Abstract

Accurate measurement of centre of mass (CoM) motion can provide valuable insight into the biomechanics of human running. However, full-body kinematic measurement protocols can be time consuming and difficult to implement. Therefore, this study was performed to understand whether CoM motion during running could be estimated from a model incorporating only lower extremity, pelvic and trunk segments. Full-body kinematic data was collected whilst (n=12) participants ran on a treadmill at two speeds (3.1 and 3.9 ms^{-1}). CoM trajectories from a full-body model (16-segments) were compared to those estimated from a reduced model (excluding the head and arms). The data showed that, provided an offset was included, it was possible to accurately estimate CoM trajectory in both the anterior-posterior and vertical direction, with root mean square errors of 5mm in both directions and close matches in waveform similarity (r=0.975-1.000). However, in the ML direction, there was a considerable difference in the CoM trajectories of the two models (r=0.774-0.767). This finding suggests that a full-body model is required if CoM motions are to be measured in the ML direction. The mismatch between the reduced and full-body model highlights the important contribution of the arms to CoM motion in the ML direction. We suggest that this control strategy, of using the arms rather than the heavier trunk segments to generate CoM motion, may lead to less variability in CoM motion in the ML direction and subsequently less variability in step width during human running.

Keywords: Centre of Mass; Running; Full-Body Gait; Arm Motion

Introduction

Precise measurement of centre of mass (CoM) motion is essential for understanding different aspects of running gait, such as energy fluctuations [1] and gait asymmetry [2]. CoM motion is typically calculated either from a weighted sum of individual segment centroids, or by using a simplified model that assumes CoM motion can be derived using a reduced set of markers [3, 4]. However, these simplified models have been associated with errors of up to 1-2 cm [3, 4] and therefore may not be appropriate for running-related research. However, it is common practice to collect data from only the pelvis and lower limbs during running [5, 6]. With this set up, it would be relatively straightforward to add a trunk segment to this model. Depending on the precise contribution of the arms to CoM motion, such a model may prove an accurate method of estimating CoM during running, and therefore be of considerable practical benefit.

To date, there has been limited study of the biomechanical function of the arms during human running. Although it is accepted that the arms acts to counteract the angular momentum generated by the lower limbs, about the vertical axis [7], the contribution of the arms and head to linear CoM motion, in each plane, is not clear. Such insight may improve our understanding of the biomechanical mechanisms that facilitate mediolateral CoM motion during running. Given this limitation in the current knowledge and the potential practical benefit identified above, we carried out a study to determine the effect of excluding the arms and head on CoM trajectory during human running.

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Methods

Twelve participants (age 41(8)years, height 1.75(0.10)m and body mass 73(13)kg), familiar with treadmill-running, participated in this investigation. Informed consent was obtained and ethical approval provided by the Local Ethics Committee. Full body (upper limbs, head, thoracic and lumbar spine, pelvis, and lower limbs) kinematic data were collected for each participant whilst running on a treadmill at two speeds (3.1 and 3.9ms^{-1}), representative of average recreational running speeds [8].

Twelve Qualisys Oqus 3D cameras (240Hz) were used for kinematic data collection. Lower limb, pelvis and trunk segments were modelled and tracked using the approach described in Preece et al. [9]. In addition, markers were placed on the acromion processes, lateral shoulders, medial and lateral epicondyles of the humeri, styloid processes of the ulnae and radii, as well as on the 2nd and 5th metacarpal heads. Head markers were placed bilaterally in anterior and posterior positions. Data from Dempster [10] were used to define segment masses and inertial properties were then calculated from marker positions, assuming the head to be an ellipsoid, the upper arms and forearms to be frusta of cones, and the hands to be spheres.

To understand the effect of excluding the arms and head on CoM motion, two models were defined. The reduced model consisted of nine segments: the feet, shanks, thighs, pelvis, and lumbar and thoracic spine. The full-body model comprised of 16 segments, those in the reduced model, as well as the upper arms, forearms, hands and head. Data processing methods as outlined in Preece et al. [9] were used, in which raw marker data were first low pass filtered (10Hz). A kinematic approach [11] was then used to define gait events for 10 consecutive gait cycles and CoM trajectories calculated using the Visual3D software. With this approach the CoM for each model was obtained for each subject at both running speeds.

Including the head and arms may result in a systematic shift in CoM trajectory in the AP (anterior-posterior) and vertical directions. Therefore, a correction factor was determined, in both planes, and expressed as a percentage of participant height. The difference between the reduced and full model, with/without correction, was then characterised using a number of statistics. Firstly, root mean square error (RMSE) was calculated for both position and velocity from individual ensemble average data and then averaged across all participants. RMSE in the range of movement (RoM) over the 10 gait cycles was also calculated and averaged across participants. Finally, a correlation coefficient was used to compare curve similarity [12] between ensemble average trajectories which was also averaged across participants.

Results

There was minimal variation in the vertical and AP correction factors with speed. Therefore a consistent 0.3% correction was applied to all AP data, which lead to a mean RMSE of 5mm in position and mean RMSE of 2mm in RoM (Table 1). In this plane, there was a close match in waveform similarity between the two models (Figure 1) with mean correlations of r=0.975-0.978 (Table 1). However, in the ML direction, there was less similarity in CoM trajectories (Figure 1) resulting in lower correlation coefficients (Table 1). In this plane, the reduced model appeared to underestimate the full-body RoM and although the RMSE in position/RoM was only 3/4mm (Table 1), this was comparable with the overall RoM of approximately 10mm (Figure 1).

In the vertical direction, a correction of 4.5% was applied to the data from both speeds. With this correction, there was a very close match in the CoM trajectory of the two models (Figure 1), with correlation coefficients of 0.999-1.000 (Table 1). Moreover, the mean RMSE for position was only 5-6mm with a similar error in the RoM estimation (Table 1).

Discussion

This study sought to establish the possibility of estimating both CoM position and velocity, at two running speeds, from a model incorporating only lower extremity and trunk segments. The data showed a good match in waveform similarity between the reduced and full-body model in both the AP and vertical directions but not in the ML direction. If the RMSE in the CoM position is compared with the corresponding RoM during over ground running [9], it appears small in the AP (0.2%) and vertical (7%) directions, but substantial in the ML (40%) direction. Thus, it would appear that the reduced model may only be appropriate for estimating AP and vertical CoM trajectory and velocity and that a full-body model would be required for estimating ML motions.

The mismatch between the full-body and reduced model, at both running speeds, provides insight into the relative contribution of the arms to CoM motion in the ML direction. Previous research has shown that humans will adopt a small, but non-zero, step width during unconstrained treadmill running, typically about 2-4cm [13, 14]. Running with a non-zero step width will require a displacement between the CoM and the stance foot in order to generate the moment, about the base of support, required to transition onto the contralateral foot. Figure 1 illustrates this idea, showing that the CoM moves away from the stance foot from late stance until ipsilateral foot contact. Interestingly, this pattern is not evident in the reduced model (Figure 1). It would therefore appear that the ML motion of the CoM is primarily generated by the motion of the arms and is not the result of motion of the heavier trunk segments. Given the small ML RoM of the CoM and the more challenging task of achieving these small changes with the heavier trunk segments, this strategy may lead to less variability in ML CoM motions. This idea is consistent with previous research which has suggested that the arms may function to minimise step width variability [15] and so minimise the energetic cost of running. However, further research is required to fully confirm this idea.

Conflict of Interest

Conflict of interest: none

References

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Figures and Tables

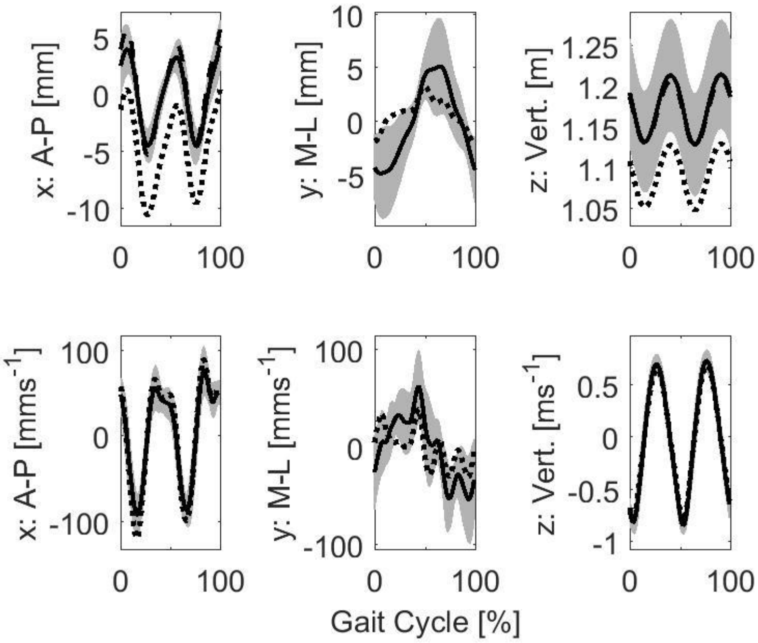

Figure 1 - Ensemble averages of CoM position (top) and velocity (bottom) from the reduced model (dotted), reduced model including offset (dashed) and full-body model (solid) at speed 1. The grey outline represents the standard deviation of the full-body model, and therefore the variability in CoM motion across participants not the difference between the two models. Positive x represents forward movement, while positive y represents motion towards the contralateral side. Note, data is plotted from right initial contact (RIC) to the following RIC and for plotting purposes the CoM position data (AP and ML) were referenced to mean position of the full-body model.

Table 1 - Root mean square error (mean (SD)) between the full-body and reduced model for the CoM position, velocity and the RoM, as well as the correlation coefficient (mean (SD)) indicating waveform similarity between the full-body and reduced model. * indicates correlation was significant ($p < 0.005$) for all participants.

Anatomical Plane	Speed	RMSE			Correlation Coefficient
		Position [mm]	Velocity [mms^{-1}]	RoM [mm]	
AP	1	6 (5)	19 (5)	2 (1)	0.975 (0.016) *
	2	6 (5)	22 (7)	3 (1)	0.978 (0.013) *
AP – incl. 0.3 % offset	1	5 (3)	19 (5)	2 (1)	0.975 (0.016) *
	2	5 (2)	22 (7)	3 (1)	0.978 (0.013) *
ML	1	3 (1)	27 (6)	4 (2)	0.774 (0.218)
	2	3 (1)	30 (8)	4 (3)	0.767 (0.223) *
Vert.	1	84 (6)	38 (11)	6 (1)	1.000 (0.000) *
	2	83 (7)	42 (13)	6 (2)	0.999 (0.000) *
Vert. – incl. 5 % offset	1	6 (3)	38 (11)	6 (1)	1.000 (0.000) *
	2	5 (2)	42 (13)	6 (2)	0.999 (0.000) *