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The effect of walking speed on center of mass displacement

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Abstract—The movement of the center of mass (COM) during human walking has been hypothesized to follow a sinusoidal pattern in the vertical and mediolateral directions. The vertical COM displacement has been shown to increase with velocity, but little is known about the mediolateral movement of the COM. In our evaluation of the mediolateral COM displacement at several walking speeds, 10 normal subjects walked at their self-selected speed and then at 0.7, 1.0, 1.2, and 1.6 m/s in random order. We calculated COM location from a 15-segment, full-body kinematic model using segmental analysis. Mediolateral COM displacement was 6.99 +/– 1.34 cm at the slowest walking speed and decreased to 3.85 +/– 1.41 cm at the fastest speed ($p < 0.05$). Vertical COM excursion increased from 2.74 +/– 0.52 at the slowest speed to 4.83 +/– 0.92 at the fastest speed ($p < 0.05$). The data suggest that the relationship between the vertical and mediolateral COM excursions changes substantially with walking speed. Clinicians who use observational gait analysis to assess walking problems should be aware that even normal individuals show significant mediolateral COM displacement at slow speeds. Excessive vertical COM displacement that is obvious at moderate walking speeds may be masked at slow walking speeds.

Key words: adult, biomechanics, center of mass, COM displacement, gait, normal, rehabilitation, walking velocity.

INTRODUCTION

During human walking, the center of mass (COM) translates along the direction of travel but also moves in a sinusoidal pattern in the vertical and lateral directions. In both the vertical and lateral directions, two maxima appear: the first near 30 percent of the gait cycle in single-limb stance and another near 80 percent of the gait cycle in mid-swing; minima appear at 0 percent and 100 percent of the gait cycle in loading. Therefore, the COM reaches its highest and most lateral point as it passes over the planted foot and its lowest and most central point passing from one foot to the other. Since human walking is staggeringly complex, analysis of the COM movements has been suggested to simplify and illuminate the disturbances due to a broad range of pathologies—Saunders suggested six determinants of gait that act to reduce the excursion of the COM, smoothing out the abrupt changes in COM position [1]. Despite the lack of any actual data in Saunder's paper, or any testable hypothesis, the postulates are so attractive at face value that they have often been endorsed in monographs on human gait [2–14]. The determinants of gait are pelvic rotation, pelvic tilt, knee flexion in stance, foot mechanisms, knee mechanisms, and lateral pelvic displacement [1]. The validity of these mechanisms has recently been challenged [15–20], but the concept of minimizing the vertical

Abbreviations: ANOVA = analysis of variance, COM = center of mass, fps = frames per second, SS = self-selected.

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excursion of the COM has been generally accepted as one goal of human walking.

Extremes in the vertical displacement of the COM are thought to be energetically and metabolically costly. Kerrigan et al. have shown that vertical COM displacement is highly correlated with oxygen consumption during human gait [21]. Human walking is hypothesized to be efficient because the vertical COM excursion is minimized by the limb motions just described. Despite the theoretical cost savings of minimizing the vertical COM displacement during gait, a diminishing return to the mechanisms is likely, which makes reaching zero vertical displacement impractical from either a control cost or an energy cost standpoint.

One of the determinants of gait is hypothesized to minimize the mediolateral displacement of the COM for reasons of efficiency. Saunders suggests that the adduction of the hip and valgus position of the knee reduce the mediolateral displacement of the pelvis during gait, stating that ". . . the deviation of the center of gravity is almost symmetrical in both the horizontal and vertical planes" [1]. Other mechanisms may also be present that minimize the lateral displacement of the COM during gait, such as step width. Forcing individuals to walk with step widths wider than normal has been shown to increase mechanical and metabolic costs by approximately 50 percent [22].

The most efficient movement would result in forward translation of the COM without any vertical or mediolateral COM displacement. However, because of human anatomical structure and articulation geometry, some vertical and mediolateral COM displacement is necessary to achieve forward progression. These mechanical constraints are integrated with control strategies to produce locomotion that is economical in a wide array of organisms [23].

Despite the accepted usefulness of analysis of COM excursion to understand the overall impact on functional walking capacity due to movement pathologies, little is known about the effects of walking velocity on COM displacement. This study examined the effect of walking speed on the COM displacement in the mediolateral and vertical directions. We hypothesized that the COM would have equal vertical and mediolateral excursions at all walking speeds and that both would increase as walking speed increased.

METHODS

Ten subjects gave their informed consent to participate in this study after the protocol was approved by the human subjects institutional review board governing this institution. Their ages were 26.9 ± 5.7 yr (range 21 to 45 yr), weight 74.4 ± 9.4 kg (range 56.8 to 83.6 kg), and height 1.76 ± 0.41 m (range 1.68 to 1.85 m); three were female. All were free from musculoskeletal and neurological problems by self-report. Thirty-six reflective markers were placed on their feet, legs, pelvis, trunk, head, arms, and hands according to the Plug-In Gait model described by Vicon (Oxford Metrics, Oxford, UK). While the subjects walked along a 10 m walkway, a 10-camera Vicon 612 system recorded the displacement of the markers in three-dimensional space at 120 Hz; synchronized digital video was also collected at 30 Hz.

Subjects walked first at their self-selected (SS) speed and completed five trials. Each subject then walked five times at speeds of 0.7, 1.0, 1.2, and 1.6 m/s in random order. Timing lights were placed so that the subject's average speed was measured over a 2 m distance at the center of his or her path. At each speed, only trials that were within 10 percent of the target speed were accepted, and subjects were given feedback to achieve the target speed.

The marker displacements were smoothed with a quintic spline with a mean square error of 20, labeled, and foot contact events defined with Vicon's Workstation software. Vertical (Z) and mediolateral (X) displacement of the COM were calculated in Workstation by segmental analysis. The full-body model consisted of 15 segments: two feet, two shanks, two thighs, two hands, two forearms, two upper arms, and the pelvis, trunk, and head. Each segment was assigned a percentage of the subject's total mass with the use of the anthropomorphic data of Dempster [24]. The COM location along the long axis of each segment and radius of gyration, were taken from Dempster [24]. Because no experimental data exist on the radius of gyration for the pelvis or trunk, these were both estimated as 0.31. This segmental analysis method has been shown to have good agreement with both a single sacral marker method and force platform-derived COM calculation; however, at faster walking speeds, the sacral marker method tended to underestimate COM motion [25], so we chose to use segmental analysis to calculate the COM position. The COM position was determined in the Z and X directions for the stride where force-plate contact occurred.

Cadence, step length, stride length, and step width were calculated as well. Cadence was calculated as steps per minute. Step length was the forward (*Y*) linear distance between the ankle joint centers from foot contact to subsequent contralateral foot contact. Stride length was the forward (*Y*) linear distance between the ankle joint centers from foot contact to ipsilateral foot contact. Stride width was the linear (*X*) distance between ankle joint centers from foot contact to contralateral foot contact.

We compared stride length, step length, step width, COM *Z*-range, and COM *X*-range across walking speeds using mixed effects repeated measures analyses of variance (ANOVAs) with linear contrasts post hoc. Significance was set at $p < 0.05$ a priori.

RESULTS

For the COM *Z* displacement, an overall walking speed effect emerged ($p < 0.0001$), with COM vertical displacement of 2.74 ± 0.52 cm at 0.7 m/s, which reached 4.83 ± 0.92 cm at 1.6 m/s. Linear contrasts revealed significant differences between all adjacent speeds for COM *Z* displacement except for 1.6 m/s versus the self-selected walking speed. The results are summarized in the **Table**.

In the *X* (mediolateral) direction, the COM displacement showed a decreasing trend as walking speed increased (**Figure 1**) with a significant overall effect ($p < 0.0001$). Each speed was significantly different from adjacent speeds ($p < 0.01$), except for 1.2 m/s versus 1.6 m/s and 1.6 m/s versus SS walking speed ($p > 0.05$). At a walking speed of 1.6 m/s, COM mediolateral displacement averaged 3.85 ± 1.41, while at 0.7 m/s mediolateral displacement was 6.99 ± 1.34 cm.

Stride length and step length increased, and stride width decreased as walking speed increased. Stride length and step length were significantly greater at each subsequent walking speed ($p < 0.001$), and stride width was significantly less at each subsequent walking speed ($p < 0.001$). These data are summarized in the **Table**; step length and step width relative to the COM are shown in **Figure 2**.

DISCUSSION

Investigation of the effect of walking speed on COM displacement in the coronal plane (*X*-*Z*) produced some intriguing results. As walking speed increased the vertical excursion increased, while the mediolateral excursion decreased (**Figure 3**). The increase in COM *Z* (vertical) displacement with walking speed is consistent with previous work [18,25], but the decrease in *X* (mediolateral) displacement with increasing walking speed has not been previously reported.

These data complement and refine the understanding of the COM excursion in gait as presented in current texts. For example, Perry shows the COM moving in a 2 cm high by 4 cm wide box during gait, which was not duplicated at any of our gait speeds [6, p. 42]. The COM at 0.7 m/s showed vertical displacement of 2.74 ± 0.52 cm, but the lateral displacement at this speed was 6.99 ± 1.34 cm. At a walking speed of 1.2 m/s, the mediolateral COM displacement reached 4.06 ± 0.72, but the vertical COM displacement was 4.41 ± 1.23 cm. This is consistent with the postulates of Saunders et al., who stated that the

Table.
Center of mass (COM) mediolateral (*X*) displacement, vertical (Z) displacement, cadence, stride length, step length, and step width for 10 subjects across range of walking speeds (mean ± standard deviation [SD]).

Nominal Speed (m/s)	COM *X*-Range (cm)	COM *Z*-Range (cm)	Cadence (steps/min)	Stride Length (cm)	Step Length (cm)	Step Width (cm)
0.7	6.99 ± 1.34	2.74 ± 0.52	73.5 ± 7.2	113.4 ± 11.3	60.4 ± 6.6	22.1 ± 4.3
1.0	5.96 ± 1.68*	3.61 ± 0.66*	89.5 ± 5.7*	131.1 ± 7.4*	70.2 ± 4.9*	21.3 ± 4.7
1.2	4.41 ± 1.23*	4.06 ± 0.72*	96.0 ± 5.3*	144.2 ± 5.9*	77.4 ± 4.5*	18.7 ± 3.7*†
1.6	3.85 ± 1.41	4.83 ± 0.92*	108.7 ± 3.4*	163.8 ± 6.4*	88.1 ± 3.6*	17.1 ± 5.3*†
SS	3.29 ± 1.29†	4.89 ± 1.03†	108.7 ± 8.1	164.1 ± 14.6	88.5 ± 7.3	16.5 ± 4.0

Note: Overall significance was $p < 0.0001$.
*Individual comparisons with significant differences from speed directly above ($p < 0.01$).
†Statistically significant difference from speed two values (two rows) above ($p < 0.01$).
SS = self-selected walking speed: 1.61 ± 0.22 m/s.

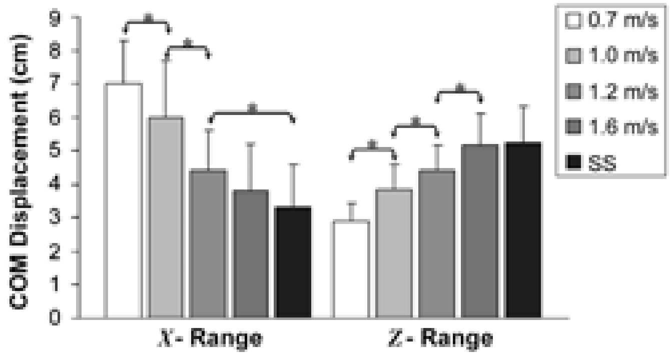

Figure 1.
Center of mass (COM) lateral (*X*) and vertical (*Z*) displacement across five walking speeds. Overall significance was $p < 0.0001$. *Individual comparisons with significant differences ($p < 0.01$).

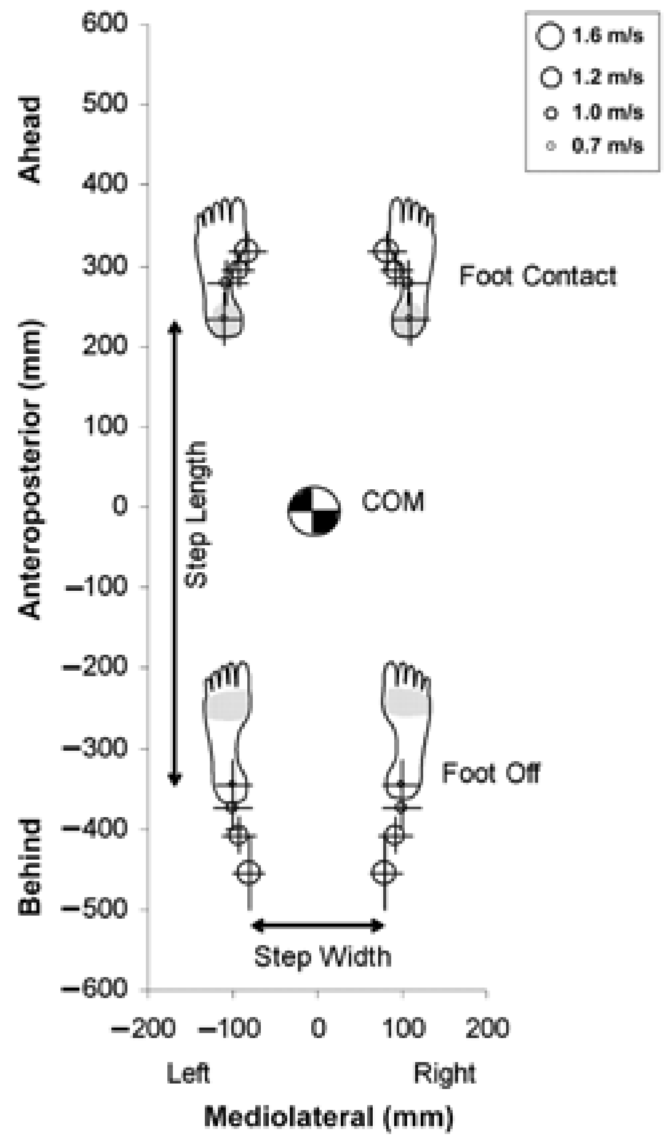

Figure 2.
Step length and step width relative to center of mass (COM) at 0.7, 1.0, 1.2, and 1.6 m/s.

COM excursion was equal in the mediolateral and vertical directions [1], but this relationship occurred only at a walking speed of 1.2 m/s. At other walking speeds, the mediolateral and vertical COM displacements were not equal.

The data show that the COM excursion in the vertical direction was not attenuated as effectively at higher speeds, suggesting a reduction in the efficacy of the mechanisms related to the six determinants of gait [1] or other factors such as heel rise [16]. These mechanisms may not be able to keep up with the increase in stride length that occurred as walking speed increased. Healthcare professionals who use visual gait analysis in a clinical setting should be aware that slow gait speed may mask excessive vertical COM excursions caused by pathological joint kinematics that would otherwise be obvious at functional walking speeds.

We hypothesized that the COM displacement would be small in both the *Z* and *X* directions at slow walking speeds and increase in magnitude as walking speed increased. We observed this with the vertical COM displacement; however, the mediolateral COM displacement showed the opposite effect, with large displacements at slow speeds and small displacements at faster walking speeds.

The SS walking speed chosen by the normal individuals in this study showed large vertical COM excursions but low mediolateral COM excursion of the COM. However, the SS speed (1.61 ± 0.22 m/s) was faster than previous studies of normal gait [15–18], but within the range cited by Waters [26]. This finding indicates that minimizing vertical COM displacement may not be a constant goal of walking for all individuals and that one might choose some speeds to minimize walking time.

The data collected in this study do not support the hypothesis that COM vertical excursion is a criterion for choosing a comfortable walking speed, because the lowest value occurred at 0.7 m/s and not close to 1.2 m/s, which is generally chosen as normal gait speed [15–18]. The data are also contrary to the notion that the joint kinematics suggested by Saunders et al. to reduce the COM

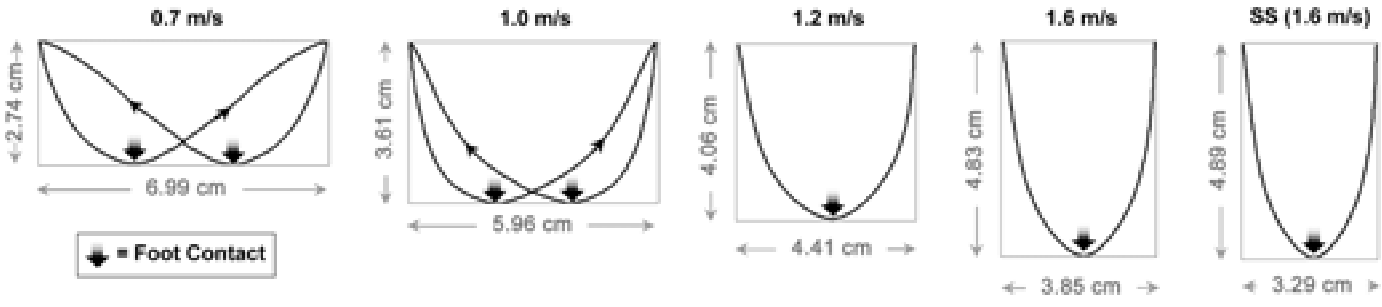

Figure 3.
Center of mass (COM) path in coronal plane (*X-Z*) across range of walking speeds. SS = self-selected walking speed.

excursion are most effective near 1.2 m/s [1]. If minimizing the vertical COM displacement was a primary goal of human walking, the preferred gait speed would be very slow. More likely, joint kinematics act to reduce the COM displacement over a range of speeds and become less effective at very slow and very fast walking speeds.

While the vertical COM excursion was less effectively attenuated at higher walking speeds, the mechanisms suggested to reduce mediolateral COM displacement [1] apparently did not function as effectively at slow walking speeds. The mediolateral COM excursion at 0.7 m/s was nearly double the value at 1.6 m/s.

Increased mediolateral COM displacement may have an impact on functional mobility for individuals with gait pathology. Walking at slow speeds may present additional balance challenges due to increased mediolateral COM motion. Clinicians often visually evaluate step width and step length to assess gait unsteadiness, and walking speed should be considered a confounding factor. Even normal individuals increase step width and mediolateral COM excursion with slow gait speed.

Donelan, Kram, and Kuo have shown that increasing step width from the preferred width of 13 percent leg length to 45 percent leg length has a dramatic effect on the cost of walking, increasing metabolic and mechanical costs by approximately 50 percent [22]. The step widths for the current study were less than those used by Donelan, Kram, and Kuo and ranged from 15.8 percent leg length at 1.6 m/s to 20.4 percent leg length at 0.7 m/s [22]. We did not know if step width had any effect on the subjects' metabolic or mechanical costs during gait.

The concept of minimizing the vertical COM displacement as a goal of human gait is so attractive and so well accepted that very little rigorous testing of the hypotheses put forth by Saunders et al. [1] has taken place. Only a handful of studies have examined the effects of the proposed determinants of gait on COM movements and these have focused on the vertical excursion exclusively [15–20]. Individuals with gait disturbances, such as limb loss, neuromuscular pathology, vestibular dysfunction, or cerebral vascular accidents, or even the healthy elderly, often have reduced gait velocity. The consequence of a slow gait may be increased mediolateral COM motion, increased balance demands, and a wider base of support. The large mediolateral excursion of the COM at slow walking speeds has some important clinical implications. Individuals have more time to accomplish the movement, which in turn means more time to sense perturbations and develop the forces necessary to correct the error. Slow walking may not be efficient, but it may be safer in terms of falling.

CONCLUSION

COM motion during normal adult walking appears to decrease in the mediolateral direction and increase in the vertical direction as walking speed increases. This expands the current descriptions of COM movement in the literature. Slow walking speeds may require significant balance response because of the large mediolateral COM displacement. Vertical COM excursions that would be obvious at functional speeds may be masked by slow walking speeds. Clinicians are advised to consider walking speed when estimating COM movements and be sensitive to mediolateral movements as well.

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