Control of the body's centre of mass motion during over-ground and treadmill walking in the pelvic reference frame: Implications for wearable sensing

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Abstract

Treadmill-based training protocols have played an important role in gait and balance training in rehabilitation settings, and the position of the body's center of mass (COM) relative to the base of support provides an important measurement of postural stability. With the advance in wearable technology, the movement of the COM has been estimated using inertial measurement units (IMU) or by placing a single marker on the pelvis. However, there has not been a consensus over the differences in the movement control of COM relative to pelvis between treadmill walking (TW) and over-ground walking (OW). The current study aimed to quantify and compare the motions of the COM with respect to the pelvic reference frame during TW and OW. Fifteen young male adults walked barefoot on an 8-meter walkway, as well as on an instrumented treadmill at their self-selected speed while their pelvis position, COM positions, and center of pressure (COP) positions were measured. Paired *t*-tests were performed between OW and TW for all the variables. The results showed that compared to OW, treadmill walking produced significantly greater variations of COM displacements in every direction, namely anterior/posterior, proximal/distal, and medial/lateral, and significantly greater excursions of the COM in the medial/lateral direction with respect to the pelvis coordinate system. The results suggest that the estimation of the COM position with an IMU attached to the pelvis is more accurate during OW than TW.

Key words : Center of mass (COM), Center of pressure (COP), Pelvic reference frame, Instrumented treadmill, Walking

1. Introduction

Falls are a leading cause of death in the older population in modern societies (Scuffham *et al.*, 2003). The risk of falling increases with age as the older adults experience a decline in balance and mobility with aging (Daley and Spinks, 2000). For people with gait impairment, treadmill-based training protocols have played an important role in gait and balance training in rehabilitation settings, providing convenient protocols and enabling continuous monitoring of the movement over multiple gait cycles at well-controlled speeds. This has been useful not only for providing insightful information into the evaluation of the training efficacy (Köse *et al.*, 2012), but also for early diagnosis and detection of debilitation and mobility decline (Betker *et al.*, 2006). However, there has not been a consensus over the differences in the movement control between treadmill walking (TW) and over-ground walking (OW), (Carpinella *et al.*, 2010; Hollman *et al.*, 2016; Regnaud *et al.*, 2006). A better understanding of such differences would be helpful for translating treadmill training outcomes into real life over-ground walking (Hollman *et al.*, 2016).

The position of the body's center of mass (COM) relative to the base of support provides an important measurement of postural stability during walking (Winter, 1995). Apart from the COM position relative to the center of pressure

(COP), their relative velocities should also be considered for a complete assessment of dynamic balance (Pai and Patton, 1997). Such measurements of the dynamic stability have been made only in a standard gait laboratory with expensive equipment and requiring technical expertise (Köse *et al.*, 2012). However, it would be extremely helpful for the clinician if the COM and COP movement during gait in the older population and patients with pathological conditions could be monitored continuously on a regular basis. With the advance in wearable technology, the movement of the COP can now be monitored on a daily basis using pressure insoles (Chevalier *et al.*, 2010), whereas those of the COM have been estimated using inertial measurement units (IMU) with human body modeling (Esser *et al.*, 2009). However, the accuracy of such an approach has not been well evaluated in the literature.

In general, IMU-based methods for daily monitoring of the COM are based on the assumption that the COM position is fixed with respect to the position of the IMU, i.e., both are on a rigid body. The COM has also been assumed to be a fixed point in the pelvis (Eames *et al.*, 1999), located at approximately 60% of the total body height during static standing (Winter, 2009). The motion of the COM is thus approximated and measured by placing a single marker on the sacrum in a standard gait laboratory. Yang and Pai investigated the accuracy of approximating the COM by using the sacral marker on a large sample size (Yang and Pai, 2014), and suggested that the sacral marker position could reasonably approximate the COM during regular gait. However, this approach disregards the influence of the relative movements of the body segments (Eames *et al.*, 1999). Moreover, these conventional methods are mainly used for motion capture system measurements, while their application to daily activities is nearly impossible. In principle, a single IMU can be attached to the pelvis to determine the temporal and spatial parameters, such as speed, cadence, etc., during level walking either indoors or outdoors. However, the accuracy of the estimated COM has not been documented and it remains unclear whether such an approach would produce reasonable results during treadmill and over-ground walking. Therefore, the purpose of the current study was to quantify and compare the motions of the COM with respect to the pelvic reference frame during TW and OW. It was hypothesized that the COM would move within the pelvis during gait, with greater excursions during TW than OW.

2. Materials and Methods

2.1 Subjects

Fifteen young male adults (age: 24.5 ± 2.3 years, height: 172.3 ± 6.3 cm, mass: 68.4 ± 8.3 kg) participated in the current study with written informed consent as approved by the Institutional Research Board. All subjects were free of neuromusculoskeletal dysfunction and had normal or corrected-to-normal vision as quantified by their visual acuity. Each subject wore 39 retroreflective markers to track the motions of the body segments (Lu *et al.*, 2007).

2.2 Data Collection

In a gait laboratory, each subject was asked to walk barefoot on an 8-meter walkway at his self-selected speed, as well as on an instrumented treadmill which had been calibrated for accurate COP measurements (Hsieh *et al.*, 2016), at the same self-selected speed (average speed of six over-ground gait trials). The subjects were allowed a 6-minute practice session on the treadmill before data collection in order to eliminate any possible effects on gait parameters due to unfamiliarity with treadmill locomotion (Matsas *et al.*, 2000). During both TW and OW, three-dimensional trajectories of the markers were measured using an 8-camera motion capture system (VICON MX System, Oxford Metrics Group, UK) at a sampling rate of 120 Hz. The ground reaction forces during OW were measured using three forceplates (AMTI OR6-7-1000, USA) and the reaction forces during TW were measured by the instrumented treadmill, both at a sampling rate of 1080 Hz. An electronic trigger was used to synchronize data collection for the instrumented treadmill and the motion capture system. For each subject, data of six complete gait cycles were collected from six trials during OW and from a single trial during TW.

2.3 Data Analysis

With a 13-segment model of the body and the measured marker data, the position of the body's COM was calculated as the weighted sum of the segmental COMs of all body segments (Lu *et al.*, 2007), while the subject-specific segmental inertial properties were determined using an optimization-based method (Chen *et al.*, 2011). The COP position was calculated using forces and moments measured by the forceplates and the instrumented treadmill. Effects of soft tissue

artifacts on the calculated COM positions were reduced using a global optimization method (Lu and O'Connor, 1999).

Temporal-spatial parameters of TW and OW, namely walking speed, cadence, step length, step width, double-limb support (DLS), single-limb support (SLS) and stance phase percentages in the gait cycle were obtained. The anterior/posterior, proximal/distal and medial/lateral displacements of the COM were described with respect to the pelvic coordinate system and normalized to the subject's leg length (%LL), and the COP was described relative to the line of progression that bisected the medial/lateral range of motion of the COM during a gait cycle, a positive value being to the side of the contralateral limb (Chien *et al.*, 2014). The three-dimensional COM excursion was calculated as the greatest absolute difference of the COM displacements during the gait cycle, and the three-dimensional COM variation was calculated as the average of the standard deviations of the COM displacements during the gait cycle. The COP excursion was calculated as the greatest absolute difference of the COP displacement during the gait cycle.

2.4 Statistical Analysis

Each of the calculated variables, including the three-dimensional variations and excursions of the COM displacements, medial/lateral excursions of the COP displacements, and temporal-spatial parameters in three dimensions, was compared using a paired *t*-test between over-ground walking and treadmill walking. All significance levels were set at $\alpha=0.05$ and all the statistical analyses were performed using SPSS version 20.0 (SPSS Inc., Chicago, IL, USA).

3. Results

No significant differences between OW and TW were found in walking speed, cadence, normalized step length, step width and maximum medial/lateral excursions of COM. However, compared to OW, TW showed significantly greater normalized maximum medial/lateral excursions of COP and a shorter SLS duration ($p<0.001$), but with increased DLS and stance phase durations ($p<0.001$) (Table 1).

The COM displacement with respect to the pelvis coordinate system showed different patterns in each direction between OW and TW (Figs. 1 and 2). During OW, the ensemble average of the displacement of the COM in the anterior/posterior, proximal/distal and medial/lateral directions were 0.43, -0.31, and 0.21 (%LL), respectively, while those during TW were -0.9, -0.09, and -0.75 (%LL), respectively.

Table 1 Means and standard deviations (SD) of the spatial-temporal parameters during treadmill walking (TW) and over-ground walking (OW). *P*-values for comparisons between TW and OW using paired *t*-tests are shown. Double-limb support (DLS) and single-limb support (SLS) percentage in the gait cycle are also shown. All significance levels were set at $\alpha=0.05$.

	TW		OW		<i>p</i> -value
	Mean	SD	Mean	SD	
Walking Speed (m/s)	1.27	0.04	1.23	0.15	0.468
Cadence (steps/min)	120.6	9.9	116.2	12.2	0.339
Step Length (% LL)	69.3	6.5	67.2	11.9	0.601
Step Width (% LL)	9.3	4.1	9.5	3.5	0.896
DLS (% cycle)	14.1	1.2	10.3	0.9	<0.001
SLS (% cycle)	35.9	1.1	39.8	1.0	<0.001
Stance Phase (% cycle)	64.4	0.5	59.6	0.9	<0.001
COM M/L Excursion (% LL)	4.1	1.0	4.3	0.6	0.659
COP M/L Excursion (% LL)	31.0	4.6	19.0	2.7	<0.001

Fig. 1 Ensemble-averaged (black line) and standard deviations (grey line) COM displacement normalized to leg length (%LL) in the anterior/posterior (x), proximal/distal (y), and the medial/lateral (M/L) directions (z), during heel-strike (HS), contralateral toe-off (CTO), contralateral heel-strike (CHS), and toe-off (TO). The averages of the displacement of the COM during over-ground walking (OW) are also shown.

Fig. 2 Ensemble-averaged (black line) and standard deviations (grey line) COM displacement normalized to leg length (%LL) in the anterior/posterior (x), proximal/distal (y), and the medial/lateral directions (z), during heel-strike (HS), contralateral toe-off (CTO), contralateral heel-strike (CHS), and toe-off (TO). The averages of the displacement of the COM during treadmill walking (TW) are also shown.

Fig. 3 Means and standard deviations (SD) of the variations and excursions normalized to leg length (%LL) in the anterior/posterior (x), proximal/distal (y), and the medial/lateral (z) directions during treadmill walking (TW) and over-ground walking (OW). The significances for comparisons between TW and OW using paired t -tests are also shown. All significance levels were set at $\alpha=0.05$.

During OW, variations (VA) and excursions (EX) of the COM in the anterior/posterior directions (VA: 0.95 ± 0.15 ; EX: 3.12 ± 0.30 mm) were found to be significantly greater than those in the proximal/distal (VA: 0.31 ± 0.07 ; EX: 1.02 ± 0.19 mm) ($P_{VA}=0.04$; $P_{EX}=0.01$) and the medial/lateral (VA: 0.38 ± 0.08 ; EX: 1.20 ± 0.19 mm) directions ($P_{VA} < 0.001$; $P_{EX} < 0.001$) (Fig. 3-a,b). However, no significant difference was found in the variations and excursions of the COM displacement with respect to the pelvis coordinate system between the proximal/distal and the medial/lateral directions (Fig. 3-a,b).

During TW, significantly greater variations and excursions of the COM were found in the anterior/posterior direction (VA: 1.23 ± 0.28 ; EX: 3.45 ± 0.88 mm) than those in the proximal/distal (VA: 0.42 ± 0.09 ; EX: 1.24 ± 0.38 mm) ($P_{VA} < 0.001$; $P_{EX} < 0.001$) and the medial/lateral directions (VA: 0.94 ± 0.13 ; EX: 2.69 ± 0.52 mm) ($P_{VA} = 0.0014$; $P_{EX} = 0.016$) (Fig. 3-a,b). During TW, significantly greater variations and excursions of the COM were found in the medial/lateral direction than those in the proximal/distal direction ($P_{VA} < 0.001$; $P_{EX} < 0.001$) (Fig. 3-a,b). Compared to OW, treadmill walking had significantly greater variations and excursions of the COM displacement with respect to the pelvis coordinate system in the medial/lateral direction ($p < 0.001$) (Fig. 3-a,b), and TW had significantly greater variation of the COM displacement with respect to the pelvis coordinate system in the anterior/posterior ($p = 0.0026$) and proximal/distal directions ($p = 0.0039$) (Fig. 3-a). TW had significantly greater medial/lateral excursions of the COP (TW: 31 mm; OW: 19 mm) than those during OW ($p < 0.001$) (Table 1).

4. Discussion

The current study aimed to quantify the motions of the COM with respect to the pelvic reference frame during TW and OW. TW showed greater variations of the COM displacements in all directions than those during OW (Fig. 3). With respect to the pelvis coordinate system, of the three directions TW had significantly greater anterior/posterior COM motion, whereas no significant difference was found between proximal/distal and medial/lateral directions during OW (Fig. 3).

Pelvic tilt about the medial/lateral axis might result in a larger COM displacement in the anterior/posterior direction both for TW and OW. Yang and Pai (2014) (Yang and Pai, 2014) showed the same results as the current study, namely that the greatest differences in the displacement between the sacral marker and COM across the entire gait cycle occurred in the anterior/posterior direction, indicating that it may not be valid to assume that the COM can be closely approximated by a single marker on the pelvis.

The increased center of pressure excursion in the medial/lateral direction during treadmill walking may result in a significantly greater variation and excursion of the COM in the medial/lateral direction than those in the proximal/distal direction, but not found during over-ground walking. Subjects may try to control foot placement by inadvertently increasing the excursion of the COP in the medial/lateral, proximal/distal and anterior/posterior directions. The literature suggests that increases in the COP excursion represent a decreased ability by the postural-control system to maintain balance (Winter, 1995).

Evaluating the outcomes of rehabilitation both for over-ground and treadmill walking is of paramount importance in numerous clinical applications. An IMU attached to the pelvis is capable of gathering information about a patient's walking ability outside the laboratory, during daily life with no space limitations and for prolonged periods of time (Köse *et al.*, 2012). Further, since IMUs can be combined directly with gait models, they may provide practical solutions for continuous daily assessments. However, treadmill walking had significantly greater variation and excursion of the COM with respect to the pelvis coordinate system compared to over-ground walking. Therefore, over-ground walking as opposed to treadmill walking may be more appropriate for estimating the COM position with an IMU.

To the best of our knowledge, this is the first study quantifying the displacements of the COM with respect to the pelvic reference frame during TW and OW. Such differences in the variations between OW and TW provide us with evidence that the simple method of measuring the sacral marker positions could reasonably approximate the COM. Moreover, the estimation is more accurate during over-ground walking than treadmill walking. Further studies are

needed to assess the performance of the method in the following aspects: First, only healthy and young subjects were included in this study. It is unclear how these results may change for elderly individuals with movement disorders, given that falls are among the leading causes of death in the older population in modern societies (Hoyert *et al.*, 2001). Second, only displacement was considered in this study. It remains unclear how velocity and acceleration of the COM may affect accuracy. Third, the pelvis rotations about the three axes could be a contributor to the differences between over-ground walking and treadmill walking. In addition, further study should also assess the COM motion using both an IMU and an optical motion capture system together to quantify their differences. Esser *et al.* (2009) compared the COM motion during walking obtained using an IMU (attached to the lower spine) with that using an optical motion capture system, giving a measurement error of 0.047 ± 0.06 cm along the z-axis. However, the study had a small sample size of only five subjects, and did not report errors along the other two axes. Despite these limitations, this study was the first to provide data on the COM displacements with respect to the pelvis coordinate system between TW and OW, which may be useful for future guidelines in using inertial measurement units to measure COM motion for fall monitoring applications.

5. Conclusions

The COM displacements with respect to the pelvis coordinate system showed different patterns in each of the three directions between over-ground walking and treadmill walking. Compared to over-ground walking, treadmill walking had significantly greater variations in COM displacements in all three directions. These results suggest that the estimation of the COM position with an IMU attached to the pelvis may be more accurate during over-ground walking than treadmill walking. These differences may have to be taken into account in future designs of wearable devices for monitoring COM motion during both treadmill and over-ground walking, when developing strategies to optimize the translation of treadmill gait training outcomes to real life over-ground walking.

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