

1 **The coordinated movement of the spine and pelvis during running**

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18

19 **Abstract**

20

21 Previous research into running has demonstrated consistent patterns in pelvic, lumbar and
22 thoracic motions between different human runners. However, to date, there has been limited
23 attempt to explain why observed coordination patterns emerge and how they may relate to
24 centre of mass (CoM) motion. In this study, kinematic data were collected from the thorax,
25 lumbar spine, pelvis and lower limbs during over ground running in n=28 participants. These
26 data was subsequently used to develop a theoretical understanding of the coordination of the
27 spine and pelvis in all three body planes during the stance phase of running. In the sagittal
28 plane, there appeared to be an antiphase coordinate pattern which may function to increase
29 femoral inclination at toe off whilst minimising anterior-posterior accelerations of the CoM.
30 In the medio-lateral direction, CoM motion appears to facilitate transition to the contralateral
31 foot. However, an antiphase coordination pattern was also observed, most likely to minimise
32 unnecessary accelerations of the CoM. In the transverse plane, motion of the pelvis was
33 observed to lag slightly behind that of the thorax. However, it is possible that the close
34 coupling between these two segments facilitates the thoracic rotation required to passively
35 drive arm motion. This is the first study to provide a full biomechanical rationale for the
36 coordination of the spine and pelvis during human running. This insight should help
37 clinicians develop an improved understanding of how spinal and pelvic motions may
38 contribute to, or result from, common running injuries.

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42 **Keywords:**

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44 Running; Coordination; Pelvis; Thorax, Centre of mass

45

46 **Introduction**

47 Running is complex movement which requires precise inter-segmental coordination to
48 create forward momentum. Given the integrated nature of running, it is possible that poorly
49 coordinated movement of the pelvis and spine could result in abnormal tissue stress not just
50 in the low back (Seay, Van Emmerik, & Hamill, 2011b), but also within more distal
51 structures of the lower limbs (Leetun, Ireland, Willson, Ballantyne, & Davis, 2004).
52 However, before interventions can be developed to address abnormalities in pelvis and spinal
53 movement, it is important to develop a clear biomechanical understanding of the coordination
54 between the spine and pelvis during normal running.

55 We suggest that there are two constraints which will play a pivotal role in determining
56 coordination patterns between the pelvis and spinal segments. In the sagittal and frontal plane
57 we suggest that coordination patterns will develop which will minimise excessive changes of
58 momentum in the anterior-posterior (AP) and medio-lateral (ML) directions respectively. It is
59 likely that this strategy, suggested as a mechanism for minimising energy consumption,
60 (Heise & Martin, 2001; Williams & Cavanagh, 1987), will lead to anti-phase coordination
61 between the pelvis and thorax. This is because rotational movements of the pelvis in either
62 the sagittal or frontal planes during stance will require a rotation of the thorax in the opposite
63 direction to minimise displacement of the centre of mass (CoM).

64 Rotations of the pelvis or trunk in the transverse plane will not displace the CoM.
65 However, it has been shown that arm motion during running functions to counterbalance the
66 rotational angular momentum of the swinging legs (Arellano & Kram, 2014; Hamner, Seth,
67 & Delp, 2010). Thus a coordination pattern between the pelvis and spine must emerge which
68 facilitates the necessary arm movement for angular momentum balance. It been suggested
69 (Pontzer, Holloway, Raichlen, & Lieberman, 2009) that this coordination is achieved via a

70 mass-damped system in which motion of the arms is driven passively by the motion of the
71 torso. Pontzer et al. (2009) also suggest that thorax motion is driven passively by motion of
72 the pelvis. If this is the case, then a phase lagged coordination pattern would be observed in
73 which rotation of the pelvis precedes that of the thorax.

74 A number of previous studies have published kinematic data describing the motions of
75 the pelvis and lumbar spine during running (MacWilliams, et al., 2014; Saunders, Schache,
76 Rath, & Hodges, 2005; Schache, Blanch, Rath, Wrigley, & Bennell, 2002). However, these
77 studies either failed to include a thoracic segment or did not analyse coordination patterns in
78 detail and therefore provide limited insight into pelvis-spinal coordination during running.
79 Only two studies have investigated the coordination patterns between the pelvis and thorax
80 during running (Seay, Van Emmerik, & Hamill, 2011a; Seay, et al., 2011b). However, these
81 studies did not include a lumbar segment, nor did they present accompanying data on CoM
82 motion. Furthermore, it was not possible to infer, from the presented analysis, whether
83 transverse plane motion of the thorax was driven by the pelvis.

84 The primary objective of this paper was to explore specific ideas around the
85 coordination of the pelvis and spine during running and to interpret these ideas in the context
86 of CoM motion. In order to address this objective, experimental data describing the three-
87 dimensional kinetics of the thorax, lumbar spine, pelvis and lower-limbs were collected from
88 a cohort of human subjects during over ground running. These data was then used to test a
89 number of specific hypotheses relating to the coordination between the thorax and pelvis
90 during stance phase. We hypothesised that there would be an anti-phase relationship between
91 the pelvis and thorax in the sagittal and frontal plane during stance. In the transverse plane,
92 we hypothesised that motion of the pelvis would lead motion of the thorax demonstrating a
93 phase-lagged coordination pattern. These kinematic descriptions were then interpreted in the
94 context of previously observed trunk EMG patterns.

95

96 **Methods**

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98 2.1 Subjects and experimental set up

99 A cohort of 28 subjects (16 male) participated in the study. The mean (SD) age of the
100 subjects was 28 (4) years, mean (SD) height 175 (9) cm and mean weight 63 (9) Kg. Ethical
101 approval was obtained from the Local Ethics Committee before data collection and all
102 subjects gave informed consent to participate in the study. For each subject, kinematic data
103 were collected for the pelvis, thoracic spine, lumbar spine, lower limbs and feet. Each subject
104 ran along a 32m running track at a target speed of 3.9 ms⁻¹ whilst data were collect using a
105 12-camera Qualisys Pro-reflex system (240Hz). In order to obtain event information, kinetic
106 data were collected from 3 AMTI force plates (1200Hz) embedded in the track. Running
107 speed was measured using optical timing gates and 7-10 trials within $\pm 2.5\%$ of the target
108 speed were collected for each subject.

109 2.2 Protocol and kinematic calculations

110 A global optimisation algorithm (Mason, Preece, Bramah, & Herrington, 2014) was
111 used to obtain segmental kinematics. With this approach, joint constraints are applied to a
112 multi-link model in which segments could rotate with three degrees of freedom but not
113 translate relative to adjacent segments. Within the nine-segment-model model, constraint
114 points were positioned at the origins of all segment coordinate frames distal to the pelvis and
115 expressed in the pelvis coordinate frame. In our previous analysis (Mason, et al., 2014) we
116 defined a pelvic segment which had an anterior-posterior axis pointing from the midpoint of
117 the posterior superior iliac spines (PSIS) to the midpoint of the anterior superior iliac spines

118 (ASIS). However, with this approach, between-subject differences in bony geometry of the
119 pelvis can lead to increased inter-subject variability in pelvic tilt (Preece, et al., 2008).
120 Therefore, for the present study, the Z (vertical) axis of the pelvic frame was aligned with the
121 laboratory in standing. The origin of this segment was modelled by a virtual marker that was
122 created midway between two iliac crest makers. These iliac crest markers were positioned at
123 the level of the iliac crests and above the hip centres (which were predicted from the ASIS
124 and PSIS locations (Bell, Brand, & Pedersen, 1989)). The X (ML axis) pointed from the
125 pelvic origin to the right iliac crest marker and the Y (anterior-posterior) axis was the mutual
126 perpendicular. This pelvic segment was tracked using markers placed on the ASISs and
127 PSISs. The coordinate frames and corresponding tracking markers for the other eight
128 segments were the same as described in our previous repeatability paper analysis (Mason, et
129 al., 2014) and are therefore only reviewed briefly in the text below.

130 The anatomical coordinate system for the lumbar spine was aligned with the pelvic
131 frame with an origin that was positioned at the point 5% from the L5S1 marker to the
132 midpoint of the ASISs. This ensured a linked segment model for the global optimisation
133 calculations. The motion of this segment was tracked using a total of four markers placed on
134 the low back. This protocol was an adaptation of the method originally proposed by Seay et
135 al. (Seay, Selbie, & Hamill, 2008) and reported earlier in a repeatability study (Mason, et al.,
136 2014) in which 7 markers are used to track the lumbar spine. The decision to use only the
137 four markers placed lateral to the spine was based on a secondary analysis of data from n=15
138 participants which showed very little difference in lumbar orientation (average Standard
139 Error in the Measurement = 0.5° - 1.9°) between the four-marker and the seven-marker
140 tracking approach.

141 Motion of the thoracic spine was tracked using three markers, mounted on a rigid
142 plate, which was attached to the sternum (van Andel, van Hutten, Eversdijk, Veeger, &

143 Harlaar, 2009). ISB recommendations (Wu, et al., 2005) were used to define a thoracic
144 reference frame, however, the origin of this frame was shifted to the point 5% along the line
145 from T12 to xiphoid process (XP). This ensured a linked segment model for the kinematic
146 calculations. Rigid plates, attached laterally, were used to track the motion of the thigh and
147 shank segments and the foot was tracked using markers positioned on the rear of the shoe and
148 over the first, second and fifth metatarsal heads. Anatomical coordinate systems for the thigh,
149 shank and foot were defined as reported earlier (Mason, et al., 2014).

150 Centre of mass position and velocity of the nine-segment model was calculated in
151 order to interpret the coordination analysis in the sagittal and frontal planes. Data from
152 Dempster (1955) were used for these calculations in which the pelvis was assumed to be an
153 elliptical cylinder which ran from the iliac crest markers to the hip centres, a diameter equal
154 to the distance between the greater trochanters and a depth equal to the distance from the
155 middle of the ASISs to L5S1 (Seay, et al., 2008). The lumbar segment was also assumed to
156 be an elliptical cylinder, which spanned the distance from the origin of the lumbar frame to
157 the level of T12. This segment had a diameter equal to the distance between the iliac crest
158 markers and a depth calculated as twice the distance from the XP to the midpoint of the line
159 from XP to T12. The geometry of the thoracic segment was again represented as an elliptical
160 cylinder using markers placed over the acromioclavicular joints and the iliac crests to define
161 distal and proximal diameters. This segment ran from the level of T12 up to C7 and had the
162 same depth as the lumbar segment. The contribution to the centre of mass position of the
163 lower extremities was calculated by assuming each segment to be a frustum of a cone with
164 proximal and distal diameters equal to the segment diameters.

165 Right and left contact phases were identified from the force platform data and a
166 second right initial contact (RIC) obtained using a pattern recognition algorithm (Stanhope,
167 Kepple, McGuire, & Roman, 1990). Using these events, each kinematic curve was

168 interpolated and then time normalised to produce 101 data point corresponding to 0-100%
169 gait cycle (RIC to RIC). All kinematic, and centre of mass, calculations were implemented in
170 Visual 3D (C-Motion) and then exported to Matlab for ensemble averaging and further
171 analysis.

172 2.2 Coordination analysis

173 In order to understand coordination patterns between the pelvis and thorax in the
174 sagittal and frontal planes, we used a technique based around angle-angle diagrams.
175 Following the vector coding method suggested by Chang et al. (2008), a coupling angle (γ)
176 was obtained for each of the 100 time points which described the change in direction of the
177 angle-angle plot between that time point and the next. Each of these changes were classified
178 as either in-phase (segments moving in the same direction), anti-phase (segments moving in
179 opposite directions), pelvis only or thorax only movement. These data were then used to
180 quantify the relative period spent in each different coordination phases when the foot was in
181 contact with the ground (stance phase).

182

183 In order to analyse the phase lag between thorax and pelvic motion in the transverse
184 plane we identified the timing of peak angular velocity for each of the two segments. This
185 corresponds to the time of zero angular acceleration and therefore when the net torque acting
186 on the segment changes direction. Peak positive angular velocity was easily identified during
187 right stance phase for every participant. Pontzer et al. (2009) suggest that motion of the pelvis
188 and thorax can be described as a mass damped system in which rotational torques from the
189 pelvis are transmitted through the trunk and drive thorax rotation. In this scenario, the inertia
190 of the torso tends to resist the rotational torque applied by the pelvis and this leads to a phase-
191 lagged coordination pattern. If this is the case then we would expect the peak angular velocity
192 of the pelvis to precede the peak angular velocity of the thorax. To test this idea we used a

193 one-sample t-test to establish if the time lag, between the peak angular velocity of the pelvis
194 and thorax, was significantly different from zero. In addition to analysing coordination
195 patterns, we also included data on lower limb motions to provide the reader with a complete
196 understanding of how transverse plane motion of the pelvis and thorax is coordinated with the
197 swinging legs.

198 **Results**

199 In the sagittal plane, all three segments displayed a biphasic pattern, in which there
200 was a peak in flexion/anterior tilt either during or immediately after stance phase (Figure 1).
201 Motion in this plane occurred about a position of relative flexion for the thoracic spine and
202 the lumbar spine in (Figures 1a & 1d) and a position of relative anterior tilt for the pelvis
203 (Figure 1g). Timing of peak thoracic forward flexion (Mean(SD) 15(4)% of gait cycle)
204 corresponded with the timing of peak posterior pelvic tilt (Mean(SD) 14(6)% of gait cycle)
205 (Figure 1a & 1g). Peak anterior tilt (Mean(SD) 28(12)% of gait cycle) occurred in early flight
206 phase at a similar time to peak hip extension (Mean(SD) 29(6)% of gait cycle) (Figure 2a).
207 Visual inspection of the kinematic trajectories for the pelvis and thorax suggested anti-phase
208 movement (Figures 1a & 1g). This was confirmed by the coordination analysis (Figure 4a)
209 which showed the anti-phase pattern to be the most common during stance. However, this
210 motion was sometimes classified as thorax-only movement due to the relatively smaller
211 amplitude of motion of the pelvis compared to the thorax.

212 **FIGURE 1 ABOUT HERE**

213 In the frontal plane, the pelvis was laterally tilted away from the stance limb (i.e.
214 lower on the contralateral side) at initial contact (Figure 1h). Following initial contact there
215 was a slight increase in this drop after which there was a rapid elevation of the contralateral
216 side of the pelvis which resulted in the pelvis being elevated relative to the stance limb at toe

217 off. During flight there was minimal frontal movement of the pelvis and then the cycle
218 repeated on the contralateral leg. Most of the movement of the thorax relative to the pelvis
219 (Figure 3b) occurred at the lumbo-pelvic junction (Figure 3h) with only minimal motion at
220 the thoraco-lumbar junction (Figure 3e).

221 **FIGURE 2 ABOUT HERE**

222 There appeared to be an anti-phase relationship in the frontal plane between thorax
223 and pelvic motion (Figures 1b & 1h) during stance. Specifically the thorax was laterally
224 flexed towards the stance limb during early stance and then moved towards a neutral position
225 during the latter half of stance, as the pelvis became elevated on the contralateral side. The
226 coordination analysis classified the frontal plane pelvis-thorax motion as either anti-phase or
227 pelvis-only during stance (Figure 4b). This latter classification resulted from the increased
228 motion of the pelvis compared to the thorax which resulted in a more vertically aligned
229 coupling vector (Seay, et al., 2011b) and therefore a coupling angle which was classified as
230 pelvis-only motion.

231 **FIGURE 3 ABOUT HERE**

232 In the transverse plane, the thorax rotated towards the contralateral leg during stance.
233 Figure 2a shows the motion of the right hip which reaches maximal extension and begins to
234 flex in late swing phase. This flexion, which continues through stance, is accompanied by a
235 corresponding rotation of the thorax (Figure 1c) towards the swing limb. The kinematic
236 trajectory of the pelvis appears to follow a similar pattern to that of the thorax (Figure 1i).
237 However, during early stance the pelvis rotates towards the stance limb before starting to
238 rotate in the same direction as the thorax (away from the stance limb) for the remainder of
239 stance. Analysis of the relative segment motion showed that motion between the thorax and
240 pelvis occurred primarily at the thoraco-lumbar junction (Figure 3f). The transverse plane

241 coordination analysis identified a pattern in which motion of the thorax preceded motion of
242 the pelvis in 22 out of the 28 subjects. The mean (SD) time lag was 4(6)% of the gait cycle
243 and this time lag was significantly different from zero ($p < 0.05$).

244 FIGURE 4 ABOUT HERE

245 The AP CoM velocity profile illustrated the characteristic braking and acceleration
246 phases of running during stance phase (Figure 5d). However, these changes were relatively
247 small ($\pm 0.1 \text{ms}^{-1}$) compared to the target running speed of 3.9ms^{-1} . In the ML direction the
248 CoM moved towards the contralateral limb during stance. However the ML changes in
249 velocity of the CoM velocity ($\pm 0.06 \text{ms}^{-1}$) were smaller than those in the AP direction (Figure
250 5e). It is interesting to note that the point of zero ML velocity of the CoM occurred at 22% of
251 the gait cycle, coinciding with the point when the pelvis reaches its neutral position in the
252 frontal plane (Figure 1h).

253 FIGURE 5 ABOUT HERE

254

255 Discussion

256

257 This study was undertaken to understand the coordinated movement of the pelvis and
258 thorax during running in healthy individuals. We hypothesised that AP accelerations of the
259 CoM would be minimised and that this would lead to an anti-phase coordination pattern in
260 the sagittal plane during stance. This idea was supported by the observation of relatively
261 small changes in the CoM velocity (Figure 5d) and a predominantly anti-phase coordination
262 pattern (Figure 4a). Posterior pelvic tilt occurred during early stance and this was
263 accompanied by flexion of the thorax. During late stance the pelvis moved into anterior tilt

264 and there was a corresponding extension of the thorax. We suggest that this anterior tilting of
265 the pelvis during late stance is a mechanism for increasing femoral inclination at toe off and
266 thereby extending stride length. In addition to the anti-phase motions between the thorax and
267 the pelvis, we also observed the thorax and the pelvis to be in a position of flexion and
268 anterior tilt respectively, relative to standing. This segmental alignment will have the effect of
269 shifting the CoM anteriorly thus creating a more posteriorly directed ground reaction force
270 which will facilitate the generation of forward momentum (Novacheck, 1998).

271 Previous EMG studies of running have shown the lumbar extensor muscles to be
272 active at foot contact and during early stance (Thorstensson, Carlson, Zomlefer, & Nilsson,
273 1982). This early activation of the back extensors will act to limit forward flexion of the trunk
274 as energy is absorbed in the lower limbs and the CoM decelerates. During this deceleration
275 phase, the thorax moves into forward flexion and there is a small corresponding posterior tilt
276 of the pelvis as gluteus maximus acts to extend the hip. In the second half of stance, the lower
277 limbs act to accelerate the CoM and so active muscle control is required to decelerate the
278 extension of the thorax. This control is most likely provided by the oblique abdominal
279 muscles which have been shown to be active later in stance (Saunders, et al., 2005). As
280 suggested above, this extension of the thorax is coordinated with anterior tilting of the pelvis
281 in order to extend stride length whilst controlling the AP CoM velocity.

282 We hypothesised that changes in the ML CoM velocity are minimised and that this
283 leads to an anti-phase coordination pattern between the pelvis and thorax in the frontal plane
284 during stance. This idea was partially supported by the data which showed relatively small
285 changes in the ML velocity of the CoM (Figure 5b) and either an anti-phase or pelvis only
286 coordination pattern during stance phase (Figure 4b). We propose that frontal plane motion of
287 the pelvis has two primary functions. Firstly, during early stance, the pelvis is laterally tilted
288 (dropped) away from the stance limb. This results in a more medial position of the CoM,

289 which in turn creates a moment about the base of support, facilitating transition onto the
290 contralateral foot. From midstance onwards the pelvis lifts on the contralateral stride until it
291 reaches its maximum position at toe off (Figure 1h). This movement serves to elevate the
292 swing leg to ensure foot clearance and also to extend stride length. We further suggest that
293 thorax motion is precisely coordinated with this pelvic kinematic pattern in order to minimise
294 the ML acceleration of the CoM. This coordination requires a smaller range of movement of
295 the thorax and explains the pelvis only classification observed in our frontal plane
296 coordination analysis (Figure 4b).

297 Gluteus medius has been shown to be active prior to foot contact and for the most of
298 stance phase of running (Gazendam & Hof, 2007; Willson, Petrowitz, Butler, & Kernozek,
299 2012). We suggest that this muscle functions to control the downward acceleration of the
300 CoM following foot contact, then later to lift the pelvis on the contralateral side. This is
301 consistent with the observation of a large proportion of frontal plane movement occurring at
302 the lumbo-pelvic junction (Figure 3e & 3h). During the latter stages of stance, the lumbar
303 spine is laterally flexed towards the contralateral limb, relative to the pelvis (Figure 3h). It is
304 possible that this motion is assisted by the contralateral oblique abdominal muscles which
305 have been shown to be active during this period (Saunders, et al., 2005).

306 Previous modelling studies have clearly shown that motion of the arms effectively
307 counterbalances the angular momentum of the lower extremities during running (Hamner &
308 Delp, 2013; Hamner, et al., 2010). It has further been suggested that arm motion is driven
309 passively by rotation of the thorax (Pontzer, et al., 2009), an idea which is supported by
310 shoulder muscle EMG data, consistent with the shoulders as spring-like linkages (Ballesteros,
311 Buchthal, & Rosenfalck, 1965). Our data are consistent with this idea, showing motion of the
312 thorax to be in the opposite direction to that of the swinging leg. Pontzer et al. (2009) also
313 suggested that motion of the thorax is driven passively by motion of the pelvis. However, our

314 data shows that the thorax reaches its peak angular velocity earlier than the pelvis, indicating
315 that thorax motion is not completely passively driven by pelvic movements.

316 The pelvic rotation observed in our study matches the patterns observed in previous
317 studies (MacWilliams, et al., 2014; Schache, et al., 2002). Specifically, the pelvis rotates
318 slightly towards the stance limb during early stance after which it rotates away from the
319 stance limb. This initial rotation towards the stance limb has been suggested to function to
320 reduce horizontal braking (Novacheck, 1998; Schache, et al., 2002), however the subsequent
321 rotation away from the stance limb may decrease stride length. We suggest the pattern of
322 transverse plane pelvic motion during running is a secondary consequence of gluteus
323 maximus activity. This muscle is active for most of stance phase (Gazendam & Hof, 2007;
324 Willson, et al., 2012) and functions primarily to extend the hip. However, gluteus maximus
325 will also act to externally rotate the hip (Delp, Hess, Hungerford, & Jones, 1999) or,
326 equivalently, rotate the pelvis away from the stance limb.

327 Although the pattern of pelvic rotation in the transverse plane would appear to reduce
328 stride length, the effect is minimal. If we assume a rotation of 10° (Figure 1i) and a distance
329 between hip centres of 15-30cm, then stride length would be reduced by only 1-2%. It is
330 therefore unlikely that the muscle work required to oppose the action of gluteus maximums
331 and produce transverse rotation of the pelvis towards the stance limb would be worth the
332 metabolic cost. Instead, we suggest pelvic motion follows the motion of the thorax in order to
333 minimise the muscle work required to passively drive arm motion. This can be understood by
334 analysing the relative transverse plane motion between the thorax and the pelvis (Figure 3c).
335 This figure shows that, from midswing until early stance, the thorax moves from a rotated to
336 a neutral position relative to the pelvis. During this period the abdominal muscles are inactive
337 (Saunders, et al., 2005) and the relative motion between the thorax and pelvis most likely
338 results from stored elastic energy in connective tissues. Around midstance, the abdominal

339 muscles become active (Saunders, et al., 2005), working both to limit extension of the trunk
340 (in the sagittal plane) and also to actively rotate the thorax relative to the pelvis. This active
341 rotation results in a larger a movement of thorax compared to the pelvis.

342 It is interesting to compare the kinematic data described in this paper with the data
343 obtained from a study in which bone pins were inserted into the individual lumbar and sacral
344 vertebrae (MacWilliams, et al., 2014). Importantly, there is good agreement between the
345 pattern of pelvic movement in each body plane. However, the range of motion observed in
346 the bone pin data is slightly lower in both the frontal and transverse planes. This difference
347 may have resulted from skin movement artefact or from differences in running speed between
348 the two studies, which may affect pelvic range of movement. MacWilliams et al. (2014) also
349 reported on the relative motion of the individual lumbar spine segments with respect to the
350 pelvis. Again, our data matches these data closely with the same caveat of lower ranges of
351 movements in the bone pin data. Our data on the thorax also matches that reported by Seay et
352 al. (2008) who used skin mounted markers to characterise the rotation of the thorax relative to
353 the lumbar spine during the stance phase of over ground running. Seay et al. (2011b) later
354 investigated treadmill running and observed that the thorax rotated through approximately
355 25° of motion throughout the whole gait cycle, slightly higher than that shown in Figure 1c.

356 It is important to identify the limitations of the present study. Firstly, in order to
357 develop a practical skin mounted marker set, we chose to segment the spine into two rigid
358 segments. Although this represents a major simplification of the multi-articular structure of
359 the spine, our data compares well with the bone pin data presented by MacWilliams et al.
360 (2014). This suggests that that our relatively easy-to-implement laboratory protocol can be
361 used to extract the salient features of pelvic-spinal coordination during running. This protocol
362 therefore appears appropriate for future studies aimed at investigating the association
363 between musculoskeletal pain and abnormal motion of the spine and pelvis. Another

364 limitation of this study was that we investigated a single running speed. However, data on
365 multiple running speeds was deemed to be outside the scope of this paper and is therefore
366 presented in a subsequent publication.

367 **Conclusion**

368 This is the first study to provide an underlying biomechanical rationale for the
369 coordination pattern between the pelvis and thorax during running in all three body planes.
370 The data showed an anti-phase relationship between these two segments in the sagittal and
371 frontal planes and we suggest that this is a consequence of the requirement to minimise
372 accelerations of the CoM in the AP and ML directions. In the transverse plane, we observed a
373 phase lagged relationship in which motion of the pelvis lagged slightly behind that of the
374 thorax. This suggests that transverse plane thoracic motion is not completely passively driven
375 by pelvic motion. However, it is likely that the closely coupled movement of these two
376 segments facilitates the thoracic rotation required to passively drive arm motion.

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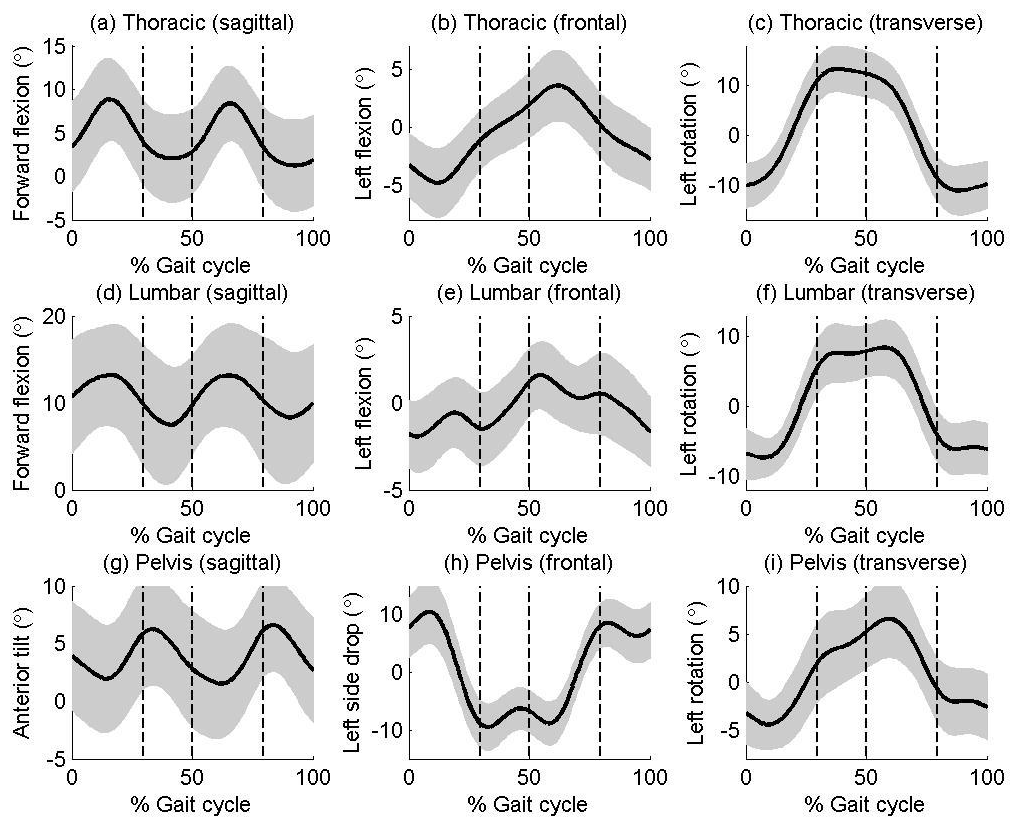
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448 **Figures:**

449 Figure 1: Ensemble average curves (across all n=28 subjects), with standard deviation
450 envelopes, for the thorax, lumbar spine and pelvis relative to the laboratory coordinate system
451 in each of the three body planes. Data is plotted from right initial contact (RIC) to the
452 following RIC with the three vertical lines showing the timing of right toe off, left initial
453 contact and left toe off respectively.



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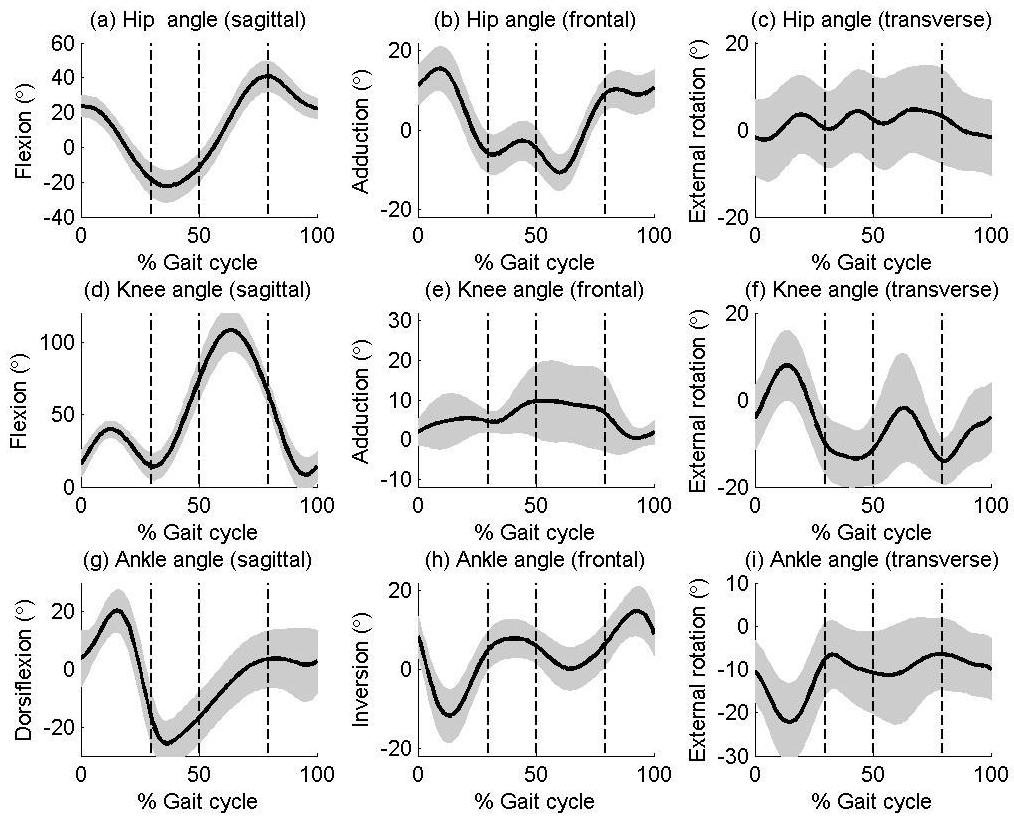
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460 Figure 2: Ensemble average curves (across all n=28 subjects), with standard deviation
461 envelopes, for the right hip, knee and ankle in each of the three body planes. Data is plotted
462 from right initial contact (RIC) to the following RIC with the three vertical lines showing the
463 timing of right toe off, left initial contact and left toe off respectively.

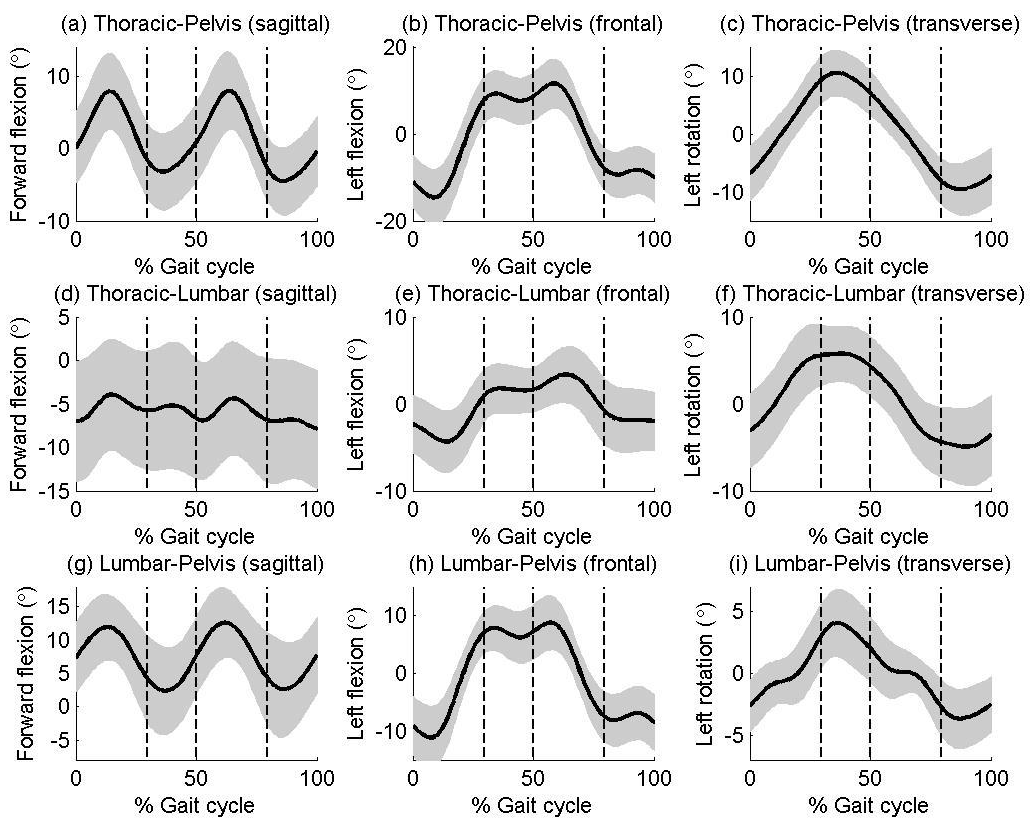


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466 Figure 3: Ensemble average curves (across all n=28 subjects), with standard deviation
467 envelopes, for relative motion between each of the pelvis and spinal segments in each of the
468 three body planes. Data is plotted from right initial contact (RIC) to the following RIC with
469 the three vertical lines showing the timing of right toe off, left initial contact and left toe off
470 respectively.

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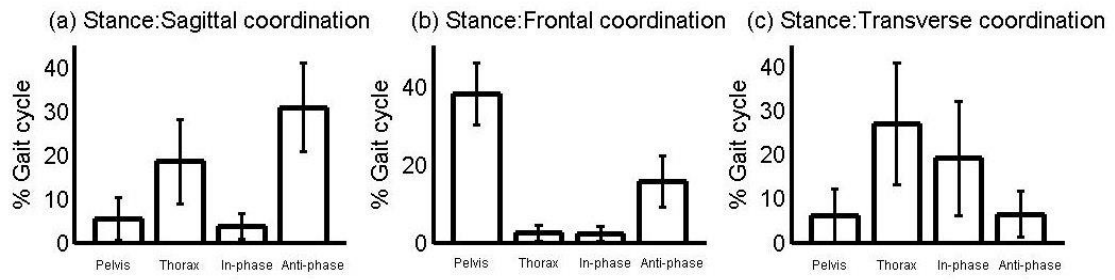


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474 Figure 4: Average and SD pelvis-thorax coordination patterns across all n=28 subjects for
475 both stance and flight phase. Each plot illustrates the proportion of the gait cycle spent in
476 each of the four coordination phases: pelvis only, thorax only, in-phase or anti-phase.

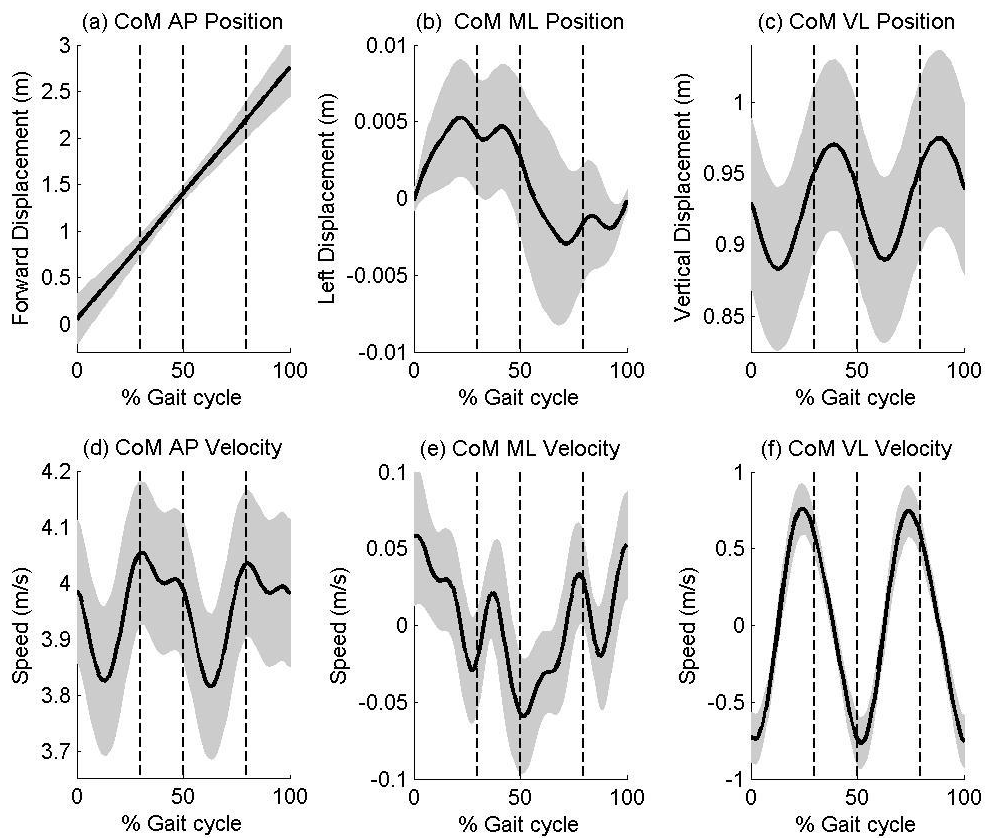
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480 Figure 5: Ensemble average centre of mass (CoM) displacements (a-c) and average CoM
481 velocities (d-f) across all n=28 subjects. Data is plotted from right initial contact (RIC) to the
482 following RIC with the three vertical lines showing the timing of right toe off, left initial
483 contact and left toe off respectively.



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