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ABSTRACT

MODEL AND CLINICAL DEVICE DEVELOPMENT FOR NONINVASIVE DIAGNOSIS OF LOW BACK PAIN AND DYSFUNCTION

by
Ravi Patraju

Millions of people suffer from acute or chronic low back pain. In order for proper treatment to be administered, a patient must receive an accurate diagnosis. Therefore, it is critical to develop an objective model to measure the motion and any dysfunction of a patient's low back. Only then can a physician effectively implement the correct therapy and measure its effectiveness through follow-up to minimize or eliminate low back pain.

Numerous cadaveric, active and passive studies have been done to understand the mechanics of low back disorders. However, only living human subjects suffer from low back pain and therefore cadaveric studies may be limiting. Furthermore, the author believes that an active study may also be deficient since the measuring device in such a study is manipulated by the test subject. This would not provide objective measured data. Therefore, this study employs the passive approach whereby objective data can be attained from analyzing a living human subject's low back.

The Anatomic Torsion Monitor (ATM) is designed to diagnose any dysfunction in a human subject's low back. The ATM is used to test the low back of a living human subject while in a passive supine position. The force-displacement responses, generated by the ATM, are used to quantify stored energy and coercive forces in the low back region of a subject. The values of the stored energy and coercive forces are then used to make inferences about the physiological condition of the subject's low back.

MODEL AND CLINICAL DEVICE DEVELOPMENT FOR NONINVASIVE DIAGNOSIS OF LOW BACK PAIN AND DYSFUNCTION

by
Ravi Patraju

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APPROVAL PAGE

MODEL AND CLINICAL DEVICE DEVELOPMENT FOR NONINVASIVE DIAGNOSIS OF LOW BACK PAIN AND DYSFUNCTION

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This thesis is dedicated to my family

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CHAPTER 1

INTRODUCTION

1.1 Objective

Low back pain continues to be a significant public health problem, with 85% of all people being affected at some time in life [National Institute of Health, 1997]. Symptoms are most common in middle-aged adults, with back pain equally common in men and women. The recurrence rate of low back pain is also high, with lifetime recurrences reported at 85%. Typical recovery rates of people reported were 60-70% in six weeks and 80-90% in twelve weeks. After twelve weeks, full recovery is usually slow. Each year about 2% of the work force have back injuries and the direct cost of treatment was estimated to be $11.4 billion dollars in 1994. The goal is to develop methods to accurately diagnose low back disorders and devise appropriate methods of treatment. The goal of this study is to present the concept of low back pain and the means of formulating a viable model to diagnose low back disorders.

1.2 Anatomy of the Lower Back

The spinal column, as shown in figure 1.1, is made up of twenty-four (24) vertebrae, which are divided into seven (7) cervical vertebrae, twelve (12) thoracic vertebrae and five (5) lumbar vertebrae. Connected to the lumbar region is the sacrum, which is a triangular bone comprising of five (5) fused vertebrae inserted like a wedge between the two pelvic bones. To the end of the sacrum is the coccyx, which is usually referred to as the tailbone and is made up of four (4) tiny fused vertebrae.

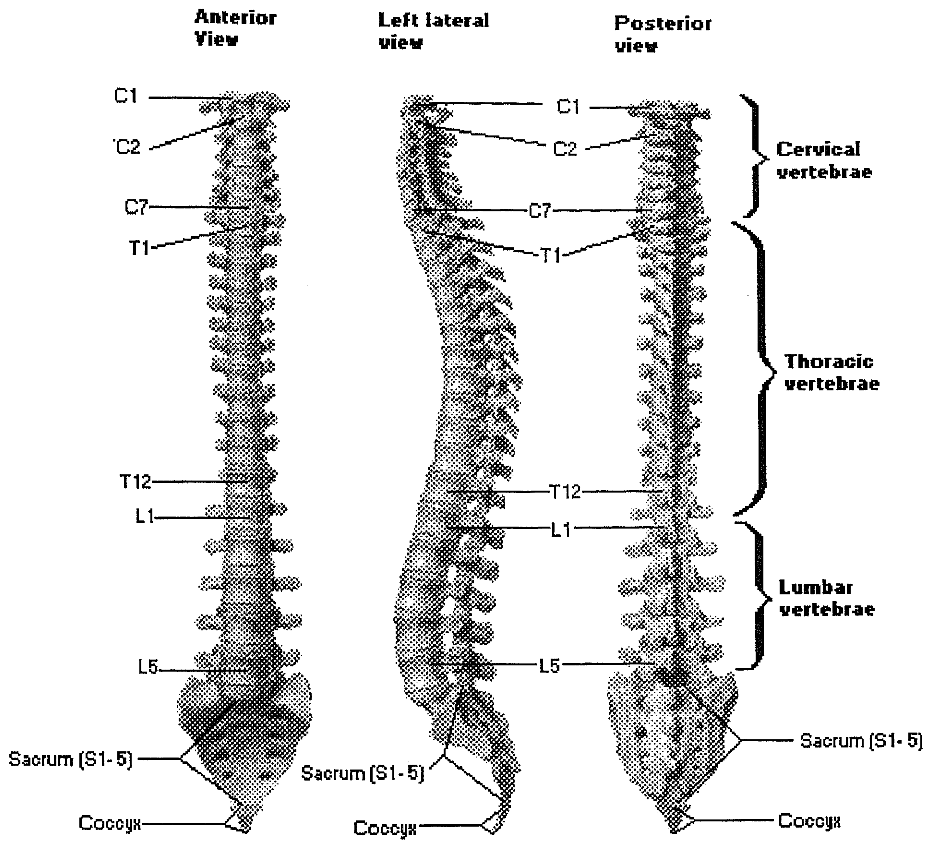

Figure 1.1 Spinal Column

Between each vertebra are connecting links called intervertebral discs, as shown in figure 1.2. The intervertebral discs function as universal joints, permitting greater motion between vertebrae than if the vertebrae were in direct contact with each other. The vertebral bodies are designed to bear mainly compressive loads, with those in the lumbar region being larger than those of the thoracic and cervical regions. The intervertebral disc itself is of great importance, since it bears and distributes loads and controls excessive motion. The inner portion of the intervertebral disc is called the nucleus pulposus, which is a gelatinous, high water content substance. The nucleus pulposus, which becomes less hydrated with aging, is very instrumental in withstanding compressive forces. Surrounding the nucleus pulposus is a tough outer covering called the annulus fibrosus (composed of fibrocartilage), which is instrumental in withstanding high bending and torsional loads. The intervertebral disc is separated from the vertebral body by the end plate, which is made up of hyaline cartilage.

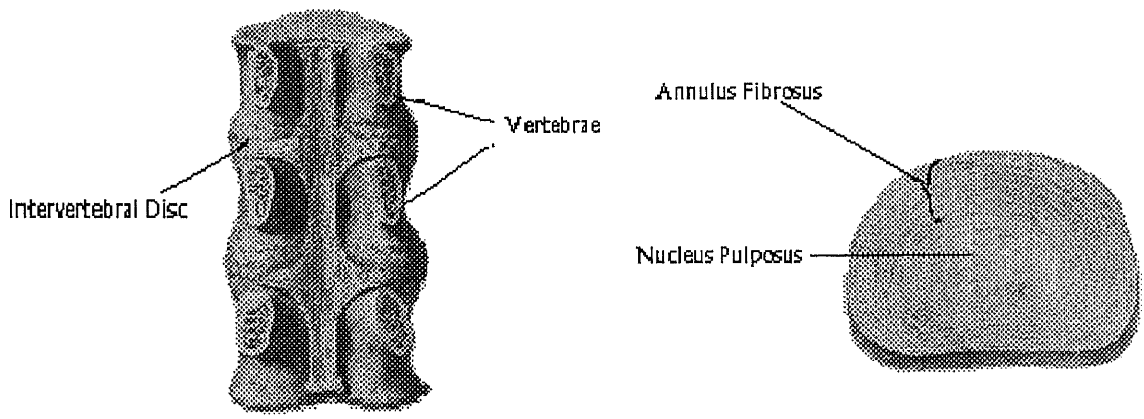

Figure 1.2 Intervertebral Disc

The vertebrae are held together by ligaments, most of which have high collagen content thus limiting their extensibility during spine motion. There are two major ligaments bordering the front and back of the vertebral bodies, which are called the anterior longitudinal ligament as shown in figure 1.3 and the posterior longitudinal ligaments as shown in figure 1.4. In the upright and supine positions, the anterior longitudinal ligament bears the greatest load, while the posterior longitudinal ligament bears its greatest load when the spine is arched forward. Other important ligaments associated with the lower back are the supraspinous ligament, which helps reduce the effects of shear forces placed on the lumber spine and the iliolumbar ligament, which limits the movement of the sacoiliac joints.

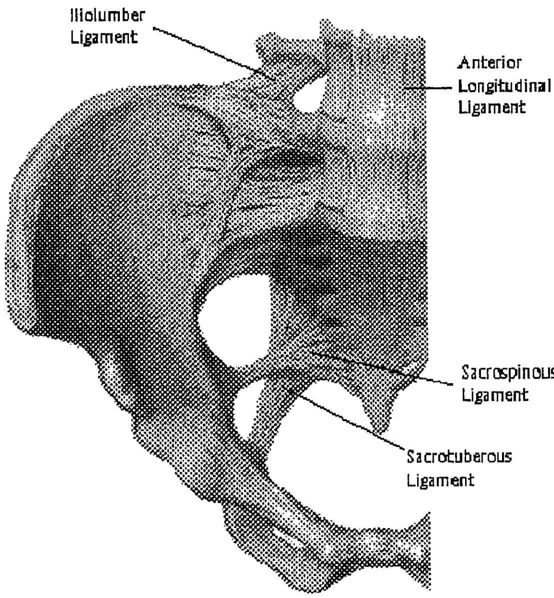

Figure 1.3 Anterior View of Ligaments of the Lumbosacral Spine

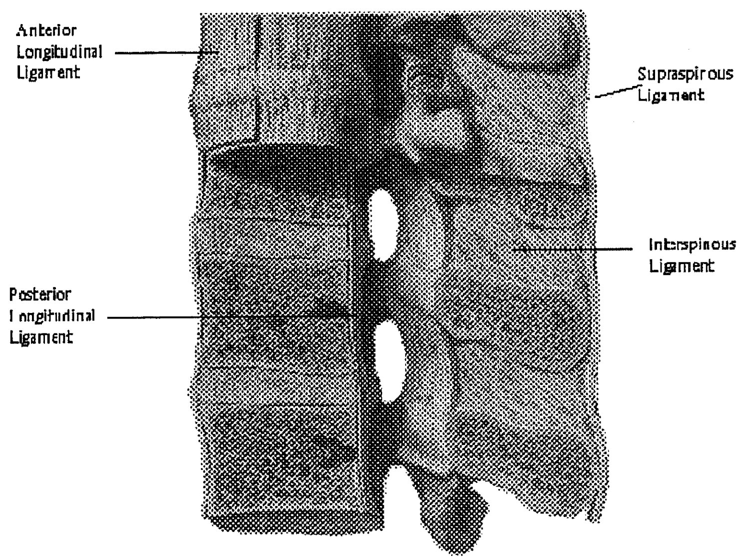

Figure 1.4 Posterior View of Ligaments of the Lumbosacral Spine

Muscles, soft tissues and nerves are also important structures of the lower back. Although not anatomically part of the lower back, the various muscle groups, such as the anterior abdominal muscles, external abdominal muscles, internal abdominal oblique, gluteal muscles, hamstrings, quadriceps, just to name a few are very important support structures to the lower back region.

1.3 Affected Regions of Low Back Pain

The region of the lower back that is the focus of disorders is the lumbosacral spine, which can be considered to be comprised of the fourth lumbar (L4), fifth lumbar (L5) and the sacrum. Loading applied to this region is primarily through body weight, muscle activity, stresses applied by ligaments and externally applied loads. Both static and dynamic loading can produce disorders to the lumbosacral spine, since attributes such as flexion, rotation, extension and shearing are present in day to day activities. Injury to tissues, ligaments or intervertebral discs, will occur when the applied loads (compressive, shearing and rotational) exceed the endurance limits of the respective structures.

In the lumbosacral spine, deep somatic pain has been determined to occur in the vertebral columns, surrounding muscles and the attaching tendons, ligaments and fascias [Borenstein and Wiesel]. This type of pain results from injury, which is referred to as spondylogenic pain and occurs as a result of lifting objects while in an awkward position.

Disruption of a normal intervertebral disc is referred to as disc herniation. The L4-L5 and L5-S1 regions are more limited in movements than the other areas of the spine, mainly due to existence of numerous ligaments and facet joints. When a disc herniates, the nucleus pulposus escapes through the fibers of the annulus fibrosus and applies pressure on the nearby nerve thus resulting in pain. Disc herniation in the L4-L5 and L5-S1 regions account for approximately 90% of lesions; approximately 80% of the population will experience significant pain in the course of a herniated disc. Most disc herniation occurs during the third and fourth decade of life while the nucleus pulposus is still gelatinous. Damage to the intervertebral discs can occur through prolonged inappropriate postures in sitting or standing, and inflammatory conditions through injury or age. Excessive (dependent on the human anatomy, inappropriate positioning and engaged activities) torsional, compressive and coupled loading applied to the lumbosacral spine may also result in injury and pain. An automobile accident and any other high velocity impact are prime candidates in causing herniated discs. However, herniated discs do not have to be the result of a high velocity impact, since it has been determined the condition may arise from many cycles of combined flexion, compression and torsional loading [McGill, 1997].

The ligaments surrounding the vertebral column and especially those connecting the L5 to the S1 are subjected to high normal stresses even from regular everyday activities. The ligaments in the lumbosacral region are very important in the support of the lower back to maintain upright, sitting and flexed positions. However, through poor posture, excessive force due to lifting and even through loss of elasticity through aging, these ligaments are sometimes extended beyond the mechanical properties, thus resulting in pain. Falling from a slip, thus driving the pelvis forward on impact and creating a posterior shearing of the lumbar joints when the spine is fully flexed may result in injury of the ligaments.

Soft-tissue disorders in the lumbosacral region also contribute to low back pain. The quadratus lumborum, which is the muscle between the bottom rib and the top of the pelvis, is a deep muscle, located underneath the paraspinal muscles and is very instrumental in coordinating upper and lower body movements. Therefore, any disorders in this region will affect the thick muscles near the surface on either side of the spine. Also, any muscle problems would contribute to tissue problems, since the lumbosacral region is rich in connective tissues such as thoracolumbar fascia and gluteal aponuerosis. The buttock muscles, which include the three gluteal muscles and the deep lateral rotators of the hip, are also prime candidates for the origination of low back pain.

1.4 Present Diagnosis of Low Back Pain

The diagnosis of low back disorders is a very involved process, which begins with a history profile of the subject with emphasis on factors relating to pain, such as primary complaint, family history, past history, social history and present illness. Other factors such as age and sex are also instrumental, since the degenerative factors and differences in structures of the lumbosacral region are also prime candidates of disorders.

The physical examination of the lumbosacral region follows the interview process, so as to identify abnormalities through static and dynamic analyses. The goal is to identify visible deformities in the L4-L5 and L5-S1 regions, through monitored activities of the patient in the standing, sitting and supine positions. Palpation is then used to identify abnormalities in the vertebral bodies. Through this method, localized tenderness can be identified, which may suggest the presence of an infection, tumor or fracture in the vertebral bodies. However, the palpation method is based on experience and subjective analyses of osteopathic physicians in assessing a possible low back disorder. Physical therapists demonstrated a much better ability to assess spring stiffness than the posteroanterior stiffness of human spines [Maher and Adams, 1994].

There are also some instruments available to the health care provider to identify disorders of the lumbosacral spine. These are radiographic techniques, some of the most popular being X-ray, magnetic resonance imaging (MRI) and computer tomography (CT) scanning. Radiographic techniques are frequently used to diagnose low back disorders by attempting to visualize the structures of the lumbosacral spine. X-rays are used to detect structural abnormalities such as spondylolisthesis, which is a condition involving all or part of a vertebra to slip on the one below it. Other deformities detected by x-rays are vertebral spacing and osteoporosis. CT scans are also instrumental in the evaluation of abnormalities of the lumbosacral spine, by creating cross-sectional images of the internal structure of the various levels. A CT scan assesses not only the bony configuration, but also the soft tissue, which allows for the assessment of ligaments, nerve roots, free fat and intervertebral disc protrusions. MRI also has demonstrated superior capabilities in assessing soft tissues in and around the spinal column and herniated discs. However, radiographic techniques must be used at the appropriate time, which is after a sound evaluation is made, in order to attain a true diagnosis.

1.5 The Need for Objective Models of Low Back Disorders

As mentioned previously, results obtained from radiographic techniques such as x-rays, MRI and CT scans are only valid when used in conjunction with a clinical assessment, since the respective results may be misinterpreted if considered without it. The present methods of diagnosing a low back disorder are associated with static assessment, which have been deficient in correcting certain low back disorders. Therefore, a dynamic assessment may be the answer to offering a better perspective of a disorder in the lumbosacral spine. Since no sound methods exist at this point to accurately identify disorders of the lumbosacral spine, the need for obtaining reliable models is critical. The goal of the study presented in this thesis is to present a model, using a load-displacement analysis to formulate a dynamic assessment of the lumbosacral spine. A reliable model of identifying disorders of the lumbosacral spine would minimize time and money in obtaining a sound clinical evaluation and may increase the success rate of correcting such disorders.

CHAPTER 2

HYSTERESIS LOOP ANALYSIS IN MEDICINE

2.1 Introduction

Inelastic and plastic materials exhibit important phenomena during loading and unloading processes. Such materials are observed to behave in a linearly elastic manner during the loading stage, but show a permanent strain during unloading. When a material is loaded cyclically in the inelastic range, the area enclosed by the diagram as shown in figure 2.1 gives the dissipated energy per cycle.

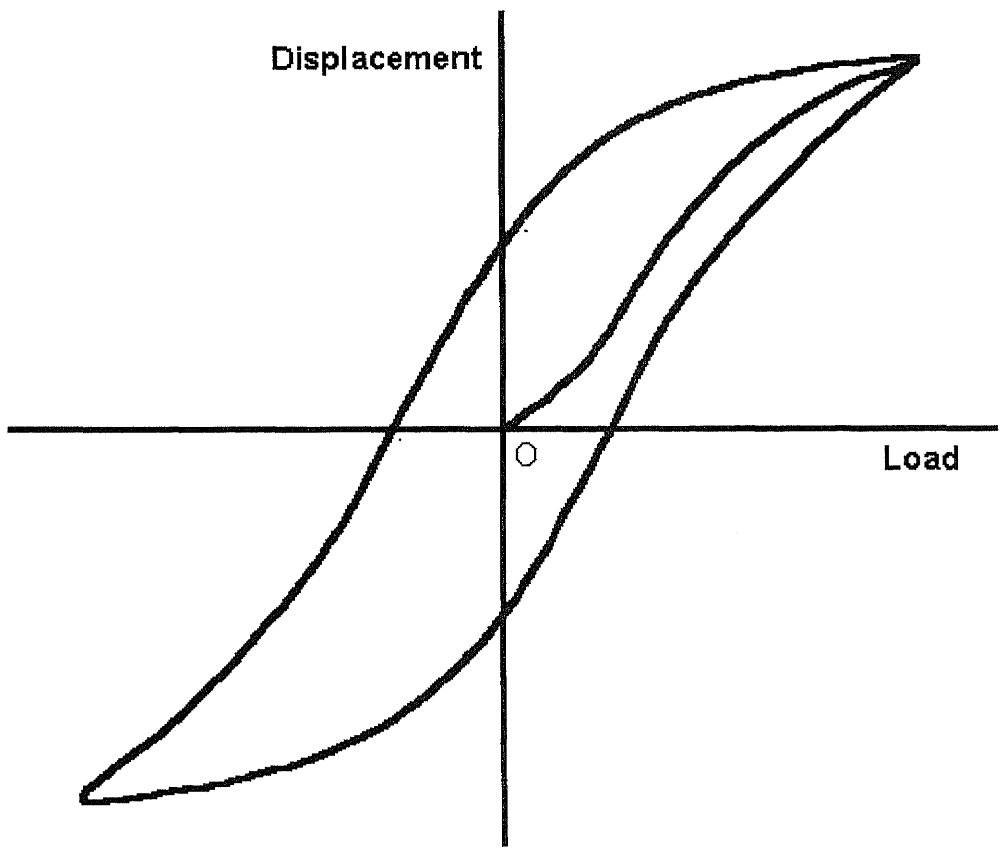

Figure 2.1 Ideal Hysteresis Loop

The variables are usually in the form of a force-displacement or stress-strain relationship and the diagram is referred to as a hysteresis loop. Many applications involving biological systems, such as cells, tissues, organs, limbs, etc employ the use of the hysteresis loop analysis. Since the focus of the present study is related to a load-displacement concept, the referenced studies involving biological systems will be limited to similar measurements.

2.2 A Microscopic Study

A microscopic study involving the osteons of the human skeleton was done by Ascenzi et al., where the cyclic loading of longitudinally distributed and alternately distributed osteons were studied [Ascenzi, Ascenzi, Benvenuti, Mango, 1997]. The study involved the investigation of cyclic loading of twenty (20) longitudinal and eighteen (18) alternate fully calcified osteonic samples of cylindrical shapes and 500 μm in length. The loading was applied through a concept called pinching, the effects of which were observed in the slope of the deflection curve of a load-deflection analysis. Each osteonic sample was loaded beyond the proportional limit and the load-deflection readings were recorded, which were subsequently converted to a stress-strain relationship. For each sample, the stress-strain relationship was plotted and the resulting diagram was described by a hysteresis loop. The varying sizes of the hysteresis loops for the various samples were used to identify the difference in behavior of the two types of osteonic samples. Further analysis concluded that as the number of cyclic loading increased so did the absorption of energy. After analyzing the resulting hysteresis loops the authors were able to conclude that the longitudinal osteons under compression were susceptible to buckling, while the alternate osteonic samples under compression were not. This study was a follow up to an earlier study involving single osteons [Ascenzi, Benvenuti, Mango, Simili, 1985], which also produced stress-strain hysteresis loops, as the osteons were exposed to compressive and tensile cyclic loading. The resulting hysteresis loops were larger for the longitudinal osteons under compression and alternate osteons under tension, which also allowed the authors to make certain conclusions about the buckling effect on the osteonic samples.

2.3 Study of Tissue

The study of tissue using the hysteresis loop analysis was done by Miller et al., where the passive stress-strain measurements in the stage-16 and stage-18 embryonic chick heart [Miller, Vanni, Taber, Keller, 1997]. Stage-16 and stage-18 refer to 2 1/2 and 3 days respectively of a 21-day incubation period. A ventricular segment was cut out from both stages of embryonic chicks and mounted longitudinally between two small wires in an oxygenated solution. The wires were attached to a force transducer, from which various cyclic uniaxial loading of the segments were applied and the respective strains were noted through the use of a real-time video tracking system. Stress versus strain plots were made that produced according to the authors, large hysteresis loops. From the various hysteresis loops the researchers were able to deduce that the mean stored energy for the ventricular segments of the stage-16 and stage-18 embryonic chick hearts were 36% and 41% respectively of the total stored strain energy. These results were determined to be instrumental as the first step in characterizing material properties for comparison with later development stages of tissue development. From the study, the researchers were able to make comparisons of impaired and altered myocardium. The authors believe that the methods and results derived in the study can be utilized to analyze biomechanical factors regulating tissue growth.

2.4 Study of Limbs

Givens and his colleagues were able to use the hysteresis loop analysis concept to analyze the limbs of humans in the study of "Joint dependent passive stiffness in paretic and contralateral limbs of spastic patients and hemiparetic stroke" [Givens, Dewald, Rymer, 1995]. Here, the ankle and elbow joints of relaxed normal subjects and patients with hemiparetic stroke were analyzed using a torque-angular displacement relationship. For each joint under observation, a low velocity displacement in the flexion and extension positions and the respective torque were recorded. The plots of the torque-angular displacements of the joints in the various positions were described by hysteresis loops. The slopes of the hysteresis loops were measured and it was noted that they were similar for both the flexion and extension positions. Also, from the hysteresis loops the elbow passive stiffness for the normal subjects and hemiparetic subjects could be measured. Furthermore, the researchers deduced that the passive stiffness of the elbows were significantly lower in magnitude than the ankles of the normal subjects. Additionally they were able to show with the assistance of the slopes that no significant differences in passive stiffness of either limb exist between the hemiparetic patients and the normal subjects. Similarly, no significant differences in passive stiffness were found by the investigators in the upper limbs of either group. However, the torque-angular displacement relationships were able to identify significant differences in the ankles of all hemiparetic patients.

CHAPTER 3

ANALYSIS OF LOW BACK DISORDERS

3.1 Introduction

In order to understand the causes of low-back pain and develop the appropriate therapy, a thorough knowledge of the effects of loading to the components of the lower back must be attained. The behaviors of the vertebral segments, including the facets, intervertebral discs and ligaments to various types of loading have been studied in some depth. However, since structures such as muscles, fascias, tendons and nerves just to name a few, also play an important role in contributing to low-back pain, it is important to have a sound knowledge of these areas as well. Studies, involving of the range of motion of the low back, have been done on cadavers and living human subjects.

3.2 Hysteresis Loop Analysis

One of the techniques, used to ascertain the existence of low back disorders in humans, was the passive approach using the hysteresis loop analysis [Warner, Mertz, Zimmerman, 1997]. The analysis was conducted with the use of a patented medical device referred to as the anatomic torsion monitor (ATM). The goal of the ATM was to imitate and replace the assessment phase of a manipulation technique referred to as the pelvic roll, which is used by osteopathic physicians to clinically assess physiological characteristics of a patient's lower back. The pelvic roll, as practiced by osteopathic physicians, is considered subjective since an accurate diagnosis is based on experience in the respective profession. Therefore, with the ATM, the goal was to develop a model by which the hysteresis loops generated through the testing of a human subject can produce a baseline by which all patients with low-back pain can be assessed.

The pelvic roll requires the patient to rest passively in the supine position on an examination table. The practitioner then applies forces to the Posterior Superior Iliac Spines (PSISs) with the hands thus causing the pelvis to roll in the direction of the applied force. By doing this to both PSISs repeatedly, the practitioner will be able to ascertain the condition of the lower back as being healthy or not by experiencing the ease of roll from side to side.

The ATM was designed to mimic this type of manual manipulation of the practitioner in the assessment of the pelvic roll. The design of the equipment is a modified examination table made of plywood attached to a steel frame. At the center of the table there exist a space where two pads sit, which are used to make contact with the posterior superior iliac spines of the subject tested. The pads are attached to lever arms protruding from both sides of the table. Attached to each lever arm is a steel platform to which weights are added and removed. The application and removal of the weights mimic the applied forces to the lower back of a subject.

A subject is then placed on the table in a supine position with the pads of the lever arms making contact with the PSISs. A platform fitted with a laser beam projector is then placed on the anterior superior iliac spines (ASISs) and during testing the beam is projected onto a chart located on the wall. The chart is graduated in a manner where one inch represents one degree of angular displacement and is placed at a distance of 57.22 inches from the center of the examination table. Weights are then added to each lever platform in increments of five (5) pounds to a maximum value of twenty-five (25) pounds. Upon attaining the maximum value, the weights are then removed in 5-pound increments until all the weights are removed. The application and removal of weights is first conducted on the right platform and then on the left platform of the lever arms of the ATM.

The application of weights to the lever arms platforms cause the attached pads to make contact with the PSISs of a subject thus displacing the PSISs. A laser beam projected unto the chart on the wall records the respective displacements (angular displacements). When plotted on a Cartesian coordinate system, the applied forces and the respective angular displacements for a subject, the resulting plot is a hysteresis loop as shown in figure 3.1.

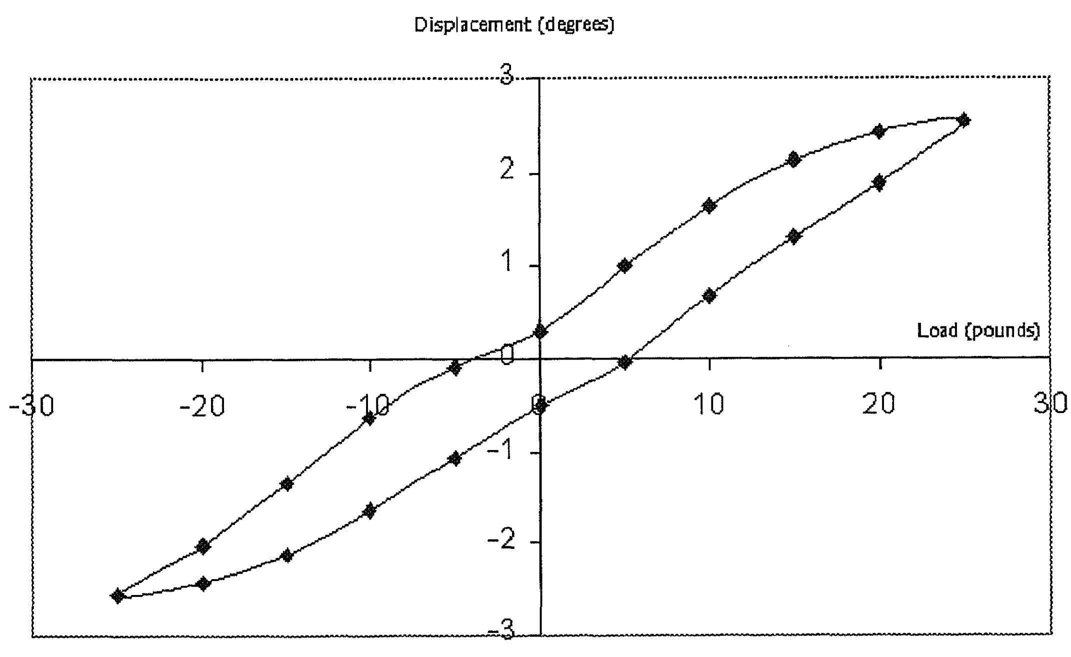

Figure 3.1 Plot of Displacement versus Applied Loads of Subject

The resulting hysteresis loop is hypothesized to reflect the condition of the low back of a subject. The area within a loop is a measure of the stored energy in the lower back resulting from the application and removal of forces. A subject with a healthier lower back should demonstrate a narrower hysteresis loop than a subject with an unhealthy back.

3.3 An Active Study

An active study, assessing the range of motion of the lumbar spine, involved the use of two measuring instruments [Dillard, Trafimow, Andersson, Cronin, 1991]. The instruments used were the Isotechnologies B-200 and the double goniometer. With the B-200 device, a subject stood on a platform, which could be raised and lowered. Two pads were placed onto the ASISs of the subject so as to hold the pelvic region fixed. Pressure was then applied through a pad onto the lower sacrum. Ranges of motion were recorded in flexion, extension, right and left lateral bending, and right and left rotation. The range of motion for the various positions were measured with potentiometers built into the B-200 instrument. The upright position of the subject represented the neutral position. With the goniometers, again the upright position of the subject was considered the neutral position. For the various ranges of motion, the arrangement of the components of the instrument varied. Any incorrect responses, from the subject for a desired range of motion, resulted in a repeat of the task.

The study involved 20 healthy volunteers, whose ages ranged from 20 to 40 years. The subjects had no history of back disorders. They were considered to be in good physical condition, and representative of a normal human population.

An analysis of data recorded by both instruments demonstrated low ranges of repeatability. For the B-200 the reproducibility was poor when flexion and extension were analyzed separately in the sagittal plane. However, when these motions were analyzed together in the sagittal plane the reproducibility of the data improved. The rotation range of motion also yielded poor repeatability. The only measures that produced significant reproducibility with the B-200 instrument were left bending and the combination of right and left bending. The goniometer technique was somewhat more repeatable, although the results were not ideal. However, both instruments were considered to have poor reliability and therefore performing a statistical analysis comparing them seemed meaningless.

3.4 Cadaveric Studies of the Low Back

3.4.1 Pre-loading of Cadaveric Lumber Spines

The loads applied to the motion segments of the human spine are determined to be of two types; those due to body posture and superimposed body weight, referred to as preload and those due to various physical activities, referred to as physiologic loads [Panjabi, Krag, White III, Southwick, 1977]. The study involved normal lumbar spine segments excised from cadavers within sixteen (16) hours of death. The vertebrae were assembled with the use of quick setting polyester cast and screws tapped axially and radially into the vertebral body. The loading arrangement consisted of preload and physiologic loads applied to the vertebral body. As the loads were applied, the effects of the three-dimensional displacement patterns of the lumbar segments motions were observed and recorded. It was determined that the elastic mechanical properties of the spine were a function of the preload and physiologic loads. The application of any physiologic loads produced a three-dimensional motion regarding rotation and translation. Furthermore, it was noted that the spine became more flexible in the presence of preload with the physiologic forces directed laterally and anteriorly or moments producing lateral bending or flexion. With the application of axial tension or torsion however, the spine became less flexible.

3.4.2 Injury and the Lumbosacral Joint

In reference to the human spine, motion that occurs in the direction of the applied load is termed main motion whereas motion that occurs in the direction other than the applied load is referred to as coupled motion [Oxland, Crisco III, Panjabi, Yamamoto, 1992]. The study involved the analysis of the changes in the coupled motion patterns at the lumbosacral joint with sequential injuries to posterior ligaments, intervertebral discs and articular facets. The specimens were nine whole fresh frozen lumbosacral spines (five L1-S1 and four L2-S1), free of all non-ligamentous soft tissues, which were excised from contributors between the ages of 35 and 62 years old and subjected to main and coupled motion.

Rather than considering all the different motion parameters, the focus was on the range of motion, which is the total motion from a neutral position to the displacement under the maximum applied load. The coupled motion consisted of axial rotation and lateral bending rotation due to flexion-extension moment, flexion-extension and lateral bending rotation due to axial torque, and flexion-extension and axial rotation due to lateral bending moments. The mean and standard deviations of all coupled rotations at the L5-S1 segments in all injury states were recorded.

The flexion moments produced no significant differences between the injuries. Using left and right axial torque, the researchers were able to show that with increasing severity of injury, the amount of coupled flexion tend to decrease and extension developed with the removal of the facets. The extension rotations at the facet injury were statistically significant under right axial torque but not left axial torque. The coupled lateral bending range of motions under left and right axial torque were applied to the same side as the axial torque for all injury conditions. No significant change occurred by transection of the posterior ligaments, but this lateral rotation increased significantly after injury to the intervertebral disc. The coupled axial rotations were to the side opposite the applied bending moment, which produced no statistical significant changes in the axial rotations after posterior ligament transection or intervertebral disc injury. With the removal of the facets however, there was a significant increase in the coupled axial rotations. With respect to the lumbosacral region, the study was able to show that the intervertebral disc was the structure that offered the greatest resistance to any coupled lateral rotation. Similarly, the facets offered the greatest resistance to coupled axial rotation and forced the L5 vertebra into flexion rotation.

3.5 Comparison of Modeling Techniques

The various studies the low back of the human anatomy provide valuable knowledge of loading limitations to the vertebrae, intervertebral discs, facets and ligaments for both healthy and diseased conditions. However, studies involving living human subjects would best serve as a means of addressing low back pain. Also, an effective study involving living humans must provide an objective model to produce quantifiable data.

CHAPTER 4

MODELING THE LOW BACK

4.1 Introduction

The numerous studies of the low back as presented in chapter 3 provide valuable knowledge of the healthy and diseased conditions in this region of the human body. More models of the low back are developed from studies on cadavers than on living humans. However, low back studies that are performed on cadavers have limitations. While they do permit the gathering of data related to this anatomic structure and data on the structure's interrelated behavior, they obviously get only a subset of data associated with the physiology and changing physiology (e.g., injury, disease) of a living human. Since it is living humans that suffer from low back disorders, the development of models of the low back for these subjects would be valuable. This study will focus on developing a model of the low back for living humans so they can be assessed for low back dysfunction.

Most of the studies done on living subjects pursue the active approach, where the living subjects control the measuring instrument [Hsieh and Pringle, 1994] [Dillard, Trafimow, Andersson and Cronin, 1991] [Gomez, 1994]. In such studies the subject is said to be active; hence, the studies, tests or subsequently developed models are referred to as active low back studies, active low back models, or just "active". Results from such studies are influenced by the directed and even coached actions from the subject. The author believes that data from active subject studies are not objective and not scientifically useful for analysis.

Although not as popular as the active approach, some low back studies are performed where the participating subject is passive [Lee, Lau, and Lau, 1993] [Inscoe, Witt, Gross and Mitchell, 1995] [Warner, Mertz and Zimmerman, 1997]. With the passive approach, the study, test, model or subject is referred to as passive. By testing the subject while passive, the effects of the somatic and autonomic nervous systems are minimized. When subject tests are conducted based upon a stable, recurrent protocol, an account in the data taken can be made for the behavior of the subject's somatic and autonomic nervous system during the test. Passive studies have the potential to be objective and gather more useful scientific data because the subject under test does not control the measuring instrument.

In one of the passive studies described in chapter 3, Warner, Mertz and Zimmerman conducted a robust analysis of the low back exclusively with living subjects. Their analysis was based on the discovery that the fundamental scientific principle of hysteresis could be used to model the low back. Subject analysis was done with a specialized medical instrument called the Anatomic Torsion Monitor (ATM). With the ATM, small forces are applied to the low back of a relaxed, supine subject and then withdrawn, thus moving the low back through a rotational range of motion. As a result of the cyclic application and removal of forces, stored energy for each cycle is left behind in the low back. Data taken are plotted on a Cartesian coordinate system, which result in closed loops called hysteresis loops. The area within each loop represents the stored energy in the low back of a human subject. The study done by Warner, Mertz and Zimmerman result in an instrument and methodology for capturing objective and scientifically useful data from the human low back.

The initial work done by Warner, Mertz and Zimmerman with the ATM clearly provided objective data of the low back for analysis. However, they did not quantify the stored energy described within the hysteresis loops. Also, they did not identify the axis intercepts (locations where the hysteresis loops cross the x-axis) in the Cartesian plots of displacements versus forces or relate them to the physiology of the subjects. Further, the reliability, validity and sensitivity of the ATM were never established. While objective data were captured it was not used for any subject analysis and their work was for the purpose of presenting their discovery of a new behavioral phenomenon of the low back.

This study will use the work by Warner, Mertz and Zimmerman to further investigate the physiology of the low back with the use of the ATM. This work will start with determining the reliability, validity and sensitivity of the ATM. Next, the hysteresis loops produced by the ATM will be quantified and enclosed loop area will be computed. Axis intercepts will be identified and related to human physiology. Finally, subjects will be tested and their data scientifically analyzed. In addition to establishing the ATM as reliable, valid and sensitive, the author believes that some day the ATM will become a valuable medical device for assessing low back disorders.

4.2 Equipment, Subjects and Procedure

This study will include the following:

1. Government approved laboratory facilities where the study was conducted.
2. The medical instrument called the Anatomic Torsion Monitor (ATM) on loan to this author so this work may be performed.

3. Test model for the ATM, called the static model.
4. A procedure for testing that is identical whether the ATM is testing the model or human subjects.
5. An analysis of the data taken to determine the reliability, validity and sensitivity of the ATM.
6. Subjects drawn from a normal population for test by the ATM.
7. Analysis of the subject tests.

The Laboratory

For this study, data were gathered from the ATM for analysis while it was located in the Gait Laboratory at the Kessler Medical Rehabilitation & Research Education Corporation (KMRREC). KMRREC is and was at the time of testing a facility approved by the Federal Government to conduct biomedical research on human subjects. The Gait Laboratory is fully enclosed in an atmosphere of constant temperature and humidity. Floors of the laboratory are made of concrete, covered with tiles. This modern facility was built for heavy utility. As an environment for these studies, the KMRREC Laboratory was an ideal test location.

The Anatomic Torsion Monitor (ATM)

The ATM is shown in figure 4.1. Each component of the ATM was chosen to satisfy the requirements of rigid elasticity (i.e., built of metals and other materials that would not flex or bend under normal operating load), accuracy and simplicity. The ATM is built with a solid, hollow steel frame. The rigid plywood surface supports a supine subject while under test. A firm contact with the floor was ensured with the adjustable feet of the ATM. The few rotating points are equipped with high precision roller bearings. The application of forces to the lower back of a subject is accomplished with the lever arms, which were made of rigid, high strength aluminum. The lever arms are maintained at equal lengths.

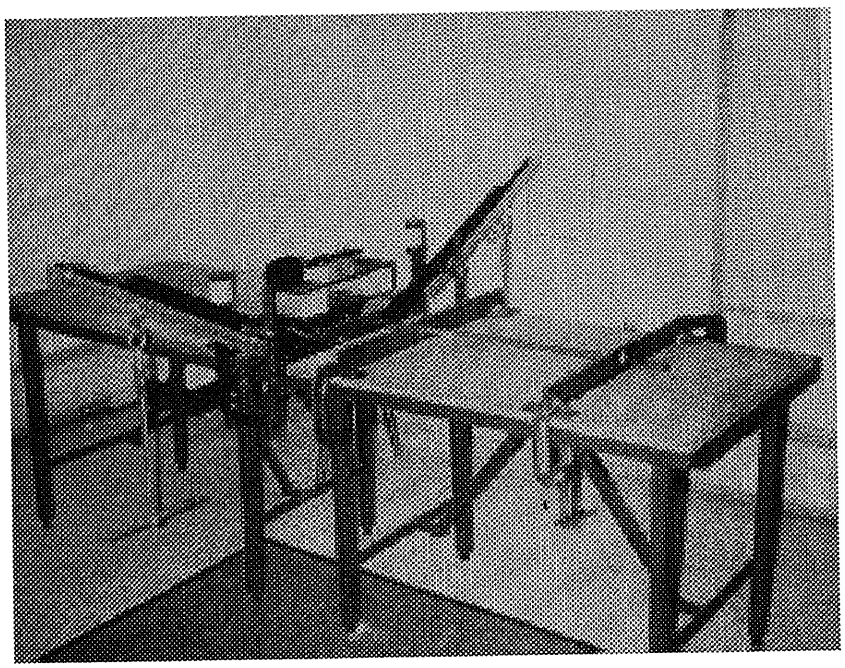

Figure 4.1. The Anatomic Torsion Monitor

Attached to the inner ends of each lever arm, at a location coinciding with the position of the lower back of a subject is a circular shaped, high carbon steel pad. Each lever arm metal pad makes contact with the respective Posterior Superior Iliac Spine (PSIS) of a subject. Also, each metal pad is made with enough surface area to allow for slippage of the PSISs while a subject is under test. The PSIS rests against the trapped superficial fat pad of a subject and the metal pad of the lever arm. At the outer end of each lever arm is a steel platform, to which the weights were added or removed.

Application of each weight onto a lever platform causes the metal pad of the lever arm to make contact with a subject's PSIS. The metal pad produces an applied force to the PSIS, resulting in an upward displacement of the PSIS from its referenced position. Similarly, the removal of each weight from the lever platform reduces the force on the PSIS thus resulting in the lowering of the PSIS. Altogether, there are ten weights used to operate the ATM; each weighing 5 pounds, and made of steel.

The Laser Platform and Chart

The laser platform is constructed of a laser device (which emits a laser beam rated at 0.8 watts) fastened onto a steel and wooden platform. The laser platform is secured with a waist strap onto the Anterior Superior Iliac Spines (ASISs) of a subject. As a subject's PSIS is lifted and lowered by a lever arm of the ATM, the respective ASIS is lifted and lowered. Any fluctuation of laser beam projected onto a chart on the wall indicates a deflection of the ASIS. A deflection of the ASIS is referred to as an angular displacement and is measured in degrees.

The chart on the wall is placed at a distance of 57.22 inches from the middle of the ATM. This distance is determined through a trigonometric relationship, thus enabling one inch on the chart to represent one degree of angular displacement. Therefore, graph paper with a grid of ten squares per inch makes an ideal chart. The chart is graduated vertically in degrees, with a range of ± 5 degrees from the midpoint of the chart.

The Static Model

The static model, as shown in figure 4.2, is made of high carbon vanadium steel. The static model is attached to a metal fixture, thus maintaining a horizontal position on the ATM. The metal fixture in turn is bolted to the ATM so as to prevent any unnecessary movement of the static model. Attached to the metal fixture is a steel platform that is used to accommodate the laser platform. The steel platform is placed on the ATM, at a location designated for the lower back of a human subject. The laser platform sits firmly on top of the steel platform. The static model and its metal fixture are fully elastic (elastic coefficient approaching 1.0).

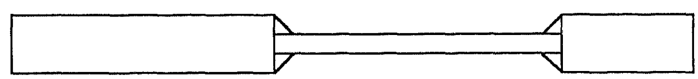

Figure 4.2. The Static Model

Function of the ATM

The ATM is a medical instrument that is used to assess the physiological characteristics of the human low back. The ATM performs the following basic function:

1. It applies and then removes a force directed post-anteriorly to the low back of a relaxed, supine subject.
2. It measures the effect of this force after its translation through the human body by recording an angular displacement. The measured angle is between the rotational displacement of the plane formed by the ASISs from the stationary plane of the shoulders (i.e., the subject's frontal (coronal) plane).

The ATM is operated by a clinician who performs a series of steps to cause a force to be applied or removed from a human subject's low back. The clinician records the angular displacement at each increment (decrement) of force. The hysteresis loop is plotted by the clinician on a Cartesian coordinate system as force vs. angular displacement. A detailed operation of the ATM is described below.

ATM Testing Procedure

A clinician operates the ATM as follows:

1. A human subject assumes a relaxed, supine position on the ATM.
2. The laser platform is strapped unto the ASISs of the subject.
3. The laser beam emitted from the platform is fixed at the zero displacement point on the chart, located on the wall.
4. Weights are added to the right lever arm steel platform (initially without weight) in 5-pound increments, until a maximum weight of 25 pounds is attained. Addition of weights to the lever arm displaces the right PSIS of the subject anteriorly, which also displaces the right ASIS anteriorly. The displacement of the right ASIS causes the laser beam on the laser platform to project upward of the zero displacement point on the chart located on the wall.
5. The angular displacement for each applied weight is read from the chart.
6. Upon attaining the 25-pound maximum weight, the weights are then removed from the lever arm steel platform, in 5-pound increments until zero weight is attained.
7. Again, the respective angular displacements are read from the chart.

8. Steps 4 through 7 are repeated on the left lever arm, where the application of weights to the left lever arm steel platform displaces the subject's left PSIS anteriorly, thus displacing the subject's left ASIS anteriorly. The laser beam strikes the chart below at the zero displacement point on the chart and is recorded as a negative value for the angular displacement.
9. Steps 4 through 8 are considered one series (cycle) of applying and subsequently removing force at the PSIS.

The procedure is applied identically whether the static model or a human is the subject of a test.

4.3 Reliability, Validity and Sensitivity of the ATM

A low back model of a living subject that relies on objective, quantifiable data needs a trustworthy, data-gathering instrument to deliver scientifically (and clinically) useful measured values. By establishing the reliability, validity and sensitivity of the ATM, such a medical instrument becomes a reality.

ATM reliability means that when the instrument is operated correctly (see operating steps above) it will reproduce any of its earlier readings when a chosen parameter is measured again under the same conditions. Validity means the instrument provides a value that is true and accurate (e.g., the instrument is calibrated against a standard). Finally, sensitivity refers to the "granularity" of the measurement (e.g., 3.2° ± 5 %).

By observation of both static model and preliminary subject tests, the following concerns were identified as having an impact on the reliability, validity and sensitivity of the ATM.

1. Values of the weights
2. Angular measurement
3. Visual interpolation when reading the angular displacement
4. Subject positioning on the ATM
5. Expressing ATM output

In some cases, tests were constructed to quantify the impact of the above concerns. The static model was employed in these tests as a model of fixed, known hysteresis. Evaluation and quantification of all concerns follows below.

Values of the Weights

The lever arm weights that create the force applied to a subject's PSIS were measured with a calibrated scale (the lever arm weight is plotted as the independent variable on a Cartesian coordinate system). The weights are labeled as 5 pounds each. However, none of the weights is exactly 5 pounds as stated and furthermore no two weights have the same value. The range of the actual values of the weights is between 4.78 pounds and 5.57 pounds as shown in table 4.1. Also, the difference in the values of the labeled and actual weights varies from 0.01 pound to 0.57 pound.

Table 4.1. Actual and Labeled Values of Weights

Weight Number	Labeled Values of Weights (pounds)	Actual Values of Weights (pounds)	Difference of Weights (pounds)
1	5	4.91	0.09
2	5	4.87	0.13
3	5	5.01	0.01
4	5	4.78	0.22
5	5	4.88	0.12
6	5	4.94	0.06
7	5	4.90	0.10
8	5	4.93	0.07
9	5	5.13	0.13
10	5	5.57	0.57

When the weights are employed during ATM calibration using the static model or during subject testing, it is far too difficult to keep track of each individual weight. Thus, an account must be made for the variation of the actual value of a weight compared to its indicated value. To accomplish this, the static model is subjected to two series of systematic loading and unloading of weights. The first series involves the use of the five heaviest weights and the second series involves the use of the five lightest weights. In the first series the heaviest combinations of weights are applied to satisfy a specific loading value. Similarly, for the second series, the lightest combinations are applied. The unloading process follows the exact reverse of the loading process. The values of the displacements for the heaviest and light combinations of weights are obtained, and are presented in table 4.2. For the specific weight values, the displacements are recorded as right side displacements using heaviest weight (RH); right side displacements using lightest weights (RL); left side displacements using heaviest weights (LH); and left side displacements using lightest weights (LL).

Table 4.2. Displacements of Static Model with Heaviest and Lightest Weights

Weights	0	5	10	15	20	25	20	15	10	5
RH	0	0.8	1.55	2.3	3.1	3.9	3.2	2.4	1.6	0.8
RL	0	0.65	1.35	2.15	2.9	3.7	3.0	2.25	1.45	0.7
|RH-RL|	0	0.15	0.2	0.15	0.2	0.2	0.2	0.15	0.15	0.1
% Change	0	±10.3	±6.9	±3.4	±3.3	±2.6	±3.2	±3.2	±4.9	±6.6
LH	0	-0.8	-1.55	-2.35	-3.1	-3.9	-3.2	-2.4	-1.65	-0.9
LL	0	-0.7	-1.4	-2.15	-2.9	-3.7	-3.0	-2.25	-1.5	-0.7
|LH-LL|	0	0.1	0.15	0.2	0.2	0.2	0.2	0.15	0.15	0.2
% Change	0	±6.6	±5.1	±4.4	±3.3	±2.6	±3.2	±3.2	±4.8	±12.5

As shown in Table 4.2 the displacement values can be affected by as much as ± 12.5 % at the application of the 5-pound weight. However, the application of the maximum weight of 25 pounds will result in a change of ± 2.6 % of the displacement values. Since the static model behaves linearly, the gradient of the percent change of the displacement versus the applied weights will remain constant. Using a linear regression the ranges of the percent change in the displacement value for each applied weight can be calculated from figure 4.3.

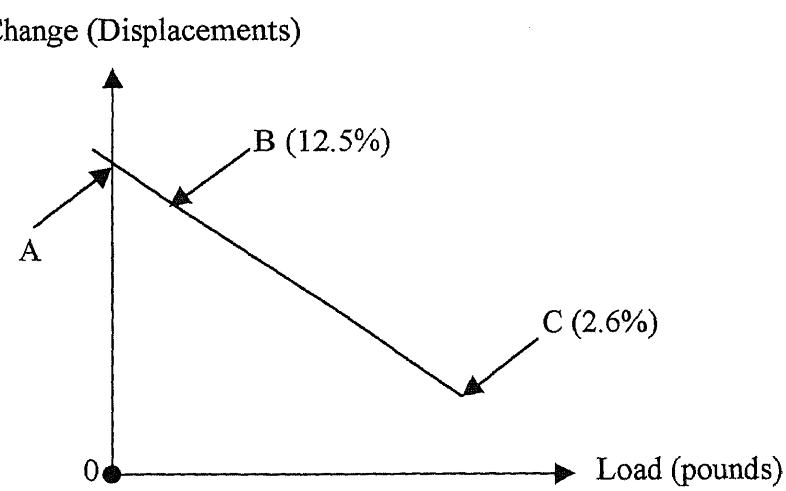

Figure 4.3 Percent Change in Displacement Value versus Load

C = The percentage change at 25 pounds.

B = The percentage change at 5 pounds.

A = The percentage change at zero pound.

The calculated values of the range of displacement values for the respective loads are given in table 4.3. Therefore, when the clinician adds weights to or removes weights from a lever arm platform and uses only the indicated weight value as reference, the impact on the dependent variable will fall within the range of $\pm$ 2.6 % to $\pm$ 14.97 %.

Table 4.3 Discrepancies in Displacement Values

Weight (lbs)	% Change in Displacement Values
0	14.97
5	12.5
10	10.03
15	7.55
20	5.08
25	2.6

Angular Measurement

The ATM measures the subject's (or static model's) angular rotation (α - plotted as the dependent variable on a Cartesian coordinate system) at the ASIS to forces applied at the PSIS. The ATM's output, the measured angle α, lies between the rotational displacement of the plane formed by the ASISs and that of the stationary plane of the shoulders. The principle used to obtain the small angles measured is the right triangle as shown in figure 4.4.

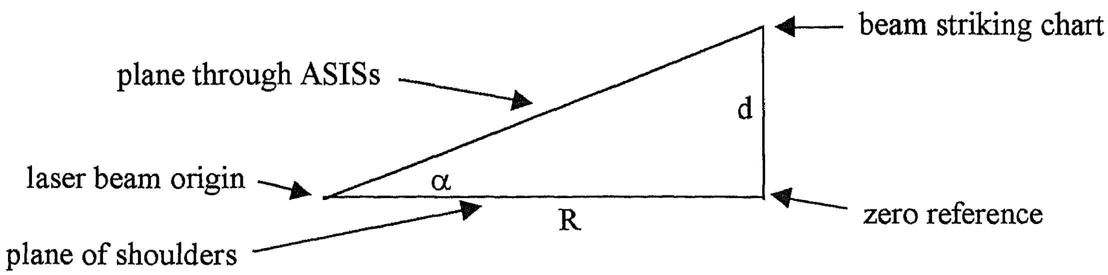

Figure 4.4 The Right Triangle with TAN α = d/R

α = angular displacement between the two planes

d = the vertical displacement from the laser beam strike on the wall chart to a zero reference; initially, the zero reference is set when α = 0 degrees and α is recorded as positive above the zero reference, negative below.

R = distance from the center line running the length of the ATM (the ATM's longitudinal centerline) to the chart hanging on the wall; also, initially, the distance from the sagittal plane of the subject while supine on the ATM to the wall chart (or equivalent in the static model).

The value of α will range between -5 through 0 to + 5 degrees. The value of R that is needed to get "d" equal to 1 degree per inch (thus allowing the use of 10 squares per inch graph paper to be the wall chart) is computed as shown in table 4.4.

Table 4.4 Computed Values of R for Various Values of Alpha

α (degrees)	**Tangent α**	**d (inches)**	**R (inches)**
0	0.00000	0	Any R
1	0.017455	1	57.2900
2	0.034921	2	57.2726
3	0.052408	3	57.2435
4	0.069927	4	57.2027
5	0.087489	5	57.1503
			Avg. R = 57.2318

Warner, Mertz and Zimmerman used a value for R as 57.22 inches. Practically, setting the ATM 57 1/4 inches from the wall chart makes sense. How much influence does the value of R have on reading α (as "d"), during any subject or calibration (i.e., static model) tests? To find out, R is set at a value of 57.25 inches, ± 1 inch as shown in table 4.5. The computation is (ATAN(2/58.25)) * (180/3.14159) or (ATAN(2/56.25)) * (180/3.14159) as examples. One can conclude from the above data that setting the ATM table top centerline (subject's sagittal plane) within an inch of 57.25 from the wall chart will produce an angular measurement reading from the laser beam spot on this chart of less that 2 % off the true or actual value of α at 5 degrees or minus 5 degrees. At values lower than this, for example angles between plus 3 and minus 3 degrees that are in the typical extent for subjects, the read α deviates less than 1.6 % off the true value. Therefore, a maximum change of ± 2 % in the values of the displacement values is possible. Warner, Mertz and Zimmerman certainly found a highly effective and robust way to measure small angles of range of motion in human subjects.

Table 4.5 Angular Displacement Values at Different Lengths of R

α (read from chart)	**α (R = 58.25)**	**α (R = 56.25)**
1	0.9835	1.0185
2	1.9665	2.0363
3	2.9483	3.0529
4	3.9283	4.0675
5	4.9061	5.0796

Visual Interpolation

One of the concerns is how the laser beam's spot or dot is read from the chart. An example of the dot on the chart is shown below in figure 4.5. The beam spot at "A" is read as minus 0.4 degrees for the rotational angular displacement. At "C" it is read as plus 0.5 degrees. "B" is a little trickier. It is read as plus 1.05 degrees. A line through the center of the dot is aligned with the grid of the chart for the reading. Thus, the reading is "x.yz°" where $+5 \geq x \geq -5$, $9 \geq y \geq 0$ and z is 0 or 5. It takes a clinician only a few minutes to become proficient at reading angular displacements from the chart.

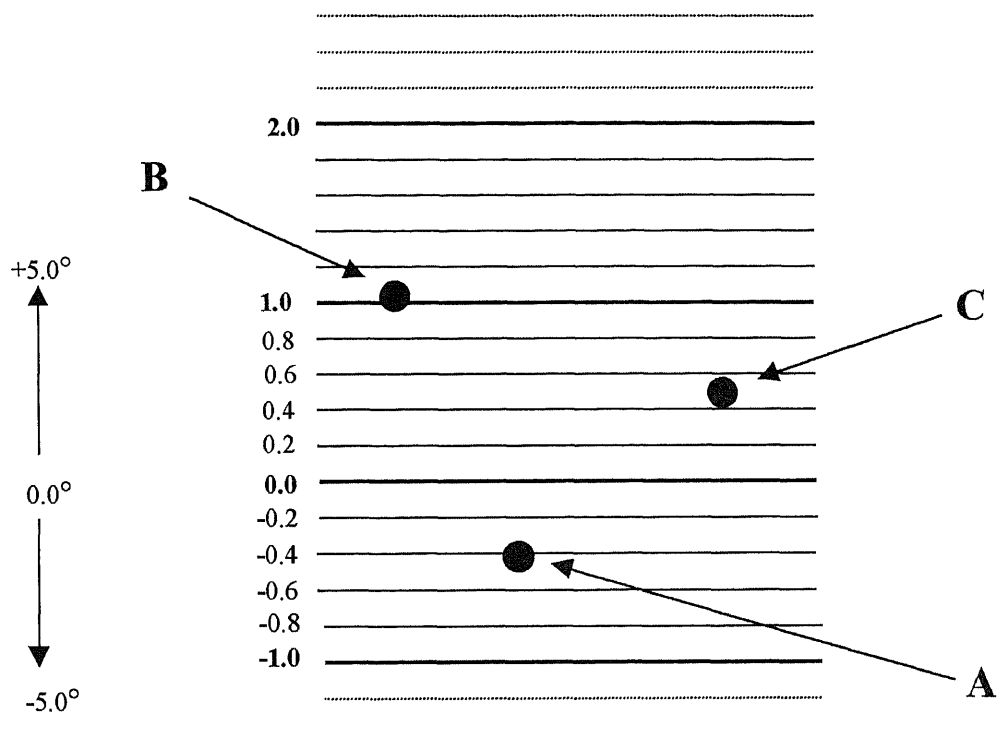

Figure 4.5 Laser Beam and Chart

Subject Positioning on the ATM

The supine subject's (or test model's) sagittal plane lies on the longitudinal centerline of the ATM table surface. There are four basic concerns:

1. The ATM longitudinal centerline is not precisely known.
2. Finding the exact location of a subject's sagittal plane is not possible.

3. During an ATM test a subject will, ever so slightly, shift position.
4. Even though the static model's longitudinal centerline (sagittal plane) is exactly known, the ATM longitudinal centerline is not; thus, model (or subject) placement on the ATM is not precise.

The four basic concerns will have an effect on the angular measurement. The remainder of this section will describe that effect.

By simple observation, the ATM longitudinal centerline can be defined within a few millimeters. An imprecise centerline has its effect because a model or subject can't be placed on the ATM with a known lateral accuracy. However, this problem can be addressed in two ways. It will impact the value of "R" (ATM longitudinal centerline distance to the wall chart) as described above in the section called Angular Measurement. However, as can be seen from computations done in that section, a change in the value of R of just a few millimeters will have no identifiable effect on the ATM's output angular measurement. In addition, an imprecise centerline means the moment arms of the two side mounted lever arms are different from their design values. As shown below, moment arm variance of just a few millimeters will have no identifiable effect on the ATM's output angular measurement.

For our purposes, bisecting the distance between a subject's PSISs defines the location of the subject's sagittal plane. But this, too, is only an estimate. Again, by observation, this estimate is within just a couple of millimeters. The impact on the angular measurement comes in two areas. Again, the value of "R" changes. Here too, the change in "R" is too small to have any practical effect on the ATM's output angular measurement. In addition, when the subject is supine on the ATM, misposition from the ATM longitudinal centerline causes the lifting arms moment arms to change. Here again, as shown below, moment arm variance of just a few millimeters will have no identifiable effect on the ATM's output angular measurement.

As the subject is lifted and then lowered at one PSIS (i.e., force applied and then removed to a PSIS via a lever arm), the subject will move, sliding on the fat pad that lies between the PSIS and the lever arm metal lifting pad. Observation shows that this movement is less that 1 cm and the maximum movement occurs at the highest force levels (e.g., when 20 or 25 lbs is on the lever arm weight carrier). Below, a number of tests are run on the ATM with the mispositioning purposely offset by 1cm. The effect on the ATM's angular displacement measure is described.

The static model is used for the tests below. It has known hysteresis, does not move or shift on the table surface of the ATM while under test and its centerline or sagittal plane is known. For these reasons, the model makes a good standard test subject. Only this model's initial placement relative to the ATM longitudinal centerline is the variable that will effect the angular displacement. As will be shown, the change in lever arm's moment arm lengths from static model positioning (and, hence, initial subject positioning or subject position change while under test) will have an effect on the ATM's angular measure. The "R" value changes during initial placement or while the subject is under test is considered as well but will have a much lesser impact.

To identify the effects of positioning on the angular displacement the static model is tested at locations along and away from the ATM's longitudinal centerline. The static model test positions are as follows:

1. Centered on the ATM along its longitudinal centerline.

2. Placed 1 cm superior from the center along the ATM's longitudinal centerline.
3. Placed 1 cm to the right of the central point of the ATM's longitudinal centerline.
4. Placed 1 cm to the left of the central point of the ATM's longitudinal centerline.

The data taken of the angular displacements for the application and removal of forces onto the static model are given in appendix A. The data are almost identical for the positioning of the static model along the ATM's longitudinal centerline. However, positioning the static model away from the longitudinal centerline produced different values. The effects of the different positioning of the static model on the ATM are shown in table 4.5. For each right and left lever arm weight carrying platform, the combination of the five weights (adding up to 25 pounds) remained the same for all test positions of the static model. Therefore, an objective comparison of the results can be made at the maximum weight of 25 pounds. The angular displacement values in table 4.6 represent the average values of the right and left displacements at the 25-pound load. We can therefore see that discrepancies exist when the sagittal plane of a model or a subject is not aligned along the ATM's longitudinal centerline.

Table 4.6 Displacement Values of Various Model Positions at 25 Pounds

Displacements From	**Centered**	**Superior**	**Position Right (1cm)**	**Position Left (1cm)**
Left Lever Arm	3.85°	3.85°	3.8°	4.1°
Right Lever Arm	4.0°	3.95°	4.11°	3.9°

The positional discrepancies that exist can be quantified. For the left lever arm, position right results in a 1.3% decrease in angular measure from the centered position of the model. Position left for the left lever arm produces a 6.5% increase in angular displacement. For the right lever arm, position right gives a 2.8% increase over the centered position, and position left gives 2.6% decrease. These results are consistent with one lever arm's moment arm increasing while the opposite lever arm has its moment arm decrease. Thus, as an estimate based on this test data, the ATM output angular displacement could vary (deviate) by as much as ±6.5%. The effect due to the change in "R" of 1 cm is negligible (see above in the section entitled Angular Displacement) in comparison (it would be about 0.66 %).

Expressing ATM Output

The subject's rotational angle is the ATM output. ATM concerns, described above, were expressed exclusively in the ATM output (note that it could have been done differently; for example, the actual weight on a lever arm weight carrier, such as 10.8 lbs. or 24.3 lbs., could have been the independent variable). The output, then, is an angular measure with a deviation, for example, 3.2° ±0.2°. The true angle (the exact value of the measured parameter) lies in the extent between 3.0 and 3.4 degrees.

The smaller the deviation, the more accurately the instrument records a parameter and the more useful the measure of that parameter is for quantification needs. In a sense, the smaller the deviation the more the instrument tells the truth about what it measures. This will be expressed in percentage terms in this study. As an example, 4° ±10% would be a typical way to express the ATM output. As a medical instrument, it would be highly desirable to have an ATM with the smallest angular measurement deviation.

Sensitivity of the ATM

Arrival at the sensitivity of the ATM comes from consideration of the above concerns listed as follows:

1. Values of the weights
2. Angular measurement
3. Visual interpolation when reading the angular displacement
4. Subject positioning on the ATM

Notice that the greatest deviation in the ATM's output comes from the lowest force application (lowest value of the weights). This results in low angular displacement. With small numbers, a change in absolute angular displacement produces a large percentage deviation. The effect of the weights is mutually exclusive of all other concerns. From table 4.2 it can be seen that α deviates $\pm$ 2.6 % at high weight levels (large angular displacements) to $\pm$ 12.5 % at low weight levels (low angular displacement).

The way in which the angular displacement is measured (the trigonometric relationship) adds at most $\pm$ 2 % to the ATM's output angular rotational deviation. In this case it comes at the highest angular displacements. It comes from the change in the value of "R" and is mutually exclusive of the value of the weights and visual interpolation.

Visual interpolation is mutually exclusive of all other concerns and is most prominent at small angles. For example, at 0.55°, $\pm$ is 0.05° makes about a 10 % deviation in angular displacement while at 4.05°, $\pm$ 0.05° makes about a 1 % deviation.

Subject positioning is mutually exclusive of all the other concerns except the trigonometric relationship used to measure the angular displacement. The value of "R" is effected as the subject moves during testing or when the subject is initially placed on the ATM tabled surface. At most it makes a $\pm$ 2 % deviation in α at large angles and less than 0.6 % at the more common angular displacements for subjects ($\pm 3°$).

In the worst case the selected weights could cause a $\pm$ 12.5 % deviation along with the "R" off by enough to add another $\pm$ 2 %, visual interpolation could add $\pm$ 10 % and, finally, subject positioning could add another $\pm$ 6.5%. In other words, selected weights, ATM mispositioning from the wall, visual interpolation and subject positioning (poor positioning before the test gets started or positional change during the test) could conspire to cause an ATM reading to be $\alpha \pm 31$ %. Notice that this case would be at low angular displacement, 0° to 1°. At higher angles of α, 3° to 4°, the weights contribute about $\pm$ 3 %, "R" value about $\pm$ 2 %, visual interpolation about $\pm$ 2 % and subject positioning about $\pm$ 6.5 % for an $\alpha \pm 13.5$ %.

While other combinations of the above concerns would lead to intermediate deviation values, the best deviation would result from the following:

- weight combination on carriers are random; contribution = $\pm$ 5 % (overall average of the 18 deviations due to each high-low weight combination)
- "R" set at 57.25 inches; contribution = $\pm$ 0 %
- visual interpolation = $\pm$ 1.5 % (experienced clinician reads angles)
- subject positioning = $\pm$ 3.5 % (initial placement within a couple of millimeters and little fat pad slippage during the test - true of most subjects)

This would result in an $\alpha \pm 9$ %.

It would be ridiculous to use $\alpha \pm 31$ % for the larger angular displacements that occur at high weight on the ATM's lever arm weight carriers just as it would make no sense to use $\alpha \pm 13.5$ % for small angles and low weight values. Also, one can not expect the best deviation, $\alpha \pm 9$ %, to occur with great frequency either. Further, to generate a table with a probability distribution based on the weights or angles to get α would be equally ridiculous. It would be far better to design the ATM with weights that are exactly 5 lbs (or very close). That would give an immediate improvement. Other considerations in the design of a better ATM are discussed in chapter 5. For purposes in this study, a compromise will be made. All values of the ATM output will be $\alpha \pm 15$ %. This will give acceptable results so the data taken can be used with confidence in subsequent calculations.

Calibration of the ATM

Before the human subjects are tested the ATM is setup and its operation is confirmed. This is done as follows:

1. The ATM is positioned at a distance of 57.25 inches from (and parallel to) the wall chart. The lever arms of the ATM were ensured to be of equal lengths.
2. The static model is placed in the centered position on the ATM, with the laser platform affixed.
3. Testing of the static model follows the same protocol as defined for the human subjects. This protocol is described in the section "ATM Testing Procedure".

4. Results from testing the static model are plotted as load versus angular displacement.

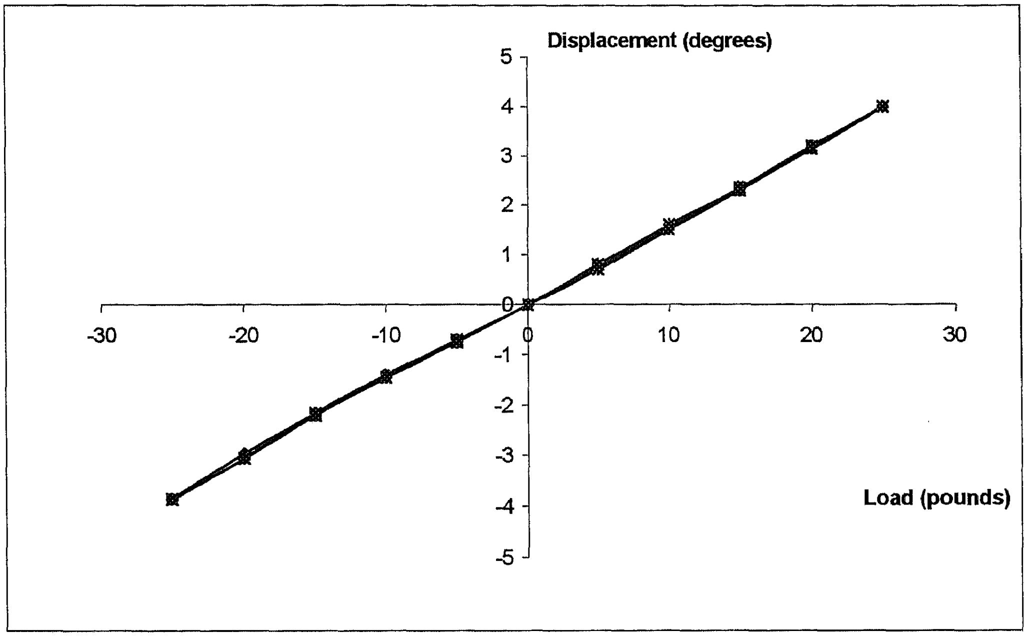

Figure 4.6 Plot of Static Model along Longitudinal Centerline

The plot of the data from all series of cyclic loading and unloading of forces is presented in figure 4.6. The resulting plot is, as expected for the static model, a straight line. The absence of a hysteresis loop indicates that the model stores no energy and is "perfectly elastic". The individual data points, at the respective loads, when compared to the average values of the data (shown in table 4.7) are seen to be within 15 percent. The ATM is now ready to test human subjects.

Table 4.7 Static Model along the Longitudinal Centerline

Weights	**0**	**5**	**10**	**15**	**20**	**25**	**20**	**15**	**10**	**5**
R	0	0.72	1.5	2.3	3.16	4	3.2	2.36	1.55	0.78
L	0	-0.7	-1.41	-2.15	-3.03	-3.85	-3.05	-2.2	-1.45	-0.75

4.4 Human Test Results

There are a total of 12 human subjects tested, whose ages range from 20 to 47 years old. The gender composition of the testing group is 8 women and 4 men. For the human subjects the average age is 29.6 years (SD= 7.8 years), the average height is 67.3 inches (SD=3.9 inches) and the average weight is 143.2 pounds (SD=26.2 pounds). Before testing each subject is interviewed to determine any existing or prior acute or chronic low back problems. All subjects stated that no such conditions exist. The body types of the subjects are assessed as slender or intermediate. Also, the subjects are considered to be representative of a normal human population.

The resulting angular displacements from testing all human subjects are tabulated and presented in appendix A (tables A.5 through A.16). These values, for each subject, are plotted on a Cartesian Coordinate of displacement versus load. The load refers to the weights on the lever arm platforms and not the force applied to the PSIS of a subject (even though the forces can be calculated from the moment arms). A plot of the variables describes a hysteresis loop and for each subject a single hysteresis loop is plotted, which is presented in appendix B. The displacement values for the entire test, at each respective load value for each subject, are combined to produce an average displacement value for that load. For example, at the 5-pound load on a subject's right PSIS, the displacement value is the average of the values recorded for each application of the 5-pound load. This is done for all load values for both the right and left PSIS of the subjects. The results are also contained in appendix A (tables A.17 through A.22).

The area, contained within each hysteresis loop, represents the stored energy in the lower back of a subject. To quantify the stored energy of each subject, as described within the respective hysteresis loop, certain approximations are made. They are:

1) The curves adjoining the displacement data values are approximated to be straight lines.

2) It is assumed that a distance of one inch on the chart represents one degree of angular rotation.

3) Each subject's tissue volume under test is considered homogeneous.

These approximations are necessary, so that the coordinate method of approximating areas [Breed, 1971] can be used to quantify the stored energy and also, to express the stored energy in units of inch.pound (in.lb) respectively.

Table 4.8 Stored Energy of All Subjects

Subject	Age	Height (in.)	Weight (lb.)	Max. Stored Energy (in.lb)	Min. Stored Energy (in.lb)
1	29	66.5	124	79	58.2
2	35	65	122	62.35	46.05
3	26	71	165	49.7	36.75
4	38	68	133	51.4	37.95
5	30	63	125	27.5	20.35
6	28	65	130	43	31.75
7	34	61	100	78.55	58
8	22	72	147	81.85	60.55
9	47	72	170	27.35	20.25
10	24	71	172	44.6	33
11	22	67	190	26.95	20
12	20	64	140	30.05	26.05

The sensitivity range of ±15%, as determined in the section on "Sensitivity of the ATM", is used to establish a maximum and minimum value of the stored energy of each subject. The values of the stored energy of the subjects are presented, along with other statistical data, in table 4.8. Table 4.9 contains data for selected subjects having a more appropriate height to weight relationship.

Table 4.9 Stored Energy of Selected Subjects

Subject	Age	Height (in.)	Weight (lb.)	Max. Stored Energy (in.lb)	Min. Stored Energy (in.lb)
1	29	66.5	124	79	58.2
2	35	65	122	62.35	46.05
3	26	71	165	49.7	36.75
7	34	61	100	78.55	58
8	22	72	147	81.85	60.55
9	47	72	170	27.35	20.25
10	24	71	172	44.6	33

The information given in tables 4.8 and 4.9 are compared to establish a pattern of association of the variables. The stored energy is determined to be the dependent variable. Therefore, the Pearson Correlation Coefficient is calculated to determine the association between stored energy and the other variables of each subject. The results are presented in tables 4.10 and 4.11. A discussion of these results will be presented in the next section.

Table 4.10 Correlation Coefficient for All Subjects

	Correlation Coefficient of Following Variables and Stored Energy for Subjects		
	Age	Height	Weight
Max. Stored Energy	-0.027	-0.026	-0.547
Min. Stored Energy	-0.057	-0.044	-0.545

Table 4.11 Correlation Coefficient for Selected Subjects

	Correlation Coefficient of Following Variables and Stored Energy for Subjects		
	Age	**Height**	**Weight**
Max. Stored Energy	-0.498	-0.539	-0.764
Min. Stored Energy	-0.5	-0.537	-0.763

Another significant contribution to the analysis of the low back is the understanding of varying values of stored energy, as the forces are applied and removed, during the testing of a subject. For this, the stored energy for the entire test is compared to the values of selective loading and unloading of forces as presented in table 4.12.

Table 4.12 A Comparison of Stored Energy

Subject	**Total Stored Energy (in.lb)**	**Stored Energy for 1st Set LUL (in.lb)**	**Stored Energy for 2nd Set LUL (in.lb)**
1	63	75	62.4
2	54.15	58.9	49.6
3	43.1	45.2	41.2
4	44.7	49.6	39.8
5	23.95	25.8	21.95
6	37.35	39.1	35.55
7	68.3	74.6	61.75
8	71.2	78.1	64.35
9	21.9	26.4	21.3
10	38.8	41.9	35.65
11	23.15	26.4	20.45
12	30.45	34.35	26.55

1st Set LUL - The first three series of loading and unloading of weights to the lever arms platforms.

2nd Set LUL - The second three series of loading and unloading of weights to the lever arms platforms.

Another analysis of the data is associated with the effects of the cyclic loading and unloading of forces on the equilibrium position (deviation of the plane through the ASISs from the coronal plane) of a subject. As a force is applied to a posterior superior iliac spine of a subject displaces it anteriorly. However, upon the removal of the force, the subject's posterior superior iliac spine does not revert to the original supine starting position. Each hysteresis plot, shown in appendix B, identifies this effect where at zero loads a residual displacement value exists. This residual displacement is called retentivity. The points where the hysteresis loops intersect the x-axis represent the forces required to return the lower back to it original supine position after it has been relieved of all external forces. These are the coercive forces. Table 4.13 contains the various coercive forces for the left and right sides for the twelve subjects tested.

Table 4.13 Right and Left Coercive Forces of Subjects

Subject	Total Energy (in.lb)	Weight (lbs)	Right Side Coercive Force (lbs)	Left Side Coercive Force (lbs)
1	63	124	6.4	1.51
2	54.15	122	7.07	2.9
3	43.1	165	9.75	0.5
4	44.7	133	2.95	3.95
5	23.95	125	6.25	0.5
6	37.35	130	5.25	3.33
7	68.3	100	5.1	4.22
8	71.2	147	8.79	3.02
9	21.9	170	3.18	5.37
10	38.8	172	5.18	3.95
11	23.15	190	2.42	4.55
12	30.45	140	11.98	5.23

4.5 Discussion of Results

Computation of the Pearson Product-Moment Correlation Coefficient (correlation coefficient) involves the strength of association between two variables [Glantz, 1997].

One variable is mutually exclusive of the other. In tables 4.8 and 4.9 the dependent variable is the stored energy for the subjects. The correlation coefficient values for the stored energy versus the other independent variables for the subjects are given in tables 4.10 and 4.11. From observation, the two variables that best correlate are the stored energy and the weights of the subjects. The correlation coefficient values (stored energy compared to weight), for selected subjects with a closer height/weight relationship, were greater than the values for the entire sampling group. However, these few variables are unable to establish any valuable information to this study. This outcome is somewhat expected since, it is clear that this statistical analysis is too simplistic to offer any meaningful conclusions. Although the correlation coefficient values did not contribute to the study, the quantification of the stored energy of each subject is very valuable to the study of the low back. Therefore, when using the value of stored energy for selected groups of subjects (as described in chapter 5), a correlation coefficient analysis may be able to make valuable inferences about this study.

The stored energy of each human subject is quantified in tables 4.8 and 4.12. When a force is applied, energy is added to a subject's low back. However, when the force is removed not all of the energy is released. Applying the first law of thermodynamics will show the energy that is added is actually work done on a subject's low back and the energy not released is converted into heat. The energy that is not released is referred to as the stored energy. The value of the stored energy is different for each subject tested. Therefore, the values of the stored energy from this study cannot establish a norm whereby signifying a healthy low back. However, based on the plot from testing the static model, the hypothesis is that a low value of stored energy (described by a narrow hysteresis loop) identifies a subject with a healthy back. The quantification of the stored energy, as presented in table 4.12, can also be used to describe the behavior of the low back of a subject in relation to the cyclic application and removal of force. Here the test procedure is broken into two portions. The value of stored energy for the second portion of the test (2^{nd} Set LUL), for each subject, is less than that of the first (1^{st} Set LUL). This analysis shows that the continued presence of intermittent forces will elicit an increasing elastic response of a subject's low back (assuming a healthy condition). However, a greater value of stored energy of the second portion may signify an unhealthy low back.

When all applied forces are removed from the PSIS of a subject, instead of returning to the original position, the PSIS remains slightly displaced. To ensure the equilibrium position is re-established, a force (known as the coercive force) has to be applied to the opposite PSIS. On a hysteresis plot this is where the curve intersects the negative x-axis at the zero displacement value. Table 4.13 contains the values of the coercive forces of each subject. The lower values of coercive forces identify a more elastic response of a subject's lower back. Furthermore, it is noticed that for each subject, the elasticity of one side of the lower back is greater than that of the other side. The conclusion that can be drawn here is; a greater elastic response would imply the ability to release energy that can cause injury. Also, the values for each subject will identify the side of the low back, which will be more susceptible to injury.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The passive study, of subjecting the lower back of living human subjects to cyclic loading and unloading of force, provided quantifiable data for analysis. The data is used to quantify the stored energy in each subject's lower back. The magnitude of the stored energy can describe the physiological condition of a subject's low back. For example, a high value of stored energy may indicate a low back disorder or the ability to suffer a disorder. Similarly, a low value may indicate a healthy low back with well-developed and conditioned muscle groups in the subject's low back region. The physiological condition of a subject's low back can also be determined from the values of the coercive forces. The lower values of the coercive forces will indicate the likelihood of healthy low back region. The converse will be true for higher values of the coercive forces. Therefore, using the value of the stored energy and the values of the coercive forces, a clinician may be able to diagnose a subject's low back region as healthy or unhealthy.

The anatomic torsion monitor has the potential to become an objective diagnostic medical device. But, to achieve this, certain discrepancies as noted in the present design of the ATM have to be addressed. In addition to improving the ATM's design the test protocol must also be revised. With sufficient funding to redesign the ATM and adopt an effective test protocol, the ATM may certainly be that medical diagnostic device.

5.2 Recommendation

Re-Designing the ATM

The input (lever arm platforms with weights) and output (laser platform and chart) devices of the present design of the ATM can conspire collectively to affect the values of the measured data. The values of the weights (as noted in chapter 4) are the major contributor to the range of values of the measured data. This is because each weight is above or below the value of 5 pounds as stated. Therefore, when the weights are applied to the lever arm platforms the values of the applied weights are greater or less the recorded values. This effect can be corrected by the following:

1. Attain specialized weights of exactly 5 pounds each.
2. Obtain weights just over the 5-pound value and remove small portions (through machining) until the destined value is attained.

As the weights are applied to the lever arm platforms the displaced values of a subject's ASIS/PSIS arrangement are measured on the chart via the laser platform. The measured values are dependent on visual interpolation of the researcher. An appropriate measurement is dependent on the researcher's awareness and perfect positioning in front of the chart. Since this task is subjective, it is impossible to separate the reliability of the ATM from the researcher's ability to read the chart accurately. An alternative would be to incorporate a readout device in a digital format. This would certainly separate the ATM's reliability from the researcher's reliability since a digital readout leaves little room for the researcher's interpretation. The sensitivity of the ATM can certainly improve with just the improvement to values of the weights and the output device.

Also affecting the measured displacement values is the varying distance of the sagittal reference plane of a subject to the measuring chart on the wall (as discussed in chapter 4). Whether with the present design or, future designs of the ATM, in order to minimize the effects of the distance factor it is imperative to establish the longitudinal centerline of the ATM. After the longitudinal centerline of the ATM is established we can discount any involvement of the ATM in affecting the distance (from the longitudinal centerline to the chart). Now, the only affecting factor is associated with subject's positioning. The distance of the sagittal reference plane of a subject to the chart can be affected by the following:

1. The sagittal reference plane is skewed to one side (anatomical defect).
2. Repositioning of the sagittal reference plane, to either side of the longitudinal centerline of the ATM, due to the lifting motion of the ATM's lever arms.

The researcher has no control over any anatomical defect. However, the repositioning effect can be minimized or eliminated by redesigning the force application mechanism. The lever arms should be replaced with quick action pistons aligned through the vertical plane of a subject's PSIS while in the supine position. This piston arrangement will not only increase the time of testing but also maintain the subject along the longitudinal reference plane of the ATM. The pistons will also establish time as an independent variable. This will enable a measurement of the decrease in energy as a function of frequency.

Subject Selection

Establishing a norm for the stored energy of a healthy low back or, conducting a meaningful statistical analysis, requires a broad selection of subjects. A particular group that should be tested is athletes. Athletes are hypothesized to have healthy low backs (assuming no injury), which would be described by low values of stored energy. Among the athletic group, a comparison should be made between men and women to identify similarities and differences in the values of stored energy. Another study should involve everyday people, who are more apt to suffer low-back pain while engaged in regular activities. The study of such group should satisfy the following criteria:

1. Subjects with various body-mass indices.
2. Men compared to women.
3. Comparison of individuals engaged in same and different activities.
4. People with low-back disorders (verified with MRI).

The measured data from the above groups of human subjects may be able to produce a meaningful statistical analysis and a norm for the value of stored energy for a healthy low back.

APPENDIX A

TABULATED DATA

Appendix A is a compilation of displacement values for the series of cyclic loading and unloading of forces to the static model and the lower back of human subjects. The following is common to both the static model and the human subject:

1. R - Displacement values of the respective ASIS/PSIS arrangement resulting from the application and removal of weights to the right lever arm platform of the ATM.
2. L - Displacement values of the respective ASIS/PSIS arrangement resulting from the application and removal of weights to the left lever arm platform of the ATM.

Data for the static model is presented in tables A-1 through A-4 whereas the recorded data for the human subjects is presented in tables A-5 through A-16. Tables A-17 through A-28 contain the analyzed data from that presented in tables A-5 through A-16.

Table A.1 Loading and Displacement of Static Model Placed in Centered Position.

Name: Static Model **Time** **Start:** 8:30 PM

Date: 5/27/98 **End:** 8:45 PM

Weights	0	5	10	15	20	25	20	15	10	5
R1	0	0.75	1.5	2.35	3.2	4	3.2	2.35	1.55	0.75
L1	0	-0.7	-1.4	-2.15	-2.95	-3.85	-3.05	-2.2	-1.45	-0.75
R2	0	0.7	1.5	2.3	3.15	4	3.2	2.4	1.55	0.8
L2	0	-0.7	-1.4	-2.15	-3.05	-3.85	-3.05	-2.2	-1.45	-0.75
R3	0	0.7	1.5	2.3	3.15	4	3.2	2.35	1.55	0.8
L3	0	-0.7	-1.4	-2.15	-3.05	-3.85	-3.05	-2.2	-1.45	-0.75
R4	0	0.75	1.5	2.3	3.15	4	3.2	2.35	1.55	0.75
L4	0	-0.7	-1.4	-2.15	-3.05	-3.85	-3.05	-2.2	-1.45	-0.75
R5	0	0.7	1.5	2.3	3.15	4	3.2	2.35	1.6	0.8
L5	0	-0.7	-1.45	-2.15	-3.05	-3.85	-3.05	-2.2	-1.45	-0.75
R6	0	0.75	1.5	2.3	3.15	4	3.2	2.35	1.55	0.8
L6	0	-0.7	-1.4	-2.15	-3.05	-3.85	-3.05	-2.2	-1.45	-0.75
R7	0	0.7	1.5	2.3	3.2	4	XXXX	XXXX	XXXX	XXXX

Table A.2 Loading and Displacement of Static Model Placed 1 cm to Left from Center of Table.

Name: Static Model **Time** **Start:** 8:55 PM

Date: 5/27/98 **End:** 9:12 PM

Weights	**0**	**5**	**10**	**15**	**20**	**25**	**20**	**15**	**10**	**5**
R1	0	0.7	1.5	2.25	3.1	3.9	3.1	2.3	1.55	0.8
L1	0	-0.7	-1.45	-2.25	-3.15	-4.1	-3.2	-2.25	-1.5	-0.75
R2	0	0.7	1.5	2.3	3.1	3.9	3.1	2.35	1.55	0.8
L2	0	-0.7	-1.45	-2.25	-3.15	-4.1	-3.2	-2.3	-1.5	-0.75
R3	0	0.7	1.5	2.3	3.1	3.9	3.1	2.3	1.55	0.8
L3	0	-0.7	-1.45	-2.25	-3.15	-4.1	-3.2	-2.3	-1.5	-0.75
R4	0	0.7	1.5	2.25	3.1	3.9	3.1	2.3	1.55	0.8
L4	0	-0.7	-1.45	-2.25	-3.15	-4.1	-3.2	-2.25	-1.5	-0.75
R5	0	0.7	1.5	2.25	3.1	3.9	3.1	2.3	1.55	0.8
L5	0	-0.7	-1.45	-2.25	-3.15	-4.1	-3.2	-2.3	-1.5	-0.75
R6	0	0.7	1.5	2.25	3.1	3.9	3.1	2.3	1.55	0.8
L6	0	-0.7	-1.45	-2.25	-3.15	-4.1	-3.2	-2.25	-1.5	-0.75
R7	0	0.7	1.5	2.25	3.1	3.9	XXXX	XXXX	XXXX	XXXX

Table A.3 Loading and Displacement of Static Model Placed 1 cm to Right from Center of Table

Name: Static Model **Time** **Start:** 9:17 PM

Date: 5/27/98 **End:** 9:35 PM

Weights	**0**	**5**	**10**	**15**	**20**	**25**	**20**	**15**	**10**	**5**
R1	0	0.8	1.6	2.4	3.35	4.1	3.35	2.45	1.6	0.8
L1	0	-0.65	-1.35	-2.15	-2.9	-3.8	-2.9	-2.15	-1.35	-0.65
R2	0	0.75	1.55	2.4	3.35	4.1	3.4	2.45	1.6	0.8
L2	0	-0.65	-1.35	-2.15	-2.9	-3.8	-2.9	-2.15	-1.35	-0.65
R3	0	0.75	1.55	2.4	3.35	4.1	3.35	2.45	1.6	0.8
L3	0	-0.65	-1.4	-2.15	-2.85	-3.8	-2.9	-2.15	-1.45	-0.65
R4	0	0.75	1.55	2.45	3.3	4.1	3.35	2.45	1.6	0.8
L4	0	-0.65	-1.4	-2.15	-2.85	-3.8	-2.9	-2.15	-1.45	-0.65
R5	0	0.75	1.55	2.4	3.3	4.1	3.35	2.45	1.6	0.8
L5	0	-0.65	-1.4	-2.15	-2.85	-3.8	-2.9	-2.15	-1.45	-0.65
R6	0	0.75	1.6	2.4	3.3	4.1	3.35	2.45	1.6	0.8
L6	0	-0.65	-1.4	-2.15	-2.85	-3.8	-2.85	-2.15	-1.45	-0.65
R7	0	0.75	1.55	2.45	3.3	4.1	XXXX	XXXX	XXXX	XXXX

Table A.4 Loading and Displacement of Static Model Placed 1 cm to Superior Position of Center of Table.

Name: Static Model **Time** **Start:** 9:45 PM

Date: 5/27/98 **End:** 10:00 PM

Weights	0	5	10	15	20	25	20	15	10	5
R1	0	0.7	1.5	2.3	3.15	3.95	3.2	2.35	1.55	0.75
L1	0	-0.75	-1.4	-2.15	-3	-3.85	-3.05	-2.2	-1.45	-0.75
R2	0	0.7	1.5	2.3	3.1	3.95	3.15	2.35	1.55	0.75
L2	0	-0.75	-1.4	-2.15	-3	-3.85	-3.05	-2.2	-1.45	-0.75
R3	0	0.7	1.5	2.25	3.15	3.95	3.2	2.3	1.55	0.75
L3	0	-0.7	-1.4	-2.2	-3	-3.85	-3.05	-2.2	-1.45	-0.75
R4	0	0.7	1.5	2.25	3.1	3.95	3.2	2.3	1.55	0.75
L4	0	-0.7	-1.4	-2.15	-3	-3.85	-3.1	-2.2	-1.45	-0.75
R5	0	0.7	1.5	2.25	3.1	3.95	3.2	2.3	1.55	0.75
L5	0	-0.7	-1.4	-2.15	-3	-3.85	-3.05	-2.15	-1.45	-0.75
R6	0	0.7	1.5	2.25	3.1	3.95	3.15	2.35	1.55	0.8
L6	0	-0.7	-1.4	-2.15	-3	-3.85	-3.05	-2.2	-1.45	-0.75
R7	0	0.7	1.5	2.3	3.1	3.95	XXXX	XXXX	XXXX	XXXX

Table A.5 Loading and Displacement of PSISs for Subject 1.

Name: Subject 1 **Date:** 4/29/98 **Time** **Start:** 12:18 PM **End:** 12:35 PM

Sex/Age: F/29 **Weight:** 124 lbs **Height:** 66.5 in

Handed: Right

Weights	**0**	**5**	**10**	**15**	**20**	**25**	**20**	**15**	**10**	**5**
R1	0	0.4	1.6	2.9	4.5	6.8	5.8	4.8	3.4	1.8
L1	0.6	-0.2	-1.1	-2	-3	-4.2	-4	-3.4	-2.8	-2
R2	-0.8	-0.2	1	2.3	4.2	5.6	5.2	4.2	3	1.4
L2	0.3	-0.5	-1.4	-2.3	-3.4	-4.5	-4.2	-3.6	-3	-2.1
R3	-1	-0.4	0.8	2	3.6	5.5	5	4	2.8	1.3
L3	0.2	-0.6	-1.5	-2.3	-3.4	-4.5	-4.2	-3.5	-2.9	-2.1
R4	-1	-0.4	0.9	2.1	3.6	5.3	4.9	3.8	2.7	1.3
L4	0.1	-0.6	-1.6	-2.4	-3.3	-4.3	-4	-3.5	-2.9	-2
R5	-1	-0.4	0.9	2.1	3.5	5.4	4.9	3.8	2.7	1.3
L5	0.1	-0.7	-1.6	-2.4	-3.3	-4.2	-4	-3.5	-2.9	-2
R6	-1	-0.4	0.9	2.2	3.6	5.4	4.8	3.8	2.6	1.3
L6	0.1	-0.6	-1.6	-2.3	-3.2	-4.1	-3.9	-3.4	-2.8	-1.9
R7	-1	-0.3	0.9	2.2	3.7	5.4	XXXX	XXXX	XXXX	XXXX

Table A.6 Loading and Displacement of PSISs for Subject 2.

Name: Subject 2 **Date:** 4/29/98 **Time** **Start:** 4:09 PM **End:** 4:27 PM

Sex/Age: F/35 **Weight:** 122 lbs **Height:** 65 in

Handed: Right

Weights	0	5	10	15	20	25	20	15	10	5
R1	0	0.4	1	1.6	2.3	3.3	3.1	2.6	2.1	1.4
L1	0.7	0.2	-0.6	-1.6	-2.9	-4.2	-3.9	-3.1	-2.2	-1.2
R2	-0.6	-0.1	0.6	1.3	2	3	2.8	2.4	1.9	1.2
L2	0.5	0.1	-0.9	-2.3	-3.4	-4.5	-4.2	-3.5	-2.7	-1.6
R3	-0.9	-0.3	0.5	1.1	1.8	2.6	2.4	2	1.6	0.9
L3	0.2	-0.1	-1.2	-2.2	-3.3	-4.4	-4	-3.4	-2.6	-1.5
R4	-0.8	-0.3	0.5	1.2	1.8	2.8	2.5	2.1	1.6	0.9
L4	0.1	-0.3	-1.2	-2.3	-3.3	-4.5	-4.1	-3.5	-2.7	-1.6
R5	-0.9	-0.4	0.4	1	1.6	2.4	2.2	1.8	1.3	0.7
L5	0	-0.6	-1.5	-2.5	-3.5	-4.6	-4.3	-3.6	-2.8	-1.8
R6	-1	-0.5	0.4	1	1.6	2.4	2.2	1.7	1.3	0.8
L6	0	-0.4	-1.3	-2.4	-3.4	-4.5	-4.1	-3.6	-2.7	-1.6
R7	-1	-0.4	0.4	1	1.6	2.4	XXXX	XXXX	XXXX	XXXX

Table A.7 Loading and Displacement of PSISs for Subject 3.

Name: Subject 3 **Date:** 4/29/98 **Time** **Start:** 1:18 PM **End:** 1:36 PM

Sex/Age: M/26 **Weight:** 165 lbs **Height:** 71 in

Handed: Right

Weights	**0**	**5**	**10**	**15**	**20**	**25**	**20**	**15**	**10**	**5**
R1	0	0.1	0.4	0.8	1.4	2.3	2.1	1.8	1.4	0.9
L1	0.5	0.2	-0.2	-0.7	-1.2	-2.3	-2	-1.7	-1.2	-0.9
R2	-0.7	-0.2	0.2	0.6	1.3	2	1.8	1.5	1.2	0.7
L2	0.4	0.2	-0.2	-0.6	-1.2	-2.1	-1.8	-1.5	-1.2	-0.8
R3	-0.5	-0.1	0.2	0.7	1.3	2.1	1.9	1.5	1.2	0.7
L3	0.3	0.1	-0.3	-0.8	-1.3	-2.1	-2	-1.6	-1.3	-1.2
R4	-0.7	-0.4	0	0.5	1	1.8	1.6	1.3	0.9	0.5
L4	0.3	-0.1	-0.4	-0.9	-1.5	-2.4	-2.1	-1.8	-1.3	-1
R5	-0.7	-0.4	0	0.5	1.2	2.1	1.9	1.5	1	0.5
L5	0.2	-0.2	-0.5	-1.1	-1.5	-2.4	-2.2	-1.6	-1.4	-1.1
R6	-0.9	-0.7	-0.2	0.3	1.1	2	1.8	1.4	0.9	0.4
L6	0.1	-0.3	-0.6	-1.1	-1.6	-2.5	-2.3	-2	-1.5	-1.2
R7	-0.9	-0.5	-0.1	0.4	1.1	1.9	XXXX	XXXX	XXXX	XXXX

Table A.8 Loading and Displacement of PSISs for Subject 4.

Name: Subject 4 **Date:** 4/29/98 **Time** **Start:** 3:13 PM
End: 3:35 PM

Sex/Age: F/38 **Weight:** 133 lbs **Height:** 68 in

Handed: Right

Weights	**0**	**5**	**10**	**15**	**20**	**25**	**20**	**15**	**10**	**5**
R1	0	0.3	0.9	1.5	2.4	3.3	3	2.5	2.2	1.6
L1	0.9	0.4	-0.2	-0.8	-1.7	-2.5	-2.2	-1.8	-1.4	-0.9
R2	-0.3	0.3	1	1.7	2.3	3	2.8	2.5	2	1.5
L2	0.7	0.1	-0.5	-1	-1.7	-2.5	-2.2	-1.7	-1.3	-0.9
R3	-0.3	0.4	1	1.6	2.2	2.9	2.7	2.4	2	1.5
L3	0.7	0	-0.5	-1	-1.8	-2.7	-2.5	-2.1	-1.6	-1.1
R4	-0.7	-0.1	0.5	1	1.6	2.3	2	1.7	1.3	0.7
L4	0	-0.4	-0.9	-1.4	-2	-2.8	-2.5	-2.2	-1.8	-1.4
R5	-0.8	-0.1	0.5	1	1.7	2.3	2.1	1.8	1.4	0.9
L5	0.2	-0.4	-0.9	-1.5	-2.2	-3	-2.7	-2.3	-1.9	-1.4
R6	-0.8	0	0.8	1.2	1.8	2.5	2.3	2	1.5	1
L6	0.2	-0.4	-0.9	-1.4	-2.2	-3.1	-2.7	-2.3	-1.8	-1.4
R7	-0.8	-0.2	0.4	0.9	1.5	2.2	XXXX	XXXX	XXXX	XXXX

Table A.9 Loading and Displacement of PSISs for Subject 5.

Name: Subject 5 **Date:** 5/26/98 **Time** **Start:** 3:18 PM **End:** 3:33 PM

Sex/Age: F/30 **Weight:** 125 lbs **Height:** 63 in

Handed: Right

Weights	0	5	10	15	20	25	20	15	10	5
R1	0	0.4	0.8	1.2	1.8	2.3	2.2	1.9	1.6	1.2
L1	0.6	0.1	-0.3	-0.8	-1.3	-1.8	-1.7	-1.4	-1	-0.6
R2	0	0.5	0.9	1.3	1.7	2.2	2	1.8	1.5	1.1
L2	0.6	0.1	-0.3	-0.8	-1.3	-1.7	-1.5	-1.3	-0.9	-0.5
R3	0	0.5	0.9	1.3	1.7	2.1	2	1.7	1.5	1.1
L3	0.6	0.1	-0.3	-0.8	-1.2	-1.5	-1.4	-1.2	-0.9	-0.4
R4	0.1	0.5	0.9	1.3	1.7	2.1	1.9	1.7	1.4	1
L4	0.6	0.1	-0.3	-0.7	-1.1	-1.6	-1.4	-1.2	-0.8	-0.4
R5	0	0.4	0.8	1.2	1.6	2	1.8	1.6	1.3	1.1
L5	0.6	0.1	-0.3	-0.7	-1.1	-1.5	-1.4	-1.1	-0.8	-0.4
R6	0.1	0.5	0.9	1.2	1.6	2	1.9	1.6	1.4	1
L6	0.5	0.1	-0.3	-0.7	-1	-1.4	-1.3	-1.1	-0.8	-0.4
R7	0.1	0.5	0.9	1.2	1.6	2	XXXX	XXXX	XXXX	XXXX

Table A.10 Loading and Displacement of PSISs for Subject 6.

Name: Subject 6 **Date:** 5/6/98 **Time** **Start:** 3:55 PM **End:** 4:10 PM

Sex/Age: F/28 **Weight:** 130 lbs **Height:** 65 in

Handed: Right

Weights	0	5	10	15	20	25	20	15	10	5
R1	0	0.5	1.1	1.6	2.4	3.3	2.9	2.5	1.9	1.2
L1	0.5	0.1	-0.4	-1.2	-2.1	-2.8	-2.5	-2.2	-1.5	-0.9
R2	-0.4	0.1	0.8	1.4	2.2	3	2.7	2.2	1.6	1
L2	0.4	-0.1	-0.6	-1.3	-2.2	-2.8	-2.5	-2	-1.8	-0.6
R3	-0.4	0	0.7	1.4	2.2	2.9	2.6	2.1	1.6	0.9
L3	0.3	-0.1	-0.7	-1.4	-2.1	-2.8	-2.6	-2.2	-1.6	-1
R4	-0.4	0	0.6	1.3	2	2.8	2.5	2	1.4	0.8
L4	0.3	-0.2	-0.8	-1.5	-2.1	-2.8	-2.6	-2.3	-1.8	-1.1
R5	-0.5	-0.1	0.4	1.2	1.8	2.6	2.3	1.8	1.2	0.6
L5	0.1	-0.4	-0.9	-1.6	-2.2	-2.9	-2.6	-2.3	-1.7	-1.2
R6	-0.6	-0.2	0.4	1.2	1.9	2.7	2.4	2	1.5	0.8
L6	0.2	-0.2	-0.7	-1.5	-2	-2.7	-2.5	-2.2	-1.6	-1
R7	-0.4	0	0.5	1.2	1.8	2.6	XXXX	XXXX	XXXX	XXXX

Table A.11 Loading and Displacement of PSISs for Subject 7.

Name: Subject 7 **Date:** 5/6/98 **Time** **Start:** 4:40 PM **End:** 4:57 PM

Sex/Age: F/34 **Weight:** 100 lbs **Height:** 61 in

Handed: Right

Weights	0	5	10	15	20	25	20	15	10	5
R1	0	0.3	1.2	2.2	3.7	5.5	5.1	4.1	3.1	1.7
L1	0.7	0.2	-0.8	-2	-3.4	-5.8	-5.2	-4.2	-2.9	-1.7
R2	-0.6	0	1	2.2	3.5	5.2	4.7	3.7	2.7	1.5
L2	0.5	0	-1	-2.4	-3.9	-5.6	-5.2	-4.1	-3	-1.7
R3	-0.6	0	1	2.2	3.4	5.2	4.6	3.7	2.6	1.4
L3	0.4	-0.1	-1.2	-2.4	-3.8	-5.5	-4.8	-4	-2.8	-1.6
R4	-0.6	0	1	2.1	3.3	4.9	4.5	3.6	2.6	1.4
L4	0.3	-0.2	-1.2	-2.5	-3.8	-5.4	-4.8	-3.9	-2.9	-1.6
R5	-0.6	0	1	2.1	3.3	5	4.4	3.5	2.5	1.3
L5	0.4	-0.2	-1.2	-2.5	-3.8	-5.4	-4.8	-3.9	-2.8	-1.6
R6	-0.6	0	1	2.1	3.4	4.8	4.3	3.4	2.5	1.3
L6	0.3	-0.2	-1.2	-2.5	-3.8	-5.5	-4.8	-4	-2.8	-1.7
R7	-0.6	-0.1	1	2.1	3.3	4.8	XXXX	XXXX	XXXX	XXXX

Table A.12 Loading and Displacement of PSISs for Subject 8.

Name: Subject 8 **Date:** 5/6/98 **Time** **Start:** 2:50 PM **End:** 3:04 PM

Sex/Age: M/22 **Weight:** 147 lbs **Height:** 72 in

Handed: Right

Weights	0	5	10	15	20	25	20	15	10	5
R1	0	0.5	1.1	1.8	2.5	3	2.8	2.4	1.3	0.8
L1	-0.1	-0.8	-1.6	-2.7	-3.8	-4.9	-4.7	-4.4	-3.9	-3.5
R2	-2.8	-1.6	-0.6	0.6	1.2	2.2	2	1.8	1.2	0.6
L2	-0.2	-0.8	-1.4	-2.6	-3.4	-4.3	-4.1	-3.9	-3.5	-2.9
R3	-2.2	-1.1	-0.4	0.5	1.4	2.4	2.3	2.1	1.7	1.1
L3	0.5	-0.2	-0.8	-1.8	-2.7	-3.6	-3.4	-3.1	-2.7	-2
R4	-1.2	-0.5	0.2	0.8	1.7	2.8	2.7	2.4	1.8	1.1
L4	0.2	-0.4	-1.3	-2.1	-2.9	-3.9	-3.8	-3.4	-3	-2.4
R5	-1.6	-0.5	0.3	1.2	2.1	2.9	2.8	2.4	2	1.6
L5	0.6	0	-0.6	-1.6	-2.4	-3.2	-3.2	-2.8	-2.3	-1.4
R6	-0.9	0	0.7	1.4	2.2	3	2.9	2.6	2.2	1.8
L6	1.1	0.8	-0.1	-1.1	-2.1	-3	-2.8	-2.4	-2	-1.2
R7	-0.4	0.5	0.8	1.4	2.2	3.2	XXXX	XXXX	XXXX	XXXX

Table A.13 Loading and Displacement of PSISs for Subject 9.

Name: Subject 9 **Date:** 6/3/98 **Time** **Start:** 1:50 PM **End:** 2:07 PM

Sex/Age: M/47 **Weight:** 170 lbs **Height:** 72 in

Handed: Right

Weights	0	5	10	15	20	25	20	15	10	5
R1	0	0.15	0.55	0.95	1.4	1.9	1.75	1.5	1.15	0.75
L1	0.35	0.05	-0.4	-0.8	-1.2	-1.55	-1.5	-1.3	-1	-0.6
R2	-1.5	0.15	0.6	1	1.5	1.9	1.75	1.5	1.2	0.75
L2	0.4	0.05	-0.35	-0.8	-1.15	-1.5	-1.4	-1.2	-0.9	-0.5
R3	0	0.15	0.65	1.1	1.5	1.95	1.8	1.55	1.2	0.75
L3	0.4	0.1	-0.35	-0.75	-1.1	-1.5	-1.4	-1.2	-0.9	-0.45
R4	0	0.2	0.65	1.1	1.5	1.9	1.8	1.55	1.2	0.7
L4	0.4	-0.1	-0.35	-0.8	-1.15	-1.5	-1.4	-1.2	-0.9	-0.5
R5	-0.05	0.15	0.6	1	1.45	1.9	1.75	1.5	1.15	0.75
L5	0.35	0.05	-0.4	-0.8	-1.15	-1.5	-1.35	-1.2	-0.9	-0.45
R6	-0.1	0.15	0.6	1	1.45	1.9	1.75	1.5	1.15	0.7
L6	0.35	0.05	-0.4	-0.8	-1.15	-1.5	-1.35	-1.2	-0.9	-0.5
R7	-0.05	0.15	0.6	1	1.45	1.9	XXXX	XXXX	XXXX	XXXX

Table A.14 Loading and Displacement of PSISs for Subject 10.

Name: Subject 10 **Date:** 6/10/98 **Time** **Start:** 4:07 PM
End: 4:25 PM

Sex/Age: M/24 **Weight:** 172 lbs **Height:** 73 in

Handed: Right

Weights	0	5	10	15	20	25	20	15	10	5
R1	0	0.3	0.9	1.5	2.1	2.9	2.7	2.3	1.85	1.35
L1	0.45	0.1	-0.5	-1.3	-2	-2.6	-2.5	-2.1	-1.7	-1.1
R2	-0.5	0	0.7	1.4	2	2.7	2.55	2.2	1.7	1
L2	0.35	-0.1	-0.6	-1.35	-2.1	-2.6	-2.45	-2.1	-1.65	-1.1
R3	-0.5	0.05	0.7	1.4	1.9	2.6	2.45	2.1	1.65	1
L3	0.3	-0.1	-0.6	-1.3	-2	-2.6	-2.45	-2.15	-1.7	-1
R4	-0.5	-0.1	0.7	1.3	1.9	2.5	2.35	2.1	1.6	0.9
L4	0.25	-0.1	-0.7	-1.4	-2	-2.55	-2.4	-2.15	-1.6	-1.1
R5	-0.5	-0.05	0.7	1.3	1.9	2.5	2.3	2	1.55	0.9
L5	0.25	-0.15	-0.7	-1.3	-1.95	-2.5	-2.4	-2.1	-1.6	-1
R6	-0.5	0	0.65	1.25	1.85	2.5	2.3	2	1.5	0.9
L6	0.2	-0.15	-0.7	-1.4	-2	-2.5	-2.35	-2.1	-1.6	-1
R7	-0.4	-0.05	0.65	1.25	1.8	2.45	XXXX	XXXX	XXXX	XXXX

Table A.15 Loading and Displacement of PSISs for Subject 11.

Name: Subject 11 **Date:** 6/10/98 **Time** **Start:** 5:45 PM
End: 6:02 PM

Sex/Age: F/22 **Weight:** 190 lbs **Height:** 67 in

Handed: Right

Weights	0	5	10	15	20	25	20	15	10	5
R1	0	0.3	0.7	1.2	1.7	2.2	2.1	1.75	1.3	0.7
L1	0.2	-0.1	-0.4	-0.9	-1.5	-2	-2.8	-1.4	-1	-0.6
R2	-0.2	0.1	0.6	1.1	1.6	2.6	2.25	1.9	1.3	0.8
L2	0.3	0.1	-0.3	-0.7	-1.2	-1.8	-1.6	-1.2	-0.8	-0.4
R3	-0.1	0.15	0.7	1.2	1.8	2.5	2.25	1.9	1.3	0.7
L3	0.2	0	-0.4	-0.9	-1.5	-2	-1.8	-1.3	-0.9	-0.5
R4	-0.1	0.2	0.6	1.1	1.7	2.3	2.1	1.7	1.2	0.7
L4	0.2	0	-0.5	-0.9	-1.4	-2	-1.8	-1.3	-0.9	-0.4
R5	-0.1	0.2	0.7	1.2	1.7	2.2	2	1.7	1.2	0.6
L5	0.1	-0.1	-0.6	-0.9	-1.45	-2	-1.7	-1.3	-1	-0.6
R6	-0.2	0.2	0.7	1.2	1.7	2.3	2	1.7	1.3	0.7
L6	0.2	0	-0.4	-0.9	-1.4	-1.9	-1.6	-1.2	-0.9	-0.5
R7	-0.2	0.1	0.6	1.2	1.8	2.3	XXXX	XXXX	XXXX	XXXX

Table A.16 Loading and Displacement of PSISs for Subject 12.

Name: Subject 12 **Date:** 6/10/98 **Time** **Start:** 5:11 PM **End:** 5:29 PM

Sex/Age: F/20 **Weight:** 140 lbs **Height:** 64 in

Handed: Right

Weights	0	5	10	15	20	25	20	15	10	5
R1	0	0.1	0.5	1.1	1.7	2.2	2.1	1.7	1.1	0.5
L1	0.1	-0.1	-0.6	-1.2	-2.2	-3.1	-2.8	-2.3	-1.6	-0.9
R2	-0.5	-0.3	0	0.7	1.4	2	1.8	1.3	0.7	0.1
L2	-0.2	-0.4	-0.9	-1.7	-2.4	-3.3	-3	-2.3	-1.6	-1
R3	-0.5	-0.3	-0.2	0.5	1.15	1.75	1.6	1.2	0.5	-0.2
L3	-0.5	-0.75	-1.2	-1.9	-2.8	-3.8	-3.4	-2.8	-2.2	-1.4
R4	-1	-0.8	-0.4	0.2	1	1.7	1.4	0.9	0.4	-0.3
L4	-0.5	-0.7	-1.2	-2	-2.8	-3.6	-3.2	-2.7	-2.1	-1.2
R5	-0.9	-0.7	-0.3	0.35	1	1.8	1.5	1	0.5	-0.1
L5	-0.4	-0.7	-1.1	-1.9	-2.7	-3.4	-3	-2.6	-1.9	-1.3
R6	-0.7	-0.6	-0.3	0.3	1	1.7	1.4	1	0.4	-0.2
L6	-0.5	-0.7	-1.3	-1.9	-2.7	-3.5	-3.2	-2.7	-2	-1.3
R7	-0.9	-0.7	-0.3	0.3	1	1.7	XXXX	XXXX	XXXX	XXXX

Table A.17 Loading and Displacement of PSISs for Subject 1.

Name:	Subject 1	**Date:**	4/29/98	**Time**	**Start:** 12:18 PM
					End: 12:35 PM
Sex/Age:	F/29	**Weight:**	124 lbs	**Height:**	66.5 in
Handed:	Right				

	Weights	**0**	**5**	**10**	**15**	**20**	**25**	**20**	**15**	**10**	**5**
Avg. Disp.	R	-0.97	-0.35	0.90	2.15	3.70	5.43	5.10	4.07	2.87	1.40
Total LUL	L	0.23	-0.53	-1.47	-2.28	-3.27	-4.30	-4.05	-3.48	-2.88	-2.02
Max. Total	R	-1.11	-0.40	1.04	2.47	4.26	6.25	5.87	4.68	3.30	1.61
Avg. Disp.	L	0.27	-0.61	-1.69	-2.63	-3.76	-4.95	-4.66	-4.01	-3.32	-2.32
Min. Total	R	-0.82	-0.30	0.77	1.83	3.15	4.62	4.34	3.46	2.44	1.19
Avg. Disp.	L	0.20	-0.45	-1.25	-1.94	-2.78	-3.66	-3.44	-2.96	-2.45	-1.71
Avg. Disp.	R	-0.93	-0.33	0.90	2.13	3.80	5.47	5.33	4.33	3.07	1.50
1st Set LUL	L	0.37	-0.43	-1.33	-2.20	-3.27	-4.40	-4.13	-3.50	-2.90	-2.07
Avg. Disp.	R	-1.00	-0.37	0.90	2.17	3.60	5.40	4.87	3.80	2.67	1.30
2nd Set LUL	L	0.10	-0.63	-1.60	-2.37	-3.27	-4.20	-3.97	-3.47	-2.87	-1.97

Table A.18 Loading and Displacement of PSISs for Subject 2.

Name:	Subject 2	**Date:**	4/29/98	**Time**	**Start:** 4:09 PM
					End: 4:27 PM
Sex/Age:	F/35	**Weight:**	122 lbs	**Height:**	65 in
Handed:	Right				

	Weights	**0**	**5**	**10**	**15**	**20**	**25**	**20**	**15**	**10**	**5**
Avg. Disp.	R	-0.87	-0.33	0.47	1.10	1.73	2.60	2.53	2.10	1.63	0.98
Total LUL	L	0.25	-0.18	-1.12	-2.22	-3.30	-4.45	-4.10	-3.45	-2.62	-1.55
Max. Total	R	-1.00	-0.38	0.54	1.27	1.99	2.99	2.91	2.42	1.88	1.13
Avg. Disp.	L	0.29	-0.21	-1.28	-2.55	-3.80	-5.12	-4.72	-3.97	-3.01	-1.78
Min. Total	R	-0.74	-0.28	0.40	0.94	1.47	2.21	2.15	1.79	1.39	0.84
Avg. Disp.	L	0.21	-0.16	-0.95	-1.88	-2.81	-3.78	-3.49	-2.93	-2.22	-1.32
Avg. Disp.	R	-0.77	-0.23	0.53	1.20	1.87	2.80	2.77	2.33	1.87	1.17
1st Set LUL	L	0.47	0.07	-0.90	-2.03	-3.20	-4.37	-4.03	-3.33	-2.50	-1.43
Avg. Disp.	R	-0.97	-0.43	0.40	1.00	1.60	2.40	2.30	1.87	1.40	0.80
2nd Set LUL	L	0.03	-0.43	-1.33	-2.40	-3.40	-4.53	-4.17	-3.57	-2.73	-1.67

Table A.19 Loading and Displacement of PSISs for Subject 3.

Name: Subject 3 **Date:** 4/29/98 **Time** **Start:** 1:18 PM
End: 1:36 PM
Sex/Age: M/26 **Weight:** 165 lbs **Height:** 71 in **Handed:** Right

	Weights	**0**	**5**	**10**	**15**	**20**	**25**	**20**	**15**	**10**	**5**
Avg. Disp.	R	-0.73	-0.38	0.02	0.50	1.17	1.98	1.85	1.50	1.10	0.62
Total LUL	L	0.30	-0.02	-0.37	-0.87	-1.38	-2.30	-2.07	-1.70	-1.32	-1.03
Max. Total	R	-0.84	-0.44	0.02	0.58	1.34	2.28	2.13	1.73	1.27	0.71
Avg. Disp.	L	0.35	-0.02	-0.42	-1.00	-1.59	-2.65	-2.38	-1.96	-1.51	-1.19
Min. Total	R	-0.62	-0.33	0.01	0.43	0.99	1.69	1.57	1.28	0.94	0.52
Avg. Disp.	L	0.26	-0.01	-0.31	-0.74	-1.18	-1.96	-1.76	-1.45	-1.12	-0.88
Avg. Disp.	R	-0.63	-0.23	0.13	0.60	1.20	1.97	1.93	1.60	1.27	0.77
1st Set LUL	L	0.40	0.17	-0.23	-0.70	-1.23	-2.17	-1.93	-1.60	-1.23	-0.97
Avg. Disp.	R	-0.83	-0.53	-0.10	0.40	1.13	2.00	1.77	1.40	0.93	0.47
2nd Set LUL	L	0.20	-0.20	-0.50	-1.03	-1.53	-2.43	-2.20	-1.80	-1.40	-1.10

Table A.20 Loading and Displacement of PSISs for Subject 4.

Name: Subject 4 **Date:** 4/29/98 **Time** **Start:** 3:13 PM
End: 3:35 PM
Sex/Age: F/38 **Weight:** 133 lbs **Height:** 68 in **Handed:** Right

	Weights	**0**	**5**	**10**	**15**	**20**	**25**	**20**	**15**	**10**	**5**
Avg. Disp.	R	-0.62	0.05	0.70	1.23	1.85	2.53	2.48	2.15	1.73	1.20
Total LUL	L	0.45	-0.12	-0.65	-1.18	-1.93	-2.77	-2.47	-2.07	-1.63	-1.18
Max. Total	R	-0.71	0.06	0.81	1.42	2.13	2.91	2.86	2.47	1.99	1.38
Avg. Disp.	L	0.52	-0.13	-0.75	-1.36	-2.22	-3.18	-2.84	-2.38	-1.88	-1.36
Min. Total	R	-0.52	0.04	0.60	1.05	1.57	2.15	2.11	1.83	1.47	1.02
Avg. Disp.	L	0.38	-0.10	-0.55	-1.01	-1.64	-2.35	-2.10	-1.76	-1.39	-1.01
Avg. Disp.	R	-0.43	0.20	0.83	1.43	2.03	2.73	2.83	2.47	2.07	1.53
1st Set LUL	L	0.77	0.17	-0.40	-0.93	-1.73	-2.57	-2.30	-1.87	-1.43	-0.97
Avg. Disp.	R	-0.80	-0.10	0.57	1.03	1.67	2.33	2.13	1.83	1.40	0.87
2nd Set LUL	L	0.13	-0.40	-0.90	-1.43	-2.13	-2.97	-2.63	-2.27	-1.83	-1.40

Table A.21 Loading and Displacement of PSISs for Subject 5.

Name:	Subject 5	**Date:**	5/26/98	**Time**	**Start:** 3:18 PM
					End: 3:33 PM
Sex/Age:	F/30	**Weight:**	125 lbs	**Height:** 63 in	**Handed:** Right

	Weights	**0**	**5**	**10**	**15**	**20**	**25**	**20**	**15**	**10**	**5**
Avg. Disp.	**R**	0.05	0.48	0.88	1.25	1.65	2.07	1.97	1.72	1.45	1.08
Total LUL	**L**	0.58	0.10	-0.30	-0.75	-1.17	-1.58	-1.45	-1.22	-0.87	-0.45
Max. Total	**R**	0.06	0.56	1.02	1.44	1.90	2.38	2.26	1.97	1.67	1.25
Avg. Disp.	**L**	0.67	0.12	-0.35	-0.86	-1.34	-1.82	-1.67	-1.40	-1.00	-0.52
Min. Total	**R**	0.04	0.41	0.75	1.06	1.40	1.76	1.67	1.46	1.23	0.92
Avg. Disp.	**L**	0.50	0.09	-0.26	-0.64	-0.99	-1.35	-1.23	-1.03	-0.74	-0.38
Avg. Disp.	**R**	0.03	0.50	0.90	1.30	1.70	2.13	2.07	1.80	1.53	1.13
1st Set LUL	**L**	0.60	0.10	-0.30	-0.80	-1.27	-1.67	-1.53	-1.30	-0.93	-0.50
Avg. Disp.	**R**	0.07	0.47	0.87	1.20	1.60	2.00	1.87	1.63	1.37	1.03
2nd Set LUL	**L**	0.57	0.10	-0.30	-0.70	-1.07	-1.50	-1.37	-1.13	-0.80	-0.40

Table A.22 Loading and Displacement of PSISs for Subject 6.

Name:	Subject 6	**Date:**	5/6/98	**Time**	**Start:** 3:55 PM
					End: 4:10 PM
Sex/Age:	F/28	**Weight:**	130 lbs	**Height:** 65 in	**Handed:** Right

	Weights	**0**	**5**	**10**	**15**	**20**	**25**	**20**	**15**	**10**	**5**
Avg. Disp.	**R**	-0.45	-0.03	0.57	1.28	1.98	2.77	2.57	2.10	1.53	0.88
Total LUL	**L**	0.30	-0.15	-0.68	-1.42	-2.12	-2.80	-2.55	-2.20	-1.67	-0.97
Max. Total	**R**	-0.52	-0.04	0.65	1.48	2.28	3.18	2.95	2.42	1.76	1.02
Avg. Disp.	**L**	0.35	-0.17	-0.79	-1.63	-2.43	-3.22	-2.93	-2.53	-1.92	-1.11
Min. Total	**R**	-0.38	-0.03	0.48	1.09	1.69	2.35	2.18	1.79	1.30	0.75
Avg. Disp.	**L**	0.26	-0.13	-0.58	-1.20	-1.80	-2.38	-2.17	-1.87	-1.42	-0.82
Avg. Disp.	**R**	-0.40	0.03	0.70	1.37	2.13	2.90	2.73	2.27	1.70	1.03
1st Set LUL	**L**	0.40	-0.03	-0.57	-1.30	-2.13	-2.80	-2.53	-2.13	-1.63	-0.83
Avg. Disp.	**R**	-0.50	-0.10	0.43	1.20	1.83	2.63	2.40	1.93	1.37	0.73
2nd Set LUL	**L**	0.20	-0.27	-0.80	-1.53	-2.10	-2.80	-2.57	-2.27	-1.70	-1.10

Table A.23 Loading and Displacement of PSISs for Subject 7.

Name:	Subject 7	**Date:**	5/6/98	**Time**	**Start:** 4:40 PM
					End: 4:57 PM
Sex/Age: F/34	**Weight:** 100 lbs	**Height:**	61 in	**Handed:**	Right

	Weights	**0**	**5**	**10**	**15**	**20**	**25**	**20**	**15**	**10**	**5**
Avg. Disp.	**R**	-0.60	-0.02	1.00	2.13	3.37	4.98	4.60	3.67	2.67	1.43
Total LUL	**L**	0.43	-0.08	-1.10	-2.38	-3.75	-5.53	-4.93	-4.02	-2.87	-1.65
Max. Total	**R**	-0.69	-0.02	1.15	2.45	3.87	5.73	5.29	4.22	3.07	1.65
Avg. Disp.	**L**	0.50	-0.10	-1.27	-2.74	-4.31	-6.36	-5.67	-4.62	-3.30	-1.90
Min. Total	**R**	-0.51	-0.01	0.85	1.81	2.86	4.24	3.91	3.12	2.27	1.22
Avg. Disp.	**L**	0.37	-0.07	-0.94	-2.03	-3.19	-4.70	-4.19	-3.41	-2.44	-1.40
Avg. Disp.	**R**	-0.60	0.00	1.00	2.17	3.40	5.10	4.80	3.83	2.80	1.53
1st Set LUL	**L**	0.53	0.03	-1.00	-2.27	-3.70	-5.63	-5.07	-4.10	-2.90	-1.67
Avg. Disp.	**R**	-0.60	-0.03	1.00	2.10	3.33	4.87	4.40	3.50	2.53	1.33
2nd Set LUL	**L**	0.33	-0.20	-1.20	-2.50	-3.80	-5.43	-4.80	-3.93	-2.83	-1.63

Table A.24 Loading and Displacement of PSISs for Subject 8.

Name:	Subject 8	**Date:**	5/6/98	**Time**	**Start:** 2:50 PM
					End: 3:04 PM
Sex/Age: M/22	**Weight:** 147 lbs	**Height:**	72 in	**Handed:**	Right

	Weights	**0**	**5**	**10**	**15**	**20**	**25**	**20**	**15**	**10**	**5**
Avg. Disp.	**R**	-1.52	-0.53	0.17	0.98	1.80	2.75	2.58	2.28	1.70	1.17
Total LUL	**L**	0.35	-0.23	-0.97	-1.98	-2.88	-3.82	-3.67	-3.33	-2.90	-2.23
Max. Total	**R**	-1.74	-0.61	0.19	1.13	2.07	3.16	2.97	2.63	1.96	1.34
Avg. Disp.	**L**	0.40	-0.27	-1.11	-2.28	-3.32	-4.39	-4.22	-3.83	-3.34	-2.57
Min. Total	**R**	-1.29	-0.45	0.14	0.84	1.53	2.34	2.20	1.94	1.45	0.99
Avg. Disp.	**L**	0.30	-0.20	-0.82	-1.69	-2.45	-3.24	-3.12	-2.83	-2.47	-1.90
Avg. Disp.	**R**	-2.07	-1.07	-0.27	0.63	1.43	2.47	2.37	2.10	1.40	0.83
1st Set LUL	**L**	0.07	-0.60	-1.27	-2.37	-3.30	-4.27	-4.07	-3.80	-3.37	-2.80
Avg. Disp.	**R**	-0.97	0.00	0.60	1.33	2.17	3.03	2.80	2.47	2.00	1.50
2nd Set LUL	L	0.63	0.13	-0.67	-1.60	-2.47	-3.37	-3.27	-2.87	-2.43	-1.67

Table A.25 Loading and Displacement of PSISs for Subject 9.

Name:	Subject 9					**Date:**	6/3/98		**Time**	**Start:**	1:50 PM	
										End:	2:07 PM	
Sex/Age:	M/47			**Weight:**	170 lbs		**Height:**	72 in		**Handed:**	Right	

		Weights	**0**	**5**	**10**	**15**	**20**	**25**	**20**	**15**	**10**	**5**
Avg. Disp.		R	-0.28	0.16	0.62	1.03	1.48	1.91	1.77	1.52	1.18	0.73
Total LUL		L	0.38	0.03	-0.38	-0.79	-1.15	-1.51	-1.40	-1.22	-0.92	-0.50
Max. Total		R	-0.33	0.18	0.71	1.19	1.70	2.19	2.03	1.74	1.35	0.84
Avg. Disp.		L	0.43	0.04	-0.43	-0.91	-1.32	-1.73	-1.61	-1.40	-1.05	-0.58
Min. Total		R	-0.24	0.13	0.52	0.88	1.25	1.62	1.50	1.29	1.00	0.62
Avg. Disp.		L	0.32	0.03	-0.32	-0.67	-0.98	-1.28	-1.19	-1.03	-0.78	-0.43
Avg. Disp.		R	-0.50	0.17	0.63	1.07	1.50	1.92	1.77	1.52	1.18	0.75
1st Set LUL		L	0.38	0.07	-0.37	-0.78	-1.15	-1.52	-1.43	-1.23	-0.93	-0.52
Avg. Disp.		R	-0.07	0.15	0.60	1.00	1.45	1.90	1.77	1.52	1.17	0.72
2nd Set LUL		L	0.37	0.00	-0.38	-0.80	-1.15	-1.50	-1.37	-1.20	-0.90	-0.48

Table A.26 Loading and Displacement of PSISs for Subject 10.

Name:	Subject 10					**Date:**	6/10/98		**Time**	**Start:**	4:07 PM	
										End:	4:25 PM	
Sex/Age:	M/24			**Weight:**	172 lbs		**Height:**	73 in		**Handed:**	Right	

		Weights	**0**	**5**	**10**	**15**	**20**	**25**	**20**	**15**	**10**	**5**
Avg. Disp.		R	-0.48	-0.03	0.68	1.32	1.89	2.54	2.44	2.12	1.64	1.01
Total LUL		L	0.30	-0.08	-0.63	-1.34	-2.01	-2.56	-2.43	-2.12	-1.64	-1.05
Max. Total		R	-0.56	-0.03	0.79	1.51	2.18	2.92	2.81	2.43	1.89	1.16
Avg. Disp.		L	0.35	-0.10	-0.73	-1.54	-2.31	-2.94	-2.79	-2.43	-1.89	-1.21
Min. Total		R	-0.41	-0.02	0.58	1.12	1.61	2.16	2.08	1.80	1.40	0.86
Avg. Disp.		L	0.26	-0.07	-0.54	-1.14	-1.71	-2.17	-2.06	-1.80	-1.40	-0.89
Avg. Disp.		R	-0.50	-0.02	0.70	1.37	1.93	2.60	2.57	2.20	1.73	1.12
1st Set LUL		L	0.37	-0.03	-0.57	-1.32	-2.03	-2.60	-2.47	-2.12	-1.68	-1.07
Avg. Disp.		R	-0.47	-0.03	0.67	1.27	1.85	2.48	2.32	2.03	1.55	0.90
2nd Set LUL		L	0.23	-0.13	-0.70	-1.37	-1.98	-2.52	-2.38	-2.12	-1.60	-1.03

Table A.27 Loading and Displacement of PSISs for Subject 11.

Name: Subject 11 **Date:** 6/10/98 **Time** **Start:** 5:45 PM **End:** 6:02 PM

Sex/Age: F/22 **Weight:** 190 lbs **Height:** 67 in **Handed:** Right

Weights		0	5	10	15	20	25	20	15	10	5
Avg. Disp.	R	-0.15	0.16	0.65	1.17	1.72	2.37	2.12	1.78	1.27	0.70
Total LUL	L	0.20	-0.02	-0.43	-0.87	-1.41	-1.95	-1.88	-1.28	-0.92	-0.50
Max. Total	R	-0.17	0.18	0.75	1.34	1.97	2.72	2.43	2.04	1.46	0.81
Avg. Disp.	L	0.23	-0.02	-0.50	-1.00	-1.62	-2.24	-2.17	-1.48	-1.05	-0.58
Min. Total	R	-0.13	0.13	0.55	0.99	1.46	2.01	1.80	1.51	1.08	0.60
Avg. Disp.	L	0.17	-0.01	-0.37	-0.74	-1.20	-1.66	-1.60	-1.09	-0.78	-0.43
Avg. Disp.	R	-0.13	0.15	0.63	1.13	1.70	2.47	2.20	1.85	1.30	0.73
1st Set LUL	L	0.23	0.00	-0.37	-0.83	-1.40	-1.93	-2.07	-1.30	-0.90	-0.50
Avg. Disp.	R	-0.17	0.17	0.67	1.20	1.73	2.27	2.03	1.70	1.23	0.67
2nd Set LUL	L	0.17	-0.03	-0.50	-0.90	-1.42	-1.97	-1.70	-1.27	-0.93	-0.50

Table A.28 Loading and Displacement of PSISs for Subject 12.

Name: Subject 12 **Date:** 6/10/98 **Time** **Start:** 5:11 PM **End:** 5:29 PM

Sex/Age: F/20 **Weight:** 140 lbs **Height:** 64 in **Handed:** Right

Weights		0	5	10	15	20	25	20	15	10	5
Avg. Disp.	R	-0.75	-0.57	-0.25	0.39	1.09	1.78	1.63	1.18	0.60	-0.03
Total LUL	L	-0.33	-0.56	-1.05	-1.77	-2.60	-3.45	-3.10	-2.57	-1.90	-1.18
Max. Total	R	-0.86	-0.65	-0.29	0.45	1.26	2.04	1.88	1.36	0.69	-0.04
Avg. Disp.	L	-0.38	-0.64	-1.21	-2.03	-2.99	-3.97	-3.57	-2.95	-2.19	-1.36
Min. Total	R	-0.64	-0.48	-0.21	0.33	0.93	1.51	1.39	1.01	0.51	-0.03
Avg. Disp.	L	-0.28	-0.47	-0.89	-1.50	-2.21	-2.93	-2.64	-2.18	-1.62	-1.01
Avg. Disp.	R	-0.67	-0.47	-0.20	0.47	1.18	1.82	1.83	1.40	0.77	0.13
1st Set LUL	L	-0.20	-0.42	-0.90	-1.60	-2.47	-3.40	-3.07	-2.47	-1.80	-1.10
Avg. Disp.	R	-0.83	-0.67	-0.30	0.32	1.00	1.73	1.43	0.97	0.43	-0.20
2nd Set LUL	L	-0.47	-0.70	-1.20	-1.93	-2.73	-3.50	-3.13	-2.67	-2.00	-1.27

APPENDIX B

HYSTERESIS LOOP PLOTS

The figures presented in appendix B represent the hysteresis loops, which are generated from the data presented in tables A-17 thorough A-22. The plot presented for each subject represents the results for the entire test procedure of that subject. The area contained within each loop represents the stored energy in the lower back of a subject after the lower back has experienced a series of cyclic application and removal of forces.

Load	Total Avg. Displacements
0	-0.97
5	-0.35
10	0.9
15	2.15
20	3.7
25	5.43
20	5.1
15	4.07
10	2.87
5	1.4
0	0.23
-5	-0.53
-10	-1.47
-15	-2.28
-20	-3.27
-25	-4.3
-20	-4.05
-15	-3.48
-10	-2.88
-5	-2.02
0	-0.97

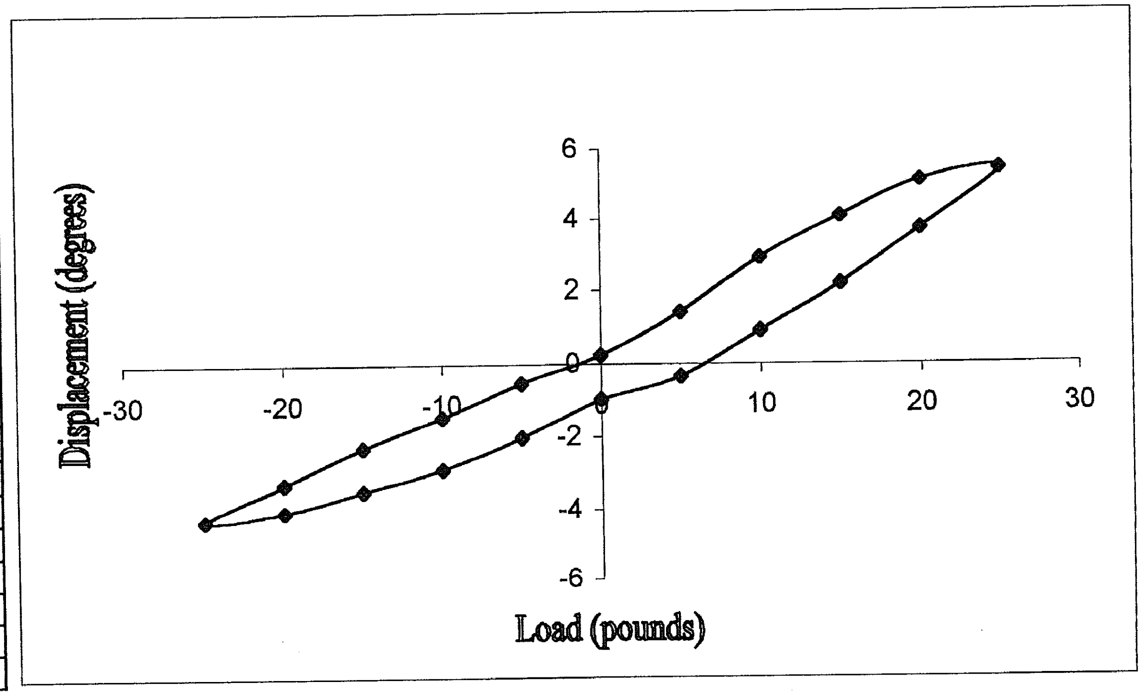

Figure B.1 Hysteresis Plot for Subject 1

Load	Total Avg. Displacements
0	-0.87
5	-0.33
10	0.47
15	1.1
20	1.73
25	2.6
20	2.53
15	2.1
10	1.63
5	0.98
0	0.25
-5	-0.18
-10	-1.12
-15	-2.22
-20	-3.3
-25	-4.45
-20	-4.1
-15	-3.45
-10	-2.62
-5	-1.55
0	-0.87

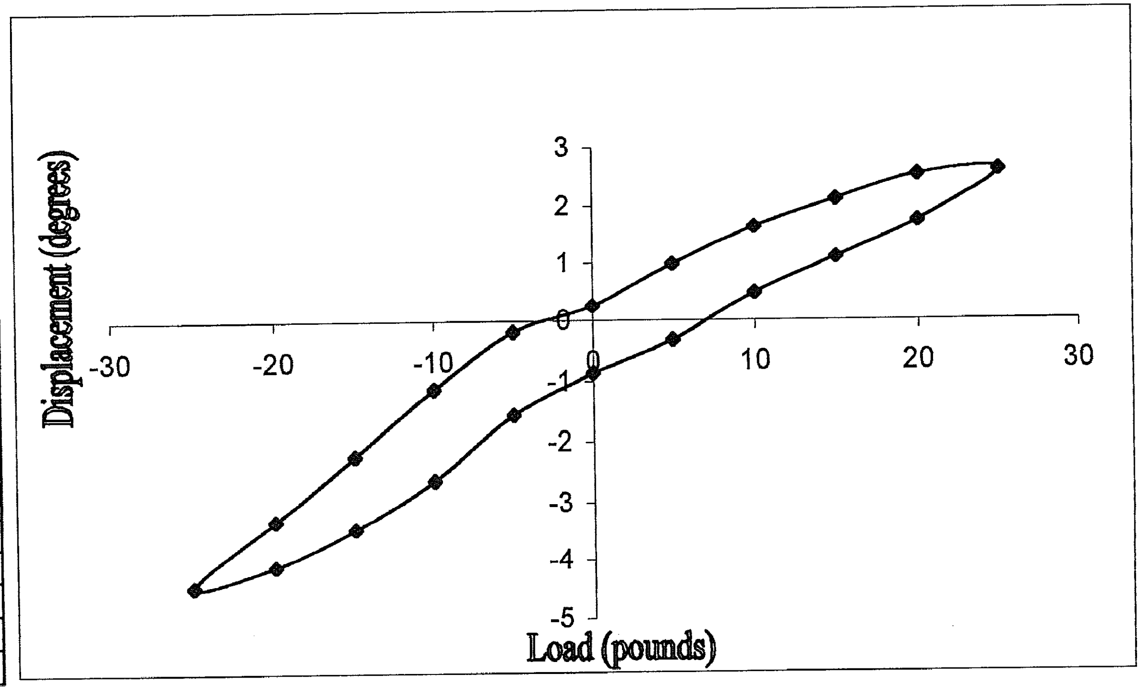

Figure B.2 Hysteresis Plot for Subject 2

Load	Total Avg. Displacements
0	-0.73
5	-0.38
10	-0.02
15	0.5
20	1.17
25	1.98
20	1.85
15	1.5
10	1.1
5	0.62
0	0.3
-5	-0.02
-10	-0.37
-15	-0.87
-20	-1.38
-25	-2.3
-20	-2.07
-15	-1.7
-10	-1.32
-5	-1.03
0	-0.73

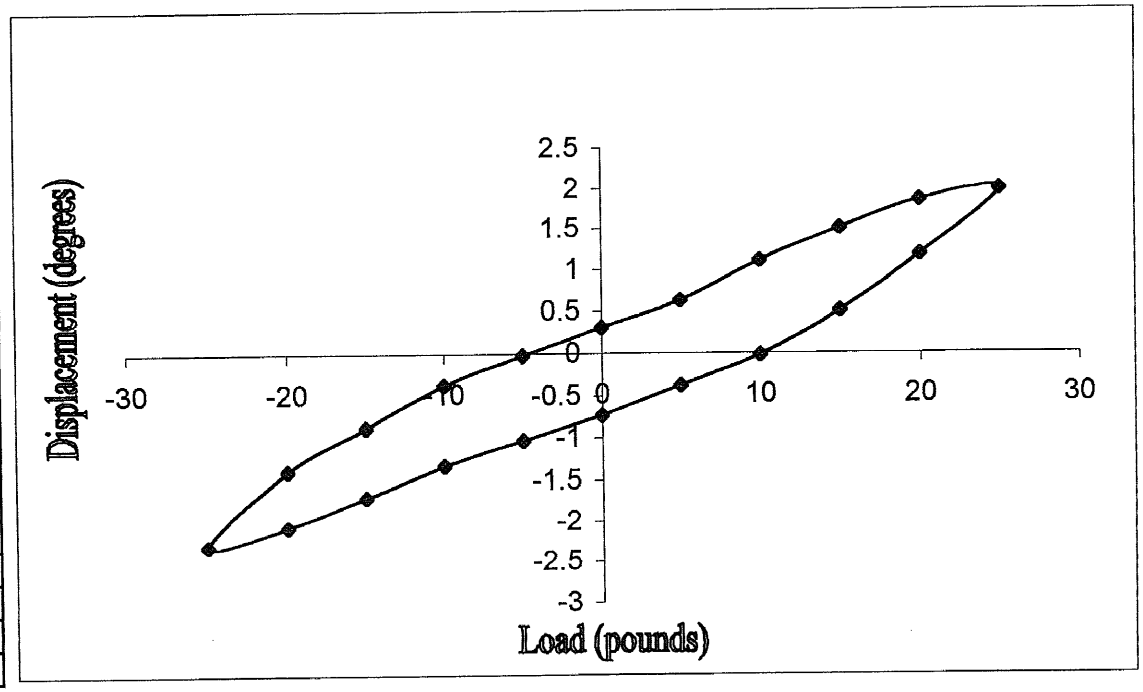

Figure B.3 Hysteresis Plot for Subject 3

Load	Total Avg. Displacements
0	-0.62
5	0.05
10	0.7
15	1.23
20	1.85
25	2.53
20	2.48
15	2.15
10	1.73
5	1.2
0	0.45
-5	-0.12
-10	-0.65
-15	-1.18
-20	-1.93
-25	-2.77
-20	-2.47
-15	-2.07
-10	-1.63
-5	-1.18
0	-0.62

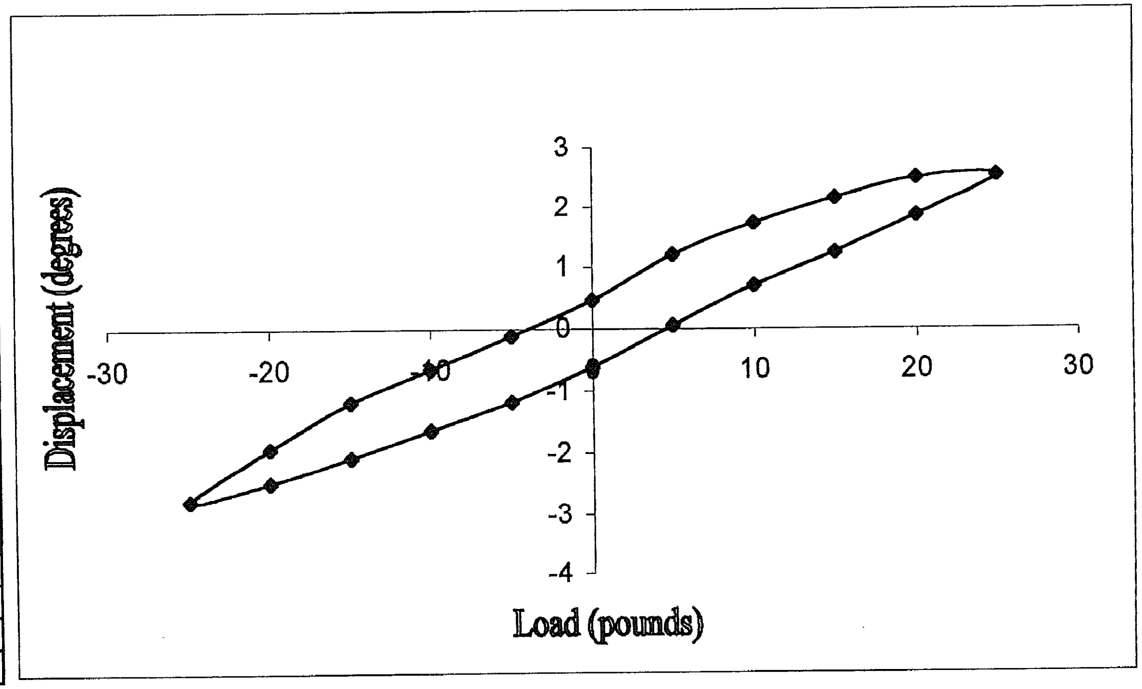

Figure B.4 Hysteresis Plot for Subject 4

Load	Total Avg. Displacements
0	0.05
5	0.48
10	0.88
15	1.25
20	1.65
25	2.07
20	1.97
15	1.72
10	1.45
5	1.08
0	0.58
-5	0.1
-10	-0.3
-15	-0.75
-20	-1.17
-25	-1.58
-20	-1.45
-15	-1.22
-10	-0.87
-5	-0.45
0	0.05

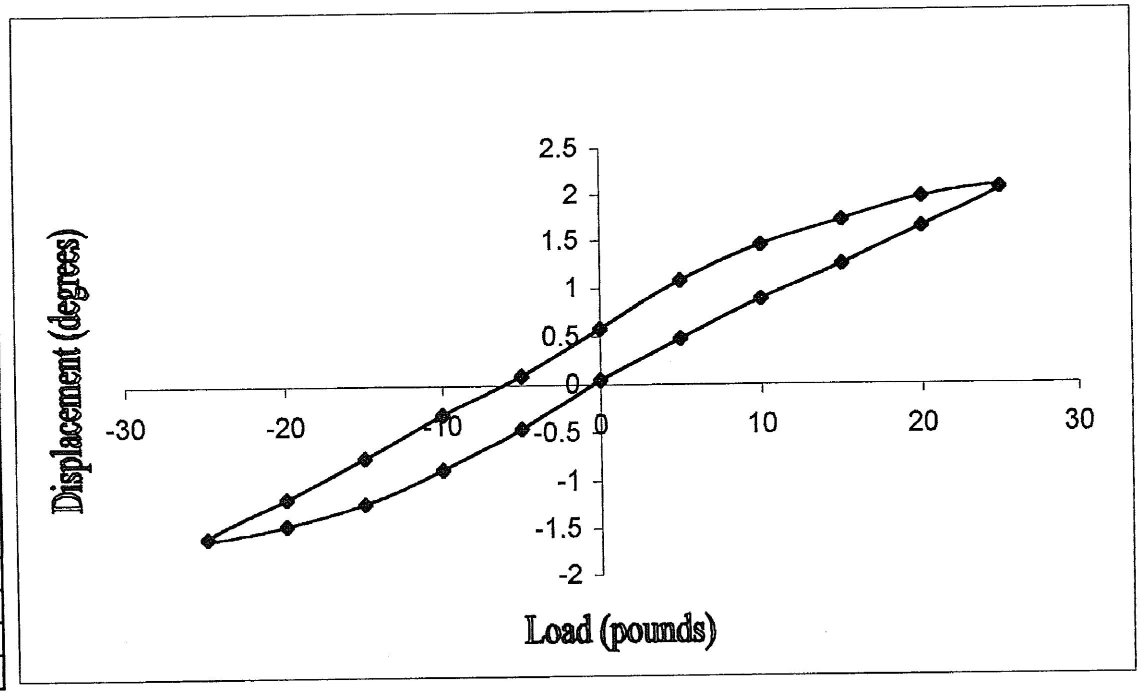

Figure B.5 Hysteresis Plot for Subject 5

Load	Total Avg. Displacements
0	-0.45
5	-0.03
10	0.57
15	1.28
20	1.98
25	2.77
20	2.57
15	2.1
10	1.53
5	0.88
0	0.3
-5	-0.15
-10	-0.68
-15	-1.42
-20	-2.12
-25	-2.8
-20	-2.55
-15	-2.2
-10	-1.67
-5	-0.97
0	-0.45

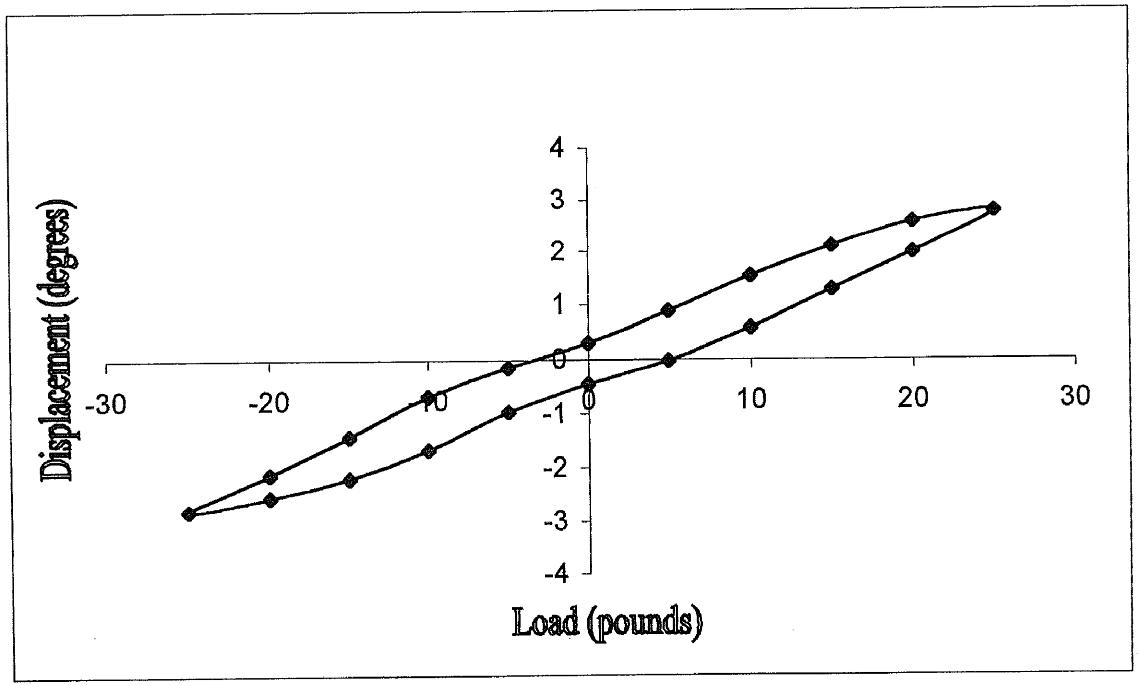

Figure B.6 Hysteresis Plot for Subject 6

Load	Total Avg. Displacements
0	-0.6
5	-0.02
10	1
15	2.13
20	3.37
25	4.98
20	4.6
15	3.67
10	2.67
5	1.43
0	0.43
-5	-0.08
-10	-1.1
-15	-2.38
-20	-3.75
-25	-5.53
-20	-4.93
-15	-4.02
-10	-2.87
-5	-1.65
0	-0.6

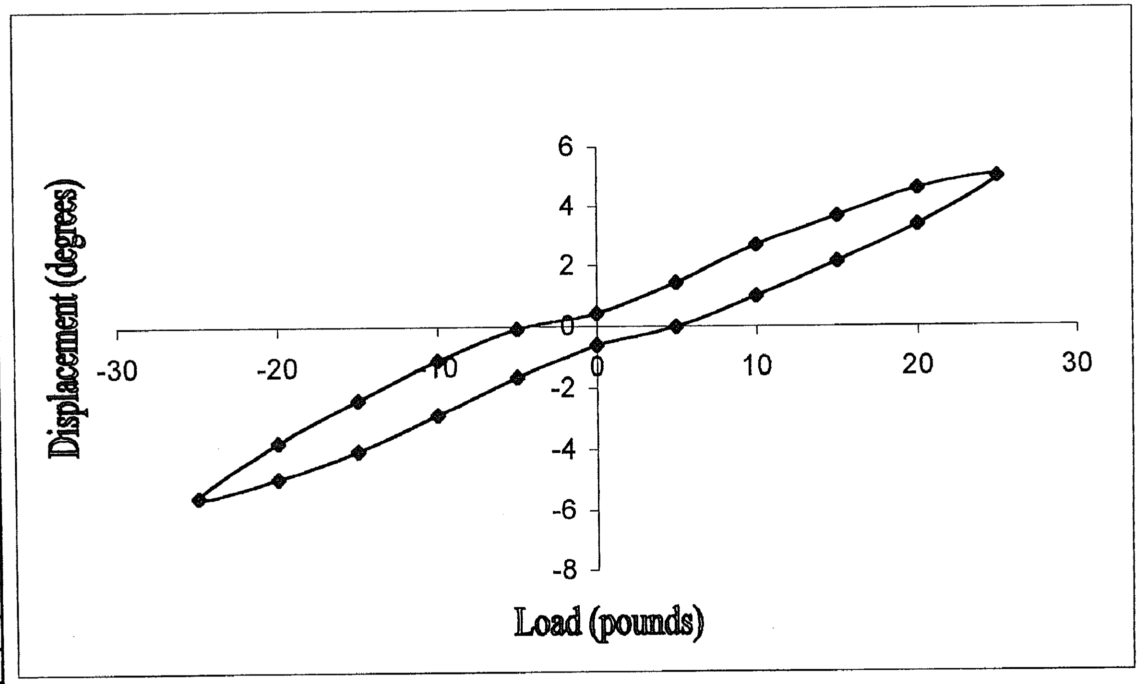

Figure B.7 Hysteresis Plot for Subject 7

Load	Total Avg. Displacements
0	-1.52
5	-0.53
10	0.17
15	0.98
20	1.8
25	2.75
20	2.58
15	2.28
10	1.7
5	1.17
0	0.35
-5	-0.23
-10	-0.87
-15	-1.98
-20	-2.88
-25	-3.82
-20	-3.67
-15	-3.33
-10	-2.9
-5	-2.23
0	-1.52

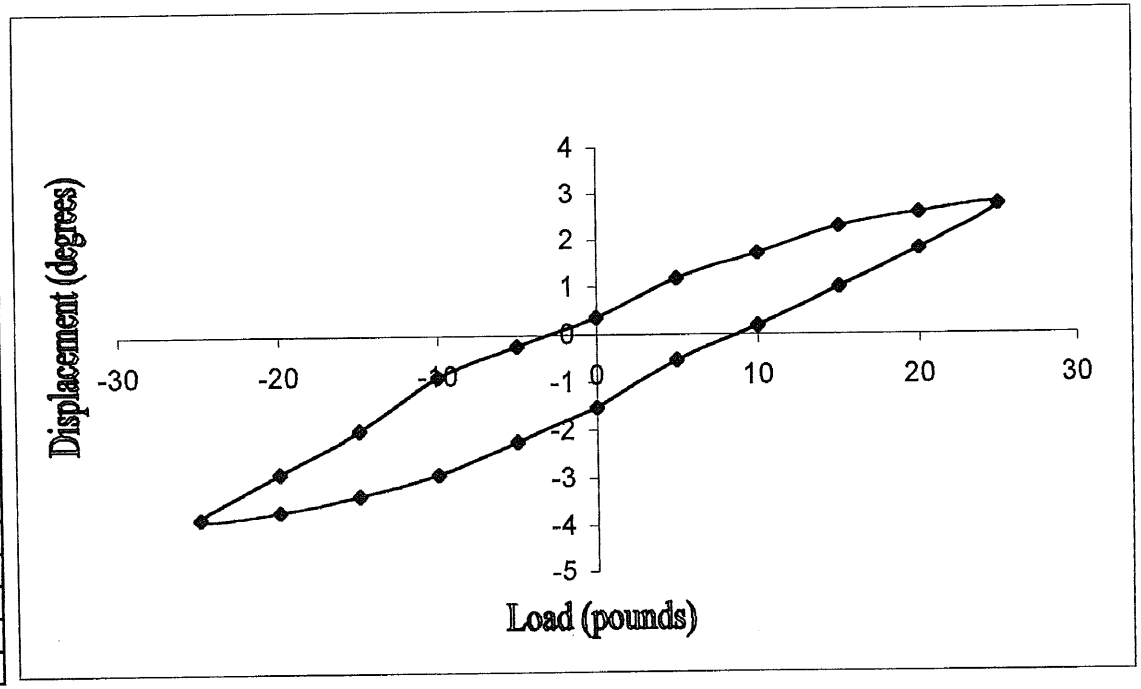

Figure B.8 Hysteresis Plot for Subject 8

Load	Total Avg. Displacements
0	-0.28
5	0.16
10	0.62
15	1.03
20	1.48
25	1.91
20	1.77
15	1.52
10	1.18
5	0.73
0	0.38
-5	0.03
-10	-0.38
-15	-0.79
-20	-1.15
-25	-1.51
-20	-1.4
-15	-1.22
-10	-0.92
-5	-0.5
0	-0.28

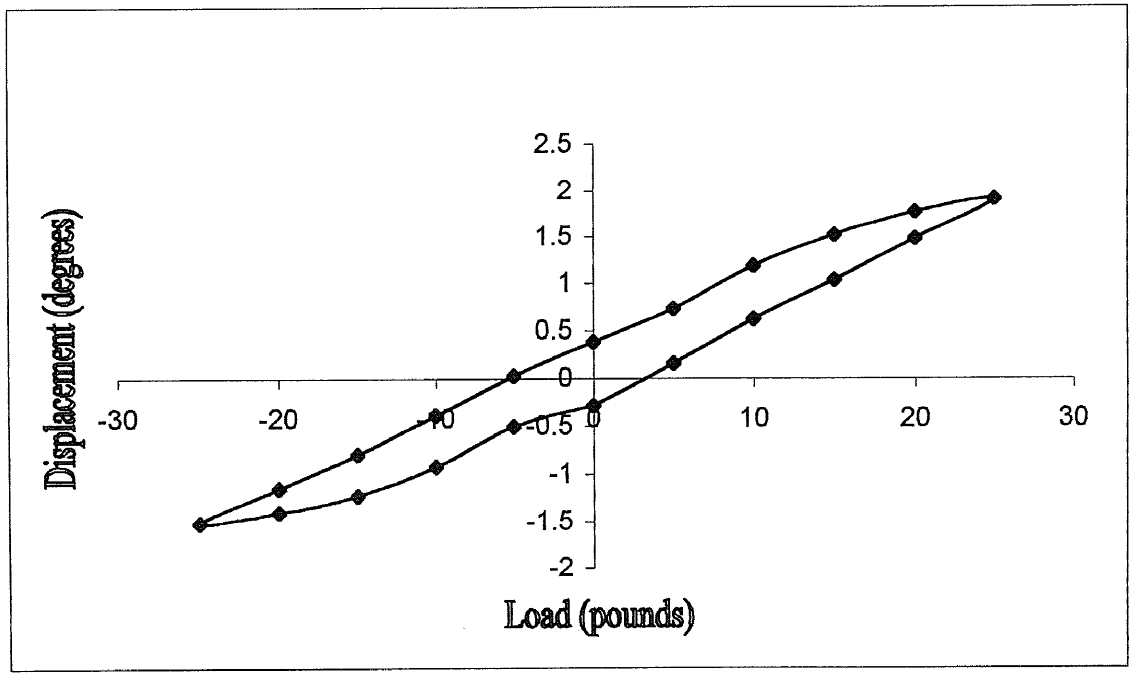

Figure B.9 Hysteresis Plot for Subject 9

Load	Total Avg. Displacements
0	-0.48
5	-0.03
10	0.68
15	1.32
20	1.89
25	2.54
20	2.44
15	2.12
10	1.64
5	1.01
0	0.3
-5	-0.08
-10	-0.63
-15	-1.34
-20	-2.01
-25	-2.56
-20	-2.43
-15	-2.12
-10	-1.64
-5	-1.05
0	-0.48

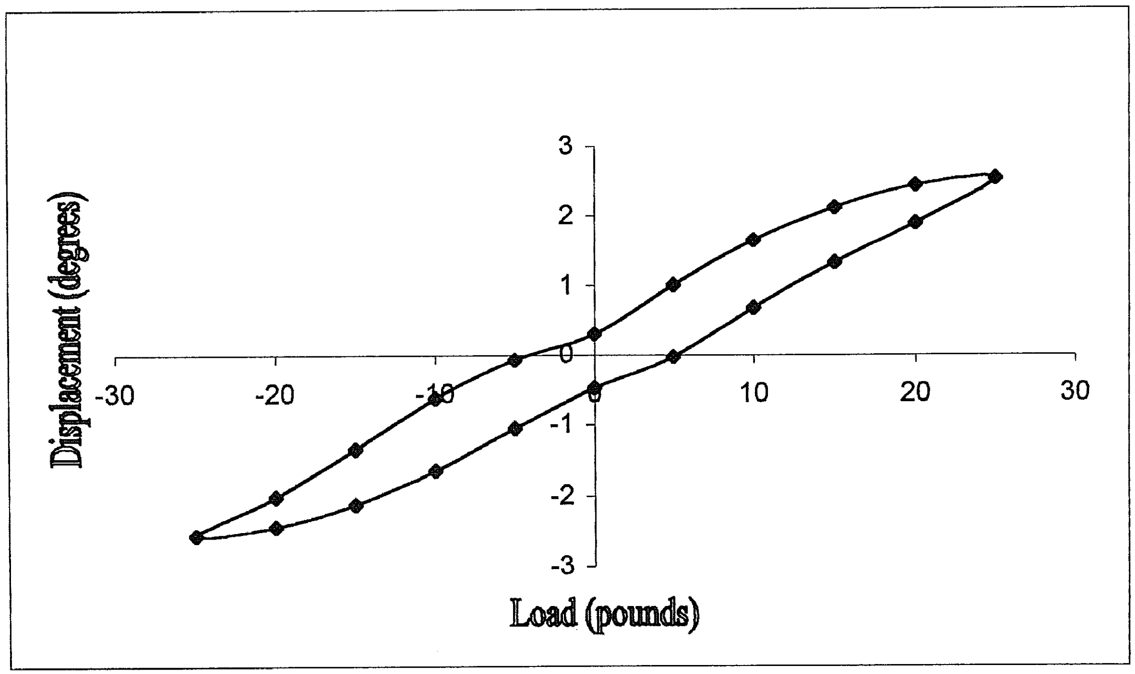

Figure B.10 Hysteresis Plot for Subject 10

Load	Total Avg. Displacements
0	-0.15
5	0.16
10	0.65
15	1.17
20	1.72
25	2.37
20	2.12
15	1.78
10	1.27
5	0.7
0	0.2
-5	-0.02
-10	-0.43
-15	-0.87
-20	-1.41
-25	-1.95
-20	-1.88
-15	-1.28
-10	-0.92
-5	-0.5
0	-0.15

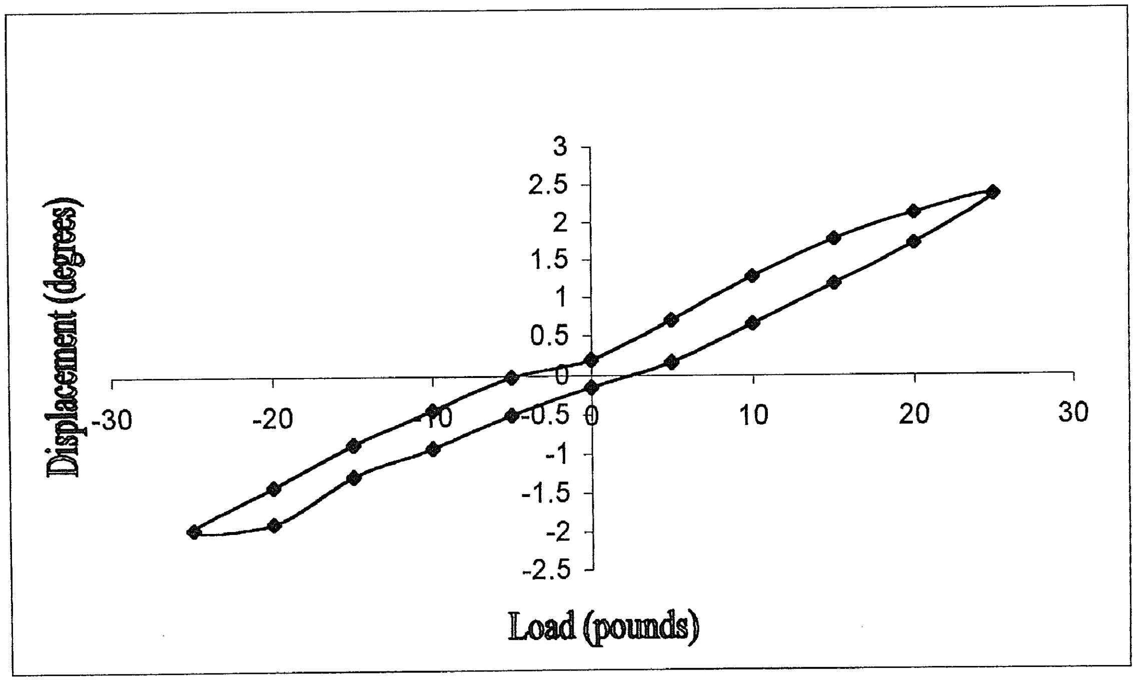

Figure B.11 Hysteresis Plot for Subject 11

Load	Total Avg. Displacements
0	-0.75
5	-0.57
10	-0.25
15	0.39
20	1.09
25	1.78
20	1.63
15	1.18
10	0.6
5	-0.03
0	-0.33
-5	-0.56
-10	-1.05
-15	-1.77
-20	-2.6
-25	-3.45
-20	-3.1
-15	-2.57
-10	-1.9
-5	-1.18
0	-0.75

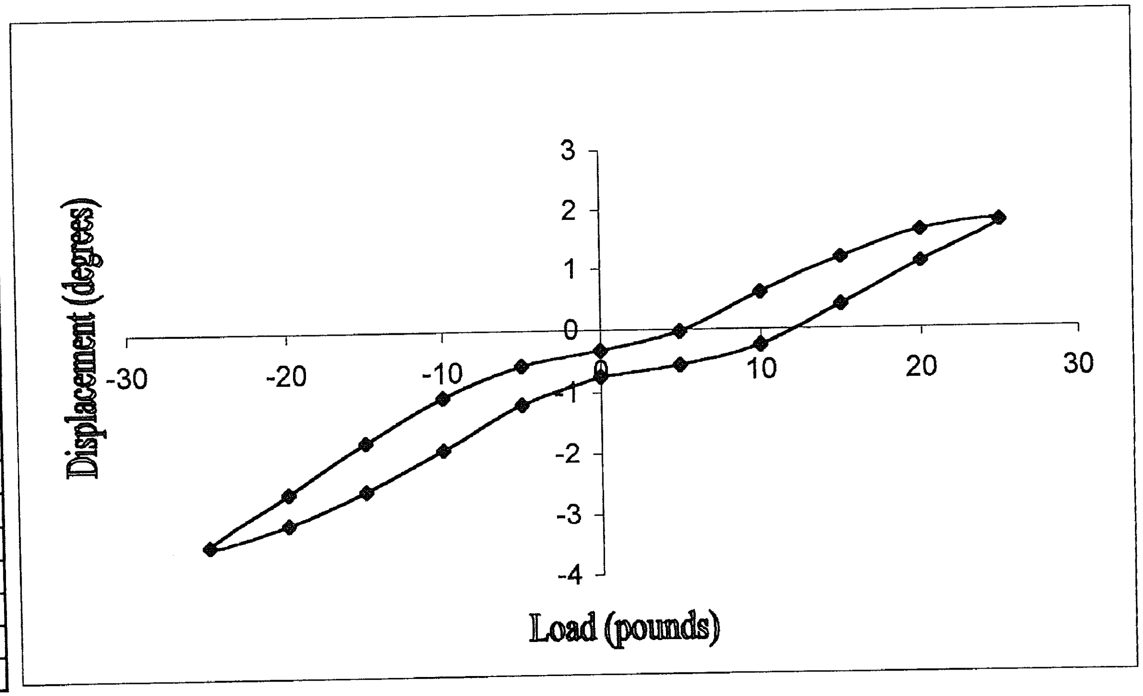

Figure B.12 Hysteresis Plot for Subject 12

REFERENCES

1. Ascenzi, M.G. Ascenzi, A. Benvenuti and F. Mango, "Pinching in longitudinal and alternate osteons during cyclic loading," *J. Biomechanics*, Vol. 30, No. 7, pp 689-695, 1997.

2. Ascenzi, A. Benvenuti, F. Mango and R. Simili, "Mechanical hysteresis loops from single osteons: technical devices and preliminary results," *J. Biomechanics*, Vol. 18, No. 5, pp 391-398, 1985.

3. D. Boesler, M. Warner and A. Alpers, "Efficacy of high-velocity low-amplitude manipulative technique in subjects with low-back pain during menstrual cramping," *JAOA*, 1993; 93:903-916.

4. D. G. Borenstein and S. W. Wiesel, *Low Back Pain: Medical Diagnosis and Comprehensive Management*, W.B. Saunders, Portland, OR, 1989.

5. B. Breed, *Surveying*, John Wiley & Sons, NY, 1971.

6. J. Dillard, J. Trafimow, G. B. J. Anderson and K. Cronin, "Motion of the lumber spine, reliability of two measurement techniques," *Spine*, Volume 16, Number 3, 1991.

7. J. D. Givens, J. P. Dewald and W. Z. Rymer, "Joint dependent passive stiffness in paretic and contralateral limbs of spastic patients with hemiparetic stroke," *J. Neorol Neurosurg Psychiatry*, 1995 Sep; 59(3): 271-279.

8. N. Ghista, S. Subbaraj, J. Mazumdar and S. M. Rezaian, "The biomechanics of back pain. Prevention through postural energization of spinal structures; treatment through percutaneous disectomy," *IEEE Engineering in Medicine and Biology*, May/June 1998.

9. S. A. Glantz, *Bio-Statistics*, McGraw Hill, San Francisco, CA, Fourth Edition, 1997.

10. V. K. Goel, S. Goyal, C. Clark, K. Nishiyama and T. Nye, "Kinematics of the whole lumbar spine; effect of disectomy," *Spine*, 10:543-554, 1985.

11. T. T. Gomez, "Symmetry of lumbar rotation and lateral flexion range of motion and isometric strength in subjects with and without low back pain," *Journal of Manipulative and Physiological Therapeutics*, Vol. 19, No. 1, January 1994.

12. J. Hsieh and R. K. Pringle, "Range of motion of the lumbar spine required for four activities of daily living," *Journal of Manipulative and Physiological Therapeutics*, Vol. 17, No. 6, July/August 1994.

13. L. Inscoe, P. L. Witt, M. T. Gross and R. U. Mitchell, "Reliability in evaluating passive intervertebral motion of the lumber spine," *Journal of Manual & Manipulative Therapy*, Vol. 3, No. 4, 1995.

14. L. E. Kazarian, "Creep characteristics of the human spinal column," *Orthop Clin North Am*, 1975; 6:3-18.

15. M. Lee and N. L. Svensson, "Effect of loading frequency on response of the spine to lumber posteroanterior forces," *Journal of Manipulative and Physiological Therapeutics*, Vol. 16, No. 7, September 1993.

16. M. Lee, H. Lau and T. Lau, "Sagittal plane rotation of the pelvis during lumbar posteroanterior loading," *Journal of Manipulative and Physiological Therapeutics*, Vol. 17, No. 3, March/April 1994.

17. K. Lewit and C. Liebenson, "Palpation-problems and implications," *Journal of Manipulative and Physiological Therapeutics*, Vol. 16, No. 9, November/December 1993.

18. Maher, and R. Adams, "Reliability of pain and stiffness assessments in clinical manual lumbar spine examinations," *Physical Therapy*, 1994; 74:801-811.

19. Maher and R. Adams, "Is the clinical concept of spinal stiffness multidimentional?" *Physical Therapy*, Volume 75, Number 10, Oct 1995.

20. S. M. McGill, "The biomechanics of low back injury: implications on current practice in industry and the clinic," *J. Biomechanics*, Volume 30, Number 5, pp 465-475, 1997.

21. E. Miller, M. A. Vanni, L. A. Taber and B. B. Keller, "Passive stress-strain measurements in the stage-16 and stage-18 embryonic chick heart," *J. Biomech Engineering*, 119 (4): 445-51, 1997 Nov.

22. National Institute of Health, "Research on low back pain and common spinal disorders," *NIH Guide*, Volume 26, Number 16, May 1997.

23. T. R. Oxland, J. J. Crisco III, M. M. Panjabi and I. Yamamoto, "The effect of injury on rotational coupling at the lumbosacral joint; a biomedical investigation," *Spine*, 1992; 17:74-80.

24. T. R. Oxland, R. M. Lin and M. M. Panjabi, "Three-dimensional mechanical properties of the thoracolumbar junction," *J. Orthop Res*, 1992; 10:573-580.

25. M. M. Panjabi, M. H. Krag, A. A. White III and W. O. Southwick, "Effects of preload on load displacement curves on the lumbar spine," *Orthopedic Clinics of North America*, Vol. 8, No. 1, January 1977.

26. M. M. Panjabi, T. R. Oxland, I. Yamamoto and J. J. Crisco, "Mechanical behavior of the human lumbar and lumbosacral spine as shown by three-dimensional load-displacement curves," *The Journal of Bone and Joint Surgery*, Vol. 76-A, No. 3, March 1994.

27. Plamondon, M. Gagnon and G Maurais, "Application of a stereo-radiographic method study of intervertebral motion," *Spine*, 13:1027-1032, 1988.

28. Skipor, A. A. Miller, D. A. Spencer and A. B. Schultz, "Stiffness properties and geometry of lumbar spine posterior elements," *J. Biomechanics*, Vol. 18, No. 11, pp 821-830, 1985.

29. L. Twomey and J. Taylor, "Flexion creep deformation and hysteresis in the lumbar vertebral column," *Spine*, 1982; 7:116-122.

30. J. M. Walker, "The sacroiliac joint, a critical review," *Physical Therapy*, 1992; 72:903-916.

31. M. J. Warner, J. A. Mertz and A. S. Zimmerman, "The hysteresis loop as a model for low back motion analysis," *JAOA*, Vol. 97, No 7, July 1997.

32. D. Williams and J. Spangler, *Physics for Science and Engineering*, D. Van Nostrand Company, New York, 1981, pp 625, 732-737.