Stability-normalised walking speed: a new approach for human gait perturbation research

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Abstract

Self-selected walking speeds or a prescribed walking speed are commonly used in gait stability research. However, a prescribed walking speed will not result in equivalent stability for all participants, which is problematic when comparing groups with different capacities. When using self-selected walking speeds, however, the difficulty in recovering stability following perturbations can vary with walking speed. Here, we present a method for decreasing inter-individual differences in gait stability by adjusting walking speed. Eighteen healthy adults walked on a treadmill (CAREN; Motekforce Link, Amsterdam, The Netherlands) for two minute bouts at 0.4m/s up to 1.8m/s in 0.2m/s intervals. The stability-normalised walking speed was calculated using the mean margin of stability (MoS) at touchdown of the final 10 steps of each speed and the participants then walked for three minutes at this speed. Large ranges in MoS were observed during the different prescribed speeds (6-10cm across speeds) and walking speed significantly ($P<0.001$) affected MoS, even within these healthy participants. The stability-normalised walking speeds resulted in MoS equal or very close to the desired outcome of 0.05m and reduced between-participant variability in MoS. No significant correlations between the determined stability-normalised walking speeds and the participants' height or leg length were found ($P=0.44$ and $P=0.52$, respectively). The current method decreases inter-individual differences in gait stability which may be beneficial for gait perturbation and stability research. An equation is provided that can be used following a single gait trial to decrease between-participant variability in gait stability.

Keywords: locomotion, margins of stability, falls, postural balance, motor control, dynamic stability

Introduction

Mechanical perturbations have been used for decades to investigate the stability of human walking [1-5] and are now frequently investigated in falls prevention contexts [6-8]. In gait perturbation studies, self-selected walking speeds [see, for example: 9] or a prescribed walking speed for all participants [e.g. 10] are commonly used, but each comes with drawbacks that complicate the interpretation of results. A prescribed walking speed will not result in comparable stability for all participants. This is problematic when comparing groups with different capacities during a gait perturbation task, as the relative challenge of the task will vary. Self-selected walking speeds, however, introduce other problems. Walking speed affects recovery strategy choice following slips [11] and trips [12], the direction of balance loss following slipping [13] and differentially affects falls risk following tripping and slipping, with faster speeds leading to an increased and decreased falls risk following tripping and slipping, respectively [11, 14, 15]. Gait stability at perturbation onset may also not be optimised at the self-selected speed, and may differ across groups [11, 16-18]. The assessment of gait stability is also confounded by walking speed, as walking speed affects measures of global [11, 17, 18] and local [19-22] dynamic gait stability. Therefore, more sophistication in the choice of walking speed may be necessary for detailed study of reactive gait stability and adaptation processes.

Two possible solutions to these issues have been applied in previous studies using gait perturbations. Two studies have used 60% of the walk-to-run velocity in order to normalise the speed during perturbation exposure to participants' neuromuscular capacities [23, 24] and a Froude number (a dimensionless parameter) for walking speed [25] has been applied in a number of studies to normalise the walking speed [26-29]. However, as these are normalisations based solely on neuromuscular capacities or body dimensions, which are not the sole determinants of gait stability, not all of the above described issues will be addressed. As a result, further attempts to tackle these issues are warranted [30, 31]. Here, we present and demonstrate a new method for decreasing inter-individual differences in gait stability and reducing the influence of walking speed on gait stability results by adjusting the walking speed.

Methods

Participants

Eighteen healthy adults participated in this study (eight males, 10 females; age: 24.4±2.5y; height: 174.9±7.4cm; weight: 74.6±15.2kg). The participants had no self-reported history of walking difficulties, dizziness or balance problems, and had no known neuromuscular condition or injury that could affect balance or walking. Informed consent was obtained and the study was conducted in accordance with the Declaration of Helsinki. The study protocol was approved by the Maastricht University Medical Centre medical ethics committee.

Setup and Procedures

The Computer Assisted Rehabilitation Environment Extended (CAREN; Motekforce Link, Amsterdam, The Netherlands), comprised of a dual-belt force plate-instrumented treadmill (Motekforce Link, Amsterdam, The Netherlands; 1000Hz), a 12 camera motion capture system (100Hz; Vicon Motion Systems, Oxford, UK) and a virtual environment that provided optic flow, was used for this study. A safety harness connected to an overhead frame was worn by the participants during all measurements. Five retroreflective markers attached to anatomical landmarks (C7, left and right trochanter and left and right hallux) were tracked by the motion capture system. Measurement sessions began with familiarisation trials with participants walking at 0.4m/s up to 1.8m/s in 0.2m/s intervals. At least 60s were used for each speed. Participants were then given approximately five to ten minutes rest before continuing with the measurements. Single two-to-three minute long measurements were then conducted at 0.4m/s up to 1.8m/s in 0.2m/s intervals. Following these measurements, the stability-normalised walking speed was calculated. In order to determine the stability-normalised walking speed, the mean anteroposterior margins of stability (MoS; see below) at foot touchdown of the final 10 steps of each walking trial (0.4m/s to 1.8m/s) were taken and were fitted with a second order polynomial function. For each participant, the walking speed that would result in MoS of 0.05m was calculated from the function. Participants then walked for three minutes at the stability-normalised walking speed. The goal of this method is to make comparisons of different-capacity groups more valid and based on our pilot testing, this value of 0.05m results in walking speeds that are feasible for a broad range of participant groups with varying locomotor capacities or (dys)function.

Data Processing and Analysis

Marker tracks were filtered using a low pass second order Butterworth filter (zero-phase) with a 12Hz cut-off frequency. Foot touchdown was detected using a combination of force plate (50N threshold) and foot marker data [32]. This combination was used to be able to accurately account for touchdowns and toe-offs occurring in the centre of the treadmill that simultaneously triggered both force plates. For all steps, the foot marker method was used and then corrected based on the average discrepancy between the force plate method and the marker method timing for all steps that contacted only one force plate. The anteroposterior MoS were calculated at foot touchdown as the difference between the anterior boundary of the base of support and the extrapolated centre of mass (X_{CoM}) as defined by Hof et al. [33], adapted for our reduced kinematic model based on Süptitz et al. [17]:

$$X_{CoM} = \frac{P_{TroL} + P_{TroR}}{2} - P_{HalluxP} + \frac{0.5\left(\frac{V_{TroL} + V_{TroR}}{2} + V_{C7}\right) + |V_{Belt}|}{\sqrt{\frac{g}{L_{Ref}}}}$$

where P_{TroL}, P_{TroR} and $P_{HalluxP}$ represent the trochanter and the rearmost hallux marker positions respectively; V_{TroL}, V_{TroR} and V_{C7} are the velocities of the trochanter and C7 markers respectively; V_{Belt} is the treadmill belt velocity; g is gravitational acceleration (9.81m/s^2); and L_{Ref} is the reference leg length.

Statistics

A one-way repeated-measures ANOVA with walking speed as a factor was used to confirm a walking speed effect on the MoS. To confirm that the stability-normalised walking speed was not associated with body dimensions and thereby confirm that a dimensional normalisation of walking speed does not assume equivalent gait stability, Pearson correlations between the stability-normalised walking speeds and participants' height and leg length were conducted. Significance was set at α=0.05. Analyses were performed using GraphPad Prism version 7.03 for Windows (GraphPad Software Inc., La Jolla, California, USA).

Results and Discussion

Walking speed significantly affected the MoS (n=17, $F_{[2.3, 37]}$=1537, P<0.0001; Fig. 1) and Tukey's multiple comparisons tests revealed significant differences for each speed compared to all other speeds (P<0.0001; Fig. 1). These results are in agreement with previous work [11, 17, 18]. A range of MoS values were observed for each speed (approximately 6-10cm across the speeds), even among these healthy participants, confirming some of the issues related to prescribed walking speeds in gait stability research discussed above. The significant relationship between walking speed and MoS (Fig. 1) is relevant for intervention studies conducting self-paced gait measurements. In such studies, participants who walk significantly faster post-intervention will demonstrate a reduction in MoS, which may be misinterpreted as a decline in gait stability, when in fact it is an artefact of the improvement in walking speed and not a worsening of gait stability *per se*.

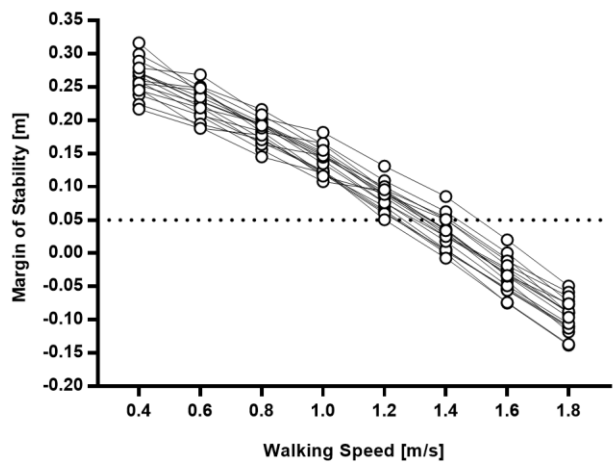

Fig. 1. Individual margins of stability at foot touchdown over the different walking speeds. The dashed line represents the margin of stability used to determine the stability-normalised walking speed.

The stability-normalised walking speeds resulted in MoS values very close to the desired outcome of 0.05m, which was within one standard deviation of the mean MoS for 15 of the 18 participants (Fig. 2A). The stability-normalised walking speed also reduced between-participant variability in MoS (as demonstrated by the group level standard deviations for the different walking speed trials; Fig. 2B). Taken together, these results indicate that the stability-normalisation was successful in reducing between-participant differences in MoS during treadmill walking, even in this homogenous group of healthy young adults. Future work should investigate if this method would lead to different patterns of results between different age or patient groups in response to mechanical gait perturbations than those commonly reported in literature. In theory, this method would reduce or remove

artefacts in the outcome measure (MoS) due to walking speed and remaining differences would reflect specific differences in gait stability.

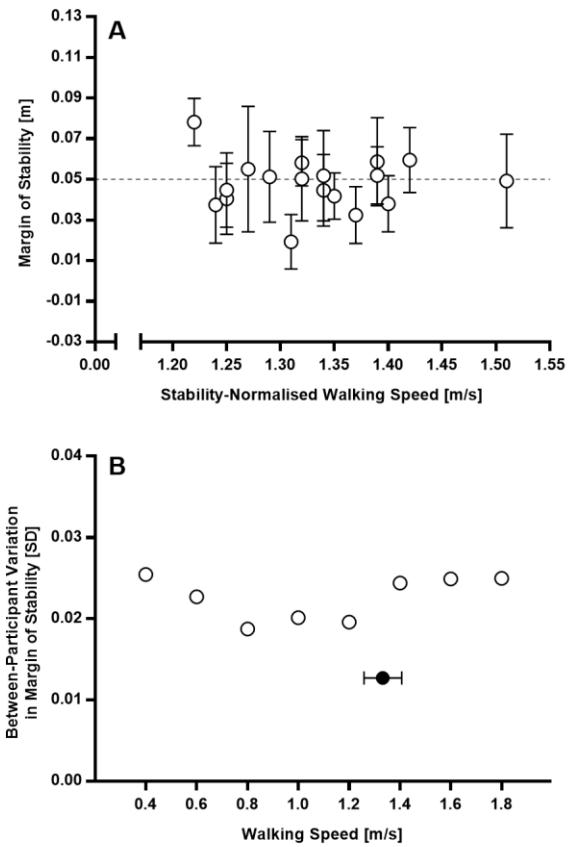

Fig. 2. A: Means and standard deviations of the margins of stability at touchdown of the final 10 steps at the stability-normalised walking speed for each individual participant. The desired MoS of 0.05m at foot touchdown is indicated by the dashed line. **B**: The between-participant variation in the margins of stability (standard deviation at group level) for the final 10 steps at each walking speed (the stability-normalised walking speed trials are indicated with the black circle; mean and standard deviation).

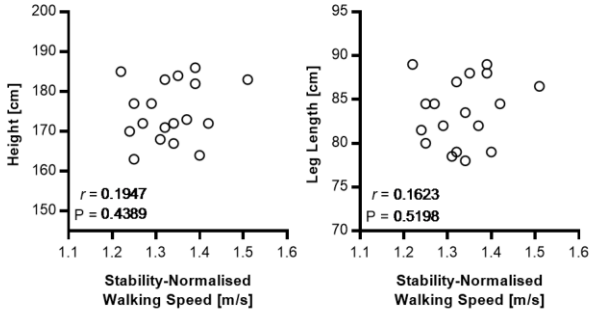

Fig. 3. Pearson correlations between the participants' stability-normalised walking speeds and their height and leg length.

Small, non-significant correlations between the determined stability-normalised walking speeds and the participants' height and leg length were found (Fig. 3). The outcomes of our correlation analysis suggest that height and leg length did not significantly affect the calculation of stability-normalised walking speed, suggesting that a normalisation of walking speed based on body dimensions (e.g. a dimensionless Froude number for walking speed [25]) does not assume equivalent gait stability, at least not when assessed by the MoS concept.

As the relationship between walking speed and MoS from 1.0-1.6m/s appeared to be consistently linear (Fig. 1), potentially due to the increasing influence of the X_{CoM} on the MoS at faster speeds [17], a simple linear regression was calculated using MoS data from 1.0-1.6m/s. A significant regression equation was found (Fig. 4). Future research could therefore use this as a simple, efficient method for decreasing the between-participant variability in MoS, by measuring participants walking at a single speed from 1.0-1.6m/s and using this equation to prescribe speeds that would result in similar MoS values. It is, however, worth highlighting that the current participants were young healthy adults and the walking speed – MoS relationship may be altered in other populations.

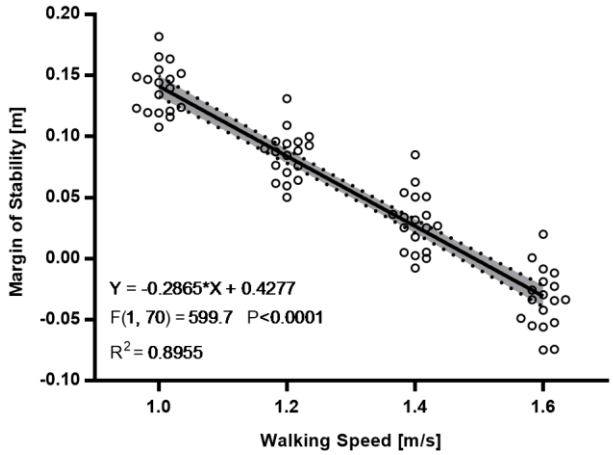

Fig. 4. Margins of stability as a function of walking speed between 1.0 and 1.6m/s. The shaded area represents the 95% confidence intervals of the regression line.

We were able to show that the method successfully reduced the inter-individual differences in the MoS, but this resulted in participants walking at different speeds (Fig. 2A). As a result, if we applied an identical mechanical perturbation to the participants, the different walking speeds would result in relatively different challenges to stability [31]. However, this issue can be addressed using a velocity-based perturbation, such as a treadmill belt acceleration, by normalising this to each individual's stability-normalised walking speed. Future research should explore such possibilities for normalising perturbation magnitude to walking speed.

In conclusion, large ranges in MoS were observed and walking speed significantly affected the MoS, even within these young healthy participants, confirming some issues related to walking speed choice in gait stability research. The current method reduced between-participant variability in MoS, meaning that the method could be beneficial for gait stability studies comparing groups with different locomotor capacities. An equation has been provided that can be used following a single gait trial to decrease between-participant variability in gait stability.

Conflict of Interest

The authors declare no conflict of interest.

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