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# Dynamic stability during split-belt walking and the relationship with step length symmetry

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ABSTRACT

*Introduction:* Walking instability is a contributor to falls and other undesired changes in walking performance. We investigated the effect of split-belt treadmill based perturbations on dynamic stability. Furthermore, we examined the relationships for dynamic stability and symmetry during unperturbed and perturbed walking.
*Method:* Twenty healthy young adults completed unperturbed and perturbed walking conditions on a split-belt treadmill. The continuous perturbation involved moving the parallel belts at unequal speeds (1.5 m/s: 0.5 m/s). Margins of stability (MoS) and step length symmetry (SYM) were assessed.
*Results:* Stability and symmetry measures each decreased at the onset of the split walking perturbation. Only anterior-posterior (AP) MoS and SYM exhibited adaptive changes. Associations were found primarily for AP MoS with immediate changes in SYM at the onset of split walking, and over the duration of the split walking condition.
*Discussion:* Our findings suggest walking strategies were adapted to maintain dynamic stability when faced with a continuous perturbation. Additionally, dynamic stability was associated with symmetry during perturbed walking.

## 1. Introduction

Each year a large percentage of individuals with common neuromusculoskeletal impairments (e.g., post amputation, stroke) experience a fall [1,2]. Not surprisingly, significant resources are directed toward identifying characteristics contributing to or preventing falls. Though falls are provoked by multiple factors, walking instability is recognized as a primary contributor, and measures assessing dynamic stability are increasingly prevalent in gait research [3–11].

Interestingly, authors using the margin of stability (MoS) [12], a measure of dynamic stability integrating center of mass (CoM) velocity effects into CoM maintenance within the base of support (BoS), suggested recently a primary objective of gait may be to maintain dynamic stability at or above a threshold level [5,13–15]. For example, stroke survivors increased stride width, and therefore medial-lateral (ML) BoS, to potentially compensate for the destabilizing effect of increased CoM movement [3,16]. Furthermore, healthy adults were observed to reactively increase their anterior-posterior (AP) MoS with repetitive unexpected gait perturbations [9], and proactively increased their backwards MoS before, during, and immediately following repeated slip perturbations [17]. Though optimization of energy cost may drive selection of gait characteristics [18,19], an innate drive to maintain stability would likewise make intuitive sense given an outcome of instability is a potentially injurious fall.

From this perspective, stability may be maintained at the expense of other characteristics of normal walking, such as symmetry. It is therefore not surprising that temporal-spatial asymmetry was closely related to performance on tasks involving dynamic balance among stroke survivors [20]. However, drawing definitive conclusions about the relationship is difficult in clinical populations, as instability and asymmetry stem from internal sources (e.g., neuromuscular weakness, somatosensory loss) or may be provoked by external conditions (e.g., walking surface, use of a prosthetic device). One way to examine the relationship between stability and symmetry is through continuous perturbations created by parallel belts of a split-belt treadmill moving at different speeds (commonly a 2:1 or 3:1 ratio). In these studies, neural processes (described in greater detail elsewhere [21]) instigate immediate reactive accommodations at perturbation onset followed by trial-and-error predictive feedforward changes as walking in the perturbed conditions continues. Step length symmetry (SYM) responds the

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most robustly with reactive asymmetry early and improvement toward baseline symmetry over time [22]. While the adaptive response for measures of dynamic stability is unknown, a split-belt testing paradigm provides the means to systematically evaluate the relationship between dynamic stability and symmetry across changing walking conditions.

The purpose of our study was twofold. Our first objective was to determine the effect of split-belt treadmill based perturbations on dynamic stability. We hypothesized MoS, our measure of dynamic stability, would initially decrease at the onset of split belt walking (greater instability), followed by adaptive changes increasing stability. An improved MoS could reflect the underlying motivation to maintain stability, and would mirror the well-known adaptive response in SYM. Our second objective was to examine the relationships for MoS and SYM during unperturbed and perturbed walking. We hypothesized stability and symmetry would demonstrate strong associations for baseline measures and with changes observed during a split walking condition.

## 2. Methods

### 2.1. Participants

Twenty healthy young adults without orthopedic or neurologic injuries were recruited to participate in the study (age 27.0 ± 5.0 years, height 1.72 ± 0.11 m, weight 73.0 ± 12.6 kg, 9 males/11 females). Participants had no prior experience walking on a split-belt treadmill with the belts moving at different speeds. All participants gave written informed consent before completing the study protocol.

### 2.2. Protocol

Stability and symmetry were assessed during normal and perturbed walking conditions created using a standardized split-belt treadmill testing paradigm [22]. The treadmill (Bertec Corp., Columbus, OH) is configured with two belts with separate controls such that both belts can move at the same speed ('tied'), or one belt can move faster than the other ('split'). The split condition creates a novel continuous perturbation well suited to assessing the relationship between stability and symmetry.

Testing consisted of baseline tied walking conditions and a split walking condition. The baseline conditions involved walking with belt speeds tied, first at a speed of 0.5 m/s then at a speed of 1.5 m/s. Each baseline condition lasted 3 min. The belts were then set to a split condition in which one belt moved at 0.5 m/s (slow belt), while the other belt was abruptly made to move at 1.5 m/s (fast belt). Participants completed a 10-s bout of the split condition to familiarize the participant to the continuous perturbation without lasting long enough to produce any adaptation. Three minutes of slow tied walking followed the familiarization to ensure any potential effects of the familiarization were minimized (washed-out). Participants then walked in the split condition for 15 min.

Motion capture data for the lower extremities, pelvis and trunk segments were collected during testing at 100 hz using a 12-camera system (Vicon, Oxford, UK) and 45 reflective markers. These data were synchronized with analog data collected at 1000 hz from force plates integrated in the treadmill. Gait events (initial contact and toe-off) were determined using vertical ground reaction forces measured by the treadmill force plates. Temporal-spatial parameters were derived from the combined motion capture and force plate data and used in calculating step-by-step values for symmetry and dynamic stability.

SYM was determined using a ratio of the difference in step length [22]:

$$\mathrm{SYM} = (\mathrm{SL}_{fast} - \mathrm{SL}_{slow})/(\mathrm{SL}_{fast} + \mathrm{SL}_{slow})$$

where $\mathrm{SL}_{fast}$ and $\mathrm{SL}_{slow}$ represent the step length for the limb assigned to the fast and slow belt respectively during the split condition. Perfect symmetry in step length would produce a value of 0. A negative symmetry value would indicate the step on the fast belt was shorter than the step on the slow belt. A positive value reflects the inverse relationship.

Dynamic stability was assessed using the margin of stability (MoS) [12]. The MoS expands upon the classic rule for stability requiring the CoM to remain within the BoS. Unlike the classic approach, MoS accounts for the effects of CoM velocity in a calculation termed the extrapolated CoM (xCoM). Theoretically, instability and the risk for falls increases as the xCoM nears the margins of the BoS even though the CoM position is at that moment within the BoS. MoS was calculated for the ML and AP directions as [12]:

$$\mathrm{MoS} = \mathrm{BoS} - \mathrm{xCoM}$$

with,

$$\mathrm{xCoM} = x + x'/\omega_0$$

MoS was calculated separately for each lower extremity and averaged. The toe marker of the leading foot was used to demarcate the anterior border of the BoS in calculating anterior-posterior (AP) MoS, and the fifth metatarsal marker was used for the lateral border when calculating the ML MoS. x represents the position of the CoM, and x' is the velocity of the CoM. CoM was approximated at the mid-point of right and left superior iliac spine markers. $\omega_0$ was the angular eigenfrequency of the pendulum according to the inverted pendulum model of human walking ($\omega_0 = \sqrt{(l/g)}$ where l is equal to leg length and g is equal to the acceleration caused by gravity).

Symmetry and dynamic stability values for each step were averaged into 5 steps epochs. Epochs representing the last 5 steps of the slow tied baseline condition, the first 5 steps taken during the split condition ("split early"), and the final 5 steps of the split condition ("split late") were used in the statistical analysis.

### 2.3. Statistical analysis

Within-subjects Analysis of Variance (ANOVA) models were used to compare means from baseline, split early, and split late values for step length for each limb, stride width, SYM, ML MoS, and AP MoS. A Greenhouse-Geisser correction was used to correct for violations of the assumption of sphericity. Follow-up tests were performed using paired *t*-tests. A Bonferroni correction of alpha/2 was used to keep family-wise alpha to the desired level. Pearson's correlation (r) was used to examine the relationship between conditions in each variable, and between AP MoS and SYM and ML MoS and SYM. Data outliers were excluded from individual correlations when Cook's Distance was greater than 1. Correlation coefficients (r) of < 0.25 were considered weak, 0.25–0.5 fair, 0.5–0.75 moderate to good, and > 0.75 good to excellent relationships [23]. Correlations were calculated in R version 3.2.3. All correlation tests were conducted with an alpha 0.05.

## 3. Results

### 3.1. Response to split walking

The testing produced anticipated changes in SYM as symmetric baseline walking became highly asymmetric during early split walking but improved toward baseline over the course of the split walking condition (Fig. 1A). A similar response to SYM was observed in MoS (Fig. 1B and C) except that ML MoS did not improve toward baseline by the conclusion of split walking. As such, ANOVA testing revealed significant differences for all parameters (all $p < 0.001$).

Overall, participants exhibited a SYM of 0.01 ± 0.05, an AP MoS of 0.40 ± 0.03 m, and a ML MoS of 0.12 ± 0.02 m during tied baseline walking at the slow speed (0.5 m/s) (Table 1). The perturbation produced by split walking resulted in reactive changes including increases

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