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Kinematic and kinetic validity of the inverted pendulum model in quiet standing

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Abstract

Movements of the whole-body center of mass during quiet standing have been estimated from measurements of body segment movements. These whole-body center of mass movements have been compared with movements of the center of mass as predicted from a simple inverted-pendulum model of standing. However, the total body center of mass is a weighted average of the center of mass of all individual body segments. The question arises as to how well the total body center of mass represents the individual segments and lower limb joint angles. This study focuses on the validity of how well the individual segments and lower limb angles temporally and spatially synchronize with the total body center of mass. Eleven healthy university students volunteered to participate. Kinematic data were collected using a 3D optoelectronic camera system; kinetic data were collected using a 3D force plate. Participants stood quietly, with eyes open, for 120 s. Segment and whole body centers of mass were calculated from a 14 segment, 3D bilateral model. Segment and joint angles were calculated for the lower limbs, bilaterally, and the trunk. Segment center of mass root-mean-square displacements were strongly correlated with center of mass height relative to the ankle joint and were synchronized, or temporally locked, to the movement of the whole body center of mass. Sagittal plane ankle angular displacements were highly correlated to sagittal plane center of mass movement; stronger correlations between body center of mass and lower limb angular displacement were observed, the result of compensatory knee joint angular displacements. These data support and extend the use of an inverted pendulum model to represent quiet standing postural control.

Keywords: Quiet stance; Kinematic; Center of mass; Segment and joint angles

1. Introduction

Methods of estimating whole-body center of mass (COM) have varied in quiet standing. COM movement has been estimated by twice integrating horizontal ground reaction shear forces [1]; unfortunately these shear forces are extremely small, and subject to low signal to noise ratios. Any small bias in the shear force results in a drift in the estimated COM position. Others have estimated COM using two markers [2] or a single rod positioned at approximately the level of the pelvis [3]. Winter and colleagues [4] estimated whole body COM location using a high-resolution optoelectronic 3D camera system (OPTOTRAK), developing a fourteen segment bilateral model of COM.

Kinetic measures during quiet standing have consisted primarily of force platform measurements of center of pressure (COP), the weighted average of pressures distributed over the surface of the area in contact with the ground. When both feet are in contact with the ground, a COP exists under each foot, and the net COP resides between the feet. With the use of EMG or through inverse dynamics, studies have demonstrated that sagittal plane COP movement is controlled using the plantar/dorsiflexor ankle musculature [5]. Frontal plane COP movement is controlled using hip ab/aductor musculature, created by a load/unload mechanism between the lower limbs [6].

Postural sway has been modeled as an inverted pendulum [4,7]. The inverted pendulum model predicts that the difference between COP and COM is proportional to the horizontal acceleration of COM [8,9]. This prediction has been validated experimentally by Winter and colleagues [4]. Modeling postural sway as an inverted pendulum assumes a rigid structure above the ankles. However, the body is a multi-linked segmented structure capable of moving at all of the joints superior to the ankle. Movement at joints other than the ankles, specifically the hips, has been demonstrated

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in response to an external perturbation [10,11]. Movement of the hips has also been demonstrated during unperturbed quiet stance [12,13]. Aramaki and colleagues [14] demonstrated movement at the ankle and hip joints, and reported reciprocal accelerations between the ankle and hip during quiet standing.

Most studies of human postural sway have been limited to COM estimates in the sagittal plane. One study has reported COM trajectories in AP and ML directions [4]. No study has detailed the individual segment COM trajectories in the AP and ML directions or lower limb joint angle changes during quiet standing. The current paper re-examines the relationship between COP and COM during quiet standing, and confirms previous reports in the literature that COP–COM is proportional to horizontal COM acceleration, and goes on to provide a detailed kinematic analysis of quiet standing. The findings support and extend the inverted pendulum model by examining movement of body segment centers of mass and lower limb joint angles.

2. Methodology

2.1. Participants

Eleven healthy young university students (mean ± S.D.: age 26.5 ± 3.9, height 169 ± 7.1 cm) with no known balance or gait pathology volunteered to participate in this study. Prior to their participation, each participant provided informed consent to the potential risks associated with their participation. Approval of this study was provided by the Office of Human Research, at the University of Waterloo, Waterloo, Ont., Canada. The participants were barefoot and wore shorts and an athletic shirt throughout the experiment. Tight fitting clothing was worn to reduce movement of markers placed on the body.

2.2. Equipment

Kinematic data was obtained using a 3D optoelectronic camera system (OPTOTRAK, Northern Digital, Waterloo, Ont., Canada). Twenty-one infrared light emitting diodes (IREDs) were affixed to the participants using double-sided tape. IRED placement was the same as that used by Winter et al. (1998); bilaterally, at the ankle, knee, greater trochantor, ASIS, iliac crest, angle of ribs, wrist, elbow, shoulder, and temple of head, and at the xyphoid process. The location of each IRED is indicated in Fig. 2. Kinematic data collection was performed at a frequency of 64 Hz. Kinetic data was collected using an AMTI 3D force plate (AMTI, Watertown, MA, USA). Kinetic data were collected at a frequency of 512 Hz.

2.3. Protocol

Participants were instructed to stand quietly with their eyes open, for a duration of 120 s. Participants stood with their feet side-by-side, approximately shoulder width apart; arms hanging relaxed at their sides. They were instructed to choose a point on the wall in front of them (a distance of 6 m) and continue to look at that point throughout the duration of the experiment.

2.4. Data reduction

Using raw IRED coordinate data, whole body COM in the anterior–posterior (AP) and medial–lateral (ML) directions was calculated according to the following equation:

$$\mathrm{COM_x} = (\mathrm{X_{COM1}} \cdot \mathrm{m_1}) + (\mathrm{X_{COM2}} \cdot \mathrm{m_2}) + \dots + (\mathrm{X_{COMn}} \cdot \mathrm{m_n})$$

where n is the number of segments included in the COM model; m, the mass fraction of the nth segment, and X is the segment COM location in the AP direction. Substituting Y into the equation for X results in the COM location in the ML direction. IRED placement allowed the construction of a 14 segment COM model, with the following segments; leg and foot (2), thigh (2), pelvis, $\mathrm{trunk_1}$, $\mathrm{trunk_2}$, $\mathrm{trunk_3}$, $\mathrm{trunk_4}$, lower arm and hand (2), upper arm (2), and head [4]. The raw signals of the vertical force (Fz), moment about the x-axis, and moment about the y-axis of the force plate were used to calculate AP and ML COP. Following a Fast Fourier Transform of the raw AP and ML COM and COP signals, the frequency below which 99% of the signal power ($F_{99\%}$) resided was determined. The $F_{99\%}$ (± 1 S.D.) was found to be 0.58(0.26), 0.82(0.36), 1.21(0.24), and 1.58(0.46) Hz for the AP COM, ML COM, AP COP and ML COP, respectively. A representative sample of the amplitude spectra of whole body COM and COP, in the AP direction, is presented in Fig. 1(a). Note the consistency in the amplitudes of the COM and COP signals at the very low frequencies, i.e. below approximately 0.2 Hz, and the greater amplitude of the COP signal at higher frequencies, up to approximately 2 Hz. Considering the large moment of inertia of the inverted pendulum (approximately 60 kg m^2) pivoting about the ankle joints, it is not surprising that the sway frequencies are this low. From these results, cutoff frequencies of 1.5 and 3.0 Hz were chosen for the COM and COP data, respectively. All kinematic and kinetic data were subsequently filtered using a fourth order, zero phase shift, digital Butterworth filter prior to any further calculations [15].

2.4.1. Individual IREDs; center of mass

The $F_{99\%}$ of each IRED, in the AP and ML directions was determined, as well as the amplitude of displacement of each marker in the AP, ML and vertical directions. The AP and ML displacement of each IRED was correlated with the displacement of all other IREDs, for each participant. The mean r^2 was calculated for each IRED across all of the participants. The mean r^2 for each IRED with all other IREDs, expect for the two knee markers, was then determined. For

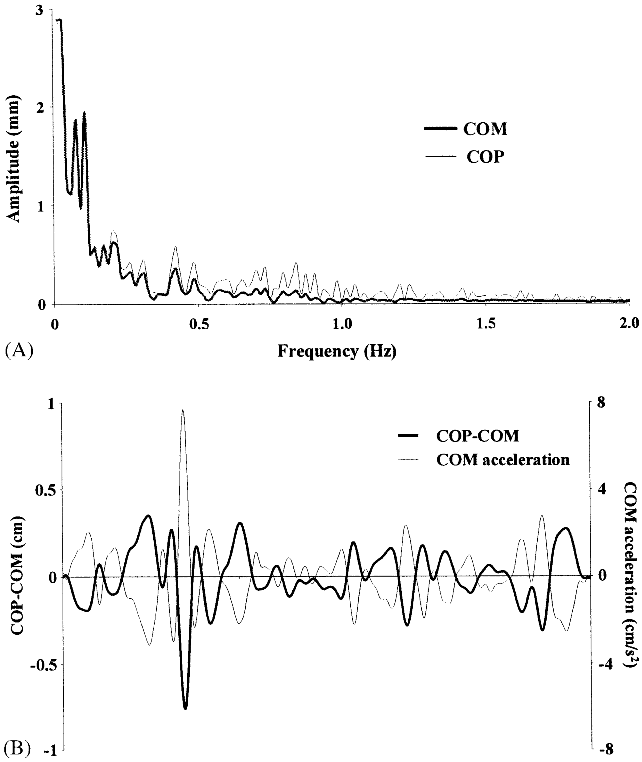

Fig. 1. (a) Representative output of FFT analysis of COM and COP signals, in the AP direction. COM and COP signal amplitudes are very similar up to approximately 0.2 Hz. The COP signal contains greater power at higher frequencies than the COM signal; (b) representative sample of the relationship between COP–COM and COM acceleration, in the AP direction.

example, the mean r^2 value for right knee IRED was determined by including all of the other IREDs except for the left knee IRED. The exclusion of the right and left knee markers from these means was done as a result of the low mean r^2 values associated with the two knee IREDs. This will be discussed further in Sections 3 and 4 of this paper.

The AP and ML COM of each individual body segment and of the whole body were calculated for each 120-s trial. The data from each trial was divided into four 30-s blocks, to allow investigation of changes in the results across the duration of each trial. The height, relative to the ankle joint, and displacement of each segment COM and of the whole body COM were calculated for the 120-s trial and each 30-s block. For each record in the AP and ML directions, the correlation coefficient (r^2) between the displacement of each segment COM and the whole body COM was calculated. The r^2 value was calculated to demonstrate the temporal synchronization in the movements of individual segment COMs and whole body COM. The slope of the relationship between COM height and displacement, in the AP and ML directions, and the associated linear regression correlation coefficient (r^2) were calculated to demonstrate the spatial synchronization between the movements of the segment COMs and the whole body COM.

2.4.2. Segment and joint angles

Segment angles were calculated for the leg (ankle to knee; bilaterally), thigh (knee to hip; bilaterally), and trunk (mean hip to mean acromion process), as well as the lower limb (ankle to hip; bilaterally). Angular displacements were calculated for the ankle, knee, and hip joints, for the entire 120-s duration, and each 30-s block, to examine joint angle changes throughout the quiet standing period. For each record, the correlation coefficient (r^2) between the AP displacement of the whole body COM and the leg segment angle (ankle angle), and between the whole body COM and the lower limb segment angle, were calculated; these correlation coefficients were calculated to examine the relationship between COM movement and lower limb joint angle changes.

2.4.3. Acceleration of whole body COM

The difference between COP and whole body COM (COP–COM) was compared with the acceleration of the whole body COM acceleration, in the AP and ML directions. The correlation coefficient (r) between COP–COM and COM acceleration was calculated to demonstrate that whole body COM movements of the participants in the current study behaved generally as an inverted pendulum, as has been reported previously in the literature [4].

3. Results

3.1. COP–COM versus COM acceleration

The mean R-values between COP–COM and COM acceleration, in the AP and ML directions, were -0.954 ± 0.020 and -0.840 ± 0.054, respectively. These values are consistent with previously reported findings, of −0.91 and −0.758 in the AP and ML directions, respectively [6]. A representative sample of the inverse relationship between COP–COM and COM acceleration is presented in Fig. 1(b). High correlation between horizontal COP–COM and COM acceleration has been considered the primary measure of validity of the inverted pendulum model [6]. The high mean r-values between COP–COM and COM acceleration in the current study confirm that the inverted pendulum nature of the quiet standing performance of the participants of this study is consistent with that of previous published work.

3.2. Individual markers

The mean IRED $F_{99\%}$ in the AP and ML directions were 0.684 Hz (range 0.544–0.973; n = 11) and 0.908 Hz (range 0.738–1.244 n = 11), respectively. These data confirmed that the chosen filter cutoff frequency of 1.5 Hz was appropriate.

Fig. 2 shows that the mean displacement of each IRED (n = 11), in the AP and ML directions, increases linearly as the height of the IRED increases. A linear regression through the mean marker displacements, passing through

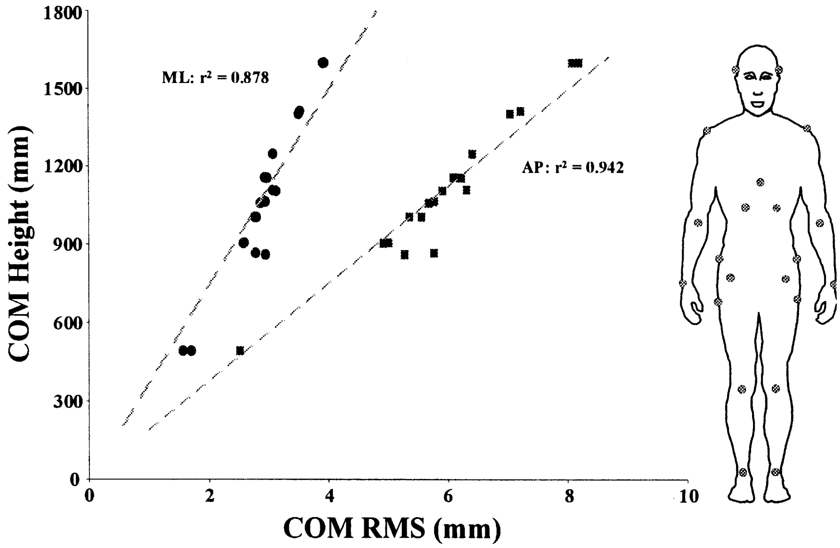

Fig. 2. Regression of mean IRED RMS displacement with IRED height (above ankle joint), in ML and AP directions. r^2 values indicate strength of relationship between IRED RMS and height. IRED locations are indicated on human figure.

(0, 0), resulted in r^2 values of 0.942 and 0.878 in the AP and ML directions, respectively. Analysis of the vertical movement of each IRED revealed mean vertical movement of 1.11 mm (range 0.73–1.43 mm). The right and left knee joint IREDs demonstrated the smallest vertical movements, 0.73 and 0.88 mm, respectively.

The mean r^2 of the right and left knee IREDs with each of the other IREDs, with the exception of the contralateral knee marker, were 0.740 and 0.676 in the AP direction, respectively, and 0.917 and 0.889 in the ML direction, respectively. The mean r^2 of all of the remaining IREDs (note: the r^2 value associated with each of the knee IREDs was removed from these means) ranged from 0.856 to 0.920 in the AP direction, and 0.838 and 0.941 in the ML direction. An ideal pendulum would have $r^2 = 1$. These results indicate that movements of all of the IREDs, in the AP and ML directions, are highly correlated, with the exception of the knee IREDs in the AP direction.

3.3. Center of mass; segment versus whole body COM

Fig. 3 presents a typical 2 min record of AP segment and whole body COM, showing that amplitude of COM displacement increases with height and that all trajectories are essentially in phase, indicated by the alignment of peaks and troughs between the different segments. Fig. 4 shows

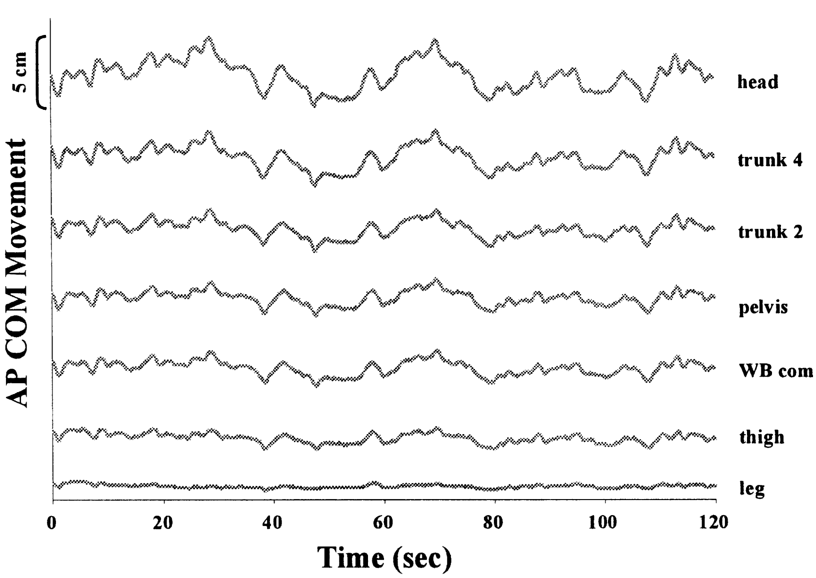

Fig. 3. Representative time series plot of the whole body (WB) COM displacement, and various segment COM displacements. All displacements are plotted on the same scale (indicated at left vertical axis). COM displacement increases with height above ankle; COM displacement signals are temporally aligned.

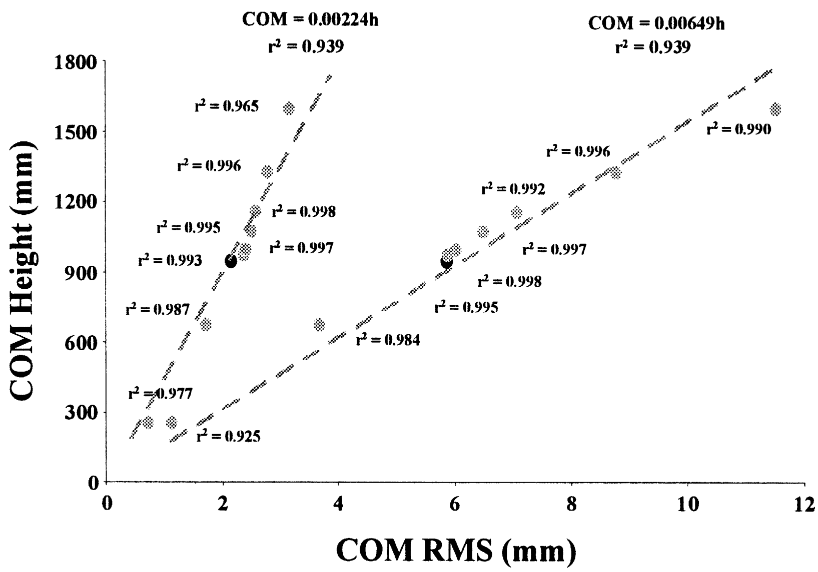

Fig. 4. Representative regression of COM RMS with COM height (above ankle joint), in ML and AP directions. r^2 values located at top of regression lines indicate strength of relationship between COM displacement and height. r^2 values located beside individual data points indicate strength of relationship between segment COM and whole body COM.

the RMS amplitude of the segment and whole body COMs versus height above the ankle joint in both AP and ML directions for Subject #1 during the 60–90-s period, a representative example of the spatial and temporal relationship between body segment and whole body COMs. A linear regression through the segment COM's passing through the ankle (at 0, 0) provides a measure of how well the human inverted pendulum approaches an ideal inverted pendulum. The r^2 values for the AP and ML sway lines were both 0.939. These regression lines indicate that each segment of this subject swayed 0.649% of its height above the ankle in the AP direction, and 0.224% of the height in the ML direction. The correlation between the whole body COM and each segment COM is shown beside each segment and is a measure of the synchronized sway evident in Fig. 3. The r^2 values of this representative sample range from 0.925 to 0.998 in the AP direction and 0.965 to 0.998 in the ML direction.

Table 1(a) and (b) summarize the slopes and correlation coefficients (r^2) of COM height versus movement amplitude for all subjects over each 30 s period and the total 120 s period, in the AP and ML directions. In the AP direction, the r^2 averaged 0.934 over the 120 s trial, and the average r^2 for the 30 s blocks ranged from 0.871 to 0.962. However, it should be noted that there were two subjects who demonstrated low r^2 in the AP direction for one of the 30 s blocks; subject #8 in the 90–120 s block, and subject #11 in the 30–60 s block. A visual examination of these trials revealed that the participants were not standing still, but were making some voluntary adjustments. Subject #8 made a voluntary adjustment at the hip joints, and subject #11 made a voluntary adjustment in head position. The ML r^2 averaged 0.916 over the 120 s trial, and the average r^2 for the 30 s blocks ranged from 0.906 to 0.968. In the AP direction the sway averaged 0.57% of height, and in the ML direction it

Table 1
Mean slopes and r^2 values for regression of COM RMS and height

	120 s		0–30 s		30–60 s		60–90 s		90–120 s	
	COM_x (%h)	r^2	COM_x (%h)	r^2	COM_x (%h)	r^2	COM_x (%h)	r^2	COM_x (%h)	r^2
(a) in AP										
Mean	0.570	0.934	0.470	0.871	0.557	0.873	0.463	0.962	0.507	0.915
S.D.	0.243	0.051	0.205	0.103	0.227	0.211	0.258	0.045	0.277	0.179
Min	0.286	0.838	0.228	0.656	0.264	0.257	0.184	0.844	0.238	0.387
Max	1.066	0.994	0.931	0.978	0.859	0.996	1.007	0.999	1.217	0.997
(b) in ML										
Mean	0.284	0.916	0.233	0.910	0.192	0.943	0.238	0.968	0.225	0.906
S.D.	0.115	0.062	0.089	0.097	0.050	0.043	0.118	0.024	0.073	0.097
Min	0.142	0.795	0.132	0.654	0.119	0.851	0.083	0.930	0.077	0.678
Max	0.526	0.983	0.351	0.984	0.281	0.988	0.495	0.989	0.339	0.995

Table 2
Mean r^2 values between body COM and segment COMs, in AP and ML (n = 11)

Segment	120		0–30		30–60		60–90		90–120	
	AP	ML	AP	ML	AP	ML	AP	ML	AP	ML
Mleg	0.805	0.973	0.803	0.970	0.920	0.979	0.931	0.983	0.907	0.976
Mthigh	0.969	0.982	0.942	0.976	0.984	0.989	0.977	0.989	0.976	0.983
Pelvis	0.984	0.988	0.989	0.978	0.993	0.991	0.989	0.993	0.987	0.991
$Trunk_1$	0.987	0.991	0.992	0.983	0.995	0.993	0.993	0.992	0.990	0.992
$Trunk_2$	0.987	0.993	0.985	0.989	0.992	0.994	0.988	0.994	0.992	0.994
$Trunk_3$	0.983	0.991	0.977	0.986	0.985	0.993	0.980	0.994	0.985	0.989
$Trunk_4$	0.981	0.987	0.987	0.978	0.989	0.992	0.991	0.993	0.986	0.990
Head	0.930	0.929	0.932	0.916	0.959	0.955	0.972	0.966	0.973	0.944

averaged 0.284% of height. These data are consistent with previous work [6] in which whole body COM sway in the ML direction was seen to be less than half of that in the AP direction. This finding was traced to higher joint spring stiffness, particularly at the hips, in the ML direction. In both directions the COM displacement (%h) was less for each 30 s block than for the total 120 s period and this was because of an extremely low frequency drift present over the total period that was reduced when the trial period was broken into four blocks.

Table 2 summarizes the r^2 values for all subjects over the 120-s duration and over each 30-s block. In the AP direction, the r^2 between the leg segment COM and the whole body COM was notably lower for the 2 min trial and for each 30-s block, than for all other segments across each duration. All other r^2 values ranged between 0.930 and 0.995.

3.4. Segment and joint angles

Table 3(a) and (b) summarize segment and joint angle displacements across the entire 120-s, and across each 30-s block. Similar to COM, angular displacements tended to be less for each 30-s block than for the entire trial. This was due to the presence of extremely low frequency drift in the joint angles. Furthermore, there was a tendency for the displacements of the ankle, knee and hip joints to be largest in the first 30-s block. It should be noted that 10 of the 11 participants demonstrated knee joint displacements that were greater than ankle joint displacements, across the 120-s trial.

Table 4 presents the correlation coefficients (r^2) for each participant, between ankle joint displacements and whole

Table 4
Correlation coefficients in the time series angular displacements of each lower limb segment and each leg segment (ankle angle) with whole body COM; mean correlation across 30 s time blocks

	COM_x			
	Right ankle	Left ankle	Right lower limb	Left lower limb
Mean	0.891	0.876	0.973	0.977
S.D.	0.108	0.105	0.017	0.011
Min	0.602	0.598	0.940	0.955
Max	0.975	0.970	0.994	0.995

Table 3
Joint and segment angle RMS (°)

	Right ankle	Left ankle	Right knee	Left knee	Right hip	Left hip	Right lower limb	Left lower limb	Trunk
(a) For entire trial (120 s); mean values									
Mean	0.37	0.38	0.44	0.56	0.47	0.54	0.35	0.36	0.39
S.D.	0.25	0.30	0.27	0.40	0.28	0.33	0.15	0.16	0.15
Min	0.2	0.1	0.2	0.2	0.2	0.3	0.2	0.2	0.2
Max	0.9	1.2	1.0	1.5	1.0	1.2	0.6	0.7	0.6
(b) for each 30 s time block (n = 11)									
Segment or joint	0–30 s		30–60 s		60–90 s		90–120 s		
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	
Right ankle	0.39	0.30	0.32	0.23	0.28	0.21	0.27	0.16	
Left ankle	0.40	0.45	0.32	0.22	0.26	0.18	0.28	0.19	
Right knee	0.44	0.38	0.23	0.17	0.19	0.12	0.21	0.12	
Left knee	0.48	0.63	0.28	0.21	0.19	0.12	0.22	0.14	
Right hip	0.33	0.14	0.28	0.10	0.21	0.10	0.28	0.18	
Left hip	0.35	0.28	0.29	0.13	0.24	0.12	0.27	0.13	
Right lower limb	0.29	0.13	0.33	0.15	0.28	0.16	0.30	0.17	
Left lower limb	0.30	0.12	0.33	0.16	0.28	0.16	0.29	0.16	
Trunk	0.28	0.14	0.34	0.15	0.27	0.13	0.36	0.16	

body COM displacement, and between lower limb segment angular displacement and whole body COM displacement. The values presented are the mean values across the four 30-s blocks, for each subject. Comparisons between ankle angle displacement and AP COM movement demonstrated strong correlations; ankle angle movement was temporally correlated with AP COM movement (average $r^2 = 0.891$ for right; average r^2=0.876 for left). Comparisons between lower limb segment angle movement and AP COM movement were, however, even stronger (average $r^2 = 0.973$ for right; average $r^2 = 0.977$ for left).

4. Discussion

The purpose of this experiment was to re-examine the relationship between COP–COM and COM acceleration to provide support for the inverted pendulum model of quiet standing, and extend this support for the inverted pendulum model by providing a detailed kinematic analysis of the movement occurring during quiet stance both in COM measures and joint angle measures. Using high precision 3D optoelectronics to construct a 14 segment COM model, individual segment and whole body COM movements, and lower limb joint angles were examined in the sagittal and frontal planes, all during quiet standing. The high precision of the camera system (0.03 mm linear displacement) allowed reporting of the ankle, knee and hip joint angles to the precision of 0.1°.

4.1. Individual IREDs; center of mass

Prior to deriving any measures of displacement in our kinematic data, an analysis of the frequency content of this data was conducted in order to determine the appropriate signal filtering parameters. Previous research has provided similar analysis. Winter [15] examined the frequency content of body segment movement during natural cadence walking, and found that the highest frequency was related to foot movement, at 6 Hz. Thus, they suggested a filter cut-off frequency of 6 Hz in the processing of kinematic data obtained during locomotion. Carpenter [16] examined the frequency content of a 2 min AP COP signal derived during quiet stance. They reported that 90% of the signal power between 0 and 5 Hz resided below 0.5 Hz. However, these findings were based on the results of one trial obtained from one subject. In the current study, the mean frequency below which 99% of the power of the AP and ML COP signals resided ($F_{99\%}$) was 1.211 and 1.580 Hz, respectively, with a sample size of 11 participants. For the AP and ML COM signals, the $F_{99\%}$ were 0.578 and 0.822 Hz, respectively. Furthermore, analysis of the frequency content of each individual marker revealed that 99% of the displacement signal power resided below 0.68 and 0.91 Hz in the AP and ML directions, respectively. Based on these findings, it is recommended that a filter cut-off frequency of 1.5 Hz be used in the processing of kinematic quiet stance displacement data, and a cut-off frequency of 3 Hz be used in the processing of kinetic quiet stance displacement data.

Winter [4] experimentally validated the inverted pendulum model of quiet stance, describing ankle joint stiffness as the controlling element in postural sway. They reported correlation coefficients between the error signal (COP–COM) and COM acceleration of 0.914 in the AP, and 0.758 in the ML. The present study confirms the data of Winter [4]: correlation coefficients of 0.954 in the AP and 0.840 in the ML. The inverted pendulum model assumes that the body above the ankle joints is rigid and rotates about the ankle. Examination of the whole body COM movement, and the movements of each segment COM, supported the inverted pendulum model; the AP and ML movements of all segment COMs were highly correlated to the movement of the whole body COM. Furthermore, the horizontal COM movements in the AP and ML directions of the whole body and each body segment increased linearly in amplitude as the height above the ankle increased. Similar results were found in an examination of the individual markers; movements of all markers above the ankle were highly correlated with one another in both the AP and ML directions, and the amplitude of each markers displacement increased linearly with the height of the marker. Relating amplitude of COM movement to COM height as a percentage of height revealed the following; in the AP direction, COM displacement RMS was 0.570% of height, and in the ML direction, COM displacement RMS was 0.284% of height. Consistent with previous research [6], AP postural sway was approximately twice the amplitude of ML postural sway. These findings indicate that the movements of the segment COMs and whole body COM are “locked” both spatially (mean $r^2 = 0.934$ in AP, mean r^2=0.916 in ML) and temporally (mean $r^2 = 0.953$ in AP, mean $r^2 = 0.979$ in ML), effectively allowing the body to rotate about the ankles as a unit.

4.2. Segment and joint angles

A premise of the inverted pendulum model is that the body above the ankles is rigid. It must be considered that the inverted pendulum model provides a description of how certain kinematic elements, namely COM and ankle joint angle, move during quiet standing. The inverted pendulum model does not dictate that other kinematic elements, for example, knee joint angles, must be rigid. It is possible that movement at these joint during quiet stance may serve to control whole body COM movement, as the ankle joint does, via subtle compensatory movements. Horizontal COM movement, or postural sway, may still be modeled as an inverted pendulum in light of subtle knee joint angle displacements. Indeed, previous research has demonstrated that joint movement above the ankles does occur during quiet stance. Accornero [13] modeled postural sway as a double inverted pendulum, and demonstrated significant rotational movement at the hip joint. Iqbal and Pai [17] modeled balance recovery following a postural perturbation. They reported that restricting knee motion in the model substantially reduced the feasible stability region, and that lower limb movements with “prominent knee motion” may be considered in the continuum between pure ankle and hip postural recovery strategies. Aramaki [14] reported movements occurring at the hip and ankle joints that demonstrated reciprocal angular accelerations during quiet stance. However, their findings are the result of non-physiological testing methods. Aramaki and colleagues [14] restricted motion of the knee joint and spinal column through the application of “stiff wooden splints”. Given that compensatory knee movements were eliminated, reciprocal accelerations at the ankle and hip joints may have resulted from the direct mechanical couple between the ankle and hip because of the splinting. An understanding of physiological knee joint movement during quiet standing would be required in order to completely appreciate the effect on postural control of removing such knee joint movement.

The current study revealed notable movement at all three major joints of the lower limb; ankle, knee, and hip (Table 3(a, b)). In fact, when considered across the entire duration of quiet standing, knee joint movement was 33% greater than movement at the ankle. Artefactual knee joint marker movement, which may inflate the calculated joint angle, was ruled out by examining the vertical movement of all of the markers. Excess vertical movement of the marker may serve to alter the lower leg and thigh segment angles, which may result in exaggerated knee joint angles. In fact, knee joint markers demonstrated the least vertical movement of all the markers used. Findings of small vertical knee joint marker movements, consistency with the pattern of increasing horizontal displacement with marker height among all of the markers, and constraint of the majority of signal power of the knee markers to very low frequencies (consistent with the remainder of the markers) suggests that the knee joint markers move in a manner very similar to the remainder of the markers. However, the time-based correlation coefficients between knee joint markers and the remainder of the markers, in the AP direction but not in the ML direction, were much lower than that of the other markers. In other words, all of the markers moved with the same temporal and spatial patterns, except for the knee joint markers, in the AP direction. Taken together, all of these findings confirm that the calculated knee joint angular displacements are true angular changes and not the result of error, experimental or otherwise.

As mentioned earlier, an extremely low frequency drift was present in the COM and joint angle data, most notably in the knee joint displacement data. Therefore, trials were broken into 30 s blocks to allow examination of measures with reduced influence of this drift. Notable knee joint movement was present, however, even within the shorter duration blocks. In the first 30 s, angular displacement of the knee joint was 20% greater than at the ankle joint, possibly representing a “settling-in period” at the beginning of quiet stance. Similarly, Carpenter [16] reported a transient component in measures of COP during the first 20–30 s of quiet stance, as did Carrol and Freedman [18]. Across the three remaining 30 s blocks (30–120 s), knee joint angular displacement was approximately 75% of ankle joint movement. In other words, knee joint angular displacement is present during quiet standing, and relatively large when compared with ankle joint displacement.

4.3. Joint angles and center of mass

Ankle joint angular displacement, determined as the leg segment angle, and AP whole body COM displacement were highly correlated; 0.890 and 0.876 for the right and left ankles, respectively, and ankle dorsiflexion occurred as the COM moved forward. However, when the orientations of the lower leg and thigh were considered by determining the lower limb segment angle, stronger correlations with whole body COM were found; 0.973 and 0.977, for the right and left limbs, respectively. These findings indicate that when the net orientation of the lower limb (a combination of the leg segment and thigh segment orientations) is considered, the lower limb angle tracks the movement of the whole body COM quite closely, more closely than when the ankle angle alone is considered. These findings suggest that compensatory knee joint movements allow the lower limb to track the COM more consistently than if no movement occurred at the knee.

5. Conclusions

The current study supports the inverted pendulum model of quiet standing; the error signal (COP–COM) and COM acceleration were strongly correlated, the movement of each segment COM was temporally synchronized with the movement of the whole body COM, and the displacement of each segment COM increased linearly with the height above the ankle joint. Angular movements of the ankle joint track the COM; knee movements, comparable in amplitude to the movements of the ankle joint, allow the net orientation of the lower limb to more closely track the movements of the whole body COM than the ankle joint alone.

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