早稲田大学審査学位論文
博士（人間科学）

# The effect of walking speed on thorax, lumbar and pelvis movements during gait in women

# 健常女性の歩行速度に対応する胸郭、腰椎および骨盤の協調運動

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*This dissertation is dedicated to my dear family.*

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# *GENERAL ABSTRACT*

The purpose of this dissertation was to systematically characterize the spatial and temporal coordination between the movements of the thorax, lumbar spine, and pelvis in the transverse planes during human treadmill gait at different but constant velocities in healthy, young female adults to find motor control of trunk and pelvis motion. For this purpose, 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. We determined the angular range of motion and the relative timing of displacement in the thorax, lumbar spine (L1, L3, and L5), and pelvis in the transverse plane during treadmill walking at three velocities. Nine healthy young females (24.6 ± 2.4 years, 1.58 ± 0.05 m, and 47.9 ± 3.6 kg) 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, ~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 during normal human gait, pelvis starts to move first and leads progressively the rotation of lumbar axis and thorax. As gait velocity increases, pelvis rotation dictates trunk rotation in the transverse plane during gait and the in-phase duration is velocity-dependent in healthy young females.

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# CHAPTER I

# INTRODUCTION

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 (Wu et al., 2002).

There is some evidence that trunk (Saunders et al., 1953) and in particular pelvis rotation (Stokes et al., 1989) both contributes to maintaining balance during gait. More recently, the movement of the trunk in the transverse plane has been also characterized (Bruijn et al., 2008; Callaghan et al., 1999; Crosbie et al., 1997a). For example, Callaghan et al. (1999) observed that lumbar spine range of motion and muscle activation around the trunk increased as gait velocity increased.

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. (2006a) reported the relative phases between thoracic and pelvic segments and between lumbar and pelvic segments in the transverse plane. van Emmerik and Wagenaar (1996) and Wagenaar and Beek (1992) 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. Crosbie et al. (1997b) found increases in the range of lumbar axial rotation with increases in gait velocity. 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 (Bruijn et al., 2008; Kubo et al., 2006; Stokes et al., 1989; van Emmerik & Wagenaar, 1996; Wagenaar & Beek, 1992). 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 inter-segmental coordination. However, previous studies focused on the kinematic description of trunk motion during gait without address 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.

## Hypothesis and Purpose

We hypothesized that as gait speed increases the magnitude of pelvis movement in the transverse plane increases and the time interval between forward and backward pelvis rotation decreases, resulting in a shortening of the in-phase duration between pelvis and thorax and lumbar spine and thorax.

Therefore, the purpose of this dissertation was to systematically characterize the spatial and temporal coordination between the movements of the thorax, lumbar spine (L1, L3, and L5), and pelvis in the transverse planes during treadmill walking at three gait velocities in healthy, young female adults. This dissertation extends previous studies, mostly kinematic findings to motor control of trunk and pelvis motion.

## Overview

Following Chapter 1 as an introduction, Chapter 2 provides a comprehensive account of the measurement details of the thorax and lumbar spine. Then, Chapter 3 describes the experiment. Next, Chapter 4 presents a general discussion of the experimental findings. Chapter 5 places the results in a clinical context. Finally, Chapter 6 provides the conclusions of this dissertation.

# CHAPTER II

# REVIEW OF LITERATURE

Trunk, in particular pelvic rotation contributes to maintaining balance during gait (Saunders et al., 1953; Stokes et al., 1989). Subsequently, the movement of the trunk, including thorax, lumbar spine, and pelvis has been studied extensively during gait, using different methods. Different from the thorax and the lumbar spine, the pelvis has much less mobility; therefore, the approach to measure the small movements of the pelvis during gait is unique. The present chapter provides a comprehensive account concerning the many details of the measurements of the thorax and lumbar spine.

## Measurement of the thorax

Trunk rotation around the longitudinal axis was reported to be about the order of nine degrees according to the studies of the 1960s (Murray et al., 1966; Chapman & Kurokawa, 1969). Thereafter, with the development of more sensitive measurement systems that improved resolution and the ability to measure three dimensional kinematic values within order-independent joint coordinate systems (Grood & Suntay, 1983), the reported values for trunk rotation have been revised down to about 1/2 of that value (Krebs et al., 1992).

Thorax is divided into upper and lower segments. During the gait cycle, the upper segment of the thorax is constrained, and its movements predictably limited, by the secure attachments of the first six or seven ribs. The lower thoracic spine has the capability to move, albeit within a limited range. Several studies have considered the entire trunk with respect to the pelvis, usually locating upper markers or measurement transducers in the region of the acromion processes or sternum (Stokes et al., 1989; Cappozzo et al., 1982). Other studies have considered movements of the lumbar spine and the pelvis (Thurston & Harris, 1983; Thurston, 1985; Bastian et al., 1991) or of the pelvis and lower limbs (Nottrodt et al., 1982).

Crosbie et al. (1997a) subdivided the spine into upper thoracic, lower thoracic, lumbar and pelvic segments (Figure 2-1) and compared the movement patterns of these segments during gait. They found that the upper and lower trunk segments were in a neutral orientation with respect to the ground at heel strike, and then rotated towards the swinging side during single support (Figure 2-2). Peak to peak range of motion demonstrated no significant difference between these segments. This result suggested that for measuring the movement of the thorax during gait, there is no need to divide it into upper and lower thorax.

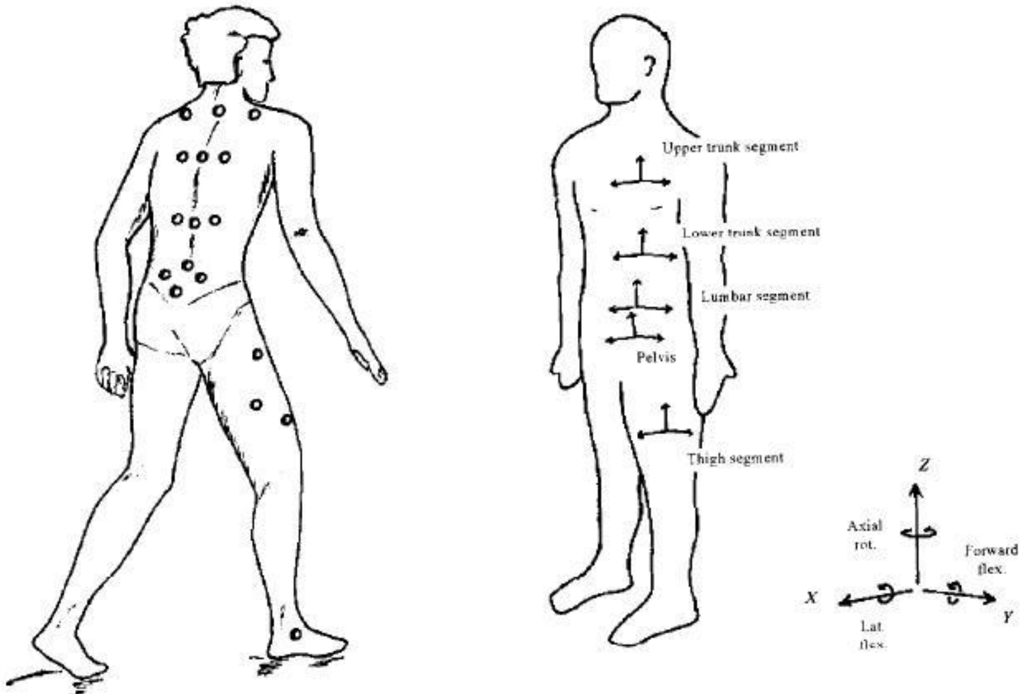


**Figure 2-1** Location of reflective markers on subject and conventions used to define axes and motions. (from Crosbie et al., 1997a)

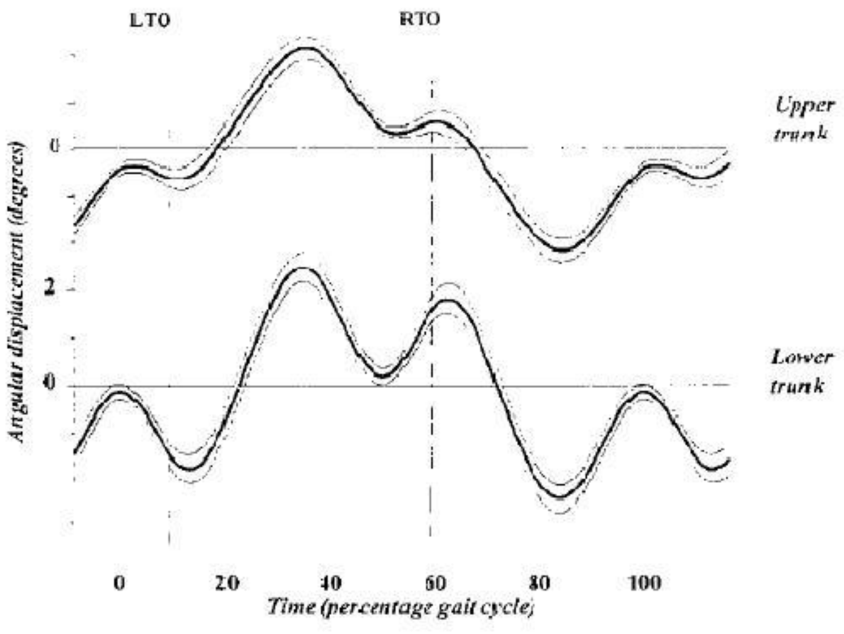


**Figure 2-2** Patterns of axial rotation of the upper and lower trunk segments with respect to the ground coordinate system. (from Crosbie et al., 1997a)

However, there was also methodologically a wide variation in how the movement of the thorax was defined because some studies used the third (Lamoth et al., 2006a, b), other studies used the sixth thoracic vertebrae (Huang et al., 2010; Wu et al., 2004), and still other studies referenced the measurements to the acromion process or to the center of the sternum (Sharpe et al., 2008; Wu et al., 2002), creating inconsistencies in the interpretation of the data. Considering the results of these studies, we found a similar trend in the rotational movement of the thorax which measured using all variation methods.

Figure 2-3 shows the characteristics rotational movement of the thorax during gait. The data were normalized as a percent of the gait cycle between two consecutive heel strikes. Thoracic rotation (blue line) was in the same direction as the initial contact leg at the start of the gait (0%). Then, thorax turned and rotated toward opposite direction to the initial contact leg at about the midpoint of the stride cycle. Finally, thorax turned and rotated toward the same direction as the initial contact leg again at the end of the gait. As gait velocity increases, the characteristics movement of the thorax revealed some time lag but this time lag seems to have no regularity.

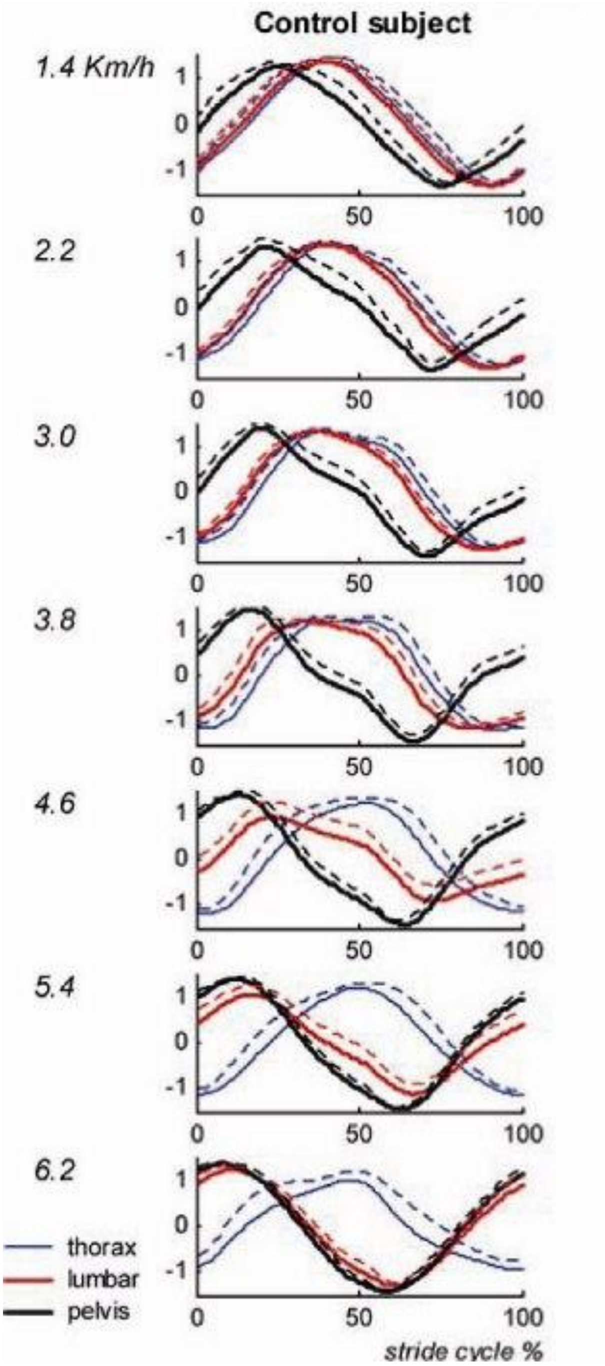


**Figure 2-3** Average time series of the global pattern of segment rotations in the transverse. The dotted lines represent the SD. (from Lamoth et al., 2006)

Some of the previous studies reported the rotational amplitude of the thorax during different walking velocities (Lamoth et al., 2006; Sharpe et al., 2008; Wu et al., 2002, 2004). The results of these studies show a decrease trend, without statistical difference, in the rotational amplitude of the thorax with increasing gait velocities (Figure 2-4).

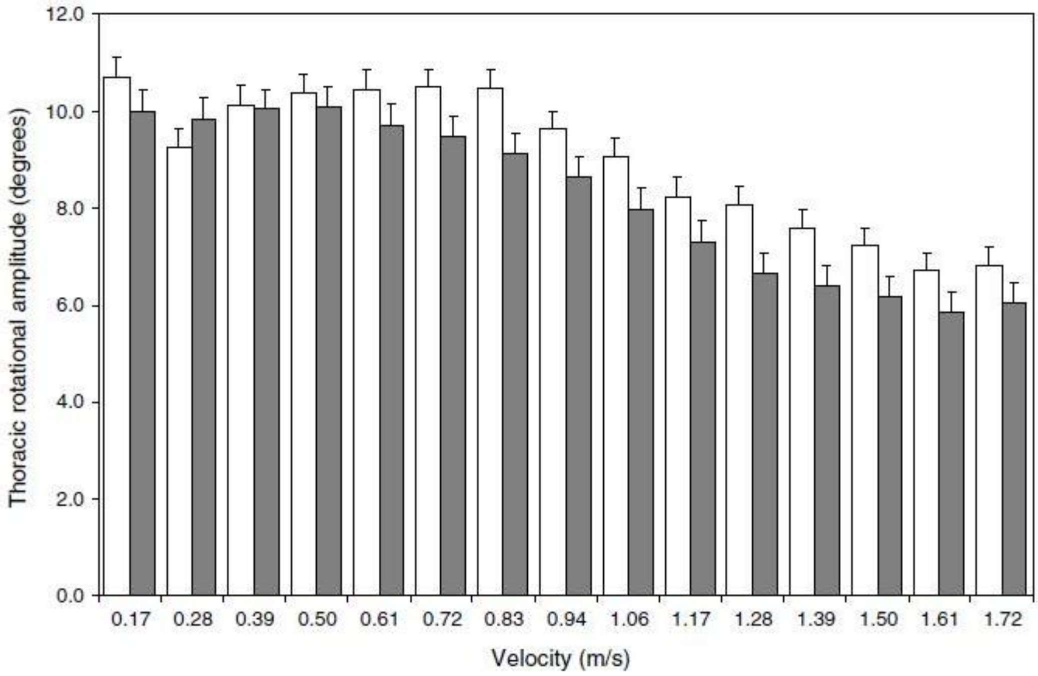


**Figure 2-4** Mean rotational amplitudes of the thorax during gait (T-bars representing standard errors) at different walking velocities of the control subjects (white) and the healthy pregnant women (grey). (from Wu et al., 2004)

As described, researchers tried to measure the characteristics of the thoracic rotational movement, the change of the characteristics with increasing gait velocities, and the different of the thoracic rotational movement between health subjects and illness subjects.

## Measurement of the lumbar spine

Various methods have been used for measuring the lumbar lordosis in an attempt to quantify its curvature. For example, goniometry (Burdett et al., 1986; Troup et al., 1963), radiography (Hansson et al., 1985), skin marks (Moll & Wright, 1971; Pearcy, 1986), and flexible rulers (Hart & Rose, 1986; Lovell et al., 1989) have all been used. Figure 2-5 and Figure 2-6 is a diagram showing the method of measuring the lumbar lordosis.

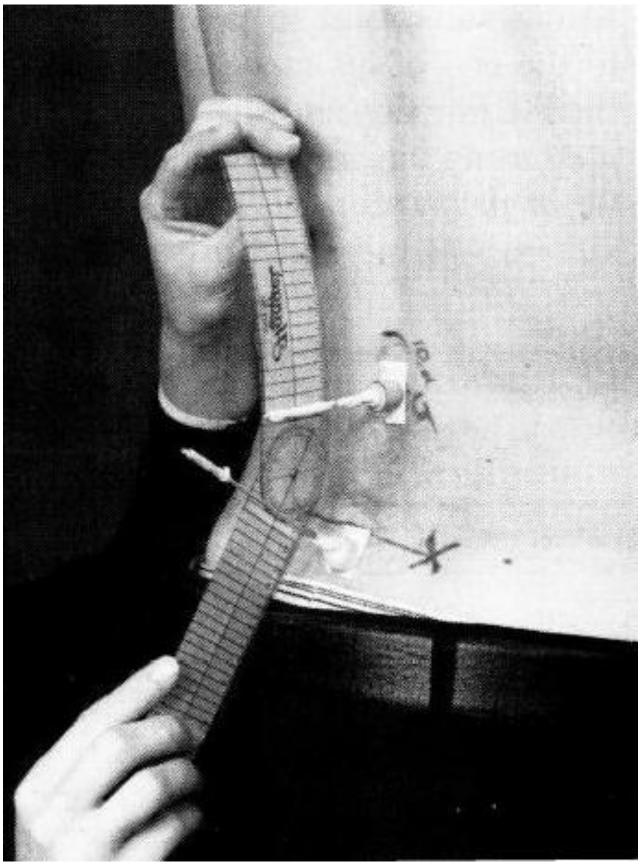

**Figure 2-5** Standard goniometer being used to measure the angle between wooden pointers mounted perpendicularly to the spine at the sacrum and thoraco-lumbar junction. (from Burdett et al., 1986)

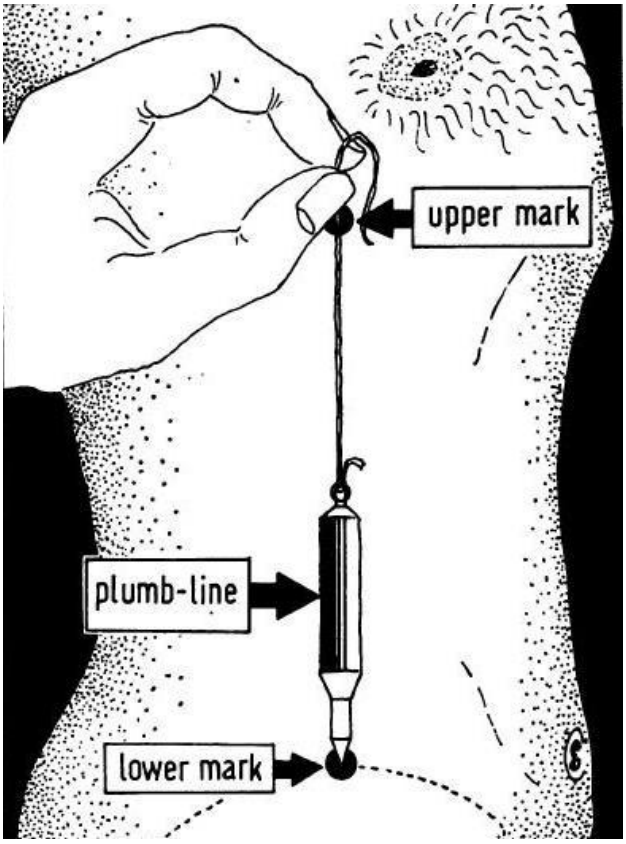


**Figure 2-6** Skin mark and plumb being used to measure the angle of thoraco-lumbar extension between the intersection of a horizontal line through the xiphisternum and the intersection of a horizontal line through the highest point on the iliac crest with the coronal line. (from Moll & Wright, 1971)

Spinal motion has also been measured during gait (Thurston et al., 1981; Thurston, 1982; Thurston & Harris, 1983). These studies used stroboscopic illumination and television cameras, interfaced to a computer, to measure the three-dimensional positions of retro reflective markers attached to the subject (Whittle, 1982). The movements of the pelvis and the lower thoracic spine were measured in a room-based coordinate system but the technique did not specifically measure the lumbar movement.

Thereafter, researchers tried to measure the movement of the lumbar spine during gait (Callaghan et al., 1999; Crosbie et al., 1997a; Taylor et al., 1999; Vogt & Banzer, 1999; Whittle & Levine, 1997, 1999). Whittle & Levine (1997) devised a way to include the measurement of lumbar movement in clinical gait analysis and compared the direct placement of markers on the lumbar spine (Figure 2-7) with the lightweight measurement rigs approach (Figure 2-8). They found that the use of skin-mounted measurement rigs, at the two ends of the lumbar curve, were sufficiently accurate and convenient for routine use in a clinical gait analysis setting (Figure 2-9), and in reliability studies showed good test retest agreement for both static and dynamic measurements of lumbar movement.

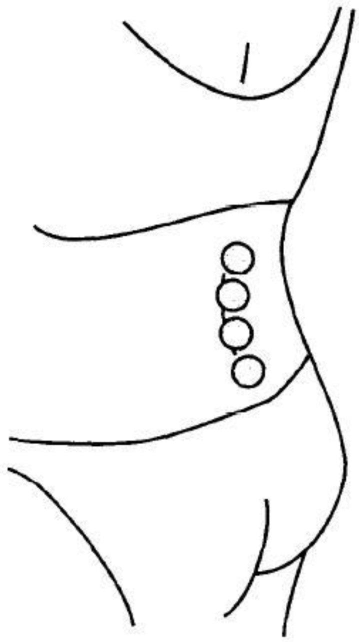

**Figure 2-7** Four-marker configuration, with 20-mm reflective markers over Ll, L3, L5 and S2 spinous processes. (from Whittle & Levine, 1997)

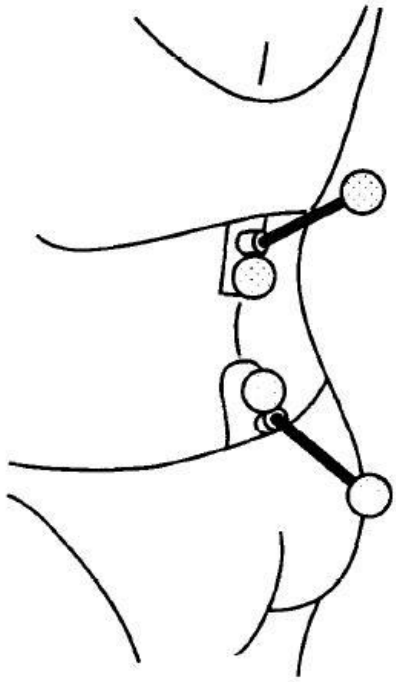

**Figure 2-8** Marker configuration using lightweight measurement rigs over thoraco-lumbar junction and upper sacrum. (from Whittle & Levine, 1997)

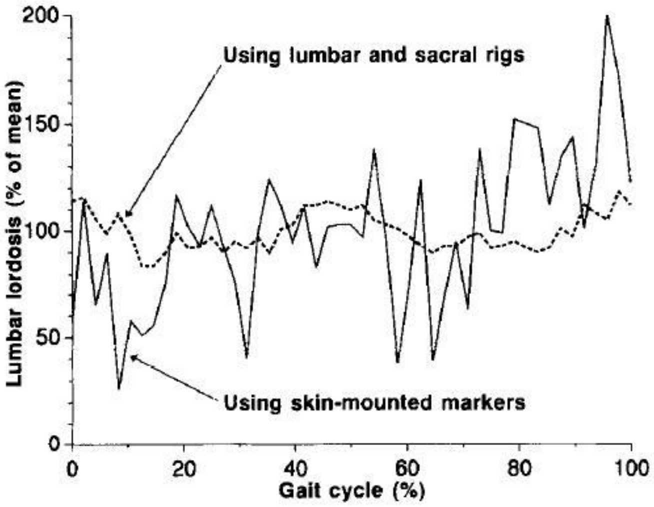


**Figure 2-9** Lordosis angle over a single gait cycle, expressed as percentage of mean value, measured using shin-mounted markers (ratio calculation) and using lumbar and sacral measurement rigs. Unsmoothed data. (from Whittle & Levine, 1997)

There are also several inconsistencies in representing the movements of the lumbar spine using measurement rigs during gait. For example, Schache et al. (2002) measured the angular kinematics of the lumbar spine during gait with only one measurement rig which was mounted over the twelfth thoracic spinous process; however, Lamoth et al. (2006a, b) fixed the measurement rig at the level of the second lumbar vertebrae. Another way, Whittle & Levine (1999) and Levine et al. (2007) defined the movement of the lumbar spine during gait as two measurement rigs attached to the skin over the sacrum and the spine at the level of the thoracolumbar junction.

The approach using measurement rig was also applied to compare healthy gait and in patients who suffered from chronic low back pain (Lamoth et al., 2006a, b), had a stroke (Wagenaar & Beek, 1992), or were pregnant (Wu et al., 2002, 2004). However, these studies seem to speculate the movement of the lumbar spine using other segments near lumbar spine or defining lumbar spine to a rigid segment.

# CHAPTER III

# EXPERIMENT

To systematically characterize the spatial and temporal coordination between the movements of the thorax, lumbar spine, and pelvis in the transverse planes during human locomotion, we experiment human treadmill gait at different constant velocities using healthy, young female adults.

## Methods

*Subjects*

Because previous studies (Crosbie et al., 1997; Lamoth et al., 2002) found no gender effect in the coordination pattern. Therefore, there was no conceptual basis for this study to examine a gender-related hypothesis. Also, using female subjects only helped to reduce the variability in the data. Nine healthy female volunteers participated in this study (Table 3-1). 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.

**Table 3-1** The mean, standard error of age (years), body height (m), body weight (kg), BMI ($kg/m^2$), and self-selected pace (m/s).

| | age | body height | body weight | BMI | self-selected pace |
|---|---|---|---|---|---|
| mean | 24.6 | 1.58 | 47.9 | 19.3 | 1.03 |
| SEM | 2.4 | 0.05 | 3.6 | 1.9 | 0.30 |

*<u>Instruments and marker set up</u>*

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 towards the negative direction of y-axis in the global coordinate system.

Figure 3-1 shows the experimental arrangements and definitions of angular positions. 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. The markers on both calcaneii and fingertips were also used for identifying events in the gait cycle

(Hreljac & Marshall, 2000). This marker set-up allowed the capturing of the thorax and the pelvis motion and heel strike and toe-off.

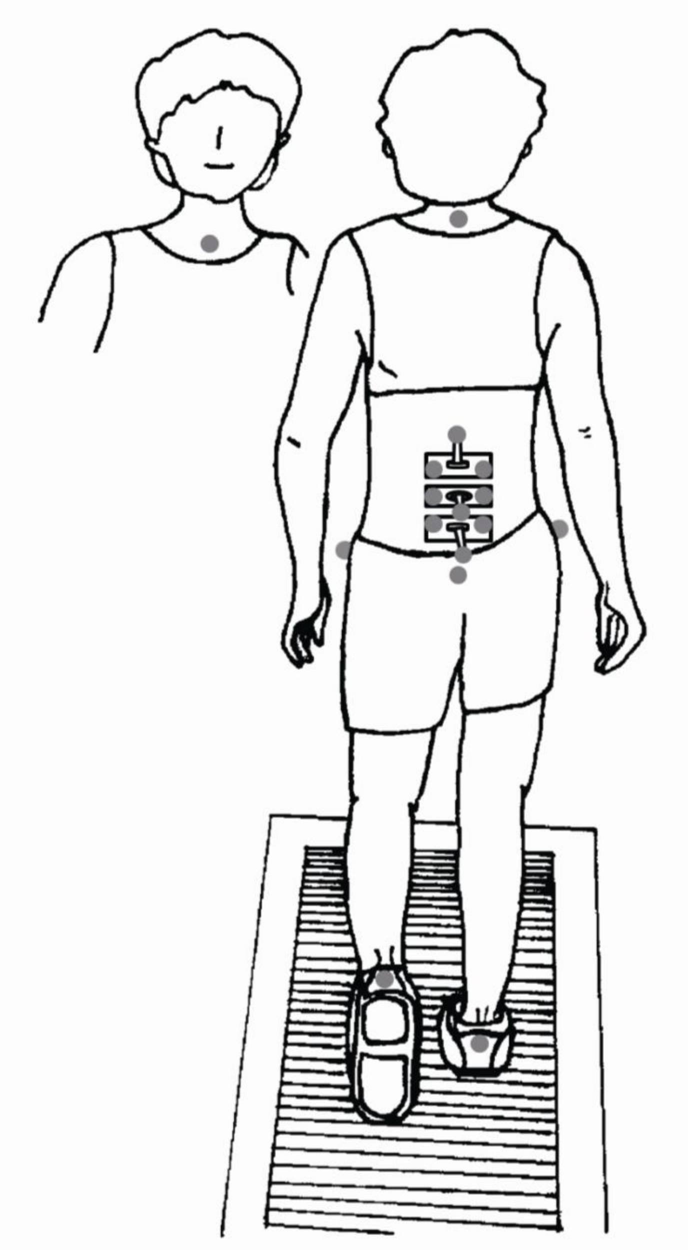

**Figure 3-1** Locations of spherical reflective markers and measurement rigs.

Three measurement rigs (Taylor et al., 1999; Whittle & Levine, 1997, 1999) were also affixed to the skin over the first (L1), the third (L3) and the fifth (L5) lumbar vertebra for capturing the axial rotation of lumbar spine. 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 to collect data for the reference position. 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 and at that time we re-checked the position of the markers and rigs. Finally, the data collection protocol at the three velocities was repeated. It took about 20 minutes to complete the entire experimental session.

*Data analysis*

Kinematic data were filtered with a fourth order Butterworth low-pass digital filter with a cutoff frequency of five 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 one (Winter, 2004).

$$\theta_{ij} = \arctan (y_j - y_i / x_j - x_i) \qquad \text{eq.1}$$

where $y_j$ and $x_j$ are the coordinate data of T1; $y_i$ and $x_i$ are the coordinate data of the sternum. The angular position of the pelvis was also calculated from equation one, where $y_j$ and $x_j$ denote the coordinate data of the S2; $y_i$ and $x_i$ denote the coordinate data of the mid-point of the both ASISs. The angular position of each lumbar segment was calculated from equation one, 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 mid-point of the two adjacent spinous processes (Figure 3-2). The positive (+) angles indicate the rotation of the right side anteriorly forwarding in a counterclockwise direction.

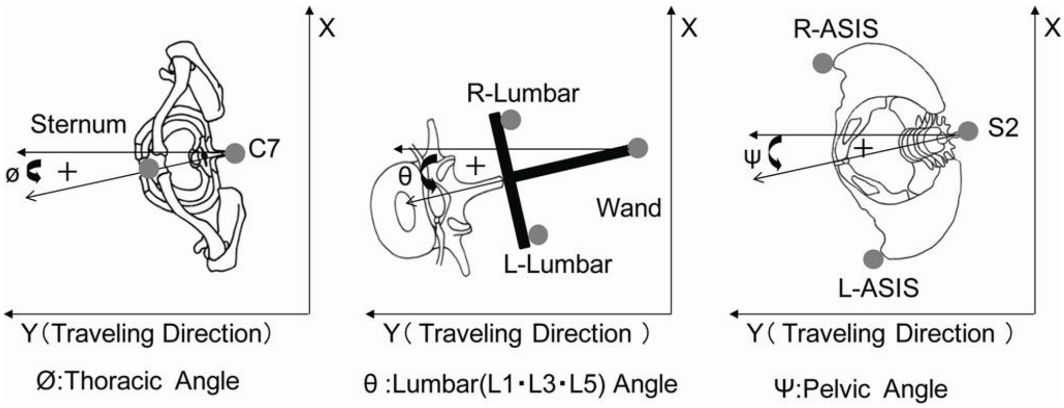


**Figure 3-2** Definitions of thoracic, lumbar, and pelvic angle.

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. Maximal twisting angle was defined as the absolute value of the difference from a segment angle to another segment angle (Figure 3-3). 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 (Bruijn et al., 2008; Lamoth et al., 2006b).

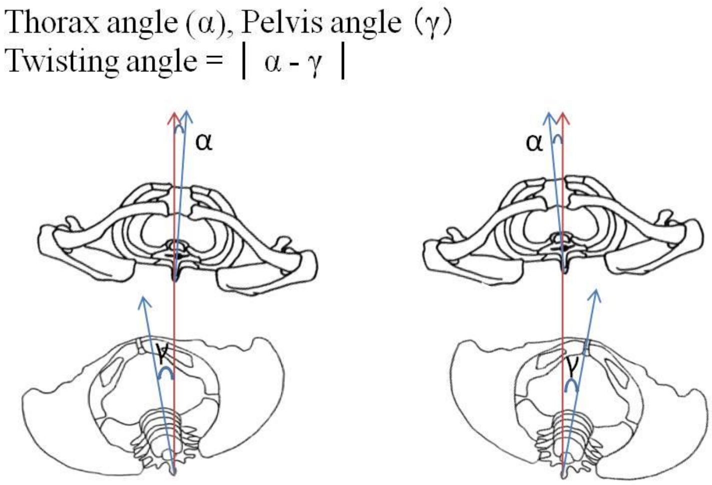


**Figure 3-3** Definitions of maximal twisting angle.

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 Mauchley's 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

Table 3-2 shows the stride characteristics during treadmill walking at three velocities. Stride length increased significantly; however, swing and stance time decreased significantly with increasing gait velocities as healthy young females walked on the treadmill.

**Table 3-2** Stride characteristics of treadmill walking at 0.40, 0.93 and 1.47 m/s.

| Variable | 0.40 m/s | 0.93 m/s | 1.47 m/s |
|---|---|---|---|
| Stride time (s) | 1.72 ± 0.07 | 1.15 ± 0.02*** | 0.95 ± 0.01***, ## |
| Stride length (m) | 0.91 ± 0.04 | 1.27 ± 0.03*** | 1.55 ± 0.02***, ### |
| Stance time (s) | 1.24 ± 0.06 | 0.75 ± 0.02*** | 0.59 ± 0.01***, ## |
| Swing time (s) | 0.48 ± 0.02 | 0.40 ± 0.01*** | 0.36 ± 0.01*** |

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.

*Rotation pattern for segments in transverse plane*

Under these conditions, we characterize the transverse plane kinematics of the thorax, lumbar spine (L1, L3, L5), and pelvis averaged for ten gait cycles during treadmill walking at three velocities in one subject (Figure 3-4).

The cycle starts at the instance of right foot strike (RFS: I) as the left foot was also on the ground towards 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).

In Figure 3-4, 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 3-2. Horizontal shaded bands indicate the stance and swing phases of the left and right leg. The vertical dotted line indicates left foot strike.

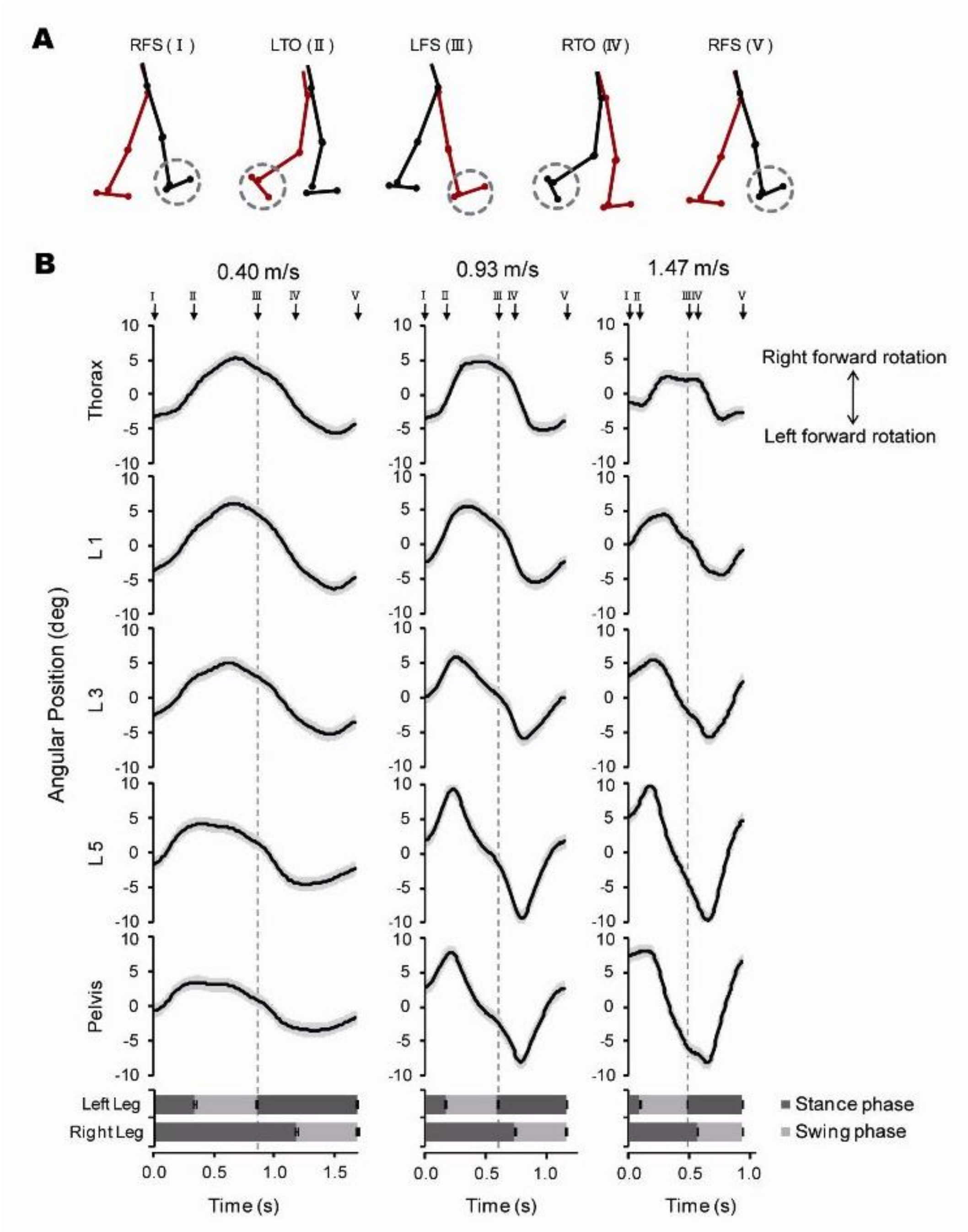


**Figure 3-4** A representative single subject example of transverse plane kinematics of the thorax, lumbar spine, and pelvis during treadmill walking.

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 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.

Figure 3-5 shows the total angular displacement (peak-to-peak deviation in Figure 3-4) at the thorax, lumbar spine (L1, L3, L5) and pelvis during gait at three velocities. Total angular displacement increased at the pelvis and decreased at the thorax as gait velocity increased. 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, $t = 0.231$, $P = 0.818$) 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 ~80% (slow = 11°, fast = 19°, $P < .001$), however, the amplitude for thorax decreased ~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.

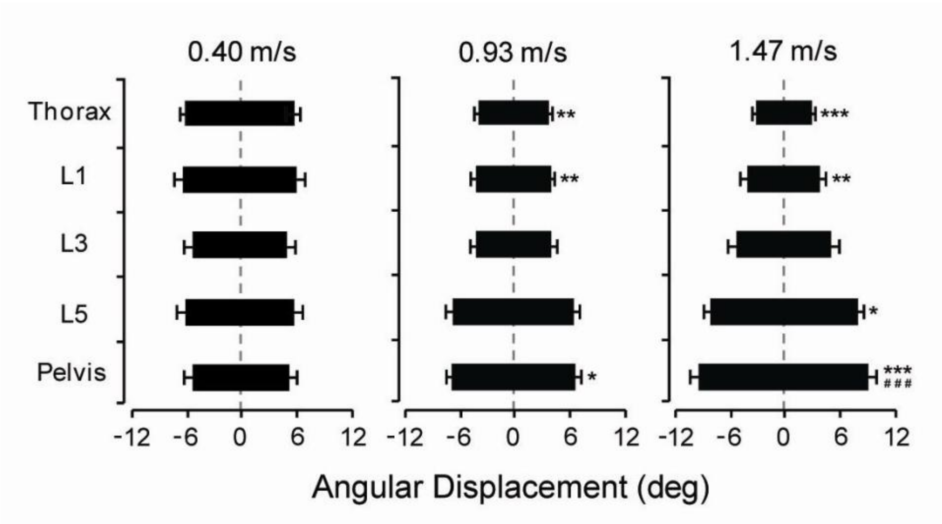


**Figure 3-5** Total angular displacement (peak-to-peak deviation in Figure 2) at the thorax, lumbar spine (L1, L3, L5) and pelvis during gait at three velocities (n = 9).

Error bars represent the standard error of the mean.

*, **, *** Significantly different between 0.40 m/s and the other two velocities (*P* < .05, .005, .001).

### Significantly different between 0.93 m/s and 1.47 m/s (*P* < .001).

Figure 3-6 shows the peak timing of pelvis, lumbar segment, and thorax and the forward shift of this timing with gait velocity. Time of reaching maximal joint position (peak timing) relative right and left foot strike at three gait velocities. Gait cycle normalized to 100% for each gait speed. Vertical dotted lines denote right and left foot strike. The peak timing progressively retarded and its forward shift with increased gait velocity. 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. Concerning the temporal coordination, the peak timing became progressively retarded and its forward shift increased with gait velocity. 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) at slow velocity during one stride cycle revolution. This trend remained as gait velocity increased. Figure 3-6 also shows that, 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.

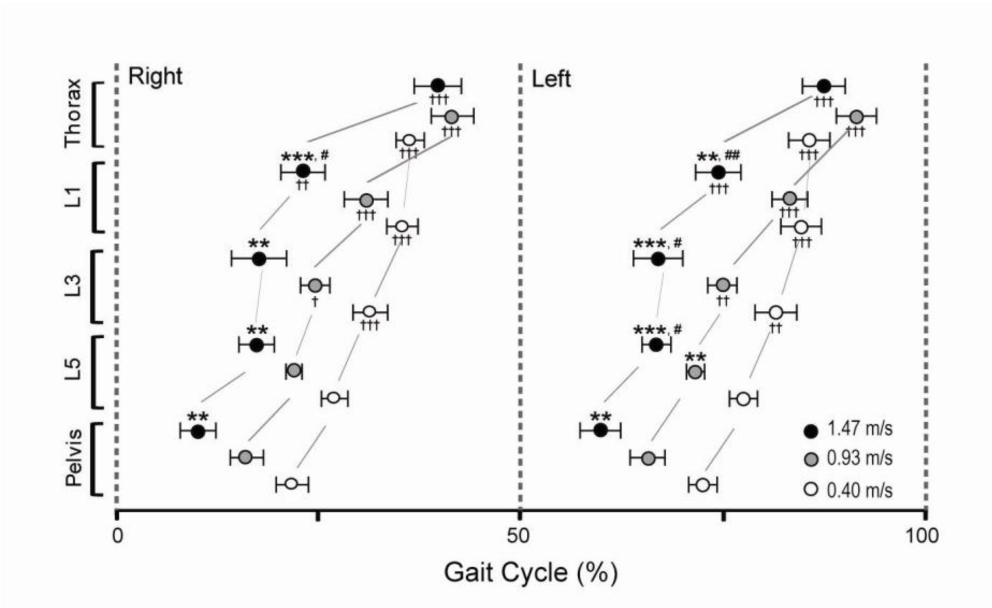


**Figure 3-6** Peak timing of pelvis, lumbar segment, and thorax and its forward shift with gait velocity (n=9).
Error bars represent the standard error of the mean.
**, *** Significantly different between 0.40 m/s and the other two velocities (*P* < .005, .001).
#, ##, ### Significantly different between 0.93 m/s and 1.47 m/s (*P* < .05, .005, .001).
†, ††, ††† Significantly different between pelvis and other segments (*P* < .05, .005, .001).

*Coordination between pairs of segments*

We express the coordination between pairs of segments using angle-angle plots (Figure 3-7), the duration of in-phase and out-of-phase (Figure 3-8), and maximal twisting angle (Figure 3-9).

Figure 3-7 shows the relationship between the angular motion of the thorax and L1, the thorax and pelvis, and L5 and pelvis at three gait velocities. 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 3-9) between segments. Each dotted line on the X and Y axes indicates neutral position (0 deg). This angle-angle plots show, for example, that during slow gait (Figure 3-7-a), thorax and L1 moved in the same direction and was temporally linked, suggesting a large percentage of in-phase coordination (Figure 3-8). The amount of in-phase coordination decreased with increasing gait velocity ($P < .05$). Motion of the thorax and pelvis (Figure 3-7-d, e, f) revealed a different pattern compared with the coordination between thorax and L1.

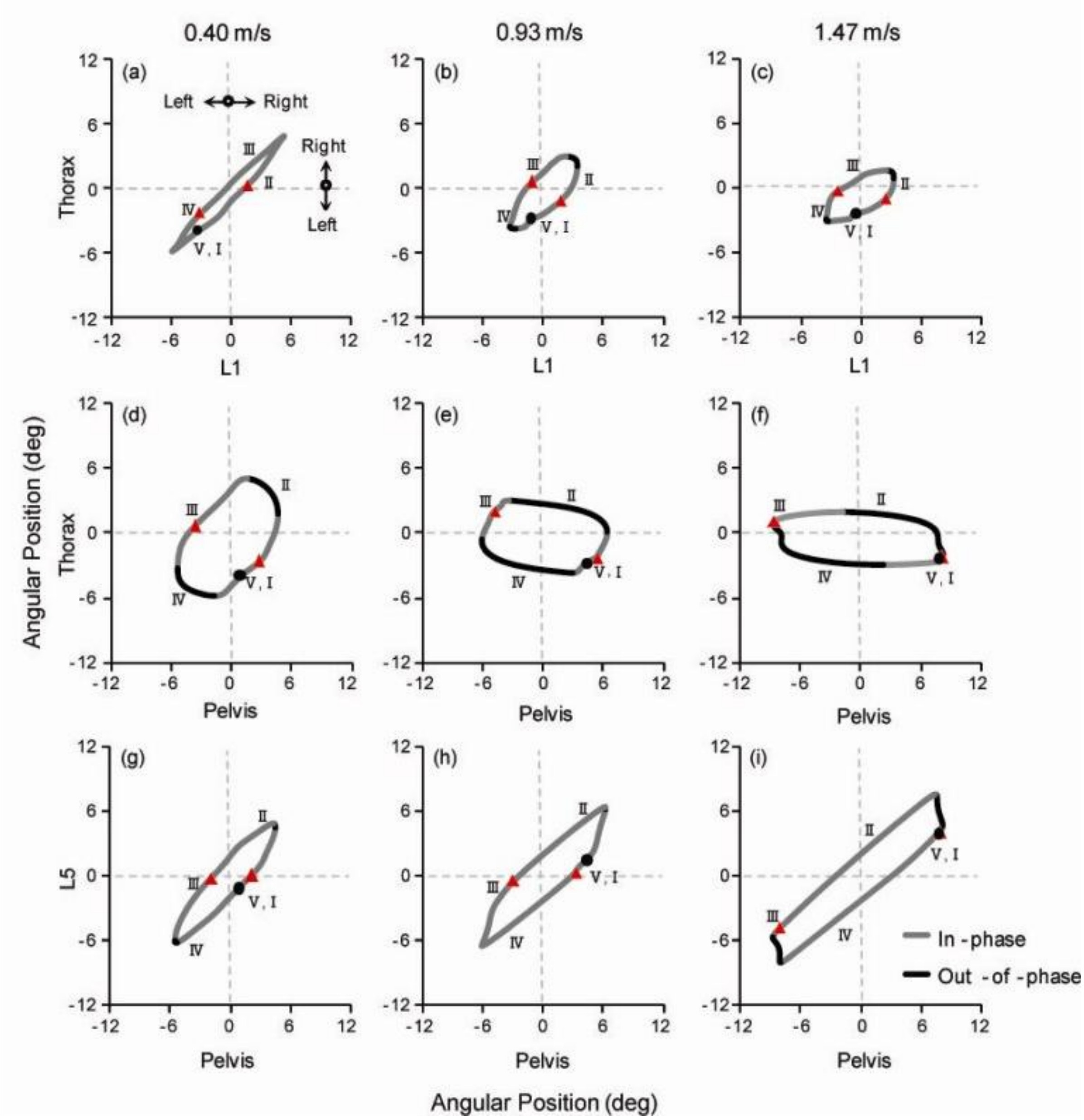


**Figure 3-7** Angle-angle plots at three gait velocities.

Figure 3-8 shows the percentage 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 during gait cycle. 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 gaits. 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.

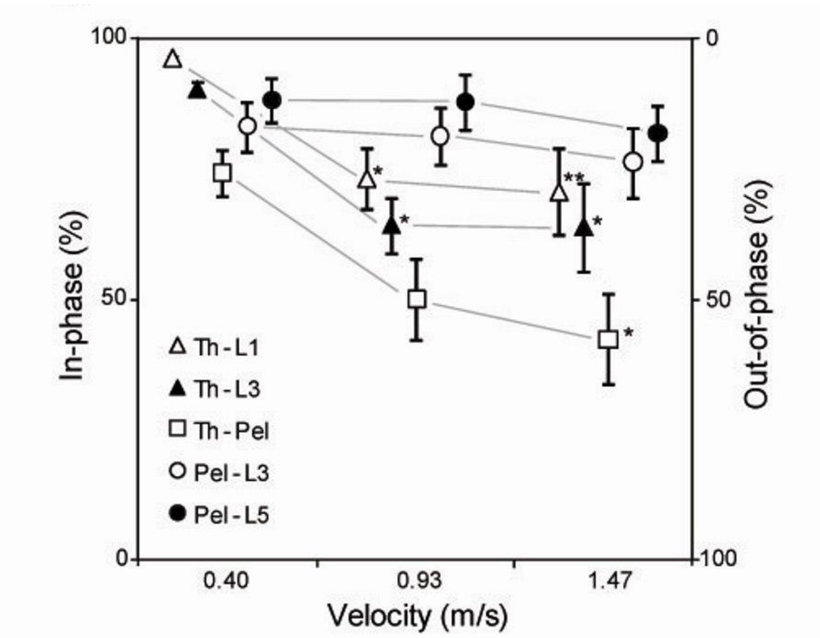


**Figure 3-8** The duration of in-phase and out-of-phase at three gait velocities (n=9).
Error bars represent the standard error of the mean.
*, ** Significantly different between 0.40 m/s and the other two velocities ($P < .05, .005$).

Figure 3-7 also indicates the timing of the maximal twisting angle (the point of maximal torsion state) between the specific segments, with Figure 3-9 showing the data for maximal twisting angle. This twisting aspect between the segments occurred during in-phase coordination between any two segments (see symbol of red triangle in Figure 3-7). 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.

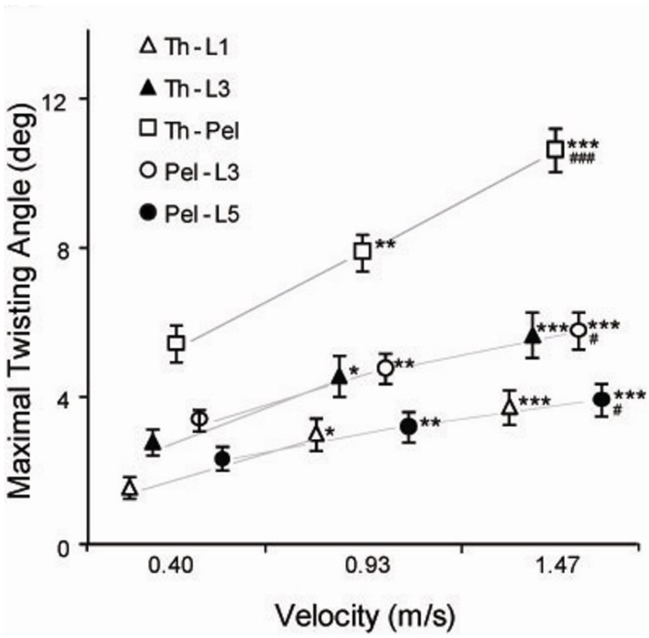


**Figure 3-9** Maximal twisting angle at three gait velocities (n=9).
Error bars represent the standard error of the mean.
*, **, *** Significantly different between 0.40 m/s and the other two velocities (*P* < .05, .005, .001).
#, ### Significantly different between 0.93 and 1.47 m/s (*P* < .05, .001).

# CHAPTER IV

# GENERAL DISCUSSION

The purpose of this dissertation was to systematically characterize the spatial and temporal coordination between the movements of the thorax, lumbar spine, and pelvis in the transverse planes during human treadmill gait at three constant 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 (Bruijn et al., 2008; Huang et al., 2010; Lamoth et al., 2002; Stoker et al., 1989; van Emmerik & Wagenaar, 1996). 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 increase 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 3-6). These results suggest that the body motion propagates from lowest to the highest segment, reaching the upper extremities last during gait (Crosbie et al., 1997a). A key finding was that the pelvis range of motion increased with gait speed. These data seem to suggest that the large pelvis motion facilitates stride length and ultimately is a moderator of gait speed (Kubo et al., 2006; Lamoth et al., 2006; Stokes et al., 1989). These data seem to suggest that the large pelvis motion facilitates stride length and ultimately is a moderator of 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 3-6).

Previous studies used Fourier analysis to examine the coordination between the movements of pelvis and thorax, and pelvis and lumbar spine during gait (Bruijn et al., 2008; Huang et al., 2010; Lamoth et al., 2002, 2006a; Sharpe et al., 2008; Wu et al., 2002, 2004). 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 3-6), angle-angle plots (Figure 3-7), the duration of in-phase and out-of-phase (Figure 3-8), and maximal twisting angle (Figure 3-9) as gait velocity increased. Previous studies also used phase shift in the EMG patterns to evaluate motor control of human lower extremities during gait (Feldman et al., 2011) and cycling (Suzuki et al., 1982), to characterize the synchronization of motor responses to a stimulus sequence (Mates, 1994), to assess the rhythmic coordination of finger tapping responses to auditory stimuli (Repp, 2001, 2005), and to quantify synchronization between stepping responses to metronome beat in hemiparetic gait (Pelton et al., 2010; Roerdink et al., 2011). 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.

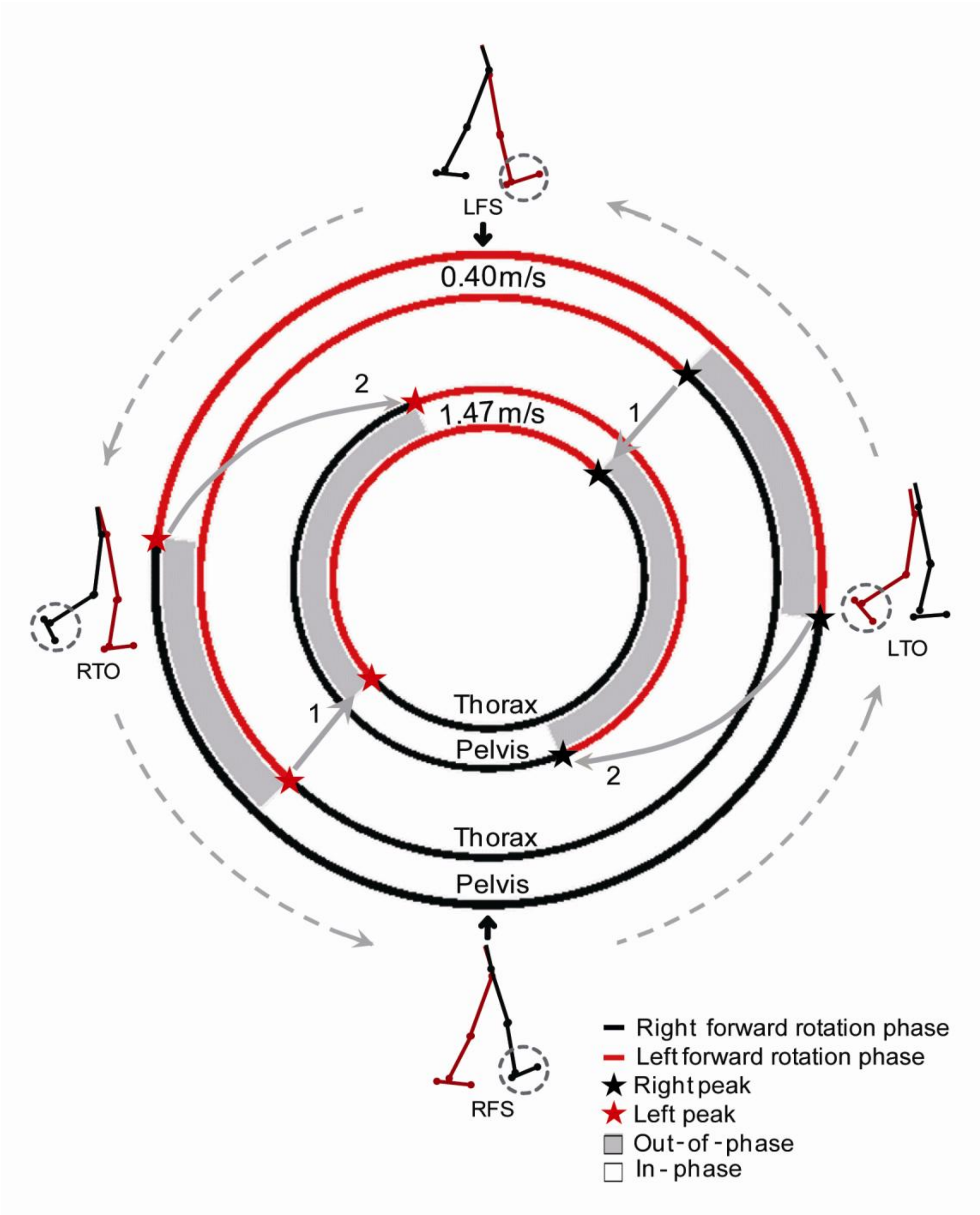


**Figure 4-1** Summary of segmental coordination between the thorax and pelvis during gait.

Figure 4-1 summarizes the coordination between pelvis and thorax movements. Concentric circles indicate the coordination pattern at 0.40 m/s (outer segments) and

1.47 m/s (inner segments). Stick figures show the phases of the gait cycle starting at the bottom center with right foot strike (RFS), left toe off (LTO), left foot strike (LFS), and right toe off (RTO) in a counterclockwise direction. Black arcs indicate rotation to the right and a black star indicates reversal point from right to left rotation. Red arcs indicate rotation to the left and red star indicates the reversal point from left to right rotation. Unfilled white bands indicate periods of in-phase and gray shaded bands indicate periods of out-of-phase coordination between thorax and pelvis. Specifically it shows a key finding that the pelvis and the thorax become out-of-phase with each other as gait velocity increases. Figure 4-1 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 relative constant across gait speed for the thorax and this consistent pattern suggests a phase dependency in relation to the upper and not the lower extremities, contributing to a balanced gait.

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 (Kubo et al., 2006).

# CHAPTER V

# CLINICAL CONTEXT

Placing the present dissertation 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 pain (LBP) (Lamoth et al., 2006; Wu et al., 2002). 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.

# CHAPTER VI

# CONCLUSION

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.

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