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Three-dimensional angular kinematics of the lumbar spine and pelvis during running

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Abstract

The objectives of this study were to: (i) describe the typical three-dimensional (3D) angular kinematics of the lumbar spine and pelvis during running and; (ii) assess whether the movements of the lumbar spine and pelvis during running are coordinated. A cohort of 20 non-injured male runners who usually ran >20 km/week were voluntarily recruited. All trials were conducted on a treadmill at a running speed of 4.0 m/second. Reflective markers were placed over anatomical landmarks of the thoraco-lumbar spine and pelvis. Data were captured using a VICON motion analysis system. The lumbar spine and pelvis both displayed complex 3D angular kinematic patterns during running. High correlations were found for the comparisons of flexion-extension of the lumbar spine with anterior–posterior tilt of the pelvis ($r = -0.84$) and lateral bend of the lumbar spine with obliquity of the pelvis ($r = -0.75$). However, a poor correlation was found for the comparison of axial rotation of the lumbar spine with axial rotation of the pelvis ($r = 0.37$). A phase difference of 21% of the running cycle was evident between axial rotation of the lumbar spine and pelvis. The identified coordinated kinematic patterns of the lumbar spine and pelvis during running serve as a basis for future investigations exploring the relationship between atypical kinematic patterns and injury.

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1. Introduction

The relative incidence of running injuries to the lumbar spine and pelvis has been shown to be approximately 11–13% of all injuries sustained (Bennell & Crossley, 1996; Walter, Hart, McIntosh, & Sutton, 1989). What is evident from the epidemiological literature is that injuries to this region in the running population are not as common as those occurring in the lower limb. However, several case studies have highlighted that overuse injuries of the lumbar spine and pelvis can frequently be debilitating requiring prolonged periods of rehabilitation (Fields, Kramer, & Delaney, 1990; Guten, 1981; Koch & Jackson, 1981). From a biomechanical point of view, the mid lumbar spine must cope with compressive loads in the range of 2.7–5.7 times body weight immediately following foot strike (Cappozzo & Berme, 1985). A typical distance runner, who may run 130 km per week in training, will subject his or her body to approximately 40,000 foot strikes per week (Cavanagh & LaFortune, 1980). With such high loads being inflicted on a repetitive basis, the potential severity of the injuries to the lumbar spine and pelvis in the running athlete is not surprising.

Anecdotal reports have been made regarding potential relationships between disturbances to the typical kinematic patterns of the lumbar spine and pelvis during running and injury. Increased lumbar lordosis and anterior pelvic tilt, associated with tightness of the hip flexor musculature, are examples of atypical kinematic patterns that have been alluded to in the literature (Bach, Green, Jensen, & Savinar, 1985; Klein & Roberts, 1976). Repetitive impingement of the vertebral facets from hyperextension of the lumbar spine is thought to be related to the onset of low back pain in runners (Jackson & Sutker, 1982; Slocum & James, 1968) whilst increased anterior tilt of the pelvis during running has been cited as a predisposing factor for hamstring strains (Geraci, 1996; Klein & Roberts, 1976). Finally, increased pelvic obliquity during running has been implicated with iliotibial band friction syndrome (Anderson, 1991) and sacroiliac joint injuries (Lloyd-Smith, Clement, McKenzie, & Taunton, 1985). Wiklander, Lysholm, and Lysholm (1987) reported a significant negative correlation between the degree of pelvic obliquity and the flexibility of the hamstrings. Interestingly, this group of investigators found that distance runners in comparison to sprinters had stiffer hamstrings, greater pelvic obliquity and suffered more exertion injuries around the lower back (Lysholm, Gillquist, & Nordin, 1982; Lysholm & Wiklander, 1985, 1987; Wiklander et al., 1987). In order to verify any of these proposed relationships, an understanding of the typical kinematic patterns of the lumbar spine and pelvis during running is clearly the crucial starting point.

Numerous studies have investigated the 3D angular kinematics of the lumbar spine and pelvis during walking (Crosbie, Vachalathiti, & Smith, 1997; Taylor, Goldie, & Evans, 1999; Thurston & Harris, 1983; Whittle & Levine, 1999). However, the kinematic behaviour of the lumbar spine and pelvis during running has received very little attention in the relevant literature (Dalichau, Scheele, Reissdorf, & Huebner, 1998; Whittle, Levine, & Pharo, 2000). Dalichau et al. (1998) measured the 3D kinematics of the lumbar spine and pelvis during level treadmill running, whilst Whittle et al. (2000) measured the sagittal plane motion of the lumbar spine and pelvis during level, uphill and downhill treadmill running. Both studies were limited by low sampling rates that allowed slow speeds of running to be considered only, and no graphical data were provided. Other studies that have investigated running have either measured the 3D kinematics of the pelvis only (Bickham, Young, & Blanch, 2000; Cairns, Burdett, Pisciotta, & Simon, 1986; Novacheck, 1995; Ounpuu, 1990; Schache, Blanch, & Murphy, 2000) or have measured gross movements of the trunk only (Carlson, Thorstensson, & Nilsson, 1988; Elliott & Blanksby, 1979; Thorstensson, Carlson, Zomlefer, & Nilsson, 1982; Thorstensson, Nilsson, Carlson, & Zomlefer, 1984). Therefore, our specific objectives were to: (i) describe the typical 3D angular kinematics of the lumbar spine and pelvis during running and; (ii) assess whether the movements of the lumbar spine and pelvis during running are coordinated.

2. Materials and methods

A cohort of 20 volunteer male runners who had no disabilities were recruited. Subjects had an average age of 32.7 (S.D. 7.3) years, height of 178.3 (S.D. 4.6) cm and body mass of 75.1 (S.D. 6.8) kg. Subjects were active runners who usually ran >20 km/week and were not suffering from any musculoskeletal injury at the time of testing. Approval was obtained from The University of Melbourne and The Australian Institute of Sport Ethics committees prior to the commencement of the experiment.

All running trials were performed on a 15 kW treadmill (Sportech Gymnasium and Electronic Sports Equipment, Australia) set with no incline. The treadmill belt speed was monitored using a digital tachometer (Lutron Electronic Enterprise Co., Ltd., Taipei, Taiwan). In order to assess the intra-stride belt speed variation of the treadmill, the digital tachometer was used to record the fluctuations in the belt speed over a three minute period with a 70 kg subject running at 4.2 m/second. 95% of the belt speeds were found to fall within a variability of 0.013 m/second of the average speed.

One day prior to data collection each subject completed an accommodation session on the treadmill which consisted of three 10 minute level treadmill runs with five minute rest periods separating each run. This degree of treadmill accommodation has been shown to be sufficient for runners to settle into a consistent treadmill running pattern (Schieb, 1986). Also, when conditioned runners are accommodated to a treadmill with a small intra-stride belt speed variation, minimal deviations have been found to exist in the angular kinematics of the lumbar spine and pelvis with respect to overground running (Schache, Blanch, Rath, Wrigley, Starr, & Bennell, 2001).

Reflective markers were positioned over specific anatomical landmarks of the thoraco-lumbar spine and pelvis using double sided adhesive tape (Fig. 1). The same operator performed all marker placements to avoid inter-tester variability. In order to define an orthogonal coordinate system (frame) at the functional upper margin of the lumbar spine, a rigid cluster was constructed based upon the design of Stokes (1984) and Pearcy, Gill, Whittle, and Johnson (1987). It was made from light weight materials to minimise potential inertial artefacts. The cluster was mounted over the 12th thoracic spinous process (T12). This location has been shown to be coincident with the average inflection point of the thoracic kyphotic and lumbar lordotic curves (Bryant, Reid, Smith, & Stevenson, 1989). As the fascia over the spinous processes is relatively rigidly fixed to bone (Lundberg, 1996), skin movement in this region has been shown to provide a reasonable approximation of bone movement (Gracovetsky, Newman, Ferron, & Lewis, 1988; Labesse, Cheze, & Dimnet, 1996).

The cluster was held in place by a tight elastic thoracic strap in an endeavour to keep the middle of the base plate over T12 and minimise skin movement and inertial artefacts. It has been suggested that the introduction of a strap may allow the measured rotations to be affected by movements of the rib cage (Pearcy et al., 1987).

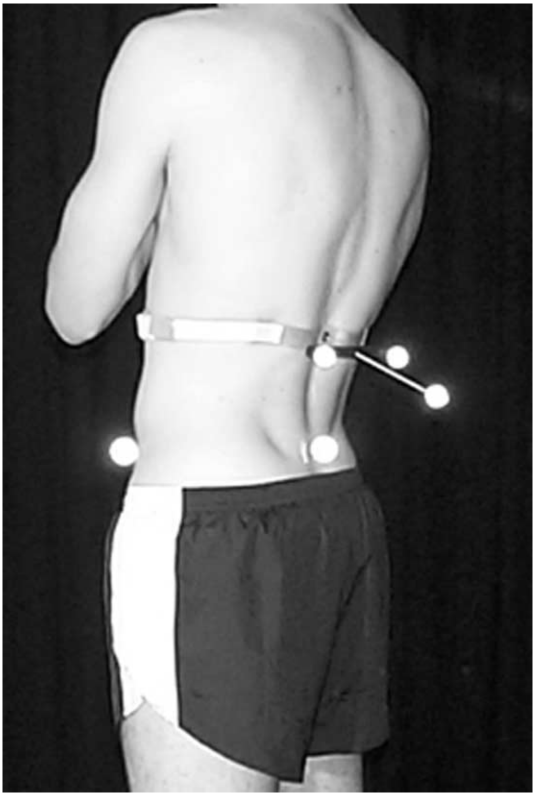

Fig. 1. Thoraco-lumber cluster and pelvic marker configuration.

However, preliminary trials without the strap demonstrated the cluster to be drawn markedly across the back during maximal axial twisting, displacing it from the midline. This finding is in accordance with the results of other studies (Hindle, Pearcy, Cross, & Miller, 1990; Pearcy & Hindle, 1989). Whilst it is acknowledged that this set up may potentially over-estimate the *amplitude* of bone movement (Pearcy et al., 1987; Pearcy & Hindle, 1989), the estimated *pattern* of movement has been shown to be very similar to that determined using radiography (Hindle et al., 1990; Pearcy et al., 1987).

For the pelvis, reflective markers (25 mm diameter) were placed over both anterior superior iliac spines (ASIS) and the midpoint between the two posterior superior iliac spines (PSIS). It has been previously demonstrated that skin movement artefacts from pelvic markers are not a major source of error for thin subjects (Drerup & Hierholzer, 1987; Lamoreux, 1996; Vanneuville et al., 1997).

The laboratory (global) frame followed the right-hand rule and had the positive x-direction orientated in the direction of forward progression, the positive y-direction orientated to the left and the positive z-direction orientated vertically upward. This axis convention is consistent with that recommended by the Scoliosis Research Society working group on 3D terminology of spinal deformity (Stokes, 1994).

A thoraco-lumbar frame was defined using the three markers on the rigid cluster (Fig. 2). The y axis was orientated as a line passing through the two markers mounted on the lateral ends of the rigid cluster's horizontal bar, with its positive

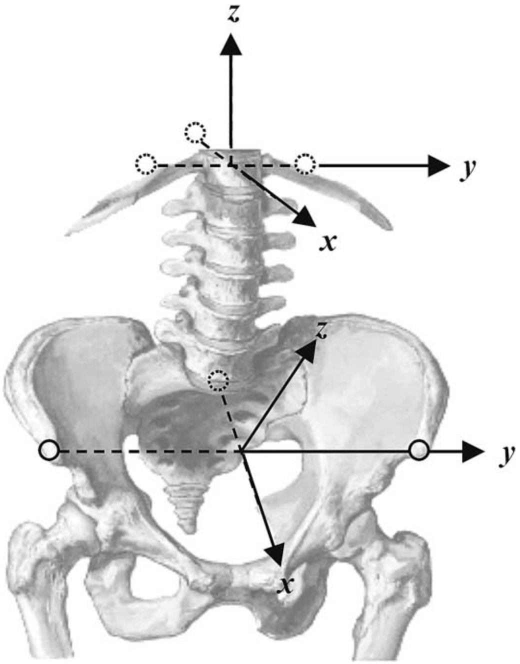

Fig. 2. The embedded thoraco-lumbar and pelvic frames (see text for further explanation).

direction to the left. The thoraco-lumbar origin was defined as the midpoint of the line connecting the centres of the two lateral markers. The x axis was constructed to lie in the plane formed by all three markers on the rigid cluster, orthogonal to the y axis at the thoraco-lumbar origin, with its positive direction forward. The z axis was perpendicular to both the x and y axes with its positive direction upward.

The anatomical bone-embedded frame of a vertebra has been previously defined by Pearcy (1985). As the spinous process is the only palpable anatomical landmark available for the non-invasive estimation of the in vivo angular kinematics of the lumbar spine, it was not possible to precisely reconstruct the anatomical bone-embedded frame of the vertebra in this experiment. Instead, with the subject in a neutral standing posture, the rigid cluster was carefully positioned over the spinous process of T12 such that its x axis was perpendicular to the skin surface in the sagittal and transverse planes and its y axis was horizontal. As none of the subjects under investigation suffered from any substantial scoliotic deformities of the spine, it was considered that a reasonable approximation of the anatomical bone-embedded frame of the vertebra was achieved with this configuration.

A pelvic frame was defined using the three pelvic markers (Fig. 2). The y axis was orientated as a line passing through both ASISs with its positive direction to the left. The pelvic origin was defined as the midpoint of the line connecting the centres of both ASIS markers. The x axis was constructed to lie in the plane formed by the right and left ASIS markers and the mid PSIS marker, orthogonal to the y axis at the pelvic origin, with its positive direction forward. The z axis was perpendicular to both the x and y axes with its positive direction upward.

Subjects were tested at a running speed of 4.0 m/second. In order to be able to calculate average curves for the data, all subjects needed to be tested at the same running speed. It was also important that all subjects were tested at a speed that was representative of their typical overground running pace. This was determined by asking each subject to perform three repeated overground runs at a speed equivalent to that which they would voluntarily choose for an intense 30 minute run. The three repeated runs were timed and averaged. The overall average self-selected overground running speed of the group was 4.37 (S.D. 0.52) m/second. As the test speed of 4.0 m/second was within one standard deviation of the average self-selected overground running speed, it was considered to be appropriate for the cohort in this investigation.

Subjects completed a short warm up at the test speed to settle into a consistent running pattern, after which the 3D trajectories of the markers were collected using a VICON 370 motion analysis system (Oxford Metrics Ltd., Oxford, England) with seven cameras (NAC Inc. Japan) operating at a sampling rate of 200 Hz. Five seconds of data were captured for each subject which contained approximately six complete running cycles. The instrumental errors were described by estimating the precision of the motion analysis system and were found to be no >1.1°, 1.0° and 1.0° about the x, y and z axes respectively (Schache et al., 2001; Schache, Blanch, Rath, Wrigley, Starr, & Bennell, 2002).

Lumbar spine movement was defined as movement of the thoraco-lumbar frame with respect to the pelvic frame. It therefore represented an estimation of the overall sum of each of the inter-vertebral movements combined. No individual inter-vertebral angular information was available from the marker configuration utilised. Pelvic movement was defined as movement of the pelvic frame with respect to the global frame. The neutral position (i.e. nil rotation values on all axes) corresponded to the situation where the two frames used to define a joint or segment were aligned.

Lumbar spine and pelvic 3D angular kinematic data were calculated using a joint coordinate system (JCS) as described by Grood and Suntay (1983). The medial–lateral (y) axis of the JCS was defined as the y axis of the reference or 'fixed' frame. The longitudinal (z) axis of the JCS was defined as the z axis of the 'moving' frame. The 'floating' anterior–posterior (x) axis was defined as the common perpendicular to the former two axes in each given instant of time. This geometrical convention is mathematically equivalent to Cardan angles obtained from three sequential rotations performed about each of the axes of the 'moving' frame in the order: (1) rotation about the y axis followed by; (2) rotation about the x axis followed by; (3) rotation about the z axis (Cole, Nigg, Ronsky, & Yeadon, 1993; Woltring, 1994). In anatomical terms, this order corresponds to: (1) flexion-extension followed by; (2) lateral bend followed by; (3) axial rotation for the lumbar spine, and: (1) anterior–posterior tilt followed by; (2) lateral tilt (obliquity) followed by; (3) axial rotation for the pelvis.

The conventions that were adopted in this experiment for the directions of the angular rotations are as follows. Positive angular rotations corresponded to: (y) lumbar spine flexion and pelvis anterior tilt; (x) lumbar spine lateral bend to the left and pelvis right side higher than the left, and; (z) lumbar spine and pelvis axial rotation to the left. Negative rotations corresponded to: (y) lumbar spine extension and pelvis posterior tilt; (x) lumbar spine lateral bend to the right and pelvis left side higher than the right, and (z) lumbar spine and pelvis axial rotation to the right.

The events of initial contact and toe off were determined from the kinematic data using both the vertical displacement and vertical velocity of additional markers placed on both lateral malleoli and the distal ends of both second metatarsals immediately adjacent to the second metatarso-phalangeal joints. Each running cycle, from right initial contact (RIC) to the following RIC, was time normalised to 101 points representing intervals from 0% to 100% using the program Igor Pro® (Wavemetrics, Lake Oswego, OR). Once time normalised, within-subject repeated running cycles were averaged to eliminate any high frequency noise. This procedure was considered appropriate as the within-subject stride to stride variability in the kinematic data was negligible. Other studies have also found minimal stride to stride variability for several lower limb kinematic parameters during treadmill running (Bates, Osternig, Mason, & James, 1979; Morgan, Martin, Krahenbuhl, & Baldini, 1991).

A set of key parameters that adequately described each of the angular kinematic waveforms in amplitude and time were extracted from the data. The selected parameters corresponded to the magnitude in degrees of crucial points on the angular kinematic waveforms (maxima or minima in stance or in swing phase, and values at particular events of the running cycle such as initial contact and toe off) as well as their timing expressed in percent (%) of the running cycle. The average and standard deviation for each of the selected parameters were then calculated.

It was hypothesised a priori that coordination between the angular rotations of the lumbar spine and pelvis during running was likely to be most prominent between coplanar movements. This was based firstly upon theoretical considerations about which movements were expected to be coordinated during running and secondly upon the findings of Crosbie et al. (1997) and Whittle and Levine (1999) for walking. These authors found coplanar angular rotations of the lumbar spine and pelvis to move in a complementary manner during walking.

In order to qualitatively analyse the coordination between the lumbar spine and pelvis during running, the average curves and standard deviation bands for coplanar angular rotations were plotted together as a function of time (% running cycle). Although useful for providing an indication of the amount of coordination between two angular rotations, position–time plots do not provide a suitable reflection of the pattern (i.e. linear versus non-linear relationship) of coordination (Mullineaux, Bartlett, & Bennett, 2001). For this purpose, the position of one angular rotation for the pelvis was plotted as a function of the position of its coplanar angular rotation for the lumbar spine. Such angle–angle plots have been recommended as the method of choice for displaying the coordinated movement patterns between two adjacent joints or segments of the body in a clear and compact manner (Cavanagh & Grieve, 1973).

In order to quantitatively evaluate the degree of coordination between the lumbar spine and pelvis during running, the average curves were used to calculate the correlations between: (1) lumbar flexion-extension and pelvic anterior–posterior tilt; (2) lumbar lateral bend and pelvic obliquity; and (3) lumbar axial rotation and pelvic axial rotation. As biological movements frequently display a phase difference between successively moving segments due to physical or other physiological factors (Amblard, Assaiante, Lekhel, & Marchand, 1994), it was anticipated that some of the coplanar angular rotations of the lumbar spine and pelvis might be coordinated in a sequential manner rather than occurring at exactly the same time points. Cross-correlation analysis was therefore utilised to identify the time lag at which the peak correlation occurred between coplanar angular rotations. In order to improve the validity of cross-correlation analysis, it must be demonstrated that the assumption of linearity between the dependent variables is not violated (Mullineaux et al., 2001). Consequently, if cross-correlation analysis revealed the presence of a phase difference, then the angle–angle plot was re-calculated with the phase difference included for one of the angular rotations.

3. Results

The lumbar spine and pelvis both displayed complex 3D angular patterns during running. As this 3D movement is difficult to visualise, rotations about each of the three axes will be presented separately. This layout is used for clarity and is not meant to detract from the fact that the rotations about the three axes occurred simultaneously during running.

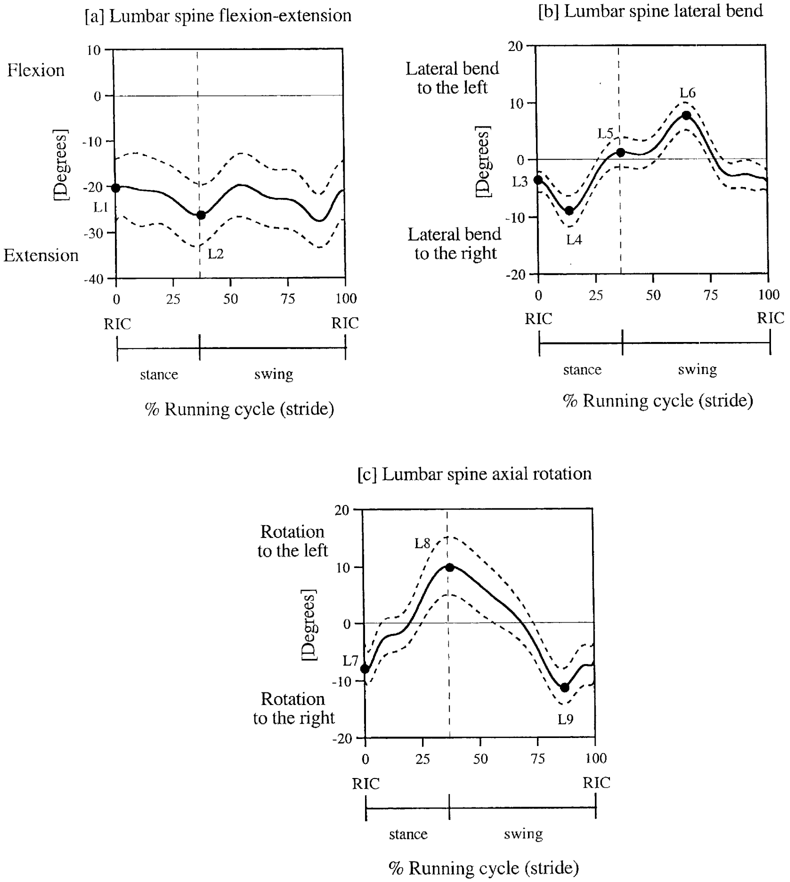

Fig. 3. (a–c) Average curves and standard deviation bands for the angular rotations of the lumbar spine over the running cycle from RIC to RIC. Toe off is indicated by the vertical dashed line. The timing of contra-lateral (left) initial contact is at 50% of the RIC to RIC running cycle. The kinematic parameters from Table 1 are labelled. Curves were smoothed by fitting a 15th order polynomial using the software program Igor Pro® (Wavemetrics, Lake Oswego, OR).

The lumbar spine and pelvis both rotated about their respective y axes (flexion-extension; anterior–posterior tilt) during running (Figs. 3(a) and 4(a)). The average amplitudes of the rotations were 13.3° (S.D. 3.8°) and 7.6° (S.D. 2.0°) for the lumbar spine and pelvis respectively. During running, the lumbar spine was extended whilst the pelvis was anteriorly tilted. The average angular positions were −22.9° (S.D. 6.2°) for the lumbar spine and 16.4° (S.D. 3.3°) for the pelvis. The lumbar spine and pelvis oscillated slightly about these average angular positions over the running cycle, displaying a biphasic movement pattern that corresponded to one phase per step. The lumbar spine flexed slightly and the pelvis posteriorly tilted slightly during loading response. These movements quickly reversed such that by mid stance the lumbar spine had begun extending and pelvis had begun anteriorly tilting. The first

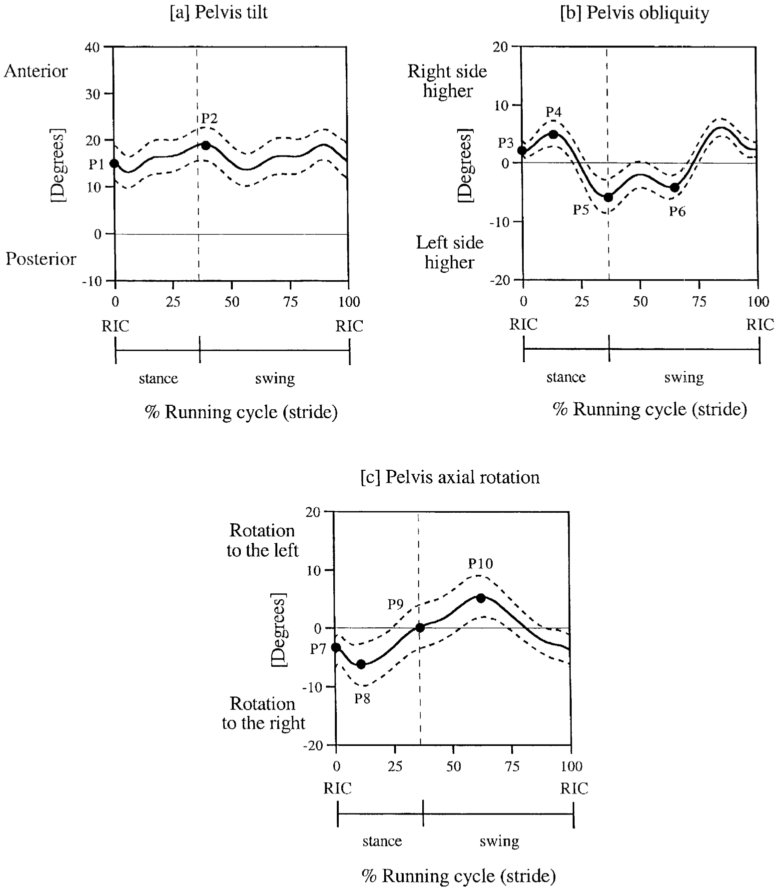

Fig. 4. (a–c) Average curves and standard deviation bands for the angular rotations of the pelvis over the running cycle from RIC to RIC. Toe off is indicated by the vertical dashed line. The timing of contra-lateral (left) initial contact is at 50% of the RIC to RIC running cycle. The kinematic parameters from Table 2 are labelled. Curves were smoothed by fitting a 15th order polynomial using the software program Igor Pro® (Wavemetrics, Lake Oswego, OR).

peak extension of the lumbar spine (L2) immediately proceeded right toe off (Fig. 3(a)) occurring at 36.2% of the running cycle (Table 1). The first peak anterior tilt of the pelvis (P2) quickly followed occurring at 39.0% of the running cycle (Table 2). This movement cycle for the lumbar spine and pelvis was then repeated following initial contact of the contra-lateral (left) lower extremity.

The lumbar spine and pelvis both rotated about their respective *x* axes (lateral bend; obliquity) during running (Figs. 3(b) and 4(b)). The average amplitudes of the rotations were 18.5° (S.D. 3.9°) and 10.6° (S.D. 3.0°) for the lumbar spine and pelvis respectively. At right initial contact the lumbar spine was laterally bent to the right and the pelvis was lower on the left side. During loading response, the lumbar spine continued to laterally bend to the right as the pelvis dropped to the left.

Table 1
Lumbar spine kinematic parameters

	Flexion-extension (y)			Lateral bend (x)						Axial rotation (z)				
	L1	L2	TL2[a]	L3	L4	TL4[a]	L5	L6	TL6[a]	L7	L8	TL8[a]	L9	TL9[a]
Average	−20.7	−28.9	36.2	−3.8	−9.9	13.2	1.1	8.6	63.4	−7.2	11.4	36.1	−11.6	86.4
Standard deviation	6.6	7.2	4.4	1.8	2.6	1.6	2.3	2.3	3.1	3.3	4.8	2.8	2.9	2.6

All parameters are measured in degrees except for parameters[a] which are measured in % of stride duration. Angular data: +ve (y) flexion, (x) lateral bend to the left, (z) rotation to the left; −ve (y) extension, (x) lateral bend to the right, (z) rotation to the right. (L1) extension at initial contact; (L2) first peak extension; (TL2) time at L2; (L3) lateral bend at initial contact; (L4) peak lateral bend to the right; (TL4) time at L4; (L5) lateral bend at toe off; (L6) peak lateral bend to the left; (TL6) time at L6; (L7) axial rotation at initial contact; (L8) peak axial rotation to the left; (TL8) time at L8; (L9) peak axial rotation to the right; (TL9) time at L9.

Table 2
Pelvis kinematic parameters

	Ant-post tilt (y)			Obliquity (x)						Axial rotation (z)					
	P1	P2	TP2[a]	P3	P4	TP4[a]	P5	P6	TP6[a]	P7	P8	TP8[a]	P9	P10	TP10[a]
Average	15.1	19.9	39.0	2.3	5.8	13.0	−5.4	−4.8	61.8	−3.9	−7.2	10.2	−0.7	6.7	58.9
Standard deviation	3.7	3.5	2.4	1.2	2.2	1.5	2.6	1.8	3.8	2.5	3.5	5.8	3.7	3.5	7.5

All parameters are measured in degrees except for parameters[a] which are measured in % of stride duration. Angular data: +ve (y) anterior tilt, (x) right side higher than the left, (z) rotation to the left; −ve (y) posterior tilt, (x) left side higher than the right, (z) rotation to the right. (P1) Tilt at initial contact; (P2) first peak tilt; (TP2) time at P2; (P3) obliquity at initial contact; (P4) first peak positive obliquity; (TP4) time at P4; (P5) obliquity at toe off; (P6) second peak negative obliquity; (TP6) time at P6; (P7) axial rotation at initial contact; (P8) peak axial rotation to the right; (TP8) time at P8; (P9) axial rotation at toe off; (P10) peak axial rotation to the left; (TP10) time at P10.

Peak lateral bend of the lumbar spine to the right (L4) and peak positive obliquity of the pelvis (P4) both occurred at approximately the same time (Tables 1 and 2). The lumbar spine then began to laterally bend towards the left as the pelvis began to elevate on the left. By right toe off, the lumbar spine was laterally bent to the left and the pelvis was elevated on the left. During right swing, lateral bend of the lumbar spine and obliquity of the pelvis moved with respect to the stance phase of the contra-lateral (left) lower extremity in a similar manner to that just described.

The lumbar spine and pelvis both rotated about their respective z axes (axial rotation) during running (Figs. 3(c) and 4(c)). The average amplitudes of the rotations were 23.0° (S.D. 4.6°) and 13.9° (S.D. 5.2°) for the lumbar spine and pelvis respectively. At right initial contact, the lumbar spine and pelvis were both rotated to the right. The lumbar spine rotated to the left during stance, reaching peak axial rotation to the left (L8) immediately proceeding right toe off (Table 1). During right swing, the lumbar spine rotated to the right reaching a peak (L9) at 86.4% of the running cycle. The lumbar spine then began rotating to the left again preceding the next right initial contact.

In contrast to the lumbar spine, the pelvis initially rotated to the right during loading response. Peak rotation to the right (P8) occurred just prior to mid stance (Fig. 4(c)). The pelvis then began rotating to the left during the later half of stance reaching a neutral position by right toe off. The pelvis continued to rotate to the left after right toe off. Peak rotation to the left (P10) occurred at 58.9% of the running cycle (Table 2) after which the pelvis began rotating to the right again.

Strong significant inverse correlations were found for the comparisons of flexion-extension of the lumbar spine with anterior–posterior tilt of the pelvis ($r = -0.84$; DF = 100; $p < 0.0001$) and lateral bend of the lumbar spine with obliquity of the pelvis ($r = -0.75$; DF = 100; $p < 0.0001$). Thus, as the angular rotations of the pelvis became more positive, the corresponding angular rotations of the lumbar spine tended to become more negative. Cross-correlation analysis revealed that the highest correlations were achieved with phase differences of <4% of the running cycle. Hence, the movements in both comparisons were essentially considered to be in phase. Flexion–extension of the lumbar spine and anterior–posterior tilt of the pelvis were coordinated and a predominant linear relationship was evident (Fig. 5(a)). Lateral bend of the lumbar spine and obliquity of the pelvis were also coordinated, but an overall non-linear relationship was evident (Fig. 5(b)) that cross-correlation analysis was unable to detect.

A significant but weak positive correlation was found for the comparison of axial rotation of the lumbar spine with axial rotation of the pelvis ($r = 0.37$; DF = 100; $p < 0.0001$). Cross-correlation analysis revealed that the highest correlation of $r = 0.95$ was achieved with a phase difference of 21% of the running cycle. Hence, axial rotation of the lumbar spine and pelvis was considered to be out of phase during running, with movement of the lumbar spine preceding that of the pelvis. A linear relationship was evident between these angular rotations when the time lag was included in the data for the pelvis (Fig. 5(c)). This supports the validity of the cross-correlation analysis in this circumstance.

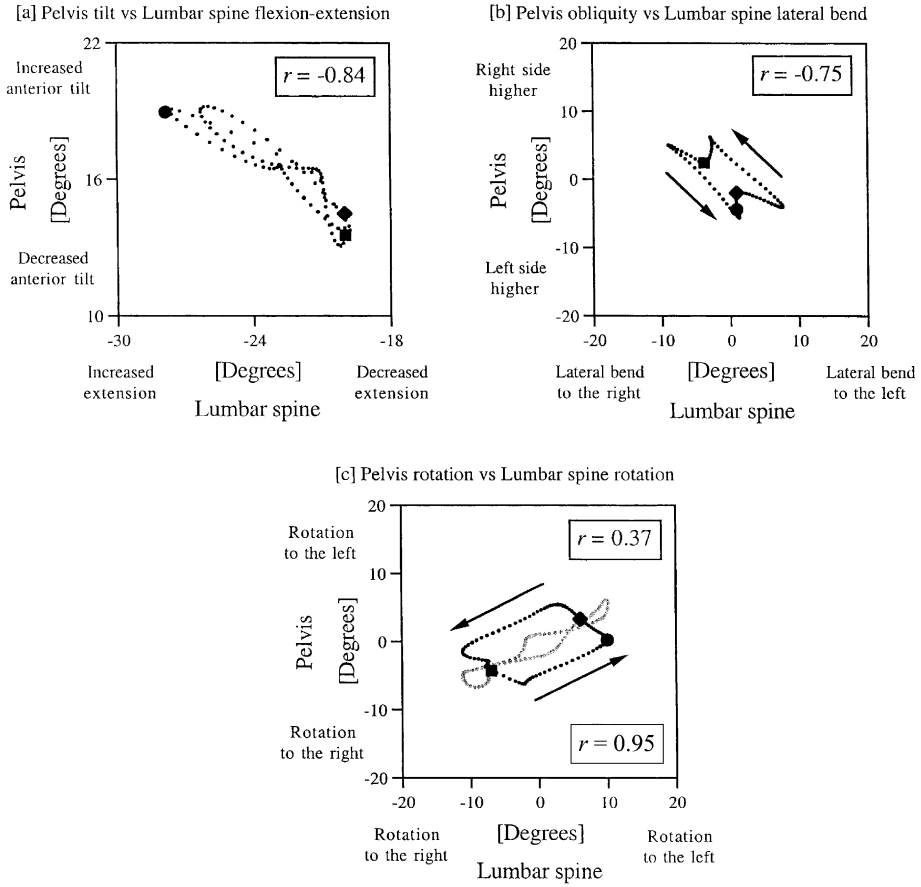

Fig. 5. (a–c) Angle–angle plots and Pearson's *r* values displaying the correlations between the angular rotations of the lumbar spine and pelvis. RIC is indicated by the filled square, right toe off is indicated by the filled circle and contra-lateral (left) initial contact is indicated by the filled diamond. For pelvis axial rotation versus lumbar spine axial rotation (c), the angle–angle plot prior to cross-correlation analysis is indicated in black and the re-computed angle–angle plot with the identified phase difference included in the data for the pelvis is indicated in grey.

4. Discussion

In order to be able to identify possible atypical kinematic patterns that may relate to injury, a detailed description of the typical kinematic patterns of the lumbar spine and pelvis during running must first be obtained. The specific objectives of this study were to: (i) describe the typical 3D angular kinematics of the lumbar spine and pelvis during running and; (ii) assess whether the movements of the lumbar spine and pelvis during running are coordinated.

Of the various parameters describing the magnitude of points on the angular kinematic waveforms, lumbar flexion–extension parameters (L1 and L2) were found to display the greatest variability across subjects (Tables 1 and 2). The lumbar flexion-extension kinematic waveform (Fig. 3(a)) was also found to display the widest standard deviation bands over the running cycle. Similar results have been previously reported by Whittle and Levine (1999) for walking. These findings are most likely due to differences in the lordotic posture of the lumbar spine between subjects. As the neutral position in this experiment corresponded to the situation where the thoraco-lumbar and pelvic frames were aligned, the lumbar flexion–extension kinematic waveform for a subject with an increased lordotic posture, whilst similar in pattern, was offset slightly towards extension with respect to the equivalent kinematic waveform for a subject with a reduced lordotic posture.

Flexion–extension of the lumbar spine and anterior–posterior tilt of the pelvis were found to be coordinated during running (Figs. 3(a) and 4(a)). Essentially, as anterior tilt of the pelvis increased during terminal stance, extension of the lumbar spine also increased (Fig. 5(a)). It was hypothesised by Slocum and James (1968) that extension of the lumbar spine and anterior tilt of the pelvis during terminal stance increased the working range of extension of the lower limb and contributed to the extensor thrust mechanism. However, this proposed role of the lumbar spine and pelvis during running is questionable. Joint moment and power calculations during jogging clearly demonstrate the propulsive mechanism during running to be primarily a product of the power generated by the ankle plantar flexors and the knee extensors prior to toe off (Winter, 1983). Data from this experiment support the later contention, as peak extension of the lumbar spine (L2) and peak anterior tilt of the pelvis (P2) were both found to occur after toe off (Figs. 3(a) and 4(a)).

Lateral bend of the lumbar spine and obliquity of the pelvis were also found to be coordinated during running (Figs. 3(b) and 4(b)). Tight coupling occurred between these movements during early and mid stance as demonstrated by the near perfect linear relationship in Fig. 5(b) after right initial contact. However, from the period commencing just prior to right toe off until contra-lateral (left) initial contact, lateral bend of the lumbar spine and obliquity of the pelvis displayed a non-linear relationship. During this time the lumbar spine maintained a relatively neutral orientation whilst the pelvis dropped slightly on the left side prior to contra-lateral (left) initial contact. In effect the whole trunk moved together with the pelvis. This is illustrated in Fig. 5(b) by the vertical orientation of the angle–angle plot for a short period after right toe off. These relationships were then repeated to the opposite side during right swing with the stance phase of the contra-lateral (left) lower limb.

Axial rotation of the lumbar spine and axial rotation of the pelvis were found to be coordinated during running but were out of phase by 21% of the running cycle (Figs. 3(c) and 4(c)). Hence, a poor correlation between these movements was found without the inclusion of the phase difference in the data (Fig. 5(c)). Peak axial rotation of the lumbar spine to the left (L8) occurred at 36.1% of the running cycle whilst peak axial rotation of the pelvis to the left (P10) occurred at 58.9% of the running cycle (Tables 1 and 2). Peak axial rotation of the lumbar spine to the left (L8) occurred just after right toe off (Fig. 3(c)). At this time, the right lower extremity would have been approaching maximal hip extension whilst the left lower extremity would have just passed maximal hip flexion (Schache, Bennell, Blanch, & Wrigley, 1999).

During running the angular momentum about a vertical axis of the upper trunk and arms has been shown to be opposite to the angular momentum about a vertical axis of the lower extremities (Hinrichs, 1987). It is therefore likely that the kinematic pattern for axial rotation of the lumbar spine during running is a reflection of the angular momentum about a vertical axis of the upper trunk and arms developed to directly counteract the angular momentum about a vertical axis of the reciprocally swinging lower extremities. The relatively neutral position of the pelvis at right toe off (Fig. 4(c)) suggests that it may be close to the central transition point between the opposing transverse plane impulses of the trunk and lower extremities.

The kinematic pattern of axial rotation of the pelvis during running is very different to that which occurs during walking. At right initial contact during walking, the pelvis has been shown to be maximally rotated to the left (Whittle & Levine, 1999). This movement aids in augmenting stride length at this time. With the loss of the double support phase during running, the pelvis is no longer required to be engaged with the lower extremities as a stride lengthening mechanism. At right initial contact during running, the pelvis was rotated slightly to the right (Fig. 4(c)). It has been suggested that this movement is important for minimising the horizontal braking forces at initial contact and thus avoiding potential loss of speed (Novacheck, 1998; Schache et al., 1999).

The findings from this experiment are consistent with those from previous investigations. The average lumbar spine extension angle during running of 22.9° found in this experiment is similar to the average lumbar lordosis angle during running of 25.9° reported by Whittle et al. (2000). Likewise, the average anterior pelvic tilt angle during running of 16.4° found in this experiment compares favourably with the range of average anterior pelvic tilt angles during running of 16.6–22.1° reported by previous researchers (Schache et al., 2000; Whittle et al., 2000). Finally, the amplitudes of movement for the angular rotations of the lumbar spine and pelvis found in this experiment approximate the reported amplitudes from previously conducted investigations (Table 3). In order to calculate angular data, most previously conducted investigations (Bickham et al., 2000; Novacheck, 1995; Ounpuu, 1990; Whittle et al., 2000) have utilised a geometrical convention consistent with this experiment. This means that the slight discrepancies between studies evident in Table 3 are more than likely explained on the basis of differences in marker protocols, the types of subjects recruited and running speeds tested.

To our knowledge, there are no published studies that have detailed the kinematic patterns for the angular rotations of the lumbar spine during running. The two-dimensional angular kinematic pattern for lateral bend of the mid trunk during running has been measured by Thorstensson et al. (1984). However, this pattern differs slightly with respect to the pattern for lateral bend of the lumbar spine in this experiment. Peak lateral bend of the mid trunk to the right occurred just prior to right initial contact whereas peak lateral bend of the lumbar spine to the right (L4) occurred just after right initial contact (Fig. 2(b)). The kinematic patterns for the angular rotations of the pelvis during running have been previously measured (Novacheck, 1995; Ounpuu, 1990). The reported angular kinematic patterns are qualitatively similar to those in this experiment (Fig. 4(a–c)) even though both

Table 3
Reported amplitudes for the angular rotations of the lumbar spine and pelvis during running (in degrees)

Reference	Speed (m/second)	Lumbar spine			Pelvis		
		y	*x*	*z*	*y*	*x*	*z*
Dalichau et al., 1998	–	7.1	6.5	5.9	7.6	4.7	6.7
Ounpuu, 1990	2.2	–	–	–	7.0	2.0	16.0
Whittle et al., 2000	2.9	12.1	–	–	8.9	–	–
Novacheck, 1995	3.2	–	–	–	5.0	7.0	16.0
Cairns et al., 1986	3.6	–	–	–	7.3	14.9	16.8
Novacheck, 1995	3.8	–	–	–	5.0	12.0	18.0
Schache et al., 2002[a]	4.0	13.3	18.5	23.0	7.6	10.6	13.9
Bickham et al., 2000	5.0	–	–	–	7.6	15.8	15.9

(*y*) lumbar flexion–extension/pelvic anterior–posterior tilt; (*x*) lumbar lateral bend/pelvic obliquity; (*z*) lumbar axial rotation/pelvic axial rotation; (–) not reported.

[a] Results from the current study.

Novacheck (1995) and Ounpuu (1990) utilised a paediatric population and tested at slower running speeds.

Several limitations should be noted. First, the results relate specifically to the marker protocol and application method utilised in this experiment. The repeatability of the protocol has been previously evaluated (Schache et al., 2002) and the reported angular data describe movements that are consistent with general clinical observations. Second, conditioned male runners were investigated only and one must be cautious about extrapolating the results from this study to conditioned female runners or to unconditioned runners. Finally, all subjects were tested at a running speed of 4.0 m/second. Whether or not similar findings exist at faster running speeds cannot be answered on the basis of this experiment.

The precise role that the angular rotations of the lumbar spine and pelvis fulfil during running is no doubt highly complex and multi-factorial. It is possible that the angular rotations of the lumbar spine and pelvis during running occur as a consequence of the rapid movements of the lower limbs. Rapid limb movements are known to perturb the trunk due to both generation of reactive forces and the additional displacement of the centre of mass resulting from a change in body configuration (Bouisset & Zattara, 1981; Horak, Esselman, Anderson, & Lynch, 1984). Hodges, Cresswell, and Thorstensson (1999) and Hodges, Cresswell, Daggfeldt, and Thorstensson (2000) found that, in response to rapid upper limb movement, the trunk displayed characteristic movements that occurred both prior to or coincident with the onset of limb movement (preparatory motion) and after the onset of limb movement due to the reactive forces (resultant motion). For similar reasons, the angular rotations of the lumbar spine and pelvis during running may be an intricate combination of preparatory and resultant motions. It is also possible that the angular rotations of the lumbar spine and pelvis may aid in the minimisation of energy expenditure during running (Anderson & Tseh, 1994). Future investigations are required to further substantiate these possible functions as well as consider potential relationships with tissue overload and injury.

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