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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-minute treadmill walking trials during 3 SL (short, normal with metronome, and long) and 3 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}) ($p = 0.0579$). 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 ($p = 0.0468$). 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.

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

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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) [13-16], 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 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.

METHODS

Thirteen young healthy adults (7 male, 6 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 minute warm-up by walking on the treadmill. The first 5 minutes were used to determine the participant’s preferred walking speed (PWS) using an established protocol [18]. During the second 5 minutes each participant walked at his or her PWS to become familiarized with walking on the treadmill. Participants then completed

three 3-minute walking trials for each of 6 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 5 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:

$$MOS = BOS - X_{coM} \quad (1)$$

where BOS was the location of the boundary of the base of support (Fig. 1A). X_{coM} was the extrapolated center of mass defined as:

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

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/s² and l was the pendulum length, approximated as the distance between the COM and the lateral heel marker ($\approx$ 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. X_{coM} was within the BOS) and negative MOS indicated instability (i.e. X_{coM} was outside of the BOS). Therefore, MOS could also be defined as, $MOS = X_{coM} - BOS$, depending on the side of the body being analyzed.

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 $\times$ 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 $\times$ Side). P-values < 0.05 were considered significant. All statistical analyses were conducted using Minitab (Minitab Inc., State College, PA).

RESULTS

SL manipulations yielded significant changes in MOS_{ap} ($p = 0.0005$) but not in MOS_{ml} ($p = 0.0579$; 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} ($p = 0.0005$) relative to NO walking. Narrow steps did not affect MOS_{ap} variability or MOS_{ml} variability ($p = 0.0796$; Fig. 3B). However, wide steps were associated with increases in both MOS_{ap} variability and MOS_{ml} variability ($p = 0.0003$).

There were significant Condition $\times$ Subject interactions for all of the MOS and MOS variability ($p = 0.0005$). Thus, subjects responded to the gait manipulations differently.

There was a significant side effect (MOS on the right side versus the left side) for MOS_{ml} ($p = 0.017$) for the SL manipulations. However, when a three-way ANOVA (Condition $\times$ Subject $\times$ Side) was subsequently performed the main effect for Side was not significant ($p = 0.292$) indicating that the significance of the two-way ANOVA result was likely due to not accounting for variance attributable to subjects. There were no significant Side effects for MOS_{ap} or MOS_{ml} for the SW manipulations.

All data points in the first-return plots for both MOS_{ap} and MOS_{ml} for both the SL (Fig. 4) and SW (Fig. 5) manipulations were in Q1. This indicates that stable steps were always followed by stable steps although the magnitude of stability may have varied.

DISCUSSION

Simple, voluntary changes in gait characteristics significantly altered both AP and ML stability during human walking. Walking with any change in SL significantly altered mean AP stability, but had no significant effect on ML stability. Conversely, walking with wider steps increased mean ML stability while decreasing AP stability. Walking with either longer or wider steps resulted in both increased AP and ML stability variability.

Our subjects did not consistently exhibit increased stability when walking with wider or shorter steps as we hypothesized. Rather, wider steps influenced ML and AP stability in opposing ways, and shorter steps had no effect on ML stability but decreased AP stability. That voluntarily changing SW could significantly alter ML stability was noteworthy as previous work demonstrated that MOS_{ml} did not change significantly when walking on different surfaces [15] and changed only minimally while undergoing physical or visual perturbations [17]. Results of those earlier studies are important because we would expect SW, and consequently the location of the BOS boundaries, to change significantly with walking surface changes or perturbations. Rosenblatt and Grabiner [15] suggested that individuals may voluntarily increase SW when walking on different surfaces to increase lateral stability; however, they proposed that the increase in SW simply maintains mean MOS. Likewise, the studies on surface type and perturbations collectively indicate that foot placement might be adjusted step-to-step to maintain some desired mean MOS_{ml} . The

present results indicate, however, that individuals can “override” the desired MOS_{ml} and that voluntary increases in SW can actually increase mean MOS_{ml} . While this result may seem contradictory, we specifically instructed our subjects to walk with wider (and narrower) steps than normal rather than allowing them to change their SW naturally in response to an outside stimulus (i.e. a change in walking surface or in response to a perturbation). Thus, voluntarily walking with wider than normal steps, in this case on a treadmill, can increase mean lateral stability.

Walking with either wider or shorter steps decreased AP stability. There seem to be reasonable physical explanations related to the BOS for both of these observations. First, when walking with wider steps, an individual’s leg length constrains the maximum feasible step one can take. This maximum step will be shorter when walking with wider steps. Second, the AP MOS is defined as the AP distance from the XcoM to the toe marker of the leading foot. Intentionally taking shorter steps will decrease MOS because the leading foot will not be placed as far anteriorly when stepping.

The second hypothesis of our study was that MOS variability would increase with any voluntary change in gait. Again, subjects did not consistently demonstrate increased variability with changes in gait. Rather, walking with wider or longer steps was associated with increased AP and ML stability variability and walking with narrower or shorter steps had no effect on variability. Walking with either wider or longer steps serves to increase the BOS in the ML or AP directions, respectively, whereas walking narrower or shorter steps decreases the BOS. Intuitively, individuals could increase their BOS (widen or lengthen their steps) in more ways than they could decrease their BOS, thus allowing for increased variability with wider or longer steps, but narrower or shorter.

Our final hypothesis focused on insights gleaned from step-to-step analysis of stability. We proposed that step-to-step analysis would yield outcomes not apparent in mean MOS or MOS variability. We expected the shift in mean lateral stability during the SW manipulations, for example, to be most evident in the distribution of step-to-step changes of MOS_{ml} (Fig. 5B). From previous work involving individuals walking in perturbing environments, we anticipated a negative relationship between the stability of one step and the immediately following step (i.e. as MOS_{i-1} increased, MOS_i decreased), which would indicate that participants were likely controlling their stability between steps [17]. In the current study, where gait changes were voluntarily applied, however, we did not see this distinctive pattern (Fig. 5B). Instead we observed that regardless of the voluntary change in gait, participants were always stable at heelstrike, though the magnitude of their MOS varied subtly (Fig. 3) and data points in the first-return plots tended to be in a circular cluster (Fig. 4 and 5). A circular cluster of data points indicates no apparent link between the stability of one step and the next and to observe such a pattern would support the idea that stability is passively controlled during walking. While AP stability maybe passively controlled during walking, ML stability is likely actively controlled [22]. Our results could be indicating that for this set of voluntary changes in step characteristics, lateral stability was being passively controlled, or else achieved with some minimal amount of active control. However, it is also possible that our voluntary changes in gait did not provide enough of a “perturbation” to the whole person, relative to normal walking, to warrant the degree of control that was necessary to walk in a visually or physically perturbing environment.

Observing differences in MOS between the right and left sides of the body indicates the presence of gait stability asymmetry. While this trend has been observed by others [15], and we anticipated observing it in the present study, the only statistically significant trend was during the SL manipulation conditions and only for MOS_{ml} ($p = 0.017$). However, when we examined this result more closely and accounted for variance attributable to subjects (3-

factor ANOVA with Condition $\times$ Subject $\times$ Side), there was no significant asymmetrical trend in MOS (Side p -value = 0.292). It is possible that we do not have sufficient subjects to observe statistical significance of these trends; however, it is also possible that the trends are simply an artifact of the subjects who participated in the study. Regardless, we still suggest that trends in asymmetry are worthy of further consideration as there are important clinical implications regarding the goal of symmetrical walking patterns if asymmetries of stability exist even in healthy, young subjects.

In conclusion, we found that MOS could be manipulated through voluntary changes in gait characteristics. Specifically, increasing SW altered both AP and ML stability as well as stability variability, whereas changing SL only affected AP stability. These changes in stability should be considered when asking individuals in fall prevention training or other gait rehabilitation programs to adopt altered gait characteristics. As only the short-term voluntary adoption of altered gait characteristics was examined in the current study, further research is needed to determine the long-term influence of voluntary gait changes on stability as well as how both short- and long-term changes in gait characteristics influence stability in older adult and/or patient populations.

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Figure 1.

(A) MOS_{ap} was defined as the distances 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.

Figure 2. (A) MOS and (B) MOS variability results for SL manipulations. Error bars indicate standard deviation of mean MOS between trials. * indicate significant difference from NM at $p < 0.05$.

Figure 3. (A) MOS and (B) MOS variability results for SW manipulations. Error bars indicate standard deviation of mean MOS between trials. * indicate significant difference from NO at $p < 0.05$.

Figure 4.

First-return maps (MOS_i vs. MOS_{i-1}) for (A) AP and (B) ML MOS for the SL manipulations. Red circles indicate MOS_{i-1} at left heel strike and black 'x' indicate MOS_{i-1} at right heel strike.

Figure 5.

First-return maps (MOS_i vs. MOS_{i-1}) for (A) AP and (B) ML MOS for the SW manipulations. Red circles indicate MOS_{i-1} at left heel strike and black 'x' indicate MOS_{i-1} at right heel strike.