

THE BEHAVIOR OF THE MARGIN OF STABILITY DURING ABLE-BODIED TRUNK-FLEXED GAIT

Soran AminiAghdam

Department of Motion Science, Institute of Sport Science, Friedrich Schiller University Jena, Jena, Germany

The dynamic margin of stability (MoS), defined as the difference between the anterior boundary of the base of support and the extrapolated whole-body center of mass (WBCM) at foot touchdown, reflects the control of gait dynamic stability. This study explores the behavior of MoS during level walking in able-bodied walkers ($n = 10$) under altered sagittal trunk orientations, including $\sim 30^\circ$, $\sim 50^\circ$ and maximal trunk flexion from the vertical compared with upright posture. Exploiting compensatory kinematic adjustments (e.g., crouched lower-limbs) possibly allowed participants to control their postural stability, as increasing trunk flexion did not lead to a significant diminish in the MoS relative to regular upright walking. Our findings might be of clinical interest to clinician interested in the nature and impact of alteration in trunk geometry on the control of gait dynamic stability.

KEYWORDS: balance, dynamic stability, posture, trunk flexion, walking.

INTRODUCTION: Given the trunk represents a substantial portion of the total body mass, investigating the impact of trunk mechanics on gait is of research importance, as it helps better understand the underlying mechanisms governing human locomotion.

In human upright locomotion, a vaulting action of the whole-body center of mass (WBCM) over the supporting limb behaves like an inverted-pendulum (Cavagna, Heglund, & Taylor, 1977). Such pendulum behavior may alter with variations in the posture orientation. For example, a forward trunk inclination may disrupt the referential control role of trunk in both posture and movement (Massion, Popov, Fabre, Rage, & Gurfinkel, 1997; Mouchnino, Aurenty, Massion, & Pedotti, 1993), resulting in a dysfunctional inverted-pendulum mechanism.

By taking into account both position and velocity of the CoM as a single outcome measure, the 'dynamic margin of stability (MoS)', measured by subtracting the MoS from the anterior boundary of base of support, theoretically estimates how close an inverted-pendulum is subject to falling (Hof, Gazendam, & Sinke, 2005). In general, positive MoS values during unperturbed walking indicate a stable locomotion, whereas negative MoS values indicate an unstable body configuration and the likelihood of fall (McCrum et al., 2014). This measure thus may reflect a control strategy (Bruijn, Meijer, Beek, & Van Dieën, 2013). While the MoS has been extensively investigated in an experimental context, the literature lacks the studies on the MoS adjustments in response to imposed trunk-flexed gaits. The study of dynamic control of gait stability with experimentally induced altered posture configurations may shed light on compensatory control strategies adopted by able-bodied walkers, providing a basis for an expanded analysis of gait stability in clinical populations exhibiting e.g. altered trunk postures. Hence, the objective of this study was to explore the dynamic control of gait stability with altered trunk orientations, in order to test the hypothesis that increasing sagittal trunk flexion decreases the MoS values, indicating a more unstable walking performance.

METHODS: Ten (50% female) healthy volunteers (mean \pm SD; age = 26 ± 3.3 years, 169.7 ± 7.4 cm, 65.0 ± 8.0 kg) with no history of orthopedic, musculoskeletal and neurologic disorders participated in this study. A consent form was signed by each participant before participation. Data collection was conducted at the Laboratory of Biomechanics at the Sports Institute within Friedrich Schiller University Jena. The experimental protocol was approved by the local Ethics Committee of the Friedrich Schiller University Jena (3532-08/12) and carried out in accordance with the Declaration of Helsinki.

Kinematic data was collected using eight infra-red Qualisys motion capture cameras (MCU1000, Qualisys, Gothenburg, Sweden) sampling at 240 Hz. GRFs during walking were measured at 1000 Hz using three consecutive force platforms (9285BA, 9281B, 9287BA, Kistler, Winterthur, Switzerland), embedded in the middle portion of a 12-m long walkway. Kinematics and GRF data were synchronized by using the Kistler's external trigger and BioWare data acquisition software. The raw coordinate data were filtered using a fourth-order low-pass, zero-lag Butterworth filter with 12 Hz cut-off frequency. A vertical GRF threshold of 0.03 body weight was used to determine the instants of touchdown at each ground contact. A thirteen-body segment model was defined using 21 surface markers of 14 mm diameter. Participants were instructed to walk at their normal walking speed under four trunk flexion conditions: regular erect trunk alignment (RE), 30° (TF1), 50° (TF2), and maximal trunk flexion (TF3) across a level walkway. Our method to define and inspect trunk angles has been described in previous studies (Aminiaghdam, Blickhan, Muller, & Rode, 2017; Aminiaghdam & Rode, 2017). Practice trials were permitted to allow participants to accommodate to the locomotion conditions and to secure step onto the force plates. While maintaining each gait posture, the participants performed eight successful trials in which each single force plate was cleanly struck by one foot.

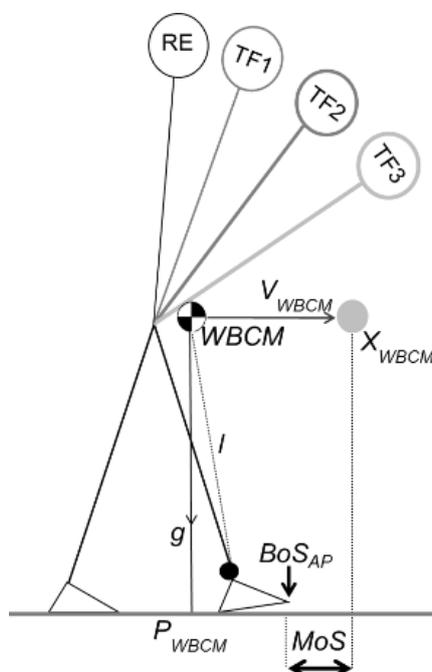


Figure 1: Schematic illustration of the inverted-pendulum model during locomotion (Hof et al., 2005). The margin of stability (MoS) was calculated as the difference between anterior boundary of the base of support (BoS_{AP}) and extrapolated ($X_{WBCM} = P_{WBCM} + V_{WBCM} / \sqrt{(g/l)}$). P_{WBCM} represents anterior-posterior component of the vertical projection of the $WBCM$ in the global coordinate system, V_{WBCM} is anterior-posterior velocity of the $WBCM$, g is acceleration due to gravity and l (pendulum length) is the distance between the $WBCM$ and the ankle.

The parameter of interest was MoS while walking on the level surface with RE, TF1, TF2 and TF3 postures (Figure 1). A one-way ANOVA used to examine differences in MoS across gait conditions and in case of a significant difference, post hoc Bonferroni testing was employed. The significance level was $\alpha = 0.05$. Results are presented as mean and standard deviation.

RESULTS: The data analysed comprises 320 step cycles. All subjects were successful on every trial in maintaining their stability (no falls). Table 1 represents the parameters pertaining to the calculation of the MoS stability. The analysis of gait dynamic stability revealed that increasing sagittal forward tilt of trunk moved the X_{WBCM} beyond the anterior

boundary of BoS, suggesting a more unstable postural configuration, but not statistically different from RE gait. (Figure 2).

Table 1: Parameters pertaining to control of dynamic gait stability.

	Posture			
	RE	TF1	TF2	TF3
BoS (cm)	67.9 ± 3.22	67.9 ± 2.90	66.9 ± 3.26	64.2 ± 3.68
X_{WBCM} (cm)	62.4 ± 8.82	68.3 ± 10.9	68.5 ± 10.6	68.0 ± 11.3
P_{WBCM} (cm)	17.7 ± 5.83	21.7 ± 6.26	22.6 ± 6.26	22.8 ± 6.29
V_{WBCM} (ms ⁻¹)	1.47 ± 0.13	1.54 ± 0.20	1.50 ± 0.15	1.36 ± 0.52
l (m)	0.87 ± 0.04	0.84 ± 0.02	0.83 ± 0.02	0.78 ± 0.03

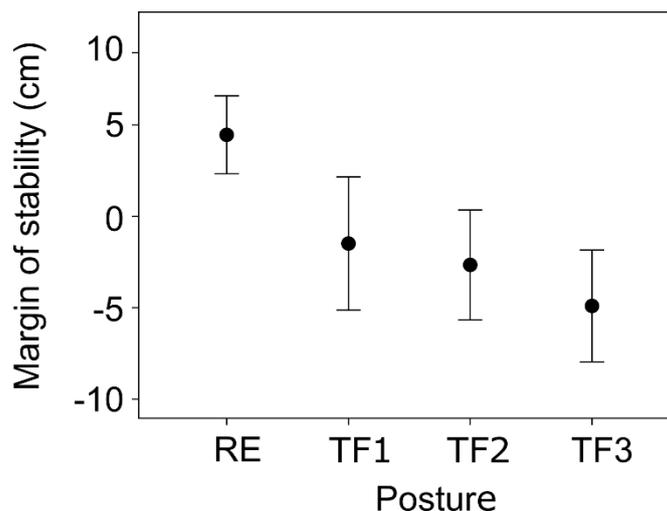


Figure 2: Margin of stability (MoS) analysis at touchdown (mean and SD). Error bars represent the 95% CI. RE, regular erect trunk; TF1, ~30° trunk flexion; TF2, ~50° trunk flexion; TF3, maximal trunk flexion.

DISCUSSION: The purpose of this study was to examine the control of dynamic gait stability while adopting altered sagittal trunk postures. Our hypothesis, that proceeding to maximal sagittal trunk-flexion causes a significant decrease in the MoS values and thus a more unstable gait stability, was not supported. Although increasing trunk flexion angles was associated with a decrease in the MoS; however, the differences were not significant ($p < 0.05$).

For a more unstable postural configuration (i.e., a diminished values of the MoS), one may require additional motor actions e.g. modulation of stepping temporal and spatial strategies (AminiAghdam & Blickhan, 2018) to control dynamic gait stability.

In fact, increasing sagittal trunk-flexion angle is increasingly associated with intralimb (i.e., toe-off versus touchdown) kinematic and kinetic asymmetries (Aminiaghdam, Rode, Müller, & Blickhan, 2017) and increased hip and knee flexion and ankle plantarflexion throughout the stance phase (i.e., crouch posture). Such a crouched lower limb is a compensatory kinematic adaptation necessary to maintain a dynamic relationship between WBCM and base of support (Saha, Gard, & Fatone, 2008). However, the control of such altered postural configuration is associated with an increased muscular demand during gait (Kluger, Major, Fatone, & Gard, 2014). Given the trunk represents a large portion of the WBCM, it is therefore likely that participants were required to apply a greater moment in the legs (Novak, Komisar, Maki, & Fernie, 2016) to arrest the forward acceleration of the large upper body mass.

Furthermore, the able-bodied walkers adjusted the spatial aspect of their stepping performance through maintaining the BoS during trunk-flexed gaits comparable to RE gait in order to compensate for a forward shift in the WBCM position induced by bending the trunk. The generalization of the results of present study should be treated with caution, since the

postural control-related capacities such as neuromuscular capabilities and sensorimotor system performance in older adults or patients with postural or spinal pathologies may manifest differently during locomotion.

CONCLUSION: The control of dynamic stability, assessed from the measure of MoS, in trunk flexed gaits was found not to be trunk posture-dependent. Able-bodied walkers were able to control the gait dynamic stability, despite a pronounced change in trunk posture, possibly through adopting compensatory neuromuscular adaptations such as increased muscle activation patterns and modulation of motor mechanisms like stepping strategies. These findings might be of clinical interest to clinician interested in the nature and impact of alteration in trunk geometry on the control of gait dynamic stability.

REFERENCES

- AminiAghdam, S., & Blickhan, R. (2018). The effects of an expected twofold perturbation on able-bodied gait: Trunk flexion and uneven ground surface. *Gait & posture*, *61*, 431-438.
- Aminiaghdam, S., Blickhan, R., Muller, R., & Rode, C. (2017). Posture alteration as a measure to accommodate uneven ground in able-bodied gait. *Plos One*, *12*(12), e0190135.
- Aminiaghdam, S., & Rode, C. (2017). Effects of altered sagittal trunk orientation on kinetic pattern in able-bodied walking on uneven ground. *Biology open*, *6*(7), 1000-1007.
- Aminiaghdam, S., Rode, C., Müller, R., & Blickhan, R. (2017). Increasing trunk flexion transforms human leg function into that of birds despite different leg morphology. *Journal of Experimental Biology*, *220*(3), 478-486.
- Bruijn, S., Meijer, O., Beek, P., & Van Dieën, J. (2013). Assessing the stability of human locomotion: a review of current measures. *Journal of the Royal Society Interface*, *10*(83), 20120999.
- Cavagna, G. A., Heglund, N. C., & Taylor, C. R. (1977). Mechanical work in terrestrial locomotion: two basic mechanisms for minimizing energy expenditure. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *233*(5), R243-R261.
- Hof, A., Gazendam, M., & Sinke, W. (2005). The condition for dynamic stability. *Journal of biomechanics*, *38*(1), 1-8.
- Kluger, D., Major, M. J., Fatone, S., & Gard, S. A. (2014). The effect of trunk flexion on lower-limb kinetics of able-bodied gait. *Hum Mov Sci*, *33*, 395-403. doi:10.1016/j.humov.2013.12.006 S0167-9457(13)00180-2 [pii]
- Massion, J., Popov, K., Fabre, J.-C., Rage, P., & Gurfinkel, V. (1997). Is the erect posture in microgravity based on the control of trunk orientation or center of mass position? *Experimental Brain Research*, *114*(2), 384-389.
- McCrum, C., Eysel-Gosepath, K., Epro, G., Meijer, K., Savelberg, H. H., Brüggemann, G. P., & Karamanidis, K. (2014). Deficient recovery response and adaptive feedback potential in dynamic gait stability in unilateral peripheral vestibular disorder patients. *Physiological reports*, *2*(12), e12222.
- Mouchnino, L., Aurenty, R., Massion, J., & Pedotti, A. (1993). Is the trunk a reference frame for calculating leg position? *Neuroreport*, *4*(2), 125-127.
- Novak, A., Komisar, V., Maki, B., & Fernie, G. R. (2016). Age-related differences in dynamic balance control during stair descent and effect of varying step geometry. *Applied ergonomics*, *52*, 275-284.
- Saha, D., Gard, S., & Fatone, S. (2008). The effect of trunk flexion on able-bodied gait. *Gait Posture*, *27*(4), 653-660. doi:S0966-6362(07)00214-7 [pii] 10.1016/j.gaitpost.2007.08.009