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Body Weight Support Impacts Lateral Stability during Treadmill Walking

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Abstract

Body weight support (BWS) systems are a common tool used in gait rehabilitation. BWS systems may alter the requirements for an individual to actively stabilize by 1) providing lateral restoring forces that *reduce the requirements for the nervous system to actively stabilize* and 2) decreasing the stabilizing gravitational moment in the frontal plane, which could *increase the requirements to actively stabilize*. The goal of the current study was to quantify the interaction between BWS and lateral stability. We hypothesized that when able-bodied people walk with BWS: 1) the lateral restoring forces provided by BWS would reduce the requirements to stabilize in the frontal plane when comparing dynamically similar gaits, and 2) increasing BWS would decrease the stabilizing gravitational moment in the frontal plane and increase the requirements to stabilize when speed is constrained. Our findings partly support these hypotheses, but indicate a complex interaction between BWS and lateral stability. With BWS, subjects significantly decreased step width variability and significantly increased step width ($p < 0.05$) for both the dynamically similar and speed-matched conditions. The decrease in step width variability may be attributable to a combination of lateral restoring forces decreasing the mechanical requirements to stabilize and an enhanced sense of position that could have improved locomotor control. Increases in step width when walking with high levels of BWS could have been due to decreases in the gravitational moment about the stance limb, which may challenge the control of stability in multiple planes.

Keywords

Gait; Biomechanics; Stability; Rehabilitation; Balance; Foot Placement; Margin of Stability; Body Weight Support

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Conflicts of interest statement

The authors declare no conflicts of interest.

Introduction

The restoration of locomotor balance after neurological injury is critical for successful independent walking (Dean and Kautz, 2015; Schmid et al., 2012). A body weight support (BWS) system is a common tool used to facilitate locomotor training after spinal cord injury (Dobkin et al., 2007) and stroke (Hornby et al., 2011) by reducing the muscle force required to counteract gravity. However, BWS exerts forces on an individual that could change the requirements of the nervous system to actively stabilize the body during gait. For BWS to be utilized effectively, it is important to understand how its implementation changes the requirements of locomotor stability. Here we focus specifically on lateral stability because simple models suggest that human walking is passively unstable in the frontal plane and requires active control (Kuo, 1999).

BWS could change the requirements to control frontal plane locomotor stability through two mechanisms (Figure 1). First, BWS systems that use cable-driven actuation routed through an overhead suspension could provide lateral restoring forces (Vallery et al., 2013) that *decrease the requirements to actively control lateral stability*. If the suspension restricts lateral translations, the BWS system will act as a pendulum and pull the user beneath the fulcrum (Pennycott et al., 2011). These lateral restoring forces may act as external stabilizers, reducing the requirements of the user to actively stabilize in the frontal plane. The lateral restoring forces provided by BWS has been estimated to be as high as 8.5 N when walking with 50% BWS (Wyss et al., 2014). Previous studies showing that people take narrower steps (Pennycott et al., 2011) and increase frontal plane trunk acceleration regularity (Aaslund and Moe-Nilssen, 2008) suggesting that BWS provides external lateral stabilization.

Gravity itself creates a stabilizing moment about the stance limb(s) that aids in maintaining the center of mass (CoM) within the base of support during walking (MacKinnon and Winter, 1993). Reducing this stabilizing gravitational moment with BWS may *increase the requirements for active lateral balance control*. During single support, the whole body lateral inertial moment about the subtalar joint is counteracted directly by a combination of a gravitational moment, subtalar joint center accelerations, and inversion/eversion muscle moments (MacKinnon and Winter, 1993). This gravitational moment is greater than 40 Nm during single support and is controlled primarily by changes in the distance of the stance foot from the CoM (MacKinnon and Winter, 1993). Thus, when gravity is reduced with BWS, the requirements to actively control lateral inertial moments during walking should increase. Previous human research has shown that sagittal plane gait kinematic (Kyvelidou et al., 2008) and kinetic (Goldberg and Stanhope, 2013) variability increase with BWS, suggesting that reducing gravity may indeed have a destabilizing effect.

To investigate these two competing effects of BWS independently, we propose that the potentially destabilizing effect of reducing the gravitational moment about the support limb can be minimized by observing gait with varying levels of BWS during dynamically similar walking conditions. The principle of dynamic similarity states that geometrically similar bodies utilizing pendulum mechanics will have similar gait dynamics when the ratio between gravitational and inertial forces are equivalent (Alexander, 1989). This ratio is

known as the Froude number (Fr). To maintain a constant Fr , the inertia and gravitational forces must be changed proportionally which can be achieved by altering walking speed (Sylos-labini et al., 2014). While Fr has been used to examine control of sagittal plane pendulum dynamics, there is evidence that lateral accelerations during walking will also decrease as walking speed is reduced (Helbostad and Moe-Nilssen, 2003). The stabilizing effect of the gravitational moment to counteract lateral inertial forces should be similar when walking in dynamically similar conditions as the ratio of gravitational to inertial forces will be constant.

We observed the effects of BWS on frontal plane stability during walking in two conditions, Dynamically Similar and Speed-Matched. In the first condition, walking speed was adjusted to produce dynamically similar (constant Fr) walking patterns across BWS levels. In this condition, stability changes should be driven by the lateral restoring force provided by BWS as the ratio of gravitational to inertial forces will be constant across conditions. We hypothesized that in Dynamically Similar conditions increasing BWS would decrease the requirements to actively stabilize in the frontal plane due to the relative increase in lateral restoring forces provided by the BWS. In a second condition, walking speed was kept constant across all BWS levels. In this Speed-Matched condition, we hypothesized an increase in the requirements for active lateral stabilization because the stabilizing effect of gravity to control the lateral CoM inertia would be decreased as BWS increased and that this effect would be greater than the stabilizing restoring forces provided by BWS.

Methods

Subjects

Eight healthy subjects participated in the experiment. Subjects gave written informed consent, and the experimental protocol was approved by the Northwestern University Institutional Review Board. Subjects were 26 ± 4 years, height 1.74 ± 0.12 m, mass 71.4 ± 10.2 kg, leg length 0.88 ± 0.08 m, and 3 males / 5 females.

Experimental setup

All walking occurred on an oversized treadmill (1.39 m belt width) with no handrails (Tuff Tread, Willis, TX). Subjects wore a trunk harness attached to a motorized overhead BWS system (Aretech, Ashburn, VA). The BWS system's actuated trolley maintained a fore-aft position directly above the subject but did not track lateral position.

12 retro-reflective markers were placed bilaterally on the pelvis and feet. Markers were affixed to the 2nd and 5th metatarsals, calcaneus, greater trochanters, and anterior and posterior superior iliac spines. A 10-camera motion capture system (Qualisys, Gothenburg, Sweden) recorded 3D marker positions at 100 Hz.

Protocol

Subjects performed 7 walking trials at different levels of BWS and speed, data were collected for 2 minutes after a 5 minute accommodation period. The order of the trials was randomized, and subjects were given rest as needed between trials.

Dynamically Similar Conditions—During the Dynamically Similar conditions, subjects walked at 4 levels of BWS: 0, 20, 40, and 60% of body weight. At 0% BWS, no support was provided. Walking speed for each BWS level was calculated from the criteria for dynamic similarity (Alexander, 1989). At all levels of BWS, subjects walked at Fr of 0.25, which corresponds to the preferred walking speed (Leurs et al., 2011), and was calculated as:

$$v = \sqrt{Fr * g * L}$$

where v is the walking velocity (m/s), g is the scaled gravitational constant (m/s^2), and L is leg length (m). The gravitational constant was scaled depending upon the level of BWS provided.

Speed-Matched Conditions—During the Speed-Matched conditions, subjects walked at three levels of BWS: 20, 40 and 60% of body weight. At all levels of BWS, walking speed was the same as the 0% BWS at $Fr = 0.25$ condition.

Analysis

Data analysis

Kinematic data was processed in Visual3D (C-Motion, Germantown, MD). Marker data was gap-filled and low-pass filtered (Butterworth, cut-off frequency 6 Hz). Gait events (initial contact and toe-off) were identified by the fore-aft position of the calcaneal and 5th metatarsal markers: initial contact was identified as the local maximum of the calcaneal marker per step and toe-off as the local minimum of the 5th metatarsal per step. All trials were visually inspected to verify accurate event detection.

Kinematic data were used to calculate the following metrics for each step: lateral restoring force, step width, step width variability, step length, step length variability, and minimum lateral margin of stability (MoS). We estimated the peak lateral restoring force $F_{lateral}$ (N), as a function of CoM excursion and vertical BWS force. Details on the method used to calculate the peak lateral restoring force are included in the supplementary material.

Step width and length were calculated as the medio-lateral and fore-aft distance, respectively, between the left and right calcaneus markers at initial contact. These variables were averaged across all steps for each subject and condition. Similarly, variability was calculated as the standard deviation of these measures.

We calculated the minimum lateral MoS (m) for each step using the procedure from Hof et al. (2005), details of which are included in the supplementary material. To account for the effect of BWS, the gravitational constant in the MoS equation was scaled to the level of BWS used during the testing condition. A left and right minimum lateral MoS was then calculated during stance for each full gait cycle. These values were then averaged over all strides for each subject and condition.

Statistical analysis

Statistical analysis was performed in SPSS (IBM, Armonk, NY). Data were compared using two one-way repeated measure analysis of variance (ANOVA) to test for differences in each metric. Dynamically Similar and Speed-Matched conditions were separated with the independent variable BWS (levels of 0, 20, 40, and 60%). When a significant main effect of BWS was found, Dunnett's test for multiple comparisons was performed to look for differences between individual BWS levels and the control condition (0% BWS). For the lateral restoring force metric, where there was no control condition, comparisons were made between all groups and a Tukey-Kramer test was used. For all statistical tests, a significance level of $p < 0.05$ was used. If sphericity was violated, the Greenhouse-Geisser F-statistic and p -value were used to test the main effects.

Results

Trajectories, Walking Speeds / Froude Numbers, and Lateral Restoring Forces

For the Dynamically Similar conditions, the walking velocities at each BWS level were 1.47 ± 0.08 m/s at 0%, 1.31 ± 0.06 m/s at 20%, 1.13 ± 0.05 m/s at 40%, and 0.93 ± 0.04 m/s at 60% BWS. For the Speed-Matched conditions subjects walked at a mean Fr of 0.31, 0.42, and 0.63 at BWS of 20%, 40%, and 60%, respectively.

Peak lateral restoring force showed a significant main effect of BWS for both the Dynamically Similar (ANOVA; $p < 0.001$) and Speed-Matched (ANOVA; $p < 0.001$) conditions. (Figure 2B). For both Dynamically Similar and Speed-Matched conditions, each BWS level was significantly different than the other two (Tukey-Kramer; $p < 0.05$) and increased from 20% to 60%.

Step Width and Variability

Step width significantly increased for the Dynamically Similar (Figure 3B, 4A) (ANOVA; $p = 0.037$) and Speed-Matched (Figure 3C, 4B) (ANOVA; $p = 0.001$) conditions as BWS increased. In both Dynamically Similar and Speed-Matched conditions, 60% BWS step width was significantly wider than 0% BWS (Dunnett's; $p < 0.05$).

There was a significant reduction in step width variability for both the Dynamically Similar (Figure 4C) (ANOVA; $p < 0.001$) and Speed-Matched (Figure 4D) (ANOVA; $p < 0.001$) conditions when BWS was provided. Pairwise comparisons found that step width variability for all three levels of BWS were significantly smaller than at 0% BWS (Dunnett's; $p < 0.05$) during both conditions.

Step Length and Variability

Step length significantly decreased for the Dynamically Similar (Figure 5A) (ANOVA; $p = 0.002$) condition as BWS increased. Pairwise comparisons found that 60% and 40% BWS produced significantly shorter steps than 0% BWS for Dynamically Similar (Dunnett's; $p < 0.05$) conditions. There was no change in step length for the Speed-Matched condition (Figure 5B) (ANOVA; $p > 0.05$).

Step length variability showed a significant main effect of BWS for both Dynamically Similar (ANOVA; $p < 0.001$) and Speed-Matched (ANOVA; $p < 0.001$) conditions. Step length variability increased for both conditions (Figure 5C and D) at 60% BWS compared to 0% BWS (Dunnett's; $p < 0.05$).

Lateral Margin of Stability

There were no significant differences in MoS across BWS levels for either the Dynamically Similar (Figure 6A) (ANOVA; $p = 0.534$) or Speed-Matched (Figure 6B) (ANOVA; $p = 0.083$) conditions.

Discussion

Our purpose was to quantify the interaction between BWS and the requirements to actively stabilize in the frontal plane. We examined two walking conditions based on our assumption that the two major factors influencing lateral stability with BWS are 1) the presence of lateral restoring forces that would decrease the requirements of active lateral stabilization, and 2) reductions in stabilizing gravitational moments that would increase the requirements to actively control stability. To investigate these two effects, individuals walked with varying BWS levels in either Dynamically Similar or Speed-Matched conditions. We assumed that the effect of BWS on the ability of the gravitational moment to counteract lateral inertial moments would be consistent across the Dynamically Similar conditions.

Our findings were mixed. In both the Dynamically Similar and Speed-Matched conditions, individuals demonstrated significant reductions in step width variability at all BWS levels when compared to 0% BWS. However, the reduction in step width variability with BWS was not accompanied by decreases in step width or lateral MoS. In both the Dynamically Similar and Speed-Matched conditions, step width actually increased at the highest BWS level. That step width variability decreased while step width was either unchanged or increased with increasing BWS levels suggests that the effects of BWS on the requirements of lateral stability are not straightforward.

The reduction of step width variability was the strongest evidence that BWS reduced the requirements of lateral stability. This decrease in variability was consistent with previous research documenting increased medio-lateral trunk regularity with BWS in both able-bodied (Aaslund and Moe-Nilssen, 2008) and hemiplegic (Aaslund et al., 2012) gait. These decreases in variability could be attributable to external lateral restoring forces created by the BWS system. Able-bodied subjects reduce their step width variability by 33% (Donelan et al., 2004) when given direct lateral external stabilization, which is comparable to the ~25% reductions in step width variability we observed in the current study. The reduced variability with external lateral stabilization has been suggested to indicate a decrease in demands on the nervous system to actively control medio-lateral foot placement (Donelan et al., 2004).

However, changes in variability are difficult to interpret. Step width variability could be reduced by either decreases in the mechanical requirements of lateral stability (i.e. the presence of external lateral stabilization) or by increases in a person's ability to control foot

placement. As such, it is possible that the reduction in step width variability was not due to BWS reducing the mechanical requirements of lateral stability. The magnitude of the lateral restoring forces we observed with BWS were fairly small, ranging from 0.36 to 1.25% body weight. While these values were similar in magnitude to those reported previously (Wyss et al., 2014), lateral restoring forces less than 0.5% body weight may not be sufficient to noticeably decrease the mechanical demands of lateral stabilization. One limitation of this study is that we calculated the restoring forces based on an assumed rather than measured constant support force provided by the BWS system, although errors in force have been previously found to be less than 1 kg during human walking (Hidler et al., 2011).

The relationship between step width variability and lateral restoring forces may not be entirely mechanical. It is possible that the major effect of the laterally directed force on mediolateral variability was to provide additional sensory information on subjects' lateral position on the treadmill. BWS may have acted as an external reference point that improved subjects' ability to control their limb trajectory. This increased position sense could have resulted in reduced step width variability and the appearance of reduced mechanical requirements for lateral stability. Indeed, other research has suggested that light touch on a hand rail during treadmill walking can significantly reduce gait variability (Dickstein and Laufer, 2004). In support of this idea, step length variability, unlike step width variability, actually increased with BWS. The BWS system used in the current study actively tracked subject's fore-aft position while resisting medio-lateral translations. Thus, the BWS forces would have provided subjects with additional haptic feedback about medio-lateral but not fore-aft position. This difference in feedback could explain the difference in changes between step width and step length variability with BWS.

In contrast to step width variability, the changes we observed in step width and lateral MoS suggest that increasing BWS may actually increase lateral stability requirements. Previous research has found that people select narrower steps and a smaller lateral MoS, when given external lateral stabilization during treadmill walking (Dean et al., 2007; Donelan et al., 2004) and tend to take wider steps and increase lateral MoS when placed in unstable environments (McAndrew et al., 2010). Consequently, if BWS were to increase the requirements to laterally stabilize, then we would expect these metrics to increase with BWS. We found that both Dynamically Similar and Speed-Matched conditions resulted in step width increases. At high levels of BWS, taking wider steps may have been a strategy used to increase the magnitude of the gravitational moment about the support limb to offset the reductions in the gravitational force. Maintaining a gravitational moment may have been necessary to counter the whole body lateral inertial moments (MacKinnon and Winter, 1993). That BWS may be destabilizing is supported by previous research demonstrating increases in sagittal plane variability (Goldberg and Stanhope, 2013; Kyvelidou et al., 2008) as well as differences in temporal-spatial and kinematic variables of able-bodied gait with high levels of BWS (Finch et al., 1991; Threlkeld et al., 2003). However, we observed a decrease in variability with BWS. While, past research has not found a relationship between step width and step width variability (Reissman and Dhaher, 2015) it is possible that these two measures are not independent. MoS tended to increase with BWS in the Speed-Matched condition, however this increase was not significant and may have been due to our small sample size ($n = 8$). In addition, step length only reduced when walking speed was decreased

in the Dynamically Similar condition, but not in the Speed-Matched condition, which is consistent with other external lateral stabilization studies (Ijmker et al., 2013; Matsubara et al., 2015), but is inconsistent with previous BWS work (Threlkeld et al., 2003).

At 60% BWS in the Speed-Matched condition, subjects walked at Fr of 0.63. This value is insightful because humans typically transition from walking to running at a Fr greater than 0.5 (Alexander, 1989; Kram et al., 1997). One possible explanation why humans transition from walking to running is that these respective modes of locomotion will improve gait stability (Diedrich and Warren, 1995) and minimize energetics cost (Srinivasan, 2011). In the current experiment, dictating walking in conditions where running should have been the preferred gait pattern may have led to increases in lateral stability requirements.

In contrast, for the Dynamically Similar condition, we hypothesized that there would be a decrease in step width and lateral MoS with BWS due to the lateral restoring force. However, for the Dynamically Similar condition we found an increase in step width at 60% BWS and no change in lateral MoS. We assumed that the ratio of inertial to gravitational forces would be consistent in the Dynamically Similar conditions by changing absolute walking speed. However, changing absolute walking speed may not influence frontal and sagittal plane inertial forces proportionally. In addition, gravitational alterations did not directly impact the swing limb. As such the Dynamically Similar conditions may not have been purely examining the effects of the lateral restoring forces. Our results appear to disagree with a previous study that had observed a decrease in step width as BWS increased (Pennycott et al., 2011). A key difference between these studies was that mass was added to the subjects' bodies to offset the BWS force in the previous work. The added inertia could have independently affected lateral stability metrics.

This study has several important clinical implications. If the goal of gait training is to improve control of frontal plane stability, it is important to realize that BWS may provide lateral restoring forces and supplemental sensory information that make it easier for individuals to control lateral stability. If stability is to be challenged, obtaining a BWS system that eliminates these lateral restoring forces could be beneficial (Vallery et al., 2013; Wyss et al., 2014). However, clinical populations often receive other direct methods of stabilization (e.g. holding hand rails) that likely have larger lateral stabilization effects than BWS. Gait training with high level of BWS presents an added complication. If a primary goal of gait training is to increase speed without imposing a stability challenge, then lower levels of BWS may be preferred to avoid situations where Fr is greater than the walk-run transition. However, if the primary goal of BWS training is to replicate joint powers (Worthen-chaudhari et al., 2015), then training in situations with a high Fr may be appropriate. Finally, it is important to understand that high levels of BWS will likely induce complex changes in walking dynamics that could create control challenges in multiple planes of motion. Walking at high speeds with high levels of BWS may create a walking environment that does not fully replicate the active control requirements needed for real world walking. Further work examining the stability implications of BWS on impaired populations are necessary to fully evaluate the clinical implications.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

(A) Schematic of the lateral restoring force, $F_{lateral}$, provided by the BWS support system as the subject deviates laterally. We expect this force to stabilize the subject, and reduce the requirements to actively stabilize in the frontal plane. (B) Schematic of the frontal plane balance control when walking with BWS (adapted from MacKinnon and Winter, 1993). During normal walking, the whole body lateral inertial moment about the subtalar joint ($I\alpha$) is balanced by a gravitational moment about the subtalar joint (M_g), ankle joint center accelerations (a_z , a_y), and inversion/eversion muscle moments (M_{sub}). With BWS, the gravitational moment is reduced due to the vertical force of the BWS. We expect that to control whole body lateral inertial moments when M_g decreases will require active control, and increase the requirements to stabilize in the frontal plane.

Figure 2. Mean estimated lateral force provided by the BWS system for (A) Dynamically Similar and (B) Speed-Matched conditions. Conditions '20', '40', and '60' represent the amount of BWS provided. Significance ($p < 0.05$) is denoted by * and indicates each level is significantly different than the other two.

Figure 3. Lateral center of mass trajectory and foot placements for a representative subject walking in three different BWS conditions: 0% BWS (A), 60% Dynamically Similar (B), and 60% Speed-Matched (C). DS is Dynamically Similar, SM is Speed Matched.

Figure 4. Mean + SD step width comparisons for (A) Dynamically Similar and (B) Speed-Matched conditions. (C) Mean + SD step width variability comparisons for Dynamically Similar and (D) Speed-Matched conditions. The units for all graphs are reported in leg length (L). Significance ($p < 0.05$) from 0% BWS is denoted by *.

Figure 5. Mean + SD step length comparisons for (A) Dynamically Similar and (B) Speed-Matched conditions. Mean + SD step length variability comparisons for (C) Dynamically Similar and (D) Speed-Matched conditions. The units for all graphs are reported in leg length (L). Significance ($p < 0.05$) from 0% BWS is denoted by *.

Figure 6. Mean + SD for Minimum lateral Margin of Stability for (A) Dynamically Similar and (B) Speed-Matched conditions. There were no significant comparisons for this measure.