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Gill, N, Preece, SJ, Young, S and Bramah, CA

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1 **Abstract**

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

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

21 **Introduction**

22 Precise measurement of centre of mass (CoM) motion is essential for understanding
23 different aspects of running gait, such as energy fluctuations [1] and gait asymmetry [2].
24 CoM motion is typically calculated either from a weighted sum of individual segment
25 centroids, or by using a simplified model that assumes CoM motion can be derived using a
26 reduced set of markers [3, 4]. However, these simplified models have been associated with
27 errors of up to 1-2 cm [3, 4] and therefore may not be appropriate for running-related
28 research. However, it is common practice to collect data from only the pelvis and lower limbs
29 during running [5, 6]. With this set up, it would be relatively straightforward to add a trunk
30 segment to this model. Depending on the precise contribution of the arms to CoM motion,
31 such a model may prove an accurate method of estimating CoM during running, and
32 therefore be of considerable practical benefit.
33

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

42 .

43

44 **Methods**

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

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

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

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

78

79 **Results**

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

87 the RMSE in position/RoM was only 3/4mm (Table 1), this was comparable with the overall
88 RoM of approximately 10mm (Figure 1).

89 In the vertical direction, a correction of 4.5% was applied to the data from both
90 speeds. With this correction, there was a very close match in the CoM trajectory of the two
91 models (Figure 1), with correlation coefficients of 0.999-1.000 (Table 1). Moreover, the
92 mean RMSE for position was only 5-6mm with a similar error in the RoM estimation (Table
93 1).

94

95 **Discussion**

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

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

120

121 **Conflict of Interest**

122 Conflict of interest: none

123

124 **References**

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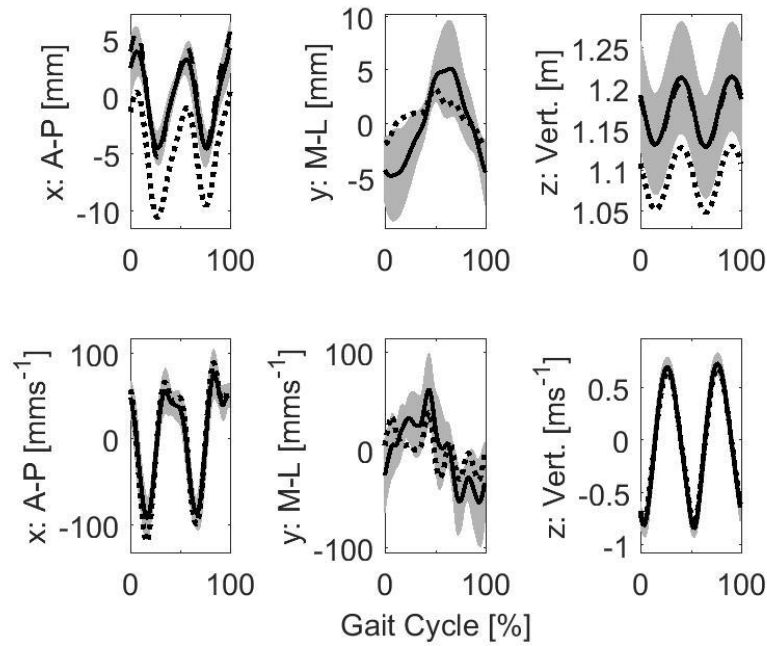
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 167 Figure 1 - Ensemble averages of CoM position (top) and velocity (bottom) from the reduced
 168 model (dotted), reduced model including offset (dashed) and full-body model (solid) at speed
 169 1. The grey outline represents the standard deviation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

175
 176 Table 1 - Root mean square error (mean (SD)) between the full-body and reduced model for
 177 the CoM position, velocity and the RoM, as well as the correlation coefficient (mean (SD))
 178 indicating waveform similarity between the full-body and reduced model. * indicates
 179 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) *