Interaction Between Thorax, Lumbar, and Pelvis Movements in the Transverse Plane During Gait at Three Velocities

Ya-Ting Yang,1 Yasuyuki Yoshida,2 Tibor Hortobágyi,3 and Shuji Suzuki1
1Waseda University; 2Ochanomizu University; 3University of Groningen Medical Center

We determined the angular range of motion and the relative timing of displacement in the thorax, lumbar spine, and pelvis in the transverse plane during treadmill walking at three velocities. Nine healthy young females walked on a treadmill for three minutes at 0.40, 0.93, and 1.47 m/s. The position of seven reflective markers and three rigs placed on the thorax, lumbar spine, and pelvis were recorded at 200 Hz by an eight-camera motion capture system. As gait velocity increased, stride length increased, cycle time decreased, and angular displacement in the thorax and L1 decreased but increased at the pelvis and L5 (all $P < .05$). The time of maximal angular rotation occurred in the following sequence: pelvis, L5, L3, L1, and thorax ($P < .001$). The thorax and L1 and L3 were in-phase for shorter duration as gait velocity increased, and this reduction was especially large, approx. 32% ($P < .05$), between thorax and pelvis. As gait velocity increased, the pelvis rotated earlier, causing the shortening of in-phase duration between thorax and pelvis. These data suggest that, as gait velocity increases, pelvis rotation dictates trunk rotation in the transverse plane during gait in healthy young females.

Keywords: phase shift, twisting angle, coordination

Human walking involves the cyclical motion of the legs predominantly in the sagittal plane but segments proximal to the legs such as the pelvis, lumbar spine, and the thorax also, albeit indirectly, contribute to normal locomotion. Surprisingly, a comprehensive analysis has not yet been performed on the interdependence of movements that occur at the pelvis, lumbar spine, and the thorax during gait. Such an analysis would be important because any disruption to the coordination between these segments would predict and quantify gait inefficiency.1 There is some evidence that trunk2 and in particular pelvis rotation3 both contribute to maintaining balance during gait. More recently, the movement of the trunk in the transverse plane has been also characterized.4–6 For example, Callaghan et al observed that lumbar spine range of motion and muscle activation around the trunk increased as gait velocity increased.5 In these studies, however, there was methodologically a wide variation in how the movement of the thorax was defined because some studies used the third,7,8 other studies used the sixth thoracic vertebra,9,10 and still other studies referenced the measurements to the acromion process or to the center of the sternum,11 creating inconsistencies in the interpretation of the data.

There are also several inconsistencies in representing the movements of the lumbar spine during gait. For example, at least three referencing systems have been used for this purpose, including the twelfth thoracic spinous process,12 the second lumbar vertebra,7,8 and the differences between the motion of the pelvis and the thoracolumbar junction13 in patients who suffered from chronic low back pain,7,8 had a stroke,14 or were pregnant.1,10 Finally, the effects of gait velocity on the coordination in terms of relative timing between trunk and pelvis movements have been characterized only in general terms. Lamoth et al reported the relative phases between thoracic and pelvic segments and between lumbar and pelvic segments in the transverse plane.7 Other studies found that coordination of thoracic and pelvis rotation in the transverse plane changes more or less from in-phase (rotate in the same direction) to out-of-phase (rotate to opposite direction) as gait velocity increases.14,15 Crosbie et al found increases in the range of lumbar axial rotation with increases in gait velocity.16 However, none of these studies addressed the motor control mechanisms underlying the interaction, expressed in angular displacement and relative timing between the movements of the thorax, lumbar spine, and pelvis in healthy adults during gait.

As gait velocity increases stride length increases and cycle time decreases so that pelvis range of motion (ROM) becomes larger.3,4,14,15,17 What is unknown is how
this increased pelvis motion affects the synchronization between the movements of the lumbar spine and trunk. Because movements of the pelvis, lumbar spine, and trunk are interlinked, one prediction is that phase shifts in angular movements in these segments would be sensitive to changes in gait speed and could provide insights into the mechanisms of intersegmental coordination. Thus, we hypothesized that as gait speed increases the magnitude of pelvis movement in the transverse plane increases, resulting in a shortening of the in-phase duration between pelvis and thorax and lumbar spine and thorax. Therefore, the purpose of this study was to systematically characterize the spatial and temporal coordination between the thorax, lumbar spine (L1, L3, and L5), and pelvis in the transverse planes during treadmill walking at three gait velocities.

**Methods**

**Subjects**

Healthy female volunteers participated in this study (n = 9) with an average age, height, and mass of 24.6 ± 2.4 years, 1.58 ± 0.05 m, and 47.9 ± 3.6 kg, respectively. None of the subjects had a history of neurological or musculoskeletal disorders. Subjects wore shorts and their own shoes suitable for walking and a sports bra, making bony landmarks accessible for marker placement. Each participant read and signed an informed consent that was approved by the human ethics committee at Waseda University in Japan.

**Instruments**

A three-dimensional motion capture system (MAC3D, Motion Analysis Corp., USA) was used to obtain position data at 200 Hz during treadmill (L7ST, LANDICE Inc., USA) walking. Eight cameras surrounded the measurement volume. The positive x-axis of the global coordinate system indicated lateral direction, the negative y-axis indicated forward direction, and the positive z-axis indicated upward direction. Walking direction was toward the negative direction of y-axis in the global coordinate system.

**Marker Setup**

Nine 15 mm diameter spherical reflective markers were affixed to the subjects’ skin with double-sided adhesive tape over the sternum, the first thoracic spinous process (T1), both anterior superior iliac spines (ASIS), and second sacrum (S2), for capturing the movements of the thorax and pelvis (Figure 1A). The markers on both calcanea and toes were also used for identifying events in the gait cycle. Three measurement rigs were affixed to the skin over the first (L1), the third (L3) and the fifth (L5) lumbar spine (Figure 1A) for capturing lumbar spine motion. The rigs consisted of two markers, one on each side of the spinous process of the lumbar spine and a third marker on the end of a 100 mm wand pointing posteriorly and superiorly. The wands were attached to the rigs at a fixed angle.

**Experimental Procedure**

First, a static standing calibration trial was performed. Next, all markers and rigs were checked whether they were firmly affixed on the correct bony landmarks before the start of the walking trials. Subjects walked on the treadmill at a self-selected pace that averaged 1.03 ± 0.30 m/s to become accustomed to the treadmill and the environment. In a random order, subjects then walked at 0.40 (slow), 0.93 (medium), and 1.47 (fast) m/s for three minutes at each velocity. Two minutes into each trial, unknown to the subject, 10 gait cycles were recorded. There was two minutes of rest between trials. Finally, the data collection protocol at the three velocities was repeated. It took about 20 minutes to complete the entire experimental session.

**Kinematic Analysis**

Kinematic data were filtered with a fourth order Butterworth low-pass digital filter with a cutoff frequency of 5 Hz. All data were normalized as a percent of the gait cycle between two consecutive heel strikes of the right foot. In each subject 10 gait cycles at each gait velocity were averaged and included in the analysis. Angular positions were calculated in the transverse plane and positive values denoted rotation of the right side forward (counterclockwise) and negative values denoted rotation of the left side forward (clockwise).

The angular position of thorax was calculated from Equation 1:

\[ \theta_y = \arctan \left( \frac{y_j - y_i}{x_j - x_i} \right) \]  

where \( y_j \) and \( y_i \) are the coordinate data of T1; \( y_j \) and \( x_j \) are the coordinate data of the sternum. The angular position of the pelvis was also calculated from Eq. 1, where \( y_j \) and \( x_j \) denote the coordinate data of the S2; \( y_i \) and \( x_i \) denote the coordinate data of the midpoint of the both ASISs. The angular position of each lumbar segment was calculated from Eq. 1, where \( y_j \) and \( x_j \) are the coordinate data of the end of the wand; \( y_i \) and \( x_i \) are the coordinate data of the midpoint of the two adjacent spinous processes (Figure 1B).

We derived kinematic descriptors of the thorax, lumbar spine (L1, L3, and L5), and pelvis in the transverse plane from marker and measurement rig data, including range of motion, the timing when an angle became maximum after right and left foot strikes (peak timing), maximal twisting angle, and the relationship between two segments in terms of being “in-phase” and “out-of-phase” during the gait cycle. In-phase coordination was defined as when both structures rotated in the same direction; out-of-phase coordination was defined as rotated simultaneously in opposite directions.
Statistical Analysis

SPSS software (version 11.0J, SPSS Inc., USA) was used for statistical analysis. Repeated-measures analysis of variance (ANOVA) was performed for all variables, with velocity and segment as within factors. The Mauchly test was performed to ensure that the ANOVA assumption of homogeneity of variance was not violated for the evaluation of the interaction effect. The Bonferroni post hoc test was used for multiple comparisons. To quantify any asymmetries and error in marker placement, we compared with a paired t test the magnitude of angular displacement to the left and to the right in the thorax, L1, L3, L5, and the pelvis at the three gait velocities. All data are presented as mean and standard error of the mean (mean ± SEM). The level of significance was set at P < .05.

Results

Stride length increased significantly; however, swing and stance time decreased significantly with increasing gait velocities as healthy young females walked on the treadmill (Table 1). Under these conditions, we characterize the transverse plane kinematics of the thorax, lumbar spine, and pelvis during treadmill walking at three velocities in one subject (Figure 2). The cycle starts at the instance of right foot strike (RFS: I) as the left foot was also on the ground toward to end of left stance phase. At RFS the pelvis rotated in a counterclockwise direction and reached the maximal angle (positive peak value) around left toe-off (LTO: II), then pelvis turned to rotate clockwise concomitantly with forward direction for left side. Then, left foot strike (LFS: III) occurred at the midpoint of the gait cycle. Clockwise rotation reached maximal angle (negative peak value) at about right toe-off (RTO: IV) and again pelvis turned to rotate in a counterclockwise direction to end the cycle (RFS: V). The data for angular position with increasing gait velocities indicate two features spatially and temporally: (1) the amplitude of the angular position at the pelvis and L5 increased; however it decreased at the thorax and L1 as gait velocity increased, and (2) the phase retardation of reversal point of angular position (the timing of maximal angle) were from pelvis to L5, L3, L1 and thorax at the three velocities. The phase retardation of the second reversal point of angular position at slow gait velocities
Table 1  Stride characteristics of treadmill walking at 0.40, 0.93, and 1.47 m/s

<table>
<thead>
<tr>
<th>Variable</th>
<th>0.40 m/s</th>
<th>0.93 m/s</th>
<th>1.47 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stride length (m)</td>
<td>0.91 ± 0.04</td>
<td>1.27 ± 0.03***</td>
<td>1.55 ± 0.02***,†††</td>
</tr>
<tr>
<td>Stance time (s)</td>
<td>1.24 ± 0.06</td>
<td>0.75 ± 0.02***</td>
<td>0.59 ± 0.01***,††</td>
</tr>
<tr>
<td>Swing time (s)</td>
<td>0.48 ± 0.02</td>
<td>0.40 ± 0.01***</td>
<td>0.36 ± 0.01***</td>
</tr>
</tbody>
</table>

Note. Values indicate mean and standard error of the mean (mean ± SEM), n = 9. Stance and swing times are averaged of right and left sides.

***Significant difference between 0.40 m/s and the other two velocities (P < .001).
††Significant (P < .005) and †††(P < .001) difference between 0.93 m/s and 1.47 m/s.

Figure 2 — A representative single subject example of transverse plane kinematics of the thorax, lumbar spine, and pelvis during treadmill walking. A The gait cycle, illustrated with stick figures, starts with right foot strike (RFS, I), left toe-off (LTO, II), left foot strike (LFS, III), right toe-off (RTO, IV), and again to right foot strike (RFS, V). B Angular position of the thorax, lumbar spine (L1, L3, L5) and pelvis in the transverse plane averaged for ten gait cycles at three gait velocities in one subject. Gray contours around the solid lines denote the standard error of the mean. Zero (0) degree refers to neutral position of each anatomical structure as defined in Figure 1. Horizontal shaded bands indicate the stance and swing phases of the left and right leg. The vertical dotted line indicates left foot strike.
among all segments was similar to the first one, which was in an order of pelvis, L5, L3, L1, and thorax. These phase retardations were observed also at the three gait velocities.

Total angular displacement increased at the pelvis and decreased at the thorax as gait velocity increased (Figure 3). The magnitude of rotation to the left (5.80° ± 0.98) and right (5.65° ± 0.77) in the thorax, L1, L3, L5, and the pelvis were statistically not different (2.6% difference, \(t = .231, P = .818\)) at the three velocities, suggesting symmetrical motions and no error due to marker placement or movement. The repeated-measures ANOVA showed that the segment main \((P < .001)\) and the velocity by segment interaction \((P < .05)\) effects were both significant. At slow gait velocity, the magnitude of total angular motion of all segments was similar. From slow to fast gait velocity, the magnitude of total angular motion of the thorax and L1 became smaller while it increased at the pelvis and L5. For instance, pelvis angular motion increased approximately 80% (slow = 11°, fast = 19°, \(P < .001\)); however, the amplitude for thorax decreased approx. 50% (slow = 12°, fast = 6°, \(P < .001\)) as gait velocity increased 3.7-fold from slow to fast. The magnitude of angular displacement in L3 was similar at the three gait velocities.

There was a significant forward shift in peak timing at the pelvis, but not at the thorax, relative to the right and left foot strike as gait velocity increased (Figure 4). Concerning the temporal coordination, the peak timing became progressively retarded and its forward shift increased with gait velocity (Figure 4). The repeated-measures ANOVA revealed that both main effects \((P < .001)\) and the interaction effect \((P < .05)\) were significant. For example, the peak timing progressed from pelvis (right = 21.8 ± 6.0%, left = 72.3 ± 5.2%), to L5 (right = 27.0 ± 4.9%, left = 77.3 ± 5.1%), L3 (right = 31.4 ± 6.4%, left = 81.3 ± 7.7%, \(P < .001\)), L1 (right = 35.4 ± 5.6%, left = 84.4 ± 7.5, \(P < .001\)) and thorax (right = 36.3 ± 5.2%, left = 85.4 ± 7.6%, \(P < .001\))
.001) at slow velocity during one stride cycle revolution. This trend remained as gait velocity increased. Except for the thorax, there was a significant forward shift in peak timing in each segment relative to the right and left foot strike as gait velocity increased (Figure 4).

The coordination between segment pairs changed across the three gait velocities (Figure 5). The angle-angle plots show, for example, that during slow gait (Figure 5A-a), thorax and L1 moved in the same direction and were temporally linked, suggesting a large percentage of in-phase coordination (Figure 5B). The amount of in-phase coordination decreased with increasing gait velocity ($P < .05$). Motion of the thorax and pelvis (Figure 5A-d, e, f) revealed a different pattern compared with the coordination between thorax and L1. The coordination between thorax and L1 and thorax and L3, respectively, shows a high percentage of in-phase behavior during slow gait with a shift toward out-of-phase coordination ($P < .05$) during faster gait (Figure 5B). The thorax and pelvis were in in-phase 74.4±7.3% of gait cycle at slow gait that decreased ($P < .05$) to 42.5±14.1% of gait cycle as gait velocity increased. Pelvis and L5 and pelvis and L3, rotated in-phase for the majority of the gait cycle independent of gait velocity. We also indicate the timing of the maximal twisting angle (the point of maximal torsion state) between the specific segments (Figure 5C). This twisting aspect between the segments occurred during in-phase coordination between any two segments (see symbol of red triangle in Figure 5A).

**Discussion**

The purpose of this study was to systematically characterize spatial and temporal coordination between the movements of the thorax, lumbar spine, and pelvis in the transverse plane during treadmill walking at three velocities in healthy, young female adults. In agreement with several previous studies we also observed that stride length increased and stride time decreased with increasing gait velocity while walking on a treadmill. Because of the interdependence between pelvis, lumbar spine, and trunk during gait, our approach was to use kinematic phase analysis that provides a comprehensive view on the mechanism of coordination between these body segments in the transverse plane. We found that as pelvis rotation increased, thorax rotation decreased with increasing gait velocity. The angle in pelvis range of motion at faster gaits was probably needed to facilitate the increase in stride length as gait velocity increased. The temporal behavior of these segments suggests the presence of a time lag between reaching maximal angular position. This time lag produced a sequence so that the extreme of the range of motion was reached, in order, by the pelvis first followed by L5, L3, L1, and the thorax (Figure 4). These results suggest that the body motion propagates from lowest to the highest segment, reaching the upper extremities last during gait. A key finding was that the pelvis range of motion increased with gait speed. There were also significant forward shifts in peak timing relative to foot strike for each segment as gait velocity increased, except for the thorax (Figure 4).

Previous studies used Fourier analysis to examine the coordination between the movements of pelvis and thorax, and pelvis and lumbar spine during gait. These studies used the measure of relative phase between two segments to describe their movements. While such an analysis provides valuable numerical insights into trunk biomechanics during gait, it cannot quantify phase shifts between segments and the maximal twisting angle. Here we analyzed the angular position data using temporal analysis that allowed us to characterize trunk coordination during gait, using the method of peak timing (Figure 4), angle-angle plots (Figure 5A), the duration of in-phase and out-of-phase (Figure 5B), and maximal twisting angle (Figure 5C) as gait velocity increased. Previous studies also used phase shift in the EMG patterns to evaluate motor control of human lower extremities during gait and cycling, to characterize the synchronization of motor responses to a stimulus sequence, to assess the rhythmic coordination of finger tapping responses to auditory stimuli, and to quantify synchronization between stepping responses to metronome beat in hemiparetic gait.

The successful detection of a phase shift under a variety of experimental conditions provided motivation for our study to use this technique and explore trunk coordination with an emphasis on the interaction between thorax and pelvis movements in the transverse plane during gait. Figure 6 summarizes the coordination between pelvis and thorax movements. Specifically it shows a key finding that the pelvis and the thorax become out-of-phase with each other as gait velocity increases. Figure 6 graphically shows the small phase shift in thorax (arrow one and inner solid line) and the large phase shift in pelvis (arrow two shows, outer solid line) as gait velocity increased. As illustrated by the gray shaded bands becoming longer inside the graph, the two segments became more out-of-phase at high compared with slow gait velocity. As a result, the length of the out-of-phase state between pelvis and thorax was getting longer as gait velocity increased. The point of reversal was relatively constant across gait speed for the thorax and this consistent pattern suggests a phase dependency in relation to the upper but not the lower extremities.

We characterized the point of maximal torsion state between two segments by computing the maximal twisting angle, calculated as the absolute value of the angular position between two segments. Maximal twisting angle between two segments was the highest between the thorax and the pelvis and the lowest between the segment pairs of pelvis-L5 and thorax-L1. The maximal twisting angle was similar between thorax-L3 and Pelvis-L3, respectively. The lower twisting values for adjacent segments (Pelvis-L5, thorax-L1) confirm these segments’ interdependence whereas the larger twisting value for remote segments (thorax-pelvis) indicate a cumulative effect of torsion, resulting from the segments lying between the thorax and pelvis. Kinetic data support our interpretation of these kinematic data because the axial stiffness between thorax and pelvis also increased as a function of gait speed.
Figure 5 — Angle-angle plots, the duration of in-phase and out-of-phase, and maximal twisting angle at three gait velocities (n = 9). A Angle-angle plots between thorax and L1 (a, b, c), thorax and pelvis (d, e, f), and L5 and pelvis (g, h, i). Black and gray trajectories indicate duration of out-of-phase and in-phase, respectively in each diagram. Black circle indicates the starting point with right foot strike (I) of the gait cycle. Traveling directions were counterclockwise (from I to V). Two red triangles in each diagram indicate the point of maximal torsion state (maximal twisting angle, see Figure 5C) between segments. Each dotted line on the X and Y axes indicates neutral position (0 deg). B Duration of in-phase (left Y axis) and out-of-phase (right Y axis) between thorax and L1, thorax and L3, thorax and pelvis, pelvis and L3, and pelvis and L5. Error bars represent the standard error of the mean. *, **Significantly different between 0.40 m/s and the other two velocities (P < .05, .005). C Maximal twisting angle (red triangle in Figure 5A) between segments. *, **, ***Significantly different between 0.40 m/s and the other two velocities (P < .05, .005, .001). #, ###Significantly different between 0.93 and 1.47 m/s (P < .05, .001). Error bars represent the standard error of the mean. Note. Maximal twisting angle (twice in a gait cycle; right to left rotation vs left to right rotation) increased during in-phase, and its timing was phase shifted to the turning point to out-of-phase as gait velocity increased.
Placing the present data in a clinical context, previous studies examined the pelvis-thorax coordination during gait at different velocities in patients who suffered from pregnancy-related pain in the pelvis (PPP) and chronic low back (LBP). In PPP patients compared with healthy controls, the rotational amplitudes of pelvis and thorax tended to be larger. In addition, the out-of-phase coordination occurred at higher gait velocities in healthy compared with PPP subjects. In LBP patients compared with pain-free controls the rotational amplitudes of pelvis and thorax were smaller at gait velocities of 0.39 m/s to 1.94 m/s, with the LBP patients also exhibiting longer in-phase states in the transverse plane at the higher walking velocities. These studies also showed that PPP and LBP patients’ gait was more rigid and less variable in terms of pelvis and thorax as gait velocity increased. Our data reveal that by including peak timing, angle-angle relationships, in-phase and out-of-phase duration, and maximal twisting angle in the analysis of patients’ gait, clinical insights can be obtained concerning the motor control mechanisms of segmental coordination.

In conclusion, the present results suggest that during normal human gait there is interdependence between the movements of the thorax, lumbar region, and pelvis. The pelvis starts to move first and leads progressively the rotation of lumbar axis and thorax. As gait velocity increased, the pelvis rotated earlier, causing the shortening of in-phase duration between thorax and pelvis. These
data suggest that pelvis rotation dictates trunk rotation in the transverse plane during gait in healthy young females and pelvis dysfunction would magnify the disruption of coordination between thorax, lumbar segment, and pelvis and contribute to gait inefficiency, especially at high gait velocities.

References


