walking. During the SW manipulations, participants were instructed to walk with wider (WI) or narrower (NA) steps than normal. During the SL manipulations, participants walked with shorter (SH) or longer (LO) steps, which were achieved by walking in time with a metronome cadence that was 10 beats faster or slower, respectively, than their cadence during NM walking (i.e. ~10% faster or slower than NM). All gait manipulations were performed at each individual's PWS. The NO condition was always presented first. The remaining five conditions were presented in a random order to minimize learning effects. Participants were allowed to rest between conditions and during this time the treadmill belt was stopped.

Participants wore 57 reflective markers on their head, trunk, arms, legs and feet and 20 additional digital markers were created using a digitizing wand (C-Motion Inc.). Ten Vicon MX (Oxford Metrics, Oxford, UK) cameras recorded motion data at 60 Hz. Vicon Nexus software was used to reconstruct, label and export data for further processing. A 13-segment model was created for each participant using Visual 3D software to determine center of mass (COM) motion. COM velocity ($\dot{COM}$) was calculated as the first derivative of the COM position using Visual3D.

The margin of stability (MOS) calculation was adapted from Hof et al. [11] and defined as

$$MOS = BOS - XcoM \quad (1)$$

where BOS was the location of the boundary of the base of support (Fig. 1A). XcoM was the extrapolated center of mass defined as

$$XcoM = COM + ((\dot{COM})/\omega_0) \quad (2)$$

where COM was the center of mass location, $\dot{COM}$ was the COM velocity and $\omega_0 = \sqrt{g/l}$ where g was 9.8 m/s^2 and l was the pendulum length, approximated as the distance between the COM and the lateral heel marker (≈leg length).

MOS was calculated at each heel strike in both the anterior–posterior (MOS_{ap}) and mediolateral (MOS_{ml}) directions, as it was previously shown that the minimum MOS occurred approximately at heel strike [11,19] (Fig. 1A). The anterior–posterior edge of the BOS was defined by the anterior–posterior position of the toe marker on the leading foot (i.e. the foot in heelstrike). The mediolateral edge of the BOS was defined by the location of the lateral heel marker, which was placed directly distal to (below) the lateral malleolus. MOS was always calculated such that positive MOS indicated stability (i.e. XcoM was within the BOS) and negative MOS indicated instability (i.e. XcoM was outside of the BOS). Therefore, MOS could also be defined as MOS = XcoM − BOS, depending on the side of the body being analyzed.

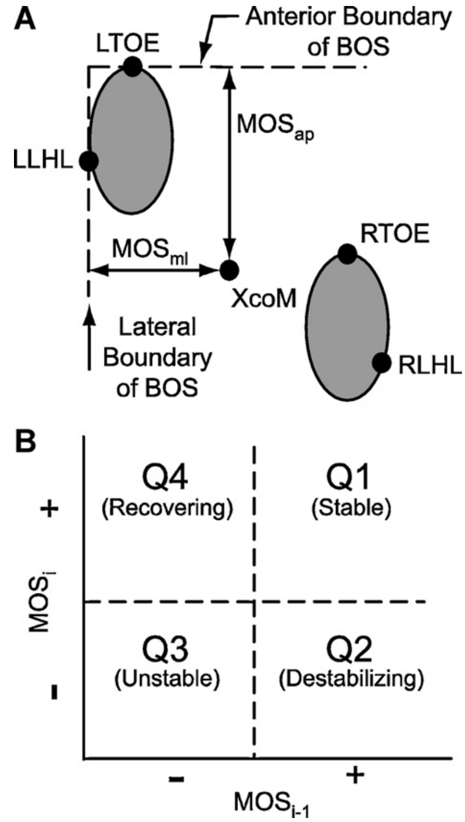

Fig. 1. (A) MOS_{ap} was defined as the distance between the anterior boundary of the BOS, defined by the leading toe marker (LTOE, as in the figure, or RTOE), and the XcoM. MOS_{ml} was defined as the distance between the lateral boundary of the BOS and the XcoM. The lateral boundary of the BOS was defined by the lateral heel marker (LLHL and RLHL for the left and right foot, respectively) of the lead foot. Here, the left foot is shown leading. (B) Quadrants of the MOS first-return maps were defined to compare step-to-step variability of MOS.

To determine how the MOS of any one step (MOS_{i-1}) directly affected the MOS of the immediately following step (MOS_i), we examined the distribution of steps in four quadrants of the MOS_i vs. MOS_{i-1} plane, similar to a first-return map [20,21] (Fig. 1B). Data points in quadrants 1 (Q1) and 2 (Q2) indicated initially stable (i.e. positive MOS) steps that were immediately followed by either stable (Q1) or unstable (Q2) steps. Data points in quadrants 3 (Q3) and 4 (Q4) indicated initially unstable steps that were immediately followed by either unstable (Q3) or stable (Q4) steps. Increases in Q4 population indicated that an individual corrected an unstable step so that the subsequent step was stable.

Two-way analyses of variance (ANOVA) (Condition × Subject) were used to determine differences in MOS_{ap}, MOS_{ml} and MOS variability for the SW (NA, NO and WI) and SL (SH, NM and LO) manipulations. Two-way ANOVA was also used to determine differences in MOS between conditions when the right vs. the left foot was in heelstrike (Condition × Side). p-Values < 0.05 were considered significant. All statistical analyses were conducted using Minitab (Minitab Inc., State College, PA).

3. Results

SL manipulations yielded significant changes in MOS_{ap} ($p \le 0.0005$) but not in MOS_{ml} ($p \ge 0.0579$; Fig. 2A). Walking with long steps increased both MOS_{ap} variability ($p = 0.0026$) and MOS_{ml} variability ($p = 0.0468$; Fig. 2B).

Walking with narrow steps caused a significant decrease in MOS_{ml} ($p = 0.0045$; Fig. 3A), and walking with wide steps caused a significant decrease in MOS_{ap} and increase in MOS_{ml} ($p \le 0.0005$) relative to NO walking. Narrow steps did not affect MOS_{ap} variability or MOS_{ml} variability ($p \ge 0.0796$; Fig. 3B). However, wide steps were associated with increases in both MOS_{ap} variability and MOS_{ml} variability ($p \le 0.0003$).