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The coordinated movement of the spine and pelvis during running

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Abstract

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

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

Running is complex movement which requires precise inter-segmental coordination to create forward momentum. Given the integrated nature of running, it is possible that poorly coordinated movement of the pelvis and spine could result in abnormal tissue stress not just in the low back (Seay, Van Emmerik, & Hamill, 2011b), but also within more distal structures of the lower limbs (Leetun, Ireland, Willson, Ballantyne, & Davis, 2004).

However, before interventions can be developed to address abnormalities in pelvis and spinal movement, it is important to develop a clear biomechanical understanding of the coordination between the spine and pelvis during normal running.

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

Rotations of the pelvis or trunk in the transverse plane will not displace the CoM. However, it has been shown that arm motion during running functions to counterbalance the rotational angular momentum of the swinging legs (Arellano & Kram, 2014; Hamner, Seth, & Delp, 2010). Thus a coordination pattern between the pelvis and spine must emerge which facilitates the necessary arm movement for angular momentum balance. It been suggested (Pontzer, Holloway, Raichlen, & Lieberman, 2009) that this coordination is achieved via a
mass-damped system in which motion of the arms is driven passively by the motion of the torso. Pontzer et al. (2009) also suggest that thorax motion is driven passively by motion of the pelvis. If this is the case, then a phase lagged coordination pattern would be observed in which rotation of the pelvis precedes that of the thorax.

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

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

2.1 Subjects and experimental set up

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

2.2 Protocol and kinematic calculations

A global optimisation algorithm (Mason, Preece, Bramah, & Herrington, 2014) was used to obtain segmental kinematics. With this approach, joint constraints are applied to a multi-link model in which segments could rotate with three degrees of freedom but not translate relative to adjacent segments. Within the nine-segment-model model, constraint points were positioned at the origins of all segment coordinate frames distal to the pelvis and expressed in the pelvis coordinate frame. In our previous analysis (Mason, et al., 2014) we defined a pelvic segment which had an anterior-posterior axis pointing from the midpoint of the posterior superior iliac spines (PSIS) to the midpoint of the anterior superior iliac spines.
However, with this approach, between-subject differences in bony geometry of the pelvis can lead to increased inter-subject variability in pelvic tilt (Preece, et al., 2008). Therefore, for the present study, the Z (vertical) axis of the pelvic frame was aligned with the laboratory in standing. The origin of this segment was modelled by a virtual marker that was created midway between two iliac crest makers. These iliac crest markers were positioned at the level of the iliac crests and above the hip centres (which were predicted from the ASIS and PSIS locations (Bell, Brand, & Pedersen, 1989)). The X (ML axis) pointed from the pelvic origin to the right iliac crest marker and the Y (anterior-posterior) axis was the mutual perpendicular. This pelvic segment was tracked using markers placed on the ASISs and PSISs. The coordinate frames and corresponding tracking markers for the other eight segments were the same as described in our previous repeatability paper analysis (Mason, et al., 2014) and are therefore only reviewed briefly in the text below.

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

Motion of the thoracic spine was tracked using three markers, mounted on a rigid plate, which was attached to the sternum (van Andel, van Hutten, Eversdijk, Veeger, &
Harlaar, 2009. ISB recommendations (Wu, et al., 2005) were used to define a thoracic
reference frame, however, the origin of this frame was shifted to the point 5% along the line
from T12 to xiphoid process (XP). This ensured a linked segment model for the kinematic
calculations. Rigid plates, attached laterally, were used to track the motion of the thigh and
shank segments and the foot was tracked using markers positioned on the rear of the shoe and
over the first, second and fifth metatarsal heads. Anatomical coordinate systems for the thigh,
shank and foot were defined as reported earlier (Mason, et al., 2014).

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

Right and left contact phases were identified from the force platform data and a
second right initial contact (RIC) obtained using a pattern recognition algorithm (Stanhope,
Kepple, McGuire, & Roman, 1990). Using these events, each kinematic curve was
interpolated and then time normalised to produce 101 data point corresponding to 0-100% gait cycle (RIC to RIC). All kinematic, and centre of mass, calculations were implemented in Visual 3D (C-Motion) and then exported to Matlab for ensemble averaging and further analysis.

2.2 Coordination analysis

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

In order to analyse the phase lag between thorax and pelvic motion in the transverse plane we identified the timing of peak angular velocity for each of the two segments. This corresponds to the time of zero angular acceleration and therefore when the net torque acting on the segment changes direction. Peak positive angular velocity was easily identified during right stance phase for every participant. Pontzer et al. (2009) suggest that motion of the pelvis and thorax can be described as a mass damped system in which rotational torques from the pelvis are transmitted through the trunk and drive thorax rotation. In this scenario, the inertia of the torso tends to resist the rotational torque applied by the pelvis and this leads to a phase-lagged coordination pattern. If this is the case then we would expect the peak angular velocity of the pelvis to precede the peak angular velocity of the thorax. To test this idea we used a
one-sample t-test to establish if the time lag, between the peak angular velocity of the pelvis and thorax, was significantly different from zero. In addition to analysing coordination patterns, we also included data on lower limb motions to provide the reader with a complete understanding of how transverse plane motion of the pelvis and thorax is coordinated with the swinging legs.

**Results**

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

**FIGURE 1 ABOUT HERE**

In the frontal plane, the pelvis was laterally tilted away from the stance limb (i.e. lower on the contralateral side) at initial contact (Figure 1h). Following initial contact there was a slight increase in this drop after which there was a rapid elevation of the contralateral side of the pelvis which resulted in the pelvis being elevated relative to the stance limb at toe
off. During flight there was minimal frontal movement of the pelvis and then the cycle repeated on the contralateral leg. Most of the movement of the thorax relative to the pelvis (Figure 3b) occurred at the lumbo-pelvic junction (Figure 3h) with only minimal motion at the thoraco-lumbar junction (Figure 3e).

**FIGURE 2 ABOUT HERE**

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

**FIGURE 3 ABOUT HERE**

In the transverse plane, the thorax rotated towards the contralateral leg during stance. Figure 2a shows the motion of the right hip which reaches maximal extension and begins to flex in late swing phase. This flexion, which continues through stance, is accompanied by a corresponding rotation of the thorax (Figure 1c) towards the swing limb. The kinematic trajectory of the pelvis appears to follow a similar pattern to that of the thorax (Figure 1i). However, during early stance the pelvis rotates towards the stance limb before starting to rotate in the same direction as the thorax (away from the stance limb) for the remainder of stance. Analysis of the relative segment motion showed that motion between the thorax and pelvis occurred primarily at the thoraco-lumbar junction (Figure 3f). The transverse plane
coordination analysis identified a pattern in which motion of the thorax preceded motion of the pelvis in 22 out of the 28 subjects. The mean (SD) time lag was 4(6)% of the gait cycle and this time lag was significantly different from zero (p<0.05).

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

Discussion

This study was undertaken to understand the coordinated movement of the pelvis and thorax during running in healthy individuals. We hypothesised that AP accelerations of the CoM would be minimised and that this would lead to an anti-phase coordination pattern in the sagittal plane during stance. This idea was supported by the observation of relatively small changes in the CoM velocity (Figure 5d) and a predominantly anti-phase coordination pattern (Figure 4a). Posterior pelvic tilt occurred during early stance and this was accompanied by flexion of the thorax. During late stance the pelvis moved into anterior tilt
and there was a corresponding extension of the thorax. We suggest that this anterior tilting of
the pelvis during late stance is a mechanism for increasing femoral inclination at toe off and
thereby extending stride length. In addition to the anti-phase motions between the thorax and
the pelvis, we also observed the thorax and the pelvis to be in a position of flexion and
anterior tilt respectively, relative to standing. This segmental alignment will have the effect of
shifting the CoM anteriorly thus creating a more posteriorly directed ground reaction force
which will facilitate the generation of forward momentum (Novacheck, 1998).

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

We hypothesised that changes in the ML CoM velocity are minimised and that this
leads to an anti-phase coordination pattern between the pelvis and thorax in the frontal plane
during stance. This idea was partially supported by the data which showed relatively small
changes in the ML velocity of the CoM (Figure 5b) and either an anti-phase or pelvis only
coordination pattern during stance phase (Figure 4b). We propose that frontal plane motion of
the pelvis has two primary functions. Firstly, during early stance, the pelvis is laterally tilted
(dropped) away from the stance limb. This results in a more medial position of the CoM,
which in turn creates a moment about the base of support, facilitating transition onto the contralateral foot. From midstance onwards the pelvis lifts on the contralateral stride until it reaches its maximum position at toe off (Figure 1h). This movement serves to elevate the swing leg to ensure foot clearance and also to extend stride length. We further suggest that thorax motion is precisely coordinated with this pelvic kinematic pattern in order to minimise the ML acceleration of the CoM. This coordination requires a smaller range of movement of the thorax and explains the pelvis only classification observed in our frontal plane coordination analysis (Figure 4b).

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

Previous modelling studies have clearly shown that motion of the arms effectively counterbalances the angular momentum of the lower extremities during running (Hamner & Delp, 2013; Hamner, et al., 2010). It has further been suggested that arm motion is driven passively by rotation of the thorax (Pontzer, et al., 2009), an idea which is supported by shoulder muscle EMG data, consistent with the shoulders as spring-like linkages (Ballesteros, Buchthal, & Rosenfalck, 1965). Our data are consistent with this idea, showing motion of the thorax to be in the opposite direction to that of the swinging leg. Pontzer et al. (2009) also suggested that motion of the thorax is driven passively by motion of the pelvis. However, our
data shows that the thorax reaches its peak angular velocity earlier than the pelvis, indicating that thorax motion is not completely passively driven by pelvic movements.

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

Although the pattern of pelvic rotation in the transverse plane would appear to reduce stride length, the effect is minimal. If we assume a rotation of 10° (Figure 1i) and a distance between hip centres of 15-30cm, then stride length would be reduced by only 1-2%. It is therefore unlikely that the muscle work required to oppose the action of gluteus maximums would be worth the metabolic cost. Instead, we suggest pelvic motion follows the motion of the thorax in order to minimise the muscle work required to passively drive arm motion. This can be understood by analysing the relative transverse plane motion between the thorax and the pelvis (Figure 3c). This figure shows that, from midswing until early stance, the thorax moves from a rotated to a neutral position relative to the pelvis. During this period the abdominal muscles are inactive (Saunders, et al., 2005) and the relative motion between the thorax and pelvis most likely results from stored elastic energy in connective tissues. Around midstance, the abdominal
muscles become active (Saunders, et al., 2005), working both to limit extension of the trunk (in the sagittal plane) and also to actively rotate the thorax relative to the pelvis. This active rotation results in a larger a movement of thorax compared to the pelvis.

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

It is important to identify the limitations of the present study. Firstly, in order to develop a practical skin mounted marker set, we chose to segment the spine into two rigid segments. Although this represents a major simplification of the multi-articular structure of the spine, our data compares well with the bone pin data presented by MacWilliams et al. (2014). This suggests that that our relatively easy-to-implement laboratory protocol can be used to extract the salient features of pelvic-spinal coordination during running. This protocol therefore appears appropriate for future studies aimed at investigating the association between musculoskeletal pain and abnormal motion of the spine and pelvis. Another
limitation of this study was that we investigated a single running speed. However, data on
multiple running speeds was deemed to be outside the scope of this paper and is therefore
presented in a subsequent publication.

Conclusion

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


Figures:

Figure 1: Ensemble average curves (across all n=28 subjects), with standard deviation envelopes, for the thorax, lumbar spine and pelvis relative to the laboratory coordinate system in each of the three body planes. Data is plotted from right initial contact (RIC) to the following RIC with the three vertical lines showing the timing of right toe off, left initial contact and left toe off respectively.
Figure 2: Ensemble average curves (across all n=28 subjects), with standard deviation envelopes, for the right hip, knee and ankle in each of the three body planes. Data is plotted from right initial contact (RIC) to the following RIC with the three vertical lines showing the timing of right toe off, left initial contact and left toe off respectively.
Figure 3: Ensemble average curves (across all n=28 subjects), with standard deviation envelopes, for relative motion between each of the pelvis and spinal segments in each of the three body planes. Data is plotted from right initial contact (RIC) to the following RIC with the three vertical lines showing the timing of right toe off, left initial contact and left toe off respectively.
Figure 4: Average and SD pelvis-thorax coordination patterns across all n=28 subjects for both stance and flight phase. Each plot illustrates the proportion of the gait cycle spent in each of the four coordination phases: pelvis only, thorax only, in-phase or anti-phase.
Figure 5: Ensemble average centre of mass (CoM) displacements (a-c) and average CoM velocities (d-f) across all n=28 subjects. Data is plotted from right initial contact (RIC) to the following RIC with the three vertical lines showing the timing of right toe off, left initial contact and left toe off respectively.