To the Graduate Council:

I am submitting herewith a dissertation written by David F. Levine entitled "Dynamic Relationships Between Lumbar Lordosis, Pelvic Tilt, and Abdominal Muscle Performance." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Education.

Wendell Liemohn, Major Professor

We have read this dissertation
and recommend its acceptance:

Accepted for the Council:

Associate Vice Chancellor and
Dean of the Graduate School

DYNAMIC RELATIONSHIPS BETWEEN LUMBAR LORDOSIS, PELVIC TILT, AND ABDOMINAL MUSCLE PERFORMANCE

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

David F. Levine

August 1994

DEDICATION

This dissertation is dedicated to my parents who have always encouraged and supported me, and deserve endless appreciation.

I am also blessed to have so many truly exceptional friends. It would take years to list them and their influences on my life, but I thank them all for sharing their lives with me.

ACKNOWLEDGMENTS

I would like to thank my major professor, Dr. Wendell Liemohn for his friendship and guidance throughout the past four years. I would also like to thank my other committee members, Dr. Schyler Huck, Dr. Craig Wrisberg, Dr. Dale Goodfellow, and Dr. Maureen Groer for their assistance and suggestions. I also would like to thank Dr. Michael Whittle for his encouragement and willingness to assist in my research career. In addition, I greatly appreciate the assistance given to me by Karen Hood in data collection, and by Dr. Michael Biderman in my statistical analysis. I am indebted to my colleagues at UTC who have supported and encouraged me for the past four years. I am especially grateful to Dr. Randy Walker and Dr. Larry Tillman for creative input. I would also like to acknowledge Martha Walker of Old Dominion University, and Dr. Marilyn Gossman of the University of Alabama for their input and recommendations. This project was also supported in part by a grant from the Foundation for Physical Therapy, Inc.

ABSTRACT

Pelvic tilt, lumbar lordosis, and abdominal strength are variables frequently assessed in relationship to low back pain. Treatment aimed at reducing the degree of anterior pelvic tilt and concurrently reducing the depth of lumbar lordosis is often prescribed in an attempt to treat the pain and dysfunction. Existing clinical literature suggests that weakened abdominal musculature is a major contributor to excessive anterior pelvic tilt and increased lumbar lordosis. Despite the theoretical reasons for believing this relationship, there has been to date no research confirmation of this hypothesis. The purpose of this study was to examine both statically and dynamically the relationships between abdominal muscle performance, pelvic tilt, and lumbar lordosis.

Measurements of abdominal muscle performance, pelvic tilt, and lumbar lordosis were obtained on 28 healthy female subjects aged 20-32. Abdominal muscle performance was measured using the double leg lowering test. Lumbar lordosis and pelvic tilt were measured using a television/computer system that obtained three-dimensional kinematic data at 20ms intervals. All measures were taken three or more times and were shown to be reliable ($p < .001$).

Twenty subjects also assumed maximal anterior and posterior pelvic tilt postures to determine the effects on lumbar lordosis. Assuming a maximal anterior pelvic tilt posture changed the pelvic attitude by an average of 11.3° and increased the depth of lumbar lordosis by an average of 11.1° ($p < .001$). Assuming a maximal posterior pelvic tilt posture changed the pelvic attitude by an average of 8.8° and decreased the depth of lumbar lordosis by an average of 8.1° ($p < .001$).

Correlations between abdominal muscle performance and pelvic tilt, and between abdominal muscle performance and lumbar lordosis, were not significant, either statically or during gait ($p > .05$). The results indicated that abdominal muscle performance did not appear to be directly related to either pelvic tilt or lumbar lordosis, measured either statically or dynamically. The results of this study indicate a need to reconsider clinical decision-making based on the assumed relationships between these variables.

TABLE OF CONTENTS

CHAPTER PAGE

I. INTRODUCTION....1
A. Statement of the Problem....1
B. Hypothesis....2

II. REVIEW OF THE LITERATURE....4

III. METHODOLOGY....11
A. Subjects....11
B. Instrumentation....11
C. Design and Procedure
1. Measurement of Pelvic Tilt....14
2. Measurement of Lumbar Lordosis....14
3. Measurement of Abdominal Muscle Performance....19

IV. RESULTS....21
A. Reliability of Pelvic Tilt 22
B. Reliability of Lumbar Lordosis 23
C. Reliability of Abdominal Muscle Performance....24
D. Reliability of Pelvic Tilt and Lumbar Lordosis During Gait....25
E. Effect of Pelvic Tilt on Lumbar Lordosis..26
F. Relationships between Static and Dynamic Measures of Pelvic Tilt and Lumbar Lordosis....27
G. Relationships between Abdominal Muscle Performance, Pelvic Tilt, and Lumbar Lordosis....28

V. DISCUSSION....30
A. Reliability of Pelvic Tilt, Lumbar Lordosis, and Abdominal Muscle Performance....30
B. Effect of Pelvic Tilt on Lumbar Lordosis..30
C. Relationships between Static and Dynamic Measures of Pelvic Tilt and Lumbar Lordosis....31
D. Relationships between Abdominal Muscle Performance, Pelvic Tilt, and Lumbar Lordosis....32
E. Limitations....35
F. Future Recommendations....36

VI. CONCLUSIONS.....38

LIST OF REFERENCES.....39

APPENDIXES.....48
A. Tables.....49
B. Figures.....61
C. Supplementary Materials.....68
1. Measurement of Lumbar Lordosis While Performing Clinical Gait Analysis.....69
2. Patient Data Form.....73
3. Data Processing Instructions.....74
4. Raw Data from Excel.....76

VITA.....94

LIST OF TABLES

TABLE PAGE

1. Physical Characteristics of Subjects.....50

2. Static (Standing) Test-Retest Reliability of Pelvic Tilt, Lumbar Lordosis, and Abdominal Muscle Performance.....51

3. Dynamic (Gait) Test-Retest Reliability of Pelvic Tilt.....52

4. Dynamic (Gait) Test-Retest Reliability of Lumbar Lordosis.....53

5. Effect of Pelvic Tilt on Lumbar Lordosis.....54

6. Correlation between Variables (Static condition).....55

7. Static Pelvic Tilt vs. Dynamic Pelvic Tilt.....56

8. Static Lumbar Lordosis vs. Dynamic Lumbar Lordosis.....57

9. Lumbar Lordosis vs. Pelvic Tilt (Dynamic Condition).....58

10. Correlation (Pearson) between Abdominal Muscle Performance and Pelvic Tilt and Lumbar Lordosis (Dynamic condition).....59

11. Correlation (Spearman) between Abdominal Muscle Performance and Pelvic Tilt and Lumbar Lordosis (Dynamic condition).....60

LIST OF FIGURES

FIGURE PAGE

1. Schematic diagram of pelvic tilt, and formula for calculation of degree of pelvic tilt.....62

2. Schematic diagram of lumbar lordosis.....63

3. Cameras and force platforms.....64

4. Lumbar Rigs in Place on Subject.....65

5. Measurement of the Angle of Lumbar Lordosis.....66

6. Starting Position for Testing Abdominal Muscle Performance.....67

CHAPTER I

INTRODUCTION

A. Statement of the Problem

Low back pain is one of the most common musculoskeletal disorders in the United States (Kelsy & White, 1980). In western countries, 80% of the population can expect to suffer from low back pain at some time during their lives (Kelsey & White, 1979; Nachemson, 1979). Health care professionals involved in the evaluation and treatment of patients with low back pain are cognizant of a multitude of variables which may be found and implicated as a possible source of pain (Magee, 1987; Donatelli & Wooden, 1989; Gould, 1990). One of the variables commonly assessed is the biomechanical factors that may be causing excessive strain in the affected area. Many authors have speculated that low back pain may occur as a result of excessive stresses at the lumbar spine and sacroiliac joints due to an exaggerated anterior pelvic tilt posture (Denslow & Chace, 1962; Thomas, 1965; Polster et al., 1974; Kendall et al., 1977; Calliet, 1981; Kisner & Colby, 1990). One author has speculated that increased lumbar lordosis may be the cause in up to 75% of low back pain patients (Calliet, 1981). The degree of pelvic tilt and lumbar lordosis present in standing, and

during gait, are frequently assessed in relationship to low back pain. Treatment based on decreasing the anterior pelvic tilt and concurrently reducing the depth of lumbar lordosis is often prescribed in an attempt to treat the pain and dysfunction (Kendall et al., 1977; Calliet, 1981; Kendall & McCreary, 1983; Kisner & Colby, 1990).

The purpose of the proposed study was to validate that in a static standing posture, increasing the degree of anterior pelvic tilt will increase the angle of lumbar lordosis, and increasing the degree of posterior pelvic tilt will decrease the angle of lumbar lordosis. This study also was designed to examine the relationships between abdominal muscle performance (strength), pelvic tilt, and lumbar lordosis, both statically, and dynamically.

B. Hypothesis

It was predicted that in a standing posture, increasing the degree of anterior pelvic tilt would increase the angle of lumbar lordosis, and increasing the degree of posterior pelvic tilt would decrease the angle of lumbar lordosis. It was also predicted that a relationship between abdominal muscle performance, and the degree of pelvic tilt and lumbar lordosis would not be found, either statically, or dynamically.

The significance of the study is that clinicians involved in the care of patients with low back pain and dysfunction often prescribe strengthening exercises for the abdominal musculature, in an attempt to change the posture of the patients pelvis and lumbar lordosis. Clinical decision-making based on the assumed relationships between these variables may change as a result of this study, if no relationship is found to exist.

CHAPTER II

REVIEW OF THE LITERATURE

Pelvic tilt is defined as the angle between the horizontal and a plane passing through the posterior superior iliac spines (PSIS) and anterior superior iliac spines (ASIS) (Figure 1)[1] (Norkin & Levangie, 1992). Lumbar lordosis is defined as the curve assumed by the lumbar spine, where the lumbar spine forms an anterior convexity (Figure 2) (Bogduk & Twomey, 1991). The degree of lumbar lordosis is variable between individuals, and is the result of many factors. The shape of the L5 vertebrae is like a wedge, where the anterior aspect of the vertebral body is approximately 3 mm thicker than the posterior aspect (Gilad & Nissan, 1985). The intervertebral discs in the lumbar area are also wedge shaped, especially at the L4-L5 and L5-S1 segments. The intervertebral disc at the L5-S1 interspace has been measured to be 6-7 mm less in height posteriorly than anteriorly (Smorl & Junghanns, 1972). The vertebrae above L5 are less wedge shaped, but due to the shape of the L5-S1 vertebral levels, the vertebrae above this level continue to lie in an alignment slightly backward to the vertebrae above. These factors contribute to producing the normal lumbar lordosis.

---

[1]All figures and tables are contained within the appendix.

Various methods of measuring the degree or angle of lumbar lordosis have been used in an attempt to quantify the curve. Goniometry, radiography, skin markers over the spinous processes, and use of flexible rulers have all been utilized (Troup et al., 1963; American Academy of Orthopaedic Surgeons, 1965; Moll & Wright, 1971; Hansson, et al., 1985; Burdett, et al., 1986; Hart & Rose, 1986; Pearcy, 1986; Lovell, et al., 1989).

The effects of voluntarily altering pelvic tilt on lumbar lordosis have been examined (Day, et al., 1984). In this study, subjects assumed three postures, a normal standing posture, a maximal anterior pelvic tilt posture, and a maximal posterior pelvic tilt posture. The maximal anterior pelvic tilt posture significantly increased the depth of lumbar lordosis ($p<.05$). Likewise, assuming a full posterior pelvic tilt posture decreased the degree of lumbar lordosis ($p<.05$). Although these relationships are generally assumed in the clinical and research communities, this study represents the only empirical evidence for these relationships.

The abdominal muscles (rectus abdominus, external oblique, internal oblique, and transversus abdominus) function to flex the trunk by drawing their attachments together (Warwick, et al., 1989). The abdominal muscles have

insertions on the pubic crests, pubic symphysis, pubic tubercles, and the anterior aspect of the iliac crest. Due to the anatomical locations of the abdominal muscles attachments on the pelvis, contraction of the abdominal muscles brings the pelvis into a posteriorly rotated position (posterior pelvic tilt) when the trunk is stabilized (Kendall et al., 1977; Calliet, 1981; Kendall & McCreary, 1983; Warwick, et al., 1989).

Existing clinical literature suggests that weakened abdominal musculature is a major contributor to excessive anterior pelvic tilt and an increased lumbar lordosis (Pheasant, 1962; Rowe, 1963; Alston, et al., 1966; Kendall et al., 1977; White & Panjabi, 1978; Calliet, 1981; Kendall & McCreary, 1983; Kisner & Colby, 1990). The rationale behind this theory is that if the abdominal muscles are weak, they become elongated and allow the pelvis to deviate from optimal normal alignment into a position of excessive anterior pelvic tilt, thereby increasing the angle of lumbar lordosis. As a result, strengthening of the abdominal musculature is a common clinical approach for correcting excessive anterior pelvic tilt and excessive lumbar lordosis. One popular theory is that persistent elongation of a muscle, due to postural deviation, may result in stretch-weakness. Stretch-weakness is defined as the weakness found in muscles which remain in an elongated

condition beyond the neutral physiological rest position, but not beyond the normal range of muscle length (Kendall, et al., 1977). They further state that the abdominal muscles are among the most common muscles affected by stretch-weakness. Based on this theory, physical therapists commonly assume that individuals with an exaggerated lumbar lordosis and an anteriorly tilted pelvis have weak abdominal muscles. As a result, these individuals are placed on abdominal strengthening exercise programs to correct the postural deviations.

There have been several previously published reports on the relationships between lumbar lordosis, pelvic tilt and abdominal muscle performance. These studies have failed to find significant relationships between these variables.

Walker et al. (1987) examined the relationships between lumbar lordosis, pelvic tilt, and abdominal strength. The correlation between abdominal muscle strength and pelvic tilt was .18, and with lumbar lordosis it was .06. The correlation between pelvic tilt and lumbar lordosis was .32. In a similar study, the relationships between lumbar lordosis, pelvic tilt, and hamstring and hip flexor muscle length were examined. These investigators found no relationship between low back or pelvic posture and hamstring or hip flexor length, or between pelvic tilt and

lumbar lordosis (Beninato, et al., 1993). In a third related study the interrelationship between spinal curves, pelvic tilt, and abdominal muscle length was examined. A correlation of .21 was found between abdominal muscle length and lumbar lordosis, and no index of muscle length was significantly related to pelvic tilt (Toppenberg & Bullock, 1986). A further study in this area examined the relationship between hip extension range of motion and postural alignment. The correlations between hip extension range of motion and pelvic tilt, lumbar lordosis, and abdominal muscle performance were -.04, -.09, and .09 respectively (Heino, et al., 1990). Suzuki and Endo (1983) investigated the relationship between trunk muscle strength and lumbar lordosis in 56 patients with low back pain. They found correlations of -.06 and .11 between lumbar lordosis and trunk flexion and extension strength, respectively.

In a related study, subjects with established abdominal weakness underwent an eight-week strengthening program to determine its effect on pelvic tilt and lumbar lordosis (Levine, et al., 1994). In one component of this project the variables were correlated with each other and correlations between abdominal muscle performance, and pelvic tilt and lumbar lordosis were -.12 and .19, respectively. Pelvic tilt and lumbar lordosis were significantly related ($r = .53$, ($p<.01$)). In the chief

component of this study, 20 subjects underwent an 8-week abdominal strengthening program, and 20 control subjects were used for comparison. In the analysis of covariance, the mean adjusted from pre-test values post-test muscle strength score of the experimental group was found to be significantly greater than that of the control group ($p<.01$). However, there was no significant difference in mean adjusted post-test pelvic tilt scores ($p<.17$), and only a moderate difference in adjusted lumbar lordosis scores ($p<.06$) between the groups.

All of the studies discussed have failed to confirm any clear relationship between the level of abdominal muscle strength and the resting positions of pelvic tilt and the angle of lumbar lordosis. Pelvic tilt and lumbar lordosis have been shown to be mildly positively correlated. One possible reason for this is the direct bony relationship between the pelvis and lumbar spine; as the pelvis moves in the sagittal plane, the lumbar spine must move with it. The relationships between abdominal muscle strength, and pelvic tilt and lumbar lordosis are not as clearly linked anatomically.

One limitation in these studies has been that the measurements of pelvic tilt, lumbar lordosis, and muscle length were all taken statically. Subjects in all of the

above-mentioned studies were positioned either standing against a stabilization board or stabilized in a supine position. The lack of significant correlation between any of these variables, especially pelvic tilt, lumbar lordosis, and abdominal strength, may be due to the fact that the relationships between these variables are dynamic in nature. In all of the aforementioned studies cited, the variables were measured in an artificial and static environment. It is possible that dynamic analysis of these variables during gait may reveal a more accurate portrayal of their relationship.

CHAPTER III

METHODOLOGY

A. Subjects

Twenty-eight female subjects with a mean age of 23.4 (range 20-32) years participated in this study (Table 1). Subjects were volunteers who met the following inclusion criteria: 1) no current low back pain or past history of low back dysfunction, 2) no known lower extremity dysfunction, and 3) palpable bony landmarks on the pelvis and lumbar spine. Each subject was required to sign an informed consent form after the methods of the study had been verbally explained in easily understood terminology.

B. Instrumentation

The Vicon System

The Vicon system is one of the most accurate and convenient systems for the measurement of human movement currently available. It was originally developed in a university environment, but has since become a commercial product (Whittle, 1982). In the Vicon system, reflective targets are fixed to the skin of the experimental subject in known

anatomical positions on the spine, pelvis, and lower limbs, using self-sticking adhesive tape. The system uses five infrared-sensing television cameras, fixed at a frequency of 50 hertz, interfaced to a DEC MicroVax minicomputer, to detect the positions of these targets. The latter are illuminated by infrared irradiation which show up as bright spots in the fields of view of the cameras (Figure 3).

A calibration program combines the two-dimensional information from the separate cameras into three-dimensional measurements. The positions of the reflective targets are measured every 20ms, using cameras with a resolution of 512 pixels (horizontal) by 256 lines (vertical). With a typical field of view of 3m x 2m, the precision with which the marker centers can be located could be expected to be of the order of 6mm x 8mm. By having markers large enough to cross several television scan lines, and by fitting a circle to the outline of the markers, the resolution is improved to about 2mm x 3mm. The angular spacing of the cameras around the room enables the third dimension (depth) to be measured with approximately the same accuracy as the width dimension, giving an overall three-dimensional system accuracy of 2-3mm (Kabada, 1987). Measurement errors cause the apparent positions of the markers to vary from one instant to the next, with corresponding variations in the angle of the line joining the markers. The amount by which this angle varies

depends on its length, which in turn depends on the distance between the markers. Thus, closely-spaced markers result in a high degree of "measurement noise." To improve the accuracy of the angular measurements, two methods were utilized: increasing marker spacing, and data smoothing.

Previous studies using the Vicon system have shown that it is possible to measure accurately at 20 ms intervals, both pelvic and spinal attitude and motion during walking (Thurston, et al., 1981; Thurston, 1982; Pearcy, et al., 1987). Reliability of the Vicon system had been previously established for the measurement of the pelvis in all planes (Thurston, 1982; Kabada, 1989), but had not been established for lumbar lordosis.

The Vicon system used in this study is located in the H. Carey Hamlin Gait Analysis Laboratory of the Siskin Hospital for Physical Rehabilitation, Chattanooga, Tennessee. The director of the laboratory is Michael Whittle, M.D., Ph.D., who has worked in the field of three-dimensional biological measurement for the past 20 years. He was Director of the Gait Laboratory of the Orthopaedic Engineering Centre at the University of Oxford, England, from 1978-1989. Dr. Whittle was directly involved in the data collection during this study.

C. Design and Procedure

1. Measurement of Pelvic Tilt

The angle of the pelvis in the room-based coordinate system was determined using one marker on the ASIS on each side, and one on the sacrum at the second sacral spinous process (S2). This triangle is large enough that three-dimensional measurement errors do not affect the angular measurements. Pelvic tilt is measured as the angle between the horizontal and a line joining the sacral marker (which is at the level of the PSIS's) to the midpoint between the two ASIS's. Pelvic motion in the sagittal (pitch), coronal (roll) and transverse (yaw) planes were determined from the relative positions of these three targets.

2. Measurement of Lumbar Lordosis

Several methods of measuring the angle of lumbar lordosis were devised and tested. The initial methods involved direct application of reflective markers to the subject's back. These methods yielded an unsuitable degree of measurement error and the method described below was then devised (Whittle & Levine, 1994) (Appendix C-1).

The angle of lumbar lordosis was determined using two measurement rigs, each of which consists of a flat plate which is firmly fixed (using double-sided adhesive tape) to

the skin over the sacrum or the upper lumbar spine (Figure 4). These rigs are of small enough size, and are made of a lightweight metal (aluminum), so that they will not affect the subject's normal gait. Each rig has one marker directly on the flat plate and one on the end of a light metal rod; the separation between the center of the two markers is approximately 117mm. The marker on the plate is positioned over the spinous process of the first lumbar vertebra for the upper plate, and over the second sacral spinous process for the lower plate; the rod on the upper rig points backwards and upwards, and the rod on the lower rig points backwards and downwards. The angle between the surface of the rig and the line joining the two markers is determined by a static trial, in which the two rigs are placed on the ground, with the skin-contact surface horizontal, and data are acquired to measure the relative positions of the two markers on each rig. The angle between the skin surface in the lumbar and sacral regions is determined from the positions of the two markers on the rig, and the known angle between the two markers and the flat surface of the measurement rig. The angles between the skin surface and the vertical in the two regions are subtracted; thus giving a "lordosis angle" (Figure 5). If there were no angle between the skin surfaces in the two regions, the lordosis angle would be zero.

Reflective markers were also located bilaterally on the lower extremities as prescribed by the manufacturers of the Vicon system, in the following locations: mid-thigh, over the lateral axis of the knee joint, mid-tibia, over the ankle joint axis, on the heels, and at the base of the second metatarsal. These markers, though not needed for acquisition of data related to pelvic tilt and lumbar lordosis, are needed for identification of events in the gait cycle, so that pelvic tilt and lumbar lordosis may be studied at identifiable events in the gait cycle such as heelstrike. Care was taken to place targets over bony landmarks, where it is possible to locate them accurately in relation to the underlying bone, and where skin movement is likely to be minimal.

Each subject in this study was required to dress in shorts or swimwear, that sufficiently exposed the areas of skin where targets were located. A number of anthropometric measurements that are required by the systems software were obtained. These included 1) leg length as measured from the ASIS of the pelvis to the medial malleolus in the supine position; 2) knee width as measured at the level of the medial and lateral epicondyles of the femur; and 3) ankle width as measured at the level of the medial and lateral malleoli of the tibia and fibula, respectively. Leg length was measured using a flexible metal tape measure; knee and

ankle width were measured using calipers. The subject's height and weight were also recorded (Appendix C-2).

While each subject was being prepared for testing, the measurement system was tested, and calibrated. Four rods with five reflective markers each, located in known positions, were hung from the ceiling; these were used to calibrate the five cameras. The calibration software ensures accuracy by providing an estimate of system measurement error.

Once the lumbar rigs and all of the skin markers were fixed to the subject, three standing trials were performed to determine the pelvic tilt and lordosis angle in the standing position, and to determine reliability of the measurements. Subjects were told to assume their normal standing posture and remain still. Data were collected in this position for approximately 500ms. Between each trial, the data were reconstructed to ensure that no errors occurred during data collection (eg, marker fell off subject and/or was obstructed from view). This process took between two and four minutes for each trial. During this lag time subjects were instructed to walk about the room for at least thirty seconds; then they were free to either walk or stand until the next trial. After the standing trials, subjects performed a number of trial walks, to familiarize themselves

with the environment, and to allow the investigator to adjust the starting position so that both feet would step on the force platforms in the course of a natural walk. Because the force platforms were barely discernable, most subjects had no knowledge of why their "start position" was adjusted, to ensure it would not affect their normal gait. Subject's performed these trials at a freely chosen "comfortable" speed. If any walk was unsatisfactory for any reason (hesitation, stumbling, etc.), it was repeated. During each walking trial, data were obtained for approximately three seconds; this provided adequate data to examine one entire gait cycle. Four walking trials were recorded for each subject to establish reliability of measures of pelvic tilt and lumbar lordosis dynamically. Data processing took between three to five minutes for each trial. Following this, three more standing trials identical to the first three were taken to further determine reliability of this measure over a longer time period.

The last data collected were during three trials with the subject 1) maintaining a maximal anterior pelvic tilt posture and 2) with the subject assuming a maximal posterior pelvic tilt posture. These measurements were taken to determine the extent to which 1) increasing the degree of anterior pelvic tilt increased the angle of lumbar lordosis and 2) increasing the degree of posterior pelvic tilt

decreased the angle of lumbar lordosis. These trials were collected in the following order; maximal anterior pelvic tilt, maximal posterior pelvic tilt, maximal anterior pelvic tilt, maximal posterior pelvic tilt, maximal anterior pelvic tilt, maximal posterior pelvic tilt. Data processing took between two and four minutes between each trial.

The data from the measurement with the markers on the floor, the standing and walking trials, and the maximal anterior and posterior pelvic tilt were then processed by the Vicon software to generate files of three-dimensional coordinates. These were then converted from the Vicon internal file structure into a form which could be read using spreadsheets in Excel. Calculations of the angles of pelvic tilt and lumbar lordosis, and the data smoothing, were then done within Excel. The exact process, which took approximately 150 minutes to complete for each subject, is described in Appendix C-3. The finished Excel files were then used for statistical analysis on the Statistical Package for the Social Sciences (SPSS).

3. Measurement of Abdominal Muscle Performance

Abdominal muscle strength was tested according to the method described by Kendall and McCreary (1983) and modified by Walker et al. (1984). This test requires that subjects maintain a contraction of their abdominal muscles as the

legs are lowered from a position of 90° of hip flexion with full knee extension in the supine position to neutral hip extension (Figure 6). The angle between the shaft of the femur and the table at which the subject cannot maintain a posterior pelvic tilt is measured by two testers, using goniometry. This angle is determined by the tester as the point at which the subject can no longer maintain a posterior pelvic tilt with the low back firmly against the table. Tester one (DL) palpated for the movement and when movement was felt as the subject's low back began to rise from the table, tester one tapped tester two (KH) on the shoulder. Tester two then recorded the goniometric measurement of the thigh angle at that moment. Tester one had no knowledge of the actual angles obtained during testing, until the trials were completed. Both testers were experienced orthopedic physical therapists. The same two testers performed the measurements on all subjects, with tester one being the author, and tester two being Karen Hood, M.S., P.T..

This measurement was taken three times with one minute of rest between the measurements. Reliability of this method had previously been established (Walker, et al., 1984; Heino, et al., 1990), and also was determined in this study. This method was reported to be the best clinical test for determination of trunk flexor strength (Smidt et al., 1987).

CHAPTER IV

RESULTS

As the method used for measuring the angle of lumbar lordosis in this study was original, the reliability of this measure needed to be estimated. Testing of reliability of measures of pelvic tilt and abdominal muscle performance were also conducted. To establish reliability two statistical procedures were chosen. Intraclass correlation coefficients (ICC's) were calculated to describe the degree of intratester agreement for the measurements of pelvic tilt, lumbar lordosis, and abdominal muscle performance. Because only one judge evaluated the same population of subjects, the formula chosen was (3,1) of the ICC, as described by Shrout and Fleiss (1979).

The other statistical procedures that were chosen to estimate reliability were Pearson and Spearman correlation coefficients. These were chosen in order to determine trends in the level of significance between each trial, for each measure. For example, if trial one and trial two for standing pelvic tilt were consistently correlated to a higher degree than trial one and trial five or six, time may have had an effect on the reliability of the measure. This specific trend, or any other significant trend, was not

found in any of these analyses. Pearson correlation coefficients were used when comparing lumbar lordosis and pelvic tilt as they are ratio data. Measurements of abdominal muscle performance were of the ordinal data type, and Spearman correlation coefficients were used in any analysis relating to this data. Data were collected on all subjects (n=28) for all trials, except for maximal anterior and posterior pelvic tilt posture where n=20.

A. Reliability of Pelvic Tilt

The reliability of pelvic tilt in normal standing was estimated by computing the correlation between all six measures of standing pelvic tilt. Three of these measures were obtained prior to the four walking trials, and three of the measures were obtained after the four walking trials. I felt that estimating reliability in this manner would be a more rigorous test, as not only time existed between the two sets of measurements, but movement of the subject occurred during gait and possible movement of the markers could have affected reliability. The ICC value was .97 ($p < .001$) (Table 2) demonstrating a strong degree of agreement between the trials. The Pearson values for pairwise correlations ranged from .94 to .98, and all six measures of pelvic tilt were significantly correlated with each other at the $p < .001$ level of significance (Table 2). Because all these measures

were highly reliable, I chose to average the six values to obtain one value for standing pelvic tilt, which was used for further analysis.

Three trials of maximal anterior pelvic tilt and three trials of maximal posterior pelvic tilt were also obtained from the subjects. The ICC value for maximal anterior pelvic tilt was .97 ($p < .001$) demonstrating a strong degree of agreement between the trials (Table 2). The Pearson values ranged from .84 to .90, and were significant at the $p < .001$ level (Table 2). Maximal posterior pelvic tilt measurements were also significant at the $p < .001$ level, with an ICC value of .78, and Pearson values ranging from .82 to .95 (Table 2). As both maximal anterior and posterior pelvic tilt were reliable between trials, I chose to average the three values to obtain one value for maximal anterior pelvic tilt, and one value for maximal posterior pelvic tilt to use for further analysis.

B. Reliability of Lumbar Lordosis

The reliability of the angle of lumbar lordosis in normal standing was calculated in the same manner as the reliability of pelvic tilt. The ICC value was .94 ($p < .001$) demonstrating a strong degree of agreement between the trials (Table 2). The Pearson values ranged from .91 to

.98, and all six measures of lumbar lordosis were significantly correlated with each other at the $p < .001$ level of significance (Table 2). As these measures were highly reliable, I chose to average the six values to obtain one value for standing lumbar lordosis; this value was used for further analysis.

The ICC value for the angle of lumbar lordosis obtained during a maximal anterior pelvic tilt posture was .90 ($p < .001$). Pearson values ranged from .88 to .92 ($p < .001$) (Table 2). Measurements of lumbar lordosis during the maximal posterior pelvic tilt posture were also significant at the $p < .001$ level, with an ICC value of .91, and Pearson values ranging from .92 to .94 (Table 2). As lumbar lordosis during both the maximal anterior and posterior pelvic tilt posture were reliable between trials, I chose to average the three values to obtain one value for lumbar lordosis during the maximal anterior pelvic tilt, and one value for lumbar lordosis during the maximal posterior pelvic tilt to use for further analysis.

C. Reliability of Abdominal Muscle Performance

The reliability of the measure of abdominal muscle performance used was estimated by computing correlations between the three trials obtained. The ICC value was .97

($p < .001$) demonstrating a strong degree of agreement between the trials (Table 2). All three Pearson values were .97, and were significant at the $p < .001$ level (Table 2). A Spearman correlation was also calculated with values ranging from .94 to .96 ($p < .001$) (Table 2). As these values were highly reliable between trials, I chose to average the three values to obtain one value for abdominal muscle performance, which was used for further analysis.

D. Reliability of Pelvic Tilt and Lumbar Lordosis During Gait

To estimate the reliability of pelvic tilt and lumbar lordosis during gait (dynamically), I chose to examine several points in the gait cycle. Each subject's gait cycle was broken down into "100 percents" (with each data point representing approximately three-tenths of a second), of which any of these data points could be analyzed. I chose to examine the reliability of pelvic tilt and lumbar lordosis at 0, 25, 50, 75, and 100 percent of the gait cycle. Data from the four trial walks were correlated across the 28 subjects to estimate reliability, resulting in correlational values for pelvic tilt and for lumbar lordosis at five points in the gait cycle. Pelvic tilt between the walks was highly reliable for all five gait segments studied

(Table 3). ICC values were all .97 ($p < .001$) demonstrating a strong degree of agreement between the trials. Pearson correlations ranged from .85 to .98 ($p < .001$). Lumbar lordosis between the walks was also shown to be highly reliable for all five gait segments. ICC values ranged from .95 to .97 ($p < .001$). Pearson correlations ranged from .94 to .98 ($p < .001$) (Table 4). As the above values were highly reliable, I chose to average them for further statistical analysis. This resulted in one value for pelvic tilt and one value for lumbar lordosis at each of the five gait segments.

E. Effect of Pelvic Tilt on Lumbar Lordosis

The difference in mean pelvic tilt from the subject's normal standing posture to their maximal anterior pelvic tilt posture was significant, $t(19) = -15.2$, $p < .001$ (Table 5). The difference in mean pelvic tilt from resting posture to maximal posterior pelvic tilt posture was also significant, $t(19) = 14.8$, $p < .001$ (Table 5).

Altering the pelvic tilt posture had a significant effect on lumbar lordosis. The difference in mean lumbar lordosis from the subject's normal resting posture to their maximal anterior pelvic tilt posture was significant,

$t(19) = -14.1$, $p < .001$ (Table 5). The difference in mean lumbar lordosis from resting posture to maximal posterior pelvic tilt posture was also significant, $t(19) = 10.1$, $p < .001$) (Table 5).

Assuming a maximal anterior pelvic tilt posture changed the pelvic attitude by an average of 11.3° and increased the depth of lumbar lordosis by an average of 11.1° ($p<.001$). Assuming a maximal posterior pelvic tilt posture changed the pelvic attitude by an average of 8.8° and decreased the depth of lumbar lordosis by an average of 8.1° ($p<.001$).

F. Relationships Between Static and Dynamic Measures of Pelvic Tilt and Lumbar Lordosis

To examine the static relationship between pelvic tilt and lumbar lordosis, a correlation was used. The correlation between pelvic tilt and lumbar lordosis in normal standing was .43 ($p <.02$) (Table 6), which is consistent with the past literature (Beninato, et al., 1993; Walker et al., 1984).

Correlations between the static data obtained for pelvic tilt, and the dynamic data obtained for pelvic tilt, and the static data obtained for lumbar lordosis, and the dynamic data obtained for lumbar lordosis were obtained. If these

correlations were high, then we could assume no relationship between abdominal muscle strength and pelvic tilt and lumbar lordosis dynamically, since no relationship was found statically. Correlations between static and dynamic pelvic tilt were high at all five segments studied. The correlations ranged from .86 to .89 ($p < .01$) (Table 7). Correlations between static and dynamic lumbar lordosis were also high at all five segments studied. The correlations ranged from .74 to .78 ($p < .01$) (Table 8).

The dynamic relationship between pelvic tilt and lumbar lordosis was also studied at all five segments of the gait cycle. These correlations ranged from .34 to .48 (Table 9).

G. Relationships Between Abdominal Muscle Performance, and Pelvic Tilt and Lumbar Lordosis

To examine the relationship between abdominal muscle performance and 1) pelvic tilt and 2) lumbar lordosis, the value of abdominal muscle performance was correlated with the static measure of pelvic tilt, and also with the static measure of lumbar lordosis. This abdominal test angle was also correlated with pelvic tilt, and with lumbar lordosis at a number of pre-determined points in the gait cycle. Both Pearson and Spearman correlations were obtained on all analyses involving the abdominal muscle performance data.

There were no dramatic differences between the results of the two correlations, and both are included in the tables.

The correlation between abdominal muscle performance and pelvic tilt in the standing position was -.06 (p = NS) (Table 6). The correlation between lumbar lordosis and abdominal muscle performance was -.05 (p = NS) (Table 6). These values are also in agreement with the literature, which has shown little relationship between these variables in a static position (Suzuki & Endo, 1983; Walker et al., 1984; Toppenberg & Bullock, 1986).

Correlations between abdominal muscle performance and pelvic tilt and lumbar lordosis at 0, 25, 50, 75, and 100 percent of the gait cycle were also calculated. Values for pelvic tilt ranged from -.08 to -.13, and all were non-significant (Tables 10 + 11). Values for lumbar lordosis ranged from -.05 to -.19, and all were non-significant (Tables 10 + 11).

CHAPTER V

DISCUSSION

A. Reliability of Pelvic Tilt, Lumbar Lordosis, and Abdominal Muscle Performance

Reliability of pelvic tilt and lumbar lordosis in both the static and dynamic conditions was excellent using the described testing methods. In the static tests, pelvic tilt and lumbar lordosis were equally reliable. In the dynamic tests, pelvic tilt scores tended to be more reliable than lumbar lordosis scores. Use of the lumbar rigs for measurement of lumbar lordosis, and the slight movement of the rigs that occurs during gait most likely accounted for this. However the measure was still highly reliable for clinical gait analysis. The measure of abdominal muscle performance was also highly reliable.

B. Effect of Pelvic Tilt on Lumbar Lordosis

This study demonstrated that in a static standing posture, increasing the degree of anterior pelvic tilt increased the angle of lumbar lordosis whereas increasing the degree of posterior pelvic tilt decreased the angle of lumbar lordosis. These results also show that a person can

voluntarily alter their pelvic tilt enough to significantly change their angle of lumbar lordosis. This lends support to performing anterior pelvic tilt exercises to increase the angle of lumbar lordosis and posterior pelvic tilt exercises for decreasing the angle of lumbar lordosis.

C. Relationships between Static and Dynamic Measures of Pelvic Tilt and Lumbar Lordosis

Pelvic tilt and lumbar lordosis were positively correlated with each other in both the static and dynamic conditions. While these correlations were statistically significant, the correlations were not high enough to conclude that there is a direct relationship between these two variables.

One possible reason as to why these two variables were correlated is the direct bony relationship between the pelvis and lumbar spine. As the pelvis moves in the sagittal plane, the lumbar spine must also move with it. The relationships between abdominal muscle performance and pelvic tilt and lumbar lordosis are not as clearly anatomically linked. Another reason may be that pelvic tilt and lumbar lordosis were measured in the same static position (standing), while abdominal muscle performance was measured dynamically, and in a different position (supine).

D. Relationships between Abdominal Muscle Performance, Pelvic Tilt, and Lumbar Lordosis

The relationships between abdominal muscle performance and 1) pelvic tilt and 2) lumbar lordosis were examined and compared to previous research. No significant relationship was found either between abdominal muscle performance and pelvic tilt, or between abdominal muscle performance and lumbar lordosis. These findings support the hypothesis, and are also consistent with the literature examining these variables in similar static positions (Walker et al., 1984; Toppenberg & Bullock, 1986; Heino et al., 1990). In addition, no greater relationship was found between the variables in a dynamic task than when measured statically. The sample size used (28), while not exceptionally large, was more than ample to show that no relationship exists, due to the extremely low correlation coefficients.

These results do not support the theory that abdominal muscle performance has a causal relationship to pelvic tilt and lumbar lordosis in either standing or in gait. This is probably because posture is the result of an equilibrium between the forces in the bony structures, the muscles, and the other connective tissues present, and is not highly dependent on the performance of a single muscle. The relationship between the strength and length of the

connective tissues may be a more important factor than abdominal muscle performance.

Biomechanical alterations in posture typically result in altered muscle, ligament, and joint forces, and compensatory postural changes at other joints. For example, if an individual has an increased anterior pelvic tilt and lumbar lordosis, then the line of gravity in relation to the lumbar spine could be expected to change, with a corresponding change in the activity of the paraspinal muscles and the forces in the spinal ligaments and intervertebral discs. There is also likely to be an increased thoracic kyphosis, to maintain the center of balance and to keep the head positioned over the pelvis.

It is thus unwise to attribute pelvic attitude to the performance of only one muscle. Resting position of the pelvis may be influenced by many muscles; for example, the hip flexors pull the pelvis into an anterior pelvic tilt when they contract. The possibility exists that if this muscle group is habitually tight in an individual, that this may be a causative factor in producing excessive anterior pelvic tilt. Habitual postures that a person may assume, such as keeping the pelvis in an anterior tilt for long time periods, may have more of an effect than an exercise program prescribed to change that posture. A range of factors will

also account for differing relationships between lumbar curvature and pelvic tilt between individuals. One person may have a large lordosis and minimal pelvic tilt due to muscle weakness or to the anatomy of their vertebrae; whereas another person may have a large lordosis with a large degree of pelvic tilt, due to tightness of the hip flexors and postural deviations in the cervical and thoracic spine. All of these factors contribute to the complex interrelationships that make up posture. Altering posture by the use of a treatment that consists of manipulating one factor, without regard for the others, is likely to be ineffectual.

The results obtained from this study demonstrate the need for caution when making general statements about the relationships between abdominal muscle performance, pelvic tilt, and lumbar lordosis. Even though an individual may have both an excessive anterior pelvic tilt and weak abdominal muscles, it does not follow that strengthening and/or stretching the muscles will change either the lumbar lordosis or the pelvic tilt. Individuals should be placed on abdominal strengthening programs for the purpose of increasing their abdominal strength, and for the benefits which follow from this such as the prevention of low back injuries, rather than to correct functional dynamic postural deviations.

E. Limitations

The first limitation of this study is that it was performed on a sample of college students devoid of low back troubles. The generalizability of the results is therefore limited. I chose this population as I felt that the relationships first needed to be understood in normal individuals before analyzing the more complex problems that may exist in individuals with low back dysfunction, and the numerous confounding variables that may exist.

Another limitation is that the activities tested, quiet standing and gait, involved relatively small changes in pelvic tilt or lumbar lordosis, and the abdominals are relatively inactive during these activities. Other forms of exercise may exist in which abdominal muscle performance is more important and has a greater effect on pelvic attitude.

The test used to measure abdominal muscle performance (double leg lowering), though widely used clinically, is relatively imprecise and may have added a further limitation to this study. A more precise strength measurement from an isokinetic dynamometer might have given more practical significance to the measurement of abdominal muscle performance. Strength is also likely to vary with position in the tested range of motion (ROM), depending upon the

characteristics of the individual abdominal muscles and their length tension relationships. Using a composite strength score based on the entire trunk ROM would probably be a better measure than the test used in this study.

F. Future Recommendations

I have a number of recommendations for further research in this area. First, we may be able to use treatment interventions to gain a better understanding of what variables contribute to posture. This could be achieved by measuring postural variables, and then trying to change them by combinations of 1) improving flexibility of tight connective tissues; 2) strengthening weak muscles; and 3) educating and training subjects to improve their posture. This should give us a better idea as to which variables most affect posture.

The use of discriminant analysis could take into account factors such as muscle length, muscle strength, anatomical variations such as length of the total lumbar curve, and other characteristics of the individual, and give us a clearer idea of the relative contributions of the variables in producing posture. Using an isokinetic dynamometer to measure abdominal muscle performance would ensure that subjects perform at a maximal effort throughout the entire

ROM, and may give a more accurate measurement of abdominal muscle performance.

Lastly, examining other activities may give us a more clear representation of the relationships between these postural variables. Activities such as running, swimming, or lifting, in which the abdominal muscles are more actively contracting than in standing and walking, may show stronger relationships since the abdominals may play more of a role in determining pelvic attitude. Of these recommendations, the use of treatment interventions probably has the most clinical relevance as it can help to validate or refute treatments directed at altering faulty posture.

CHAPTER V

CONCLUSIONS

Measurements of lumbar lordosis, pelvic tilt, and abdominal muscle performance were all found to be reliable. The results of this study also show that voluntarily altering pelvic tilt changes the angle of lumbar lordosis. This supports the use of pelvic tilting exercises to alter the degree of lumbar lordosis, at least for the time period of the exercise.

Correlations between abdominal muscle performance and pelvic tilt, and between abdominal muscle performance and lumbar lordosis, were not significant at any point in the gait cycle. The results indicated that abdominal muscle performance, pelvic tilt, and lumbar lordosis measured dynamically (during gait), did not appear to be directly related. This study demonstrated a need to reconsider clinical decision-making based on the assumed relationships between these variables.

LIST OF REFERENCES

LIST OF REFERENCES

Alston W, Carlson KE, Feldmaan DJ, et al. A quantitative study of muscle factors in the chronic low back syndrome. J Am Geriatr Soc. 1966;14:1041.

Beninato M, Hudson KR, Price KS. A study of the correlations among lumbar lordosis, pelvic tilt, and hamstring and hip flexor muscle lengths. J Orthop Sports Phys Ther. 1993;17:61.

Bogduk N, Twomey LT. Clinical Anatomy of the Lumbar Spine. 2nd ed. New York, NY: Churchill Livingstone; 1991:45-47.

Burdett RG, Brown KE, Fall MP. Reliability and validity of four instruments for measuring lumbar spine and pelvic positions. Phys Ther. 1986;66:677-684.

Cailliet R: Low Back Pain Syndrome. 3rd ed. Philadelphia, PA: FA Davis; 1981:53-68.

Day JW, Smidt GL, Lehmann T. Effect of pelvic tilt on standing posture. Phys Ther. 1984;64:510-516.

Denslow JS, Chace JA. Mechanical stresses in the human lumbar spine and pelvis. JAOA. 1962;61:706-712.

Donatelli R, Wooden MJ. Orthopaedic Physical Therapy. New York, NY: Churchill Livingstone; 1989:403-483.

Gilad I, Nissan M. Sagittal evaluation of elemental geometrical dimensions of human vertebrae. J Anat. 1985;143:115-120.

Gould JA. Orthopaedic and Sports Physical Therapy. St. Louis, MO: C.V. Mosby Company; 1990:523-573.

Hansson T, Bigos S, Beecher P, Wortley M. The lumbar lordosis in acute and chronic low-back pain. Spine. 1985;10:154-155.

Hart DL, Rose SJ. Reliability of a non-invasive method for measuring the lumbar curve. J Orthop Sports Phys Ther. 1986;8:180-184.

Heino JG, Godges JJ, Carter CL. Relationship between hip extension range of motion and postural alignment. J Orthop Sports Phys Ther. 1990;12:243-247.

Joint Motion: Method of Measuring and Recording: Chicago: American Academy of Orthopaedic Surgeons; pp 48-49, 1965.

Kadaba MP, Wootten HK, Ramakrishnan HK, Hurwitz D, Cochran GVB. Assessment of human motion with VICON. ASME Biomech Symp. 1987;84:335-338.

Kadaba MP, Ramakrishnan HK, Wootten ME, Gainey J, Gorton G, Cochran GVB. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. Journal of Orthopaedic Research 7, 1989;6:849-860.

Kelsy JL, White AA. Epidemiology and impact of low back pain. Spine. 1980;5:133-142.

Kelsey JL, White AA, Pastides H, Bisbee GE. The impact of musculoskeletal disorders on the populations of the United States. J Bone Joint Surg Am. 1979;61:959-963.

Kendall HO, Kendall FP, Boynton DA. Posture and Pain. Baltimore, Md: Williams and Wilkins; 1977:125-131.

Kendall FP, McCreary EK. Muscles: Testing and Function. 3rd ed. Baltimore, Md: Williams & Wilkins; 1983:189- 192; 219.

Kisner C, Colby LA. Therapeutic Exercise: Foundations and Techniques. 2nd ed. Philadelphia, PA: FA Davis; 1990:437-439.

Levine DF, Walker JR, Tillman LJ. The effect of abdominal muscle strengthening on pelvic tilt and lumbar lordosis. Submitted to Phys Ther, March 1994.

Lovell FW, Rothstein JM, Personius WJ. Reliability of clinical measurements of lumbar lordosis taken with a flexible rule. Phys Ther. 1989;69:96-105.

Magee DJ. Orthopaedic Physical Assessment. Philadelphia, PA: W. B. Saunders; 1987:170-238.

Moll JMH, Wright V. Normal range of spinal mobility. Ann Rheum Dis. 1971;30:381-386.

Nachemson A. A critical look at the treatment of low back pain. Scand J Rehab Med. 1979;11:143-147.

Norkin CC, Levangie P. Joint Structure and Function: A Comprehensive Analysis. 2nd ed. Philadelphia, PA, FA Davis; 1992:313-314.

Pearcy M. Measurement of back and spinal mobility. Clinical Biomechanics. 1986;1:44-51.

Pearcy MJ, Gill JM, Whittle MW. Dynamic back movement using a three-dimensional television system. Journal of Biomechanics. 1987;20:943-949.

Pheasant H. Practical posture building. Clin Orthop. 1962;25:83-91.

Polster J, Spieker U, Hoefert HR, Krenz JU. Biomechanics in lumbar lordosis. Biomechanics IV (eds. Melson RC, Morehouse CA). Baltimore, MD, University Press; 1974;365-371.

Rowe ML. Preliminary statistical study of low back pain. J Occup Med. 1963;5:336.

Schmorl G, Junghanns H. The Human Spine in Health and Disease. 2nd ed. New York, NY: Grune and Stratton; 1971;18.

Shrout PE, Fleiss JL. Intraclass correlation: Uses in assessing rater reliability. Psychol Bull 1979;86:420-428.

Smidt GL, Blanpied PR, Anderson MA, White RW. Comparison of clinical and objective methods of assessing trunk muscle strength - an experimental approach. Spine 1987;10:1020-1024.

Suzuki N, Endo S. A quantitative study of trunk muscle strength and fatigability in the low-back-pain syndrome. Spine 1983;8:69-74.

Thomas PE. An analysis of the interactions among various asymmetric osseous pelvic and lumbar structures. JAOA. 1965;64:956-957.

Thurston AJ, Whittle MW, Stokes IAF. Spinal and pelvic movement during walking - a new method of study. Engineering in Medicine. 1981;10:219-222.

Thurston AJ. Repeatability studies of a television/computer system for measuring spinal and pelvic movements. J Biomedical Engineering 1982;4:129-132.

Thurston AJ, Harris JD. Normal kinematics of the lumbar spine and pelvis. Spine 1983;6:199-205.

Toppenberg RM, Bullock MI. The interrelation of spinal curves, pelvic tilt and muscle lengths in the adolescent female. The Australian Journal of Physiotherapy. 1986;32:6-12.

Troup JDG, Hood CA, Chapman AE. Measurements of the sagittal mobility of the lumbar spine and hips. Ann Phys Med 1963;9:308-321.

Walker ML, Rothstein JM, Finucane SD, et al. Relationships between lumbar lordosis, pelvic tilt, and abdominal muscle performance. Phys Ther. 1987;67:512-516.

Warwick R, Williams PL, Dyson M, Bannister LH. Gray's Anatomy. 35th ed. New York, NY: Churchill Livingstone; 1989;595-604.

White AA, Panjabi MM. Clinical Biomechanics of the Spine. Philadelphia, PA: JB Lippincott Company; 1978;307.

Whittle MW. Calibration and performance of a three-dimensional system for kinematic analysis. Journal of Biomechanics. 1982;15:185-196.

Whittle MW, Levine DF. Measurement of lumbar lordosis while performing clinical gait analysis. Proceedings from the Third Annual Symposium on 3-D Analysis of Human Movement, Stockholm, Sweden, July 1994.

APPENDIXES

APPENDIX A

TABLES

TABLE 1

Physical Characteristics of Subjects

Age	23.4 years (Range 20-32)
Pelvic Tilt	11.9° (Range 3-19)
Lumbar Lordosis	32.4° (Range 19-47)
Abdominal Muscle Performance	52.5° (Range 18-82)

n = 28

TABLE 2

Static (Standing) Test-Retest Reliability of Pelvic Tilt, Lumbar Lordosis, and Abdominal Muscle Performance

Measurement	Values	Significance
Resting Pelvic Tilt	ICC = .95 r = .94-.98	p < .001 p < .001
Maximal Anterior Pelvic Tilt	ICC = .85 r = .84-.90	p < .001 p < .001
Maximal Posterior Pelvic Tilt	ICC = .78 r = .82-.95	p < .001 p < .001
Resting Lumbar Lordosis	ICC = .94 r = .91-.98	p < .001 p < .001
Lumbar Lordosis During Ant. Pelv. Tilt Post.	ICC = .90 r = .88-.92	p < .001 p < .001
Lumbar Lordosis During Post. Pelv. Tilt Post.	ICC = .91 r = .92-.94	p < .001 p < .001
Abdominal Muscle Performance	ICC = .97 Spearman r = .94-.96	p < .001 p < .001

n = 28 ICC = (3,1)

r = Pearson correlation coefficient

TABLE 3

Dynamic (Gait) Test-Retest Reliability of Pelvic Tilt

Percent of Gait Cycle	Values	Significance
0%	ICC = .97 r = .86-.98	p < .001 p < .001
25%	ICC = .92 r = .85-.99	p < .001 p < .001
50%	ICC = .97 r = .87-.98	p < .001 p < .001
75%	ICC = .97 r = .87-.97	p < .001 p < .001
100%	ICC = .97 r = .86-.99	p < .001 p < .001

n = 28

ICC = (3,1)

r = Pearson correlation coefficient

TABLE 4

Dynamic (Gait) Test-Retest Reliability of Lumbar Lordosis

Percent of Gait Cycle	Values	Significance
0%	ICC = .96 r = .95-.97	p < .001 p < .001
25%	ICC = .97 r = .96-.98	p < .001 p < .001
50%	ICC = .95 r = .94-.96	p < .001 p < .001
75%	ICC = .96 r = .96-.97	p < .001 p < .001
100%	ICC = .96 r = .93-.98	p < .001 p < .001

n = 28

ICC = (3,1)

r = Pearson correlation coefficient

TABLE 5

Effect of Pelvic Tilt on Lumbar Lordosis

Normal Pelvic Tilt vs. Anterior Pelvic Tilt Posture	t = -15.2	p < .001
Normal Pelvic Tilt vs. Posterior Pelvic Tilt Posture	t = 14.8	p < .001

Normal Lumbar Lordosis vs. Lumbar Lordosis in Anterior Pelvic Tilt Posture	t = -14.1	p < .001
Normal Lumbar Lordosis vs. Lumbar Lordosis in Posterior Pelvic Tilt Posture	t = 10.1	p < .001

n = 20

t = two-tailed paired t-test

TABLE 6

Correlation between Variables (Static condition)

Measurement	Values	Significance
Pelvic tilt vs. Lumbar lordosis	Pearson r = .43	p < .02
Abdominal perform. vs. Pelvic tilt	Pearson r = -.03 Spearman r = .06	p = NS p = NS
Abdominal perform. vs. Lumbar lordosis	Pearson r = -.13 Spearman r = -.05	p = NS p = NS

n = 28

NS = Not significant at the p >.05 level

TABLE 7

Static Pelvic Tilt vs. Dynamic Pelvic Tilt

Percent of Gait cycle	0%	25%	50%	75%	100%
Pelvic Tilt	r= .88 p <.01	r= .86 p <.01	r= .87 p <.01	r= .86 p <.01	r= .89 p <.01

n = 28

r = Pearson correlation coefficient

TABLE 8

Static Lumbar Lordosis vs. Dynamic Lumbar Lordosis

Percent of Gait cycle	0%	25%	50%	75%	100%
Lumbar Lordosis	r= .78 p <.01	r= .76 p <.01	r= .75 p <.01	r= .76 p <.01	r= .74 p < .01

n = 28

r = Pearson correlation coefficient

TABLE 9

Lumbar Lordosis vs. Pelvic Tilt (Dynamic Condition)

Percent of Gait cycle	0%	25%	50%	75%	100%
Lordosis vs. Tilt	r= .39 p <.05	r= .48 p <.01	r= .34 p = NS	r= .40 p <.05	r= .41 p < .05

n = 28

r = Pearson correlation coefficient

NS = Not significant at the p >.05 level

TABLE 10

Correlation (Pearson) between Abdominal Muscle Performance and Pelvic Tilt and Lumbar Lordosis (Dynamic condition)

Percent of Gait cycle	0%	25%	50%	75%	100%
Pelvic Tilt	r=-.17 p = NS	r=-.17 p = NS	r=-.20 p = NS	r=-.16 p = NS	r=-.17 p = NS
Lumbar Lordosis	r=-.20 p = NS	r=-.34 p = NS	r=-.21 p = NS	r=-.28 p = NS	r=-.20 p = NS

n = 28

r = Pearson correlation coefficient

NS = Not significant at the p >.05 level

TABLE 11

Correlation (Spearman) between Abdominal Muscle Performance and Pelvic Tilt and Lumbar Lordosis (Dynamic condition)

Percent of Gait cycle	0%	25%	50%	75%	100%
Pelvic Tilt	r=-.10 p= NS	r=-.13 p= NS	r=-.10 p= NS	r=-.11 p= NS	r=-.08 p= NS
Lumbar Lordosis	r=-.07 p= NS	r=-.19 p= NS	r=-.10 p= NS	r=-.12 p= NS	r= -.05 p= NS

n = 28

r = Spearman correlation coefficient

NS = Not significant at the p >.05 level

APPENDIX B

FIGURES

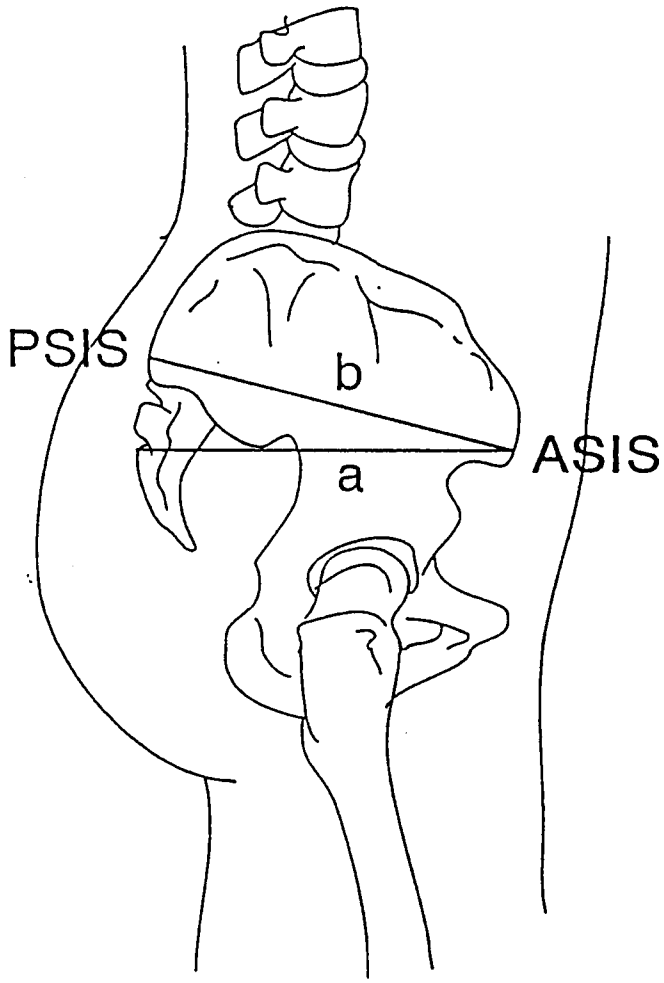


Figure 1. Schematic diagram of pelvic tilt, and formula for calculation of degree of pelvic tilt. A represents a line drawn parallel to the horizontal plane; B is the slope of a line projected through the ASIS and PSIS. ASIS = anterior superior iliac spine; PSIS = posterior superior iliac spine.



Figure 2. Schematic diagram of lumbar lordosis.

Source: Modified from Link CS, Nicholson GG, Shaddeau SA, et al. Lumbar curvature in standing and sitting in two types of chairs: relationship of hamstring and hip flexor muscle length. Phys Ther. 1990;70:614.

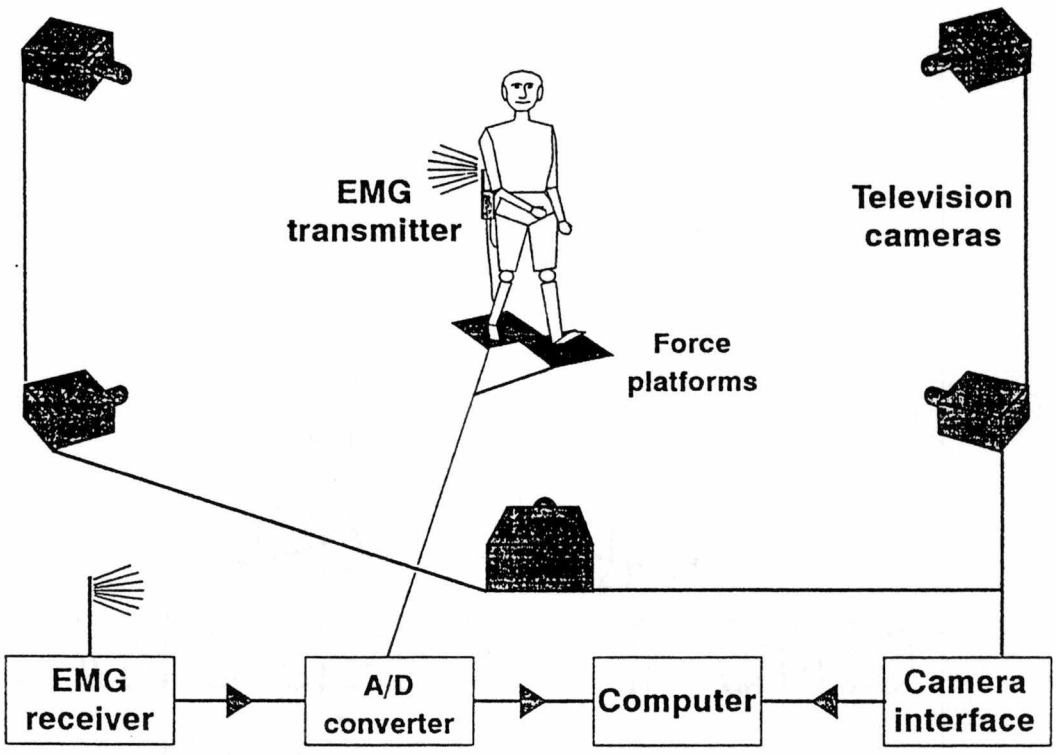


Figure 3. Cameras and force platforms.

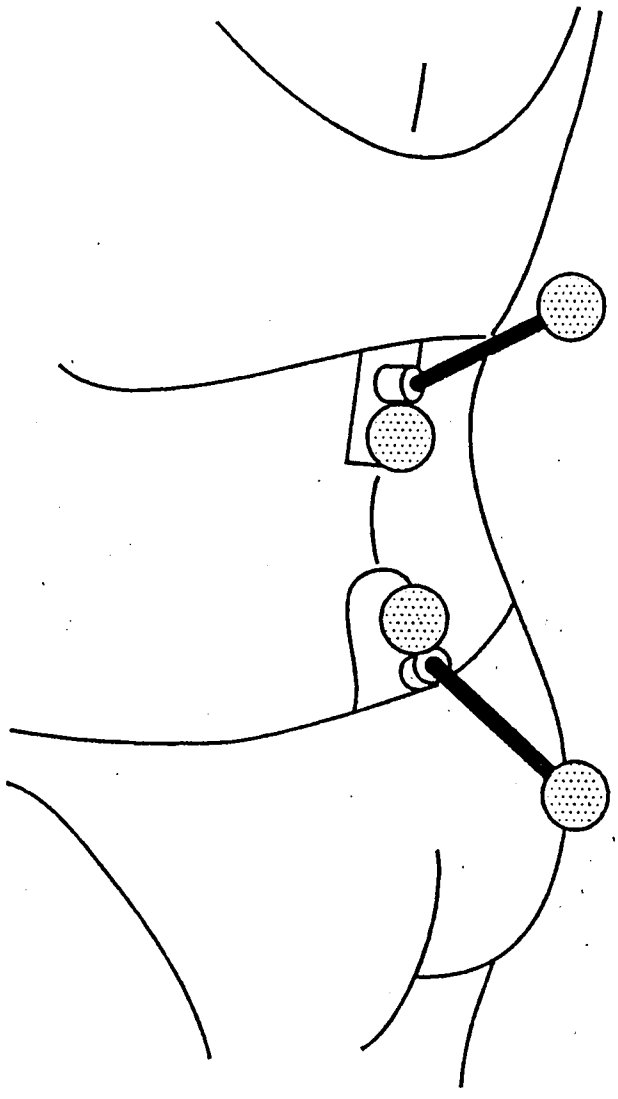


Figure 4. Lumbar Rigs in Place on Subject.

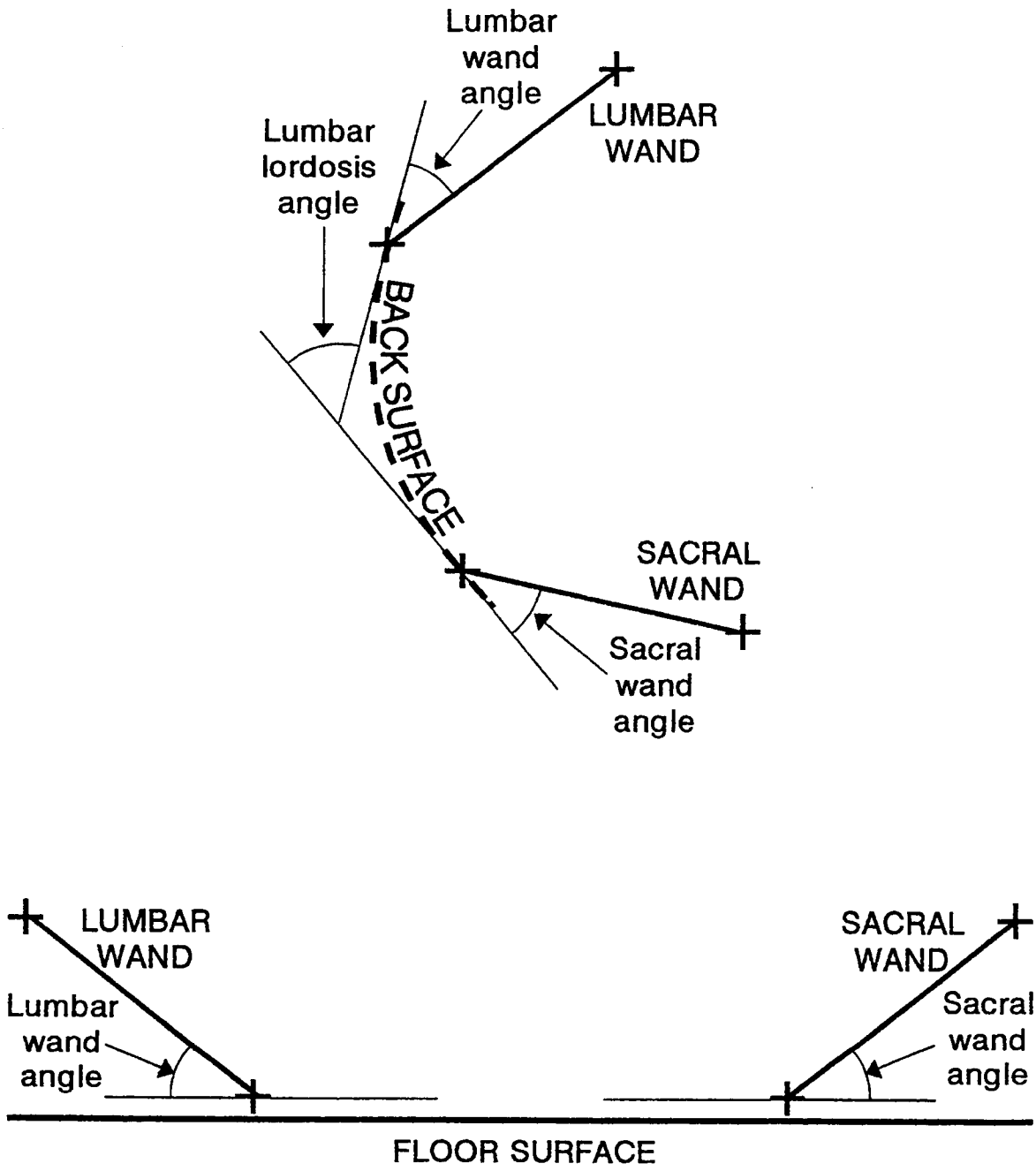


Figure 5. Measurement of the Angle of Lumbar Lordosis.

Crosses indicate positions of reflective markers.

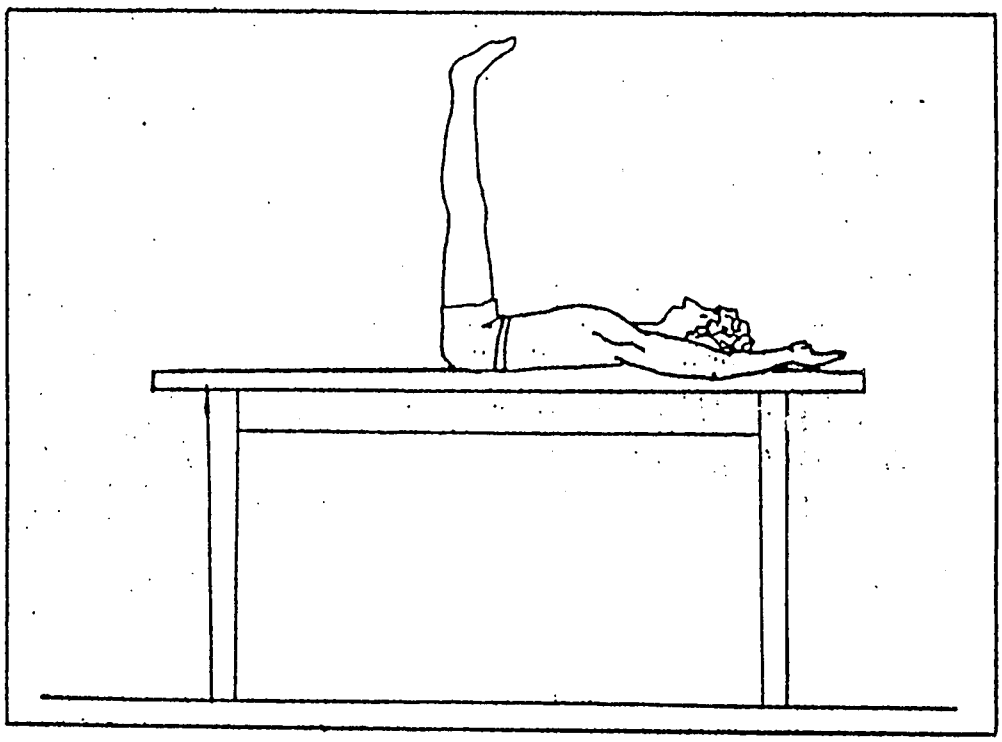


Figure 6. Starting Position for Testing Abdominal Muscle Performance.

Source: Walker ML, Rothstein JM, Finucane SD, et al. Relationships between lumbar lordosis, pelvic tilt, and abdominal muscle performance. Phys Ther. 1984;67:514.

APPENDIX C

SUPPLEMENTARY MATERIALS

Appendix C-1

MEASUREMENT OF LUMBAR LORDOSIS WHILE PERFORMING CLINICAL GAIT ANALYSIS

Michael W. Whittle and David F. Levine.

The University of Tennessee at Chattanooga
and
Siskin Hospital for Physical Rehabilitation
Chattanooga, Tennessee, U.S.A.

INTRODUCTION

Changes in the lumbar lordosis frequently occur in pathological gait, usually in association with alterations in pelvic tilt, and commonly as a compensation for a limited range of flexion/extension at the hip joint (Polster et al., 1974; Whittle, 1991). The parameters typically measured in clinical gait analysis (Kadaba et al., 1989) include the movements of the pelvis, but do not include changes in the lumbar lordosis. The aim of the present study was to find a way in which the dynamic measurement of lumbar lordosis could be included in clinical gait analysis, using the protocol for the Vicon gait analysis system (Oxford Metrics Ltd., Oxford, England).

Pearcy (1986) reviewed the methods used to measure spinal mobility, the majority of which have been restricted to movements made in the standing position. Spinal motion during walking was studied using an early version of the Vicon system by Thurston and others, in both normal individuals (Thurston et al., 1981; Thurston, 1982; Thurston & Harris, 1983) and in patients with osteoarthritis of the hip (Thurston 1985). This system used stroboscopic illumination and television cameras, interfaced to a computer, to measure the three-dimensional (3-D) positions of retroreflective markers attached to the subject (Whittle, 1982). These studies reported the movements of the pelvis and lower thoracic spine in a room-based coordinate system, but did not specifically measure the lumbar lordosis.

Thurston et. al (1981) used lightweight rigs, fixed to the spine in the lumbar and sacral regions, to record movements. The present study compared this approach with the direct placement of markers on the lumbar spine. It was hoped that it would prove unnecessary to use rigs, since the three-dimensional accuracy of video-based gait analysis systems has improved considerably since those earlier studies.

It was decided that the measurement of lumbar lordosis must not degrade the performance of the system for standard gait analysis. This meant that while it was reasonable to use additional markers on the subject, it was not feasible either to use additional cameras, or to move cameras from their normal positions. This imposed a limit on the accuracy with which marker positions could be measured, since the normal camera-to-subject distance for gait analysis requires a field of view of somewhat more than one full gait cycle.

The present paper reports the results of a pilot study, performed on six normal adults, both standing and walking, using three different marker configurations. Two marker configurations were found to be unsatisfactory, and have since been abandoned. The third marker configuration was adopted, and a reliability study is being conducted on the chosen technique.

METHODS

A comparison of three marker configurations was conducted as a series of single-subject case studies. The subjects were dressed in a swimming costume, which gave access to the lumbar spine. They were fitted with the standard marker set required by the Vicon Clinical Manager (VCM) software (Oxford Metrics, 1992), with a number of additional markers. Except as noted below, the markers were retroreflective spheres 25mm in diameter, fixed to the skin using double-sided adhesive tape. The standard marker set has three markers on the pelvis (one over each anterior superior iliac spine, and one over S2, the spinous process of the second sacral vertebra) and five on each leg (mid-thigh, knee, mid-shank, lateral malleolus, forefoot). The subjects were studied both standing and walking; for the standing trials only, markers were also applied to each heel.

Processing the data followed the normal procedure for the Vicon system, except that the additional markers were identified. The VCM software was used to process the data for all the parameters routinely studied (joint angles, moments and powers), but not the data from the additional markers.

Lumbar lordosis was determined in both the standing and walking data, using the following procedure. The

Vicon files of three-dimensional data (*.c3d) were transferred onto a personal computer. A specially-written program was used to extract the 3-D locations of the markers of interest from these files, and to store them in a form which could be read by the Microsoft Excel spreadsheet program. Subsequent processing took place using Excel, which gave the angles in the sagittal plane for lumbar lordosis and pelvic tilt. The three configurations of additional markers were as follows:

1. FOUR SPINAL MARKERS

Three additional markers were used - one each over the spinous processes of the first, third and fifth lumbar vertebrae (L1, L3 and L5). There was insufficient room on the spine of smaller individuals to accommodate 25mm diameter markers, so four smaller 20mm markers were used (Figure 1a).

2. THREE SPINAL MARKERS

Two additional standard size markers were used, one at L1 and one (known as *L4* for convenience) at the measured mid-point between the L1 and S2 markers (Figure 1b). The lumbar lordosis was estimated by first projecting the marker positions onto the plane of progression, then using one of three algorithms: using the ratio of the depth of the lordotic curve to its length, expressed as a percentage (Figure 2a); measuring the angle between the two lines joining L1-*L4* and *L4*-S2 (Figure 2b); fitting a curve to the three markers and measuring the angle between the tangents to the curve at L1 and S2 (Figure 2c). Either a parabola or the arc of a circle could be used - the results were almost identical.

3. USE OF LUMBAR AND SACRAL RIGS

Rigs with lightweight wands were fixed to the sacrum and to the upper lumbar/lower thoracic spine. The system used by Thurston et al. (1981) used specially constructed rigs, on each of which was mounted four markers. This system was not copied exactly, since it was decided to use components which could be found in most laboratories using the Vicon system, and it was also decided, for the sake of simplicity, to measure lumbar motion only in the sagittal plane, which requires only two markers on each rig. Two standard Vicon rigs were used in the present study, one having a triangular baseplate, used on the sacrum, and one with a linear baseplate, used on the lumbar spine. These rigs consisted of a flat baseplate, from the center of which protruded a 100mm long wand with a retro-reflective marker mounted at its end. A second marker was fixed on the baseplate, as closely as possible to the mounting of the wand. The wand was inclined away from the marker on the baseplate, to the limit of its adjustment. The rigs were fixed to the skin with thick double-sided adhesive tape, the sacral rig over the sacrum, so that the marker on the baseplate was directly over S2, with the wand pointing backwards and downwards. The lumbar rig was fixed to the skin over the upper lumbar and lower thoracic spine, so that the marker on the baseplate was directly over L1, with the wand pointing backwards and upwards (Figure 1c). Prior to fixing the two rigs to the skin, they were placed on the floor in the center of the measurement area, and data were captured from them in this position. This was to define, for each rig, the angle between the baseplate (assumed to be horizontal in this trial) and the line joining the centers of the two markers. Subsequent data processing used this

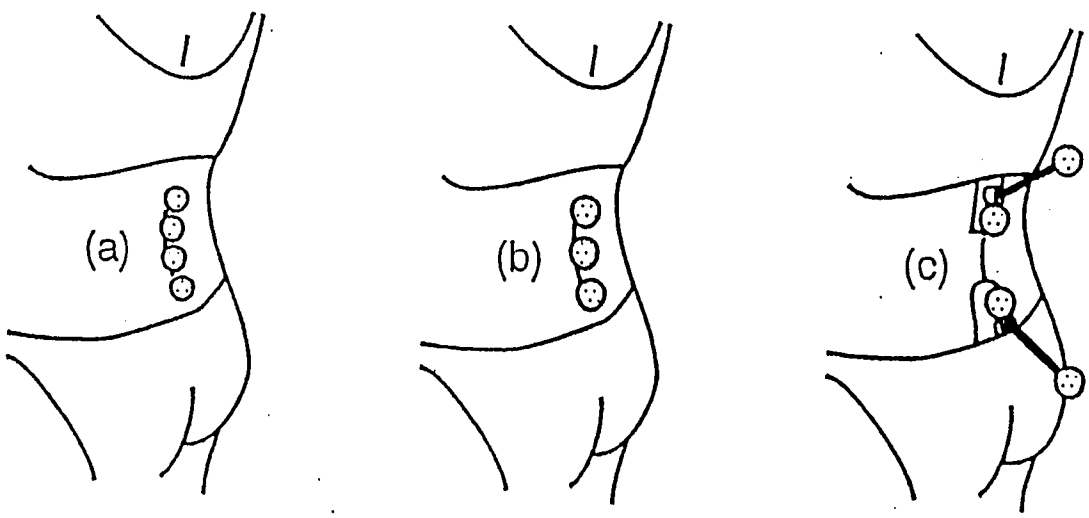


Figure 1: Experimental setups for measuring lumbar lordosis: (a) four spinal markers (b) three spinal markers; (c) lumbar and sacral rigs.

information to measure the angle in the sagittal plane between the baseplate of the rig over the sacrum and the baseplate of the rig over the lower thoracic and upper lumbar spine (Figure 2d).

RESULTS

1. FOUR SPINAL MARKERS

The 20mm diameter markers were satisfactory in larger subjects, but the Vicon system could not reliably distinguish between them in smaller subjects, particularly when they approached each other with extension of the spine. It was decided that this configuration was unsuitable for routine use, and no further testing was performed on it.

2. THREE SPINAL MARKERS

In all the subjects tested, the Vicon system had no difficulty in differentiating the three markers on L1, L4 and S2. Table 1 gives the mean value, standard deviation and coefficient of variation for the lumbar lordosis in the standing position, calculated by the methods described, over a period of 400ms in one subject. The absolute value for the lordosis depends on the algorithm by which it is calculated, but the coefficients of variation were very similar for the three methods using skin-mounted markers.

3. USE OF LUMBAR AND SACRAL RIGS

The lumbar and sacral rigs were easy to attach to the spine in the appropriate positions. For satisfactory positioning of the sacral rig, it was necessary for the subjects to wear briefs with a low cut waistband, without strong elastic. The lumbar lordosis, measured in the standing position using the lumbar and sacral rigs, is given in Table 1. The coefficient of variation was much less than that observed using skin-mounted markers.

Table 1: Mean, standard deviation (S.D.) and coefficient of variation (C.V.) of lumbar lordosis in a standing subject, measured by methods described in text.

Method	Units	Mean	S.D.	C.V.
Ratio	%	2.4	0.58	24.0
L1-L4 v. L4-S2	deg	5.5	1.33	24.0
Curve fit	deg	11.1	2.65	24.0
Using rigs	deg	24.4	0.48	2.0

Figure 3 shows the lumbar lordosis during a single gait cycle, measured simultaneously using three skin-mounted markers (curve fitting algorithm) and using the lumbar and sacral rigs. The data have been "normalized" to 100% of their mean value during the gait cycle, to allow for their different absolute values.

DISCUSSION

It would have been preferable to make measurements of lumbar lordosis based on the position of a number of points on the skin surface, particularly since "rigs", although light in weight, are bound to oscillate somewhat during gait. However, the requirement to make this measurement at the same time as performing clinical gait analysis imposed practical restrictions which made this impossible. In order to visualize a complete gait cycle for each leg, the width of the camera field of view needs to be about 2m at the average camera-to-subject distance. With a television-based system, this imposes a limit to measurement accuracy, which in the present study appeared as a 0.5mm RMS error in 3-D

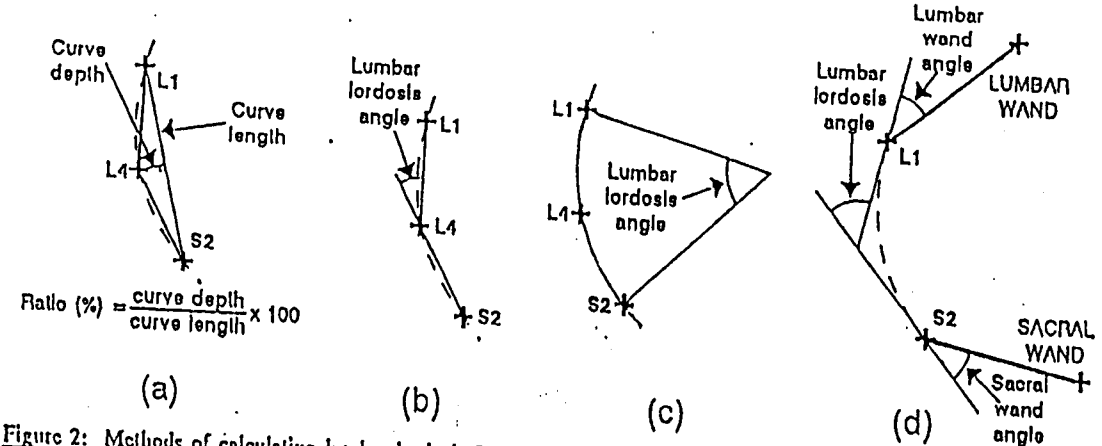


Figure 2: Methods of calculating lumbar lordosis from marker locations: (a) ratio of curve depth to curve length, as a percentage; (b) angle between lines joining L1-L4 and L4-S2; (c) tangents at L1 and S2 to curve fitted to marker locations; (d) angle between baseplates of lumbar and sacral rigs, from marker positions and angle between wand and baseplate, measured in a static trial.

marker location. Greater accuracy could have been obtained by using additional cameras, with a narrower field of view, but this was not considered practical.

It proved impossible for the Vicon system to distinguish reliably between four markers on the spine, since in smaller subjects, and in certain movements in larger subjects, the markers approached too closely together. With a field of view of 2m horizontal by 1.67m vertical, each marker occupied 3 scan lines of the television image, with a gap between them of only a single scan line, making their differentiation very difficult.

This difficulty did not apply when using only three markers on the spine. However, measurement noise did cause significant problems. Although three different algorithms were used to derive lumbar lordosis from the position of the markers, all were equally sensitive to measurement error. Indeed, when the measurements were "normalized" to their mean value, there was very little difference between them.

It is apparent from Table I and Figure 3 that the use of the rigs resulted in much less noisy data, although some measurement noise is still apparent. The use of a five-point moving average to smooth the data produced curves whose appearance was acceptable for routine use.

REFERENCES

Kadaba MP, Ramakrishnan HK, Wooten ME, Gainey J, Gorton G, Cochran GVB (1989) Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. Journal of Orthopaedic Research 7:849-860.

Oxford Metrics (1992) Vicon Clinical Manager Users Guide. Oxford: Oxford Metrics Ltd.

Pearcy M (1986) Measurement of back and spinal mobility. Clinical Biomechanics 1:44-51.

Polster J, Spiker U, Hoefert HR, Krenz JU (1974) Biomechanics in lumbar lordosis. Biomechanics IV (eds. RC Nelson, CA Morehouse). Baltimore: University Press.

Thurston AJ (1982) Reliability studies of a television/computer system for measuring spinal and pelvic movement. Journal of Biomedical Engineering 4:129-132.

Thurston AJ (1985) Spinal and pelvic kinematics in osteoarthritis of the hip joint. Spine 10:467-417.

Thurston AJ, Whittle MW, Stokes IAF (1981) Spinal and pelvic movement during walking - a new method of study. Engineering in Medicine 10:219-222.

Thurston AJ, Harris JD (1983) Normal kinematics of the lumbar spine and pelvis. Spine 8:199-205.

Whittle MW (1982) Calibration and performance of a three-dimensional television system for kinematic analysis. Journal of Biomechanics 15:185-196.

Whittle MW (1991) Gait analysis: an introduction. Oxford: Butterworth-Heinemann.

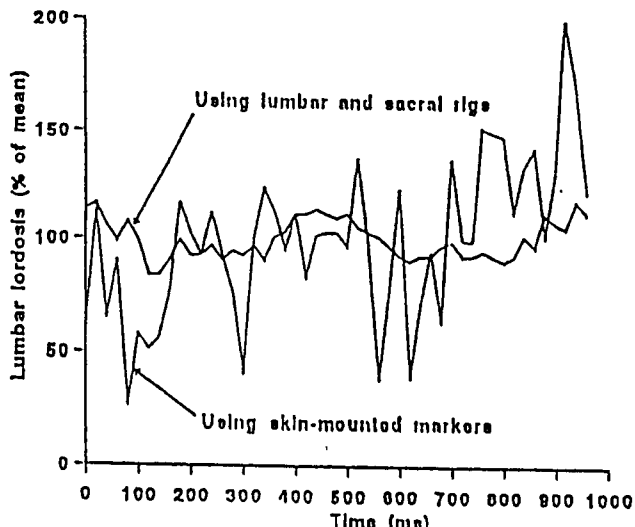


Figure 3: Lumbar lordosis during a single gait cycle (expressed as a percentage of the mean value for the cycle), measured using a) three skin-mounted markers and b) lumbar and sacral rigs.

Appendix C-2

Subject Data Form

Name _____ **Number** _____

Date _____ **Age** _____

Height (cm) _____ **Weight (Kg)** _____

	Left	Right
Leg length (mm)	_____	_____
Knee width (mm)	_____	_____
Ankle width (mm)	_____	_____

Abdominal Measurements

Angle 1 _____

Angle 2 _____

Angle 3 _____

Average _____

Appendix C-3

The following steps were taken to process the data from the raw three dimensional points in terms of distance, in millimeters, from an arbitrary coordinate origin on the laboratory floor, and final calculation of the actual angle of pelvic tilt, and lumbar lordosis, in excel.

1. Use VCM to locate left & right gait cycle start and finish.
2. Run C3D for all files, selecting x, y & z for SACR, LASI, RASI, SACW and LUMW. For static trials (including 018) process all data; for walking trials, go from (left cycle start - 2) to (right cycle finish + 2).
3. Enter Excel. Open FINTEMPL.XLS in C:\VICON\C3D. Put file headers Rnn001 - 004 and 009 - 017 in column P. Re-store as RnnFINAL.XLS.
4. Open DAVIDS.XLM, Rnn001.XLV - 004 & 009 - 017.
5. For each *.XLV file in turn: put cursor in any column below last data value; press ^M. Inspect lowest value (worst S.D.). If it is above about 2.0 inspect data. If not, switch to RnnFINAL and paste special value (^V), in the appropriate place in column O. Close (without saving) each *.XLV file when it has been done. Save RnnFINAL.

6. Open CALCTEMP.XLS; change file references in columns T & U to point to RnnFINAL.
7. Open walking trials Rnn005.XLV - 008.
8. Copy (normal copy) T1 - Y4 from CALCTEMP to each walking file. Insert timing data in Z2 (left cycle start) - AA3 (right cycle finish).
9. Copy special value (^V) columns X & Y for appropriate timing period to RnnFINAL.
10. When all data entered, save RnnFINAL, close all *.XLV files, and open SCALE51.XLS.
11. Go through data in RnnFINAL:
    a. Put cursor on first lordosis value: Press ^A
    b. Switch to SCALE51: Press ^B
    c. Select column indicated by A1: Press ^C
    d. Switch to RnnFINAL. Put cursor on numbered column in row 19 and press ^D.
12. Press ^F to enter means. Close RnnFINAL.
13. Open DTEMP018.XLS, change name in A1, edit file references in columns T & U to point to RnnFINAL, and store as Rnn018.XLS.
14. Open Rnn018.XLV. Copy columns A - S from row 2 to end of data into cell A2 of Rnn018.XLS. Close Rnn018.XLV.
15. Trim surplus rows from columns T - Z, and two extra rows from columns Y & Z.
16. Inspect graphs and adjust scales if needed. Store file.

Appendix C-4

No.	Job	Tilt	Dynam	Files	Abd1	Abd2	Abd3	MeanAb
1	R37	No	No	11	49	48	46	47.7
2	R38	No	No	11	35	33	32	33.3
3	R39	No	No	11	42	40	50	44.0
4	R40	No	No	11	85	78	83	82.0
5	R41	No	No	11	64	64	60	62.7
6	R42	One	No	13	55	58	62	58.3
7	R43	One	No	13	62	68	64	64.7
8	R44	One	No	13	65	70	66	67.0
9	R45	Three	Yes	18	66	66	64	65.3
10	R46	Three	Yes	18	28	35	35	32.7
11	R47	Three	Yes	18	50	47	50	49.0
12	R48	Three	Yes	18	60	57	56	57.7
13	R49	Three	Yes	18	50	48	46	48.0
14	R50	Three	Yes	18	60	64	61	61.7
15	R51	Three	Yes	18	42	44	45	43.7
16	R52	Three	Yes	18	45	52	50	49.0
17	R54	Three	Yes	18	42	45	48	45.0
18	R55	Three	Yes	18	50	49	46	48.3
19	R56	Three	Yes	18	52	53	54	53.0
20	R57	Three	Yes	18	80	80	78	79.3
21	R59	Three	Yes	25	22	15	18	18.3
22	R60	Three	Yes	18	47	50	48	48.3

23	R61	Three	Yes	18	63	66	64	64.3
24	R62	Three	Yes	18	31	36	30	32.3
25	R63	Three	Yes	18	55	57	56	56.0
26	R64	Three	Yes	18	37	40	36	37.7
27	R66	Three	Yes	18	58	60	59	59.0
28	R67	Three	Yes	18	65	64	62	63.7

Lumbar lordosis in normal posture

No.	-----Pre-test-----			-----Post-test----		
1	23.2	23.6	23.1	24.6	22.8	22.6
2	29.8	32.0	30.2	30.8	27.4	28.1
3	21.2	20.8	18.8	18.9	19.7	20.6
4	21.1	20.9	20.6	21.8	20.6	20.3
5	25.6	23.5	24.2	23.7	22.5	23.9
6	24.0	23.5	23.8	23.8	22.9	22.8
7	21.5	22.0	21.3	22.0	22.8	23.9
8	28.2	28.1	28.1	27.6	27.3	29.3
9	17.9	15.9	18.4	18.9	15.3	17.7
10	20.0	20.1	18.8	20.7	19.8	20.4
11	23.4	24.1	24.1	24.8	25.0	24.5
12	20.8	20.6	20.2	14.6	14.3	16.6
13	25.6	25.7	26.1	24.9	26.4	26.0
14	11.2	13.4	12.2	10.9	10.5	11.5
15	18.3	18.5	20.1	18.5	18.7	17.8
16	24.7	27.2	23.4	22.1	23.1	22.5
17	12.7	12.8	13.7	15.0	13.3	12.0
18	19.0	17.3	17.6	15.8	14.8	15.5
19	25.4	23.7	24.1	25.7	25.4	22.2
20	17.2	17.7	17.6	15.4	15.7	18.3
21	25.7	25.7	25.0	23.6	23.2	21.2
22	15.4	17.7	15.8	15.3	14.2	14.1

23	17.9	18.4	17.4	17.6	19.6	18.2
24	17.6	16.0	17.8	17.4	16.7	16.3
25	25.5	24.6	25.1	23.6	23.7	23.9
26	25.0	25.1	24.0	25.2	23.4	23.6
27	15.9	16.3	16.3	16.7	14.3	16.2
28	26.7	26.7	27.2	27.8	27.1	27.3

Pelvic tilt in normal posture

No.	-----Pre-test-----			-----Post-test----		
1	8.2	8.3	9.0	10.1	9.2	9.9
2	12.4	15.0	13.9	15.5	13.0	13.3
3	19.8	19.7	18.0	16.6	19.0	19.2
4	6.8	6.4	5.9	7.4	7.0	6.5
5	11.6	8.7	9.9	9.7	8.6	9.9
6	10.6	9.9	9.6	10.4	8.8	8.8
7	18.3	17.1	17.8	17.0	17.8	18.8
8	19.1	18.4	18.6	18.7	18.0	19.7
9	5.4	4.0	6.7	5.6	3.8	5.3
10	11.4	11.5	10.2	12.1	11.0	11.5
11	12.8	13.7	14.0	14.4	15.0	14.3
12	15.7	15.6	16.0	15.7	14.8	16.9
13	11.3	11.6	11.4	11.4	10.3	10.9
14	3.1	4.7	4.1	2.5	2.6	3.1
15	8.1	8.6	9.1	8.3	8.4	7.2
16	14.9	17.0	13.5	11.9	13.0	12.7
17	14.2	13.9	14.4	14.3	13.4	18.0
18	11.9	12.1	11.6	12.3	11.7	10.8
19	10.4	8.5	9.0	10.6	10.1	7.1
20	13.0	14.9	14.5	11.5	12.6	15.5
21	15.1	15.5	14.5	14.6	14.8	12.7
22	9.0	11.4	10.2	11.0	9.4	9.1

23	14.9	16.2	15.7	14.5	16.2	15.6
24	6.9	6.0	7.1	6.7	6.3	6.2
25	17.2	16.9	17.3	15.8	15.2	17.8
26	10.3	10.1	9.0	8.5	7.4	8.7
27	4.4	4.8	4.2	4.3	1.5	4.1
28	17.2	17.2	17.6	17.3	17.3	17.4

Pelvic Tilt and Lumbar Lordosis in Maximal Anterior Pelvic Tilt Posture

Posture:	Ant.	Ant.	Ant.	Ant.	Ant.	Ant.
Measure:	Pelv.	Pelv.	Pelv.	Lum.	Lum.	Lum.
R45002	14.2	18.0	18.1	27.0	29.8	29.1
R46002	23.7	23.3	25.4	34.0	34.1	35.6
R47002	26.6	28.7	28.8	37.0	39.8	39.5
R48002	28.8	26.9	27.8	28.3	25.5	26.6
R49002	24.5	24.4	25.1	38.0	37.8	38.5
R50002	15.0	17.9	17.2	24.6	27.9	27.2
R51002	19.1	17.7	18.9	29.6	27.6	29.1
R52002	23.0	23.7	24.7	35.6	36.4	37.0
R54002	21.0	25.4	25.0	23.0	27.3	26.3
R55002	23.1	23.5	21.7	28.7	29.4	27.2
R56002	29.0	27.2	26.2	43.0	42.1	40.7
R57002	21.6	16.1	20.9	23.8	18.3	22.9
R59002	26.3	24.9	26.7	34.5	33.8	36.3
R60002	13.9	14.8	14.3	17.5	20.5	18.2
R61002	30.7	33.6	33.5	29.9	32.9	32.4
R62002	23.5	22.4	20.4	35.6	34.0	32.3
R63002	24.2	24.1	21.6	30.7	30.2	26.2
R64002	22.3	20.1	21.9	36.7	34.1	35.0
R66002	16.4	7.0	18.1	28.7	21.9	31.3
R67002	28.9	27.0	25.2	35.2	33.5	31.7

Pelvic Tilt and Lumbar Lordosis in Maximal Posterior Pelvic Tilt Posture

Posture:	Post.	Post.	Post.	Post.	Post.	Post.
Measure:	Pelv.	Pelv.	Pelv.	Lum.	Lum.	Lum.
R45002	-4.5	-3.6	-3.4	13.1	14.4	11.8
R46002	2.6	2.1	1.6	12.0	11.1	9.8
R47002	0.8	-1.0	-0.7	12.3	9.5	8.6
R48002	7.9	6.5	9.3	8.2	8.2	11.5
R49002	3.0	2.5	3.5	17.5	18.0	18.0
R50002	-4.8	-4.8	-2.9	3.7	3.6	5.3
R51002	-0.1	-0.1	1.3	9.8	10.5	11.3
R52002	4.8	5.6	5.5	15.5	16.5	15.3
R54002	0.9	0.1	2.4	-3.3	-4.7	-1.4
R55002	-0.4	0.9	0.5	6.3	7.7	7.3
R56002	-1.1	-3.7	-2.0	13.0	10.8	12.2
R57002	7.7	9.4	9.8	11.3	12.9	15.1
R59002	9.1	11.9	10.9	18.3	21.1	19.3
R60002	8.3	7.8	3.0	17.8	12.4	14.1
R61002	6.2	6.0	4.7	9.6	11.5	9.8
R62002	-5.9	-2.4	-2.1	2.1	5.5	6.4
R63002	7.1	3.7	17.8	21.7	17.4	25.7
R64002	-1.9	-1.1	-1.2	14.2	14.6	15.4
R66002	-5.6	-5.3	-5.1	10.7	10.7	11.1
R67002	10.3	11.6	12.6	20.6	20.9	21.8

Pelvic Tilt and Lumbar Lordosis During Gait

	0% LORDOSIS				0% TILT			
No.	Walk1	Walk2	Walk3	Walk4	Walk1	Walk2	Walk3	Walk4
R37	25.9	28.3	26.4	28.5	9.1	8.2	7.9	8.7
R38	39.2	39.5	38.6	38.4	14.7	15.7	15.8	15.2
R39	27.5	25.6	28.1	27.8	16.9	16.7	18.6	18.1
R40	28.1	28.7	29.0	29.4	6.2	7.6	7.7	8.2
R41	27.3	27.4	26.7	26.3	6.5	6.2	6.2	6.1
R42	31.9	31.4	31.1	31.0	8.2	8.7	8.2	7.7
R43	33.9	34.0	27.8	32.9	20.1	20.1	8.8	18.8
R44	28.1	28.0	29.3	33.0	16.9	15.4	16.0	17.1
R45	29.0	29.5	29.6	29.4	3.2	4.7	5.5	5.8
R46	22.1	24.2	23.4	22.9	9.0	9.4	9.4	8.5
R47	30.1	33.1	31.0	32.8	9.8	11.1	9.4	10.5
R48	29.1	31.8	30.0	30.0	15.1	14.9	15.0	16.2
R49	29.1	32.5	30.6	27.3	8.3	9.2	9.9	8.2
R50	19.7	21.0	22.4	22.7	3.3	3.3	3.5	3.9
R51	24.0	24.1	25.9	24.3	5.9	6.2	6.2	5.0
R52	28.3	27.2	27.7	26.2	10.3	9.9	9.9	9.8
R54	18.9	17.6	16.8	18.2	15.4	13.9	14.2	14.8
R55	21.1	22.8	22.6	22.3	12.6	12.0	13.1	11.3
R56	31.0	31.1	30.0	31.2	11.6	10.2	9.6	9.7
R57	18.3	20.7	18.7	21.6	12.4	12.5	14.7	12.8
R59	37.0	39.1	35.9	35.7	18.9	18.0	18.1	17.5
R60	26.3	26.5	28.0	27.2	11.1	8.0	8.7	8.6

R61	20.9	21.8	20.5	22.1	12.3	12.2	12.3	13.1
R62	27.6	26.6	28.6	26.9	9.7	9.1	9.3	9.8
R63	36.6	36.4	36.4	35.7	10.3	10.7	8.4	9.8
R64	31.3	30.7	31.4	30.3	8.0	7.4	8.4	9.2
R66	16.8	18.3	18.0	19.0	3.5	3.0	2.8	3.5
R67	40.6	39.4	39.6	38.7	17.6	16.3	17.2	16.7

Pelvic Tilt and Lumbar Lordosis During Gait

	25% LORDOSIS				25% TILT			
No.	Walk1	Walk2	Walk3	Walk4	Walk1	Walk2	Walk3	Walk4
R37	25.6	24.8	24.1	25.3	11.1	11.2	7.8	10.6
R38	38.4	41.3	39.4	39.2	12.8	13.4	14.4	13.0
R39	27.7	26.5	28.6	29.7	16.7	18.1	18.1	17.6
R40	25.9	27.1	27.4	26.3	5.9	7.7	7.9	8.2
R41	25.2	25.2	24.4	24.6	6.7	7.6	7.6	6.5
R42	29.5	30.4	28.3	29.4	7.1	8.1	7.4	7.3
R43	34.5	34.5	27.8	34.0	19.8	20.4	8.8	19.8
R44	26.8	26.4	28.7	30.2	14.6	14.9	15.9	15.4
R45	25.5	27.9	27.1	26.7	2.5	4.4	3.9	4.6
R46	25.4	25.5	26.2	25.4	10.5	9.4	9.8	10.2
R47	29.0	33.0	29.4	31.7	8.2	9.4	7.1	8.2
R48	29.3	28.7	27.6	28.7	15.0	14.6	15.1	17.1
R49	31.4	30.9	31.2	30.3	9.2	8.5	10.2	9.5
R50	20.1	20.3	21.4	21.1	2.0	2.3	2.6	2.1
R51	24.4	24.8	25.5	24.4	4.7	4.7	4.9	4.6
R52	26.3	24.9	25.3	24.0	8.2	8.0	7.8	7.5
R54	18.5	17.8	16.5	18.1	14.1	14.1	12.7	14.5
R55	20.8	21.4	22.2	22.1	11.6	10.8	11.4	10.4
R56	34.9	30.7	31.0	33.5	10.8	9.5	9.2	10.7
R57	16.8	19.8	17.8	18.4	12.8	12.8	14.2	13.0
R59	41.4	42.3	40.1	39.4	19.0	19.3	17.9	19.0
R60	24.1	24.0	25.1	23.6	9.1	7.5	8.5	8.1

R61	20.5	21.1	19.9	19.3	10.3	9.6	10.3	11.0
R62	25.9	26.6	28.2	26.7	7.4	8.5	8.3	8.2
R63	37.4	36.3	35.1	35.0	10.9	11.7	8.0	10.5
R64	30.3	30.5	29.7	30.7	8.6	7.6	8.0	8.7
R66	16.5	17.4	18.8	18.6	1.3	1.3	1.4	1.7
R67	39.4	39.3	39.6	38.5	17.2	16.0	17.6	17.4

Pelvic Tilt and Lumbar Lordosis During Gait

	50% LORDOSIS				50% TILT			
No.	Walk1	Walk2	Walk3	Walk4	Walk1	Walk2	Walk3	Walk4
R37	24.6	23.6	26.3	24.4	11.2	10.1	8.9	7.9
R38	41.1	43.5	41.5	41.4	14.3	15.6	15.7	15.8
R39	28.9	25.3	28.8	29.2	17.7	18.7	17.9	16.4
R40	28.7	27.8	30.0	26.6	6.5	7.2	6.8	6.6
R41	29.1	26.3	27.5	27.5	6.3	6.5	7.0	7.2
R42	32.9	33.0	30.8	32.3	8.7	9.2	8.5	8.3
R43	34.9	33.7	27.8	33.7	18.9	19.0	8.8	17.4
R44	27.7	26.9	25.5	32.0	15.5	15.0	14.5	16.9
R45	28.5	30.7	30.8	30.0	4.4	4.2	5.2	6.7
R46	22.5	24.4	24.5	23.9	8.2	9.0	7.7	9.2
R47	28.2	34.0	30.0	33.4	9.7	10.5	8.3	10.2
R48	30.1	32.9	30.6	31.5	13.6	14.7	14.3	16.2
R49	32.4	32.2	31.5	32.6	9.0	8.2	10.2	8.5
R50	21.2	23.0	23.4	22.7	3.4	4.0	4.0	3.2
R51	26.3	26.7	25.0	25.0	6.2	6.6	5.8	5.5
R52	28.4	28.4	29.3	27.4	8.8	8.3	8.5	7.9
R54	18.0	17.8	16.6	17.6	15.6	16.4	14.2	15.5
R55	20.6	22.5	21.8	21.4	11.7	10.5	12.5	11.2
R56	33.5	31.7	31.9	32.8	12.3	10.5	10.0	11.1
R57	21.2	21.8	20.8	20.0	12.4	11.0	12.4	11.9
R59	36.7	38.9	35.6	35.8	16.8	16.9	15.3	17.0
R60	26.4	26.9	27.5	27.6	9.1	8.8	8.7	8.7

R61	20.7	22.2	21.4	20.9	11.7	12.0	13.1	12.3
R62	29.3	28.5	29.4	28.4	10.8	10.5	10.7	9.9
R63	37.5	37.5	37.2	36.8	10.1	11.0	9.7	11.3
R64	29.9	29.3	30.1	29.4	8.7	6.6	8.1	8.1
R66	19.8	21.4	21.7	23.1	2.5	2.6	3.3	3.1
R67	41.4	40.4	41.0	39.6	15.9	15.6	15.6	16.1

Pelvic Tilt and Lumbar Lordosis During Gait

	75% LORDOSIS				75% TILT			
No.	Walk1	Walk2	Walk3	Walk4	Walk1	Walk2	Walk3	Walk4
R37	26.9	26.7	27.3	27.1	12.6	11.2	9.7	9.9
R38	40.1	41.5	39.7	37.8	13.2	13.3	14.0	13.8
R39	28.4	24.9	28.1	28.7	17.9	17.8	18.3	16.5
R40	27.9	27.4	28.4	26.4	6.1	8.4	8.0	6.6
R41	26.0	25.8	26.4	26.1	8.2	7.8	8.3	8.9
R42	30.9	31.2	29.6	30.6	8.2	8.4	8.3	8.2
R43	34.6	34.2	27.8	33.8	18.9	20.0	8.8	18.4
R44	26.2	26.5	26.0	30.5	15.4	14.9	15.4	16.5
R45	29.0	31.1	29.8	30.3	6.2	5.3	5.2	5.9
R46	22.6	23.2	24.0	23.0	9.6	10.1	9.0	9.3
R47	28.1	33.3	31.7	34.7	8.3	8.6	7.7	9.0
R48	27.5	31.2	28.0	28.9	13.3	16.1	14.4	15.8
R49	32.5	32.7	32.7	32.6	9.1	8.0	8.7	9.1
R50	20.0	20.6	21.5	21.6	-1.0	0.7	1.0	1.0
R51	25.4	25.5	25.2	23.9	5.9	6.3	5.9	5.7
R52	27.4	26.2	27.1	25.8	6.7	5.8	6.7	6.2
R54	19.2	18.3	18.3	18.6	13.8	13.4	13.8	15.1
R55	19.5	21.1	21.8	20.7	12.1	10.1	13.3	10.9
R56	32.0	31.3	32.5	31.4	10.9	9.2	8.9	9.4
R57	19.6	20.0	19.4	19.0	12.3	12.3	12.1	12.8
R59	40.0	41.2	39.7	38.8	17.4	16.9	16.4	18.3
R60	24.9	25.7	24.6	25.0	8.9	8.1	8.2	9.5

R61	20.7	20.2	18.4	18.8	10.5	10.6	11.2	10.9
R62	27.4	26.6	27.9	27.7	8.8	8.0	7.7	8.1
R63	37.7	36.7	36.4	36.2	11.2	10.7	9.6	11.4
R64	31.7	30.0	31.5	30.5	9.3	9.3	8.0	9.2
R66	17.5	19.1	18.6	20.2	2.0	1.3	1.4	2.2
R67	39.6	39.3	40.6	40.3	16.1	15.5	16.0	16.5

Pelvic Tilt and Lumbar Lordosis During Gait

	100% LORDOSIS				100% TILT			
No.	Walk1	Walk2	Walk3	Walk4	Walk1	Walk2	Walk3	Walk4
R37	27.6	26.9	26.1	26.6	12.6	10.1	8.6	9.7
R38	38.6	39.0	38.4	38.3	14.1	13.6	13.9	14.9
R39	28.8	27.1	28.1	28.5	18.7	18.4	17.7	17.4
R40	29.1	28.6	28.7	29.1	5.8	8.0	6.4	8.5
R41	26.6	26.0	25.1	26.5	5.8	6.0	6.6	7.2
R42	33.0	33.3	33.3	32.0	8.3	8.5	8.3	8.8
R43	33.9	34.9	27.8	34.6	18.9	20.2	8.8	19.1
R44	29.0	28.4	30.3	33.1	17.5	16.1	15.4	16.0
R45	29.4	30.8	30.2	30.2	5.5	6.0	5.9	5.3
R46	22.6	22.5	22.5	22.5	10.1	8.8	8.9	8.7
R47	31.9	34.1	30.8	34.5	10.5	10.5	8.8	10.0
R48	29.5	32.9	32.3	29.7	15.7	16.0	16.5	16.2
R49	27.6	31.3	30.2	29.4	7.8	8.3	7.9	8.5
R50	21.6	22.9	23.9	23.8	2.5	2.2	3.5	3.5
R51	23.9	23.9	24.6	22.3	5.9	6.3	6.0	6.3
R52	28.5	28.1	27.5	27.3	9.2	8.3	9.9	9.2
R54	19.1	18.4	18.4	17.6	15.6	14.1	14.4	14.5
R55	21.8	23.1	22.8	21.2	12.4	11.5	13.4	12.2
R56	31.6	30.0	31.5	32.7	11.2	9.9	9.9	9.8
R57	20.6	20.9	22.1	20.6	12.8	11.9	12.3	12.2
R59	37.5	40.2	40.7	38.2	17.3	17.1	17.8	16.6
R60	27.8	26.5	26.9	27.0	10.4	8.9	9.6	9.4

R61	21.9	21.7	21.4	21.5	13.2	12.5	12.3	11.2
R62	27.8	28.1	28.3	28.3	8.8	9.9	8.1	9.8
R63	34.1	34.7	36.8	36.0	9.6	9.5	9.4	10.6
R64	30.3	31.1	31.1	32.6	9.1	8.7	8.1	8.6
R66	17.6	18.1	16.0	21.8	3.1	2.0	2.3	3.8
R67	39.5	41.0	40.2	40.7	16.7	15.8	17.1	17.5

VITA

David Levine was born in Monticello New York on July 13, 1965. He graduated from Monticello High School in 1982. He attended The University of New England in Biddeford Maine, and received a Bachelor of Science in Physical Therapy in 1986. He received a Master of Science in Orthopedics from Boston University in 1990. He attended The University of Tennessee, Knoxville from Spring of 1991 until August of 1994 when he received the degree of Doctor of Philosophy, with a major in Education.

He is currently employed as an Assistant Professor of Physical Therapy at The University of Tennessee at Chattanooga.