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THREE-DIMENSIONAL KINEMATIC ANALYSIS OF THE THORAX IN STANDING AND SITTING

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THREE-DIMENSIONAL KINEMATIC ANALYSIS OF THE THORAX IN STANDING AND SITTING

VOLUME I

By

Gordon J. Alderink

A DISSERTATION

Submitted to
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ABSTRACT

THREE-DIMENSIONAL KINEMATIC ANALYSIS OF THE THORAX IN STANDING AND SITTING

By

Gordon J. Alderink

Back injuries affect eight of ten people, with direct and indirect costs approximating over $20 billion annually in the United States. Poor control of costs stems partially from inadequate understanding of normal spine function and difficulty in accurately diagnosing spinal disorders. Many diagnosis and intervention strategies used in manual medicine depend on a model of spinal behavior described by Harrison Fryette (1918). Presently, there is no consensus regarding thoracic three-dimensional motion characteristics, and no one has systematically examined Fryette's laws of vertebral movement. Fryette stated the following: (1) When sidebending is introduced with the thoracic spine in a neutral posture, axial rotation will always be coupled to the opposite side, (2) When sidebending is introduced with the thoracic spine in a non-neutral posture (flexed or hyperextended) axial rotation will always be coupled to the same side, and (3) When spinal motion is introduced in one plane, mobility will be reduced in secondary planes. The purpose of this investigation was to examine Fryette's laws using a video-based motion analysis system to parameterize (with Cardan and helical axis analysis) the three-dimensional kinematics of the thoracic spine/cage in healthy subjects with normal spinal alignment.

When subjects were motion tested with their spine in a neutral position only 22% exhibited contralateral coupling of sidebending and axial rotation, thus there are insufficient data to support Fryette's law of neutral spine mechanics for the thoracic spine. In non-neutral postures (either flexed or hyperextended) subjects demonstrated ipsilateral coupling of sidebending and axial rotation 79% of the time, although with axial rotation in a slouched position 46% of the subjects showed contralateral coupling. Overall, data support Fryette's second law. There was borderline support for Fryette's third law that says that motion is reduced in secondary planes of motion. The finite helical axis unit vectors were found to correspond with Cardan parameterizations of three-dimensional thoracic spine movements suggesting some clinical relevance for the use of helical paramters.

Results suggest manual medicine practitioners, who base their diagnostic and intervention strategies on Fryette's laws of spinal behavior, may need to re-examine their working assumptions. It appears also that helical axis analysis of the spine might have a more important role in the clinical setting than previously thought. Further research on normal subjects and application to clinical cases will continue to add to our understanding of dysfunction of the thoracic spine.

To Sally, Jenny and Liz.

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DEFINITIONS OF TERMS

Kinematics. That phase of mechanics concerned with the study of motion of rigid bodies, with no consideration of the forces involved.

Osteokinematics. Refers to the study of motion of the bones that articulate to form a joint regardless of motion which occurs at the joint surface.

Arthokinematics. Refers to the study of motion of one bone relative to another at the joint surfaces.

Rotation. A rigid body is said to be in rotation when it's movement is such that all particles along some straight line in the body or a hypothetical extension of it have zero velocity relative to a fixed axis system. Rotation is a spinning or angular displacement of a body about some axis. Rotation is measured in degrees or radians.

Flexion/extension (forward bending/backward bending). This occurs when one or more bones rotate about a frontal (coronal) axis.

Anterior/posterior. This is a rotation when one or more appendicular (peripheral) bones rotate about a paracoronal axis.

> **Abduction/adduction**. This occurs when one or more bones rotate about a sagittal axis.
>
> **Sidebending (lateral flexion, lateral bending)**. This occurs when a vertebral bone (skull, vertebral column) rotates about a sagittal axis.
>
> **Medial/lateral**. This occurs when one or more appendicular bones rotate about a vertical or longitudinal axis.
>
> **Axial**. This occurs when a vertebral bone rotates about a vertical or longitudinal axis.

Translation. A body is said to be in translation when its movement is such that all particles in the body at a given time have the same direction of motion relative to a fixed axis system. Translation can occur along posteroanterior, mediolateral and vertical axes. Translation is measured using metric (e.g., millimeters) or English units (e.g., inches).

Protrusion. Anterior translation of a segment(s), as in translating the head and neck forward or anteriorly.

Retrusion. Posterior translation of a segment(s), as in translating the head and neck backward or posteriorly.

Range of motion. The difference between the physiological extremes of movement is the range of motion. The range of motion can be expressed for the translation or rotation of vertebrae for different directions of movement.

Instantaneous axes of rotation. At every instant, for a rigid body moving in a plane, there is a line in the body or its hypothetical extension that does not move. This is the instantaneous axis of rotation (IAR). Plane motion is fully defined by the position of IAR and the magnitude of the rotation about it. Woltring suggests that IARs are often inappropriately used since merely the beginning and end of segment displacements are studied. He suggested that the more appropriate description of the position and attitude change of the planar image of a distal segment with respect to the planar image of a proximal segment is described in terms of a single rotation about a calculated, **fixed center of rotation**.

Instantaneous helical axes of rotation (screw axis). At every instant, for a rigid body moving in space, there is a line in the body or its hypothetical extension that does not move. This is the instantaneous helical (screw) axis (IHA). Spatial motion of a rigid body relative to another rigid body or a fixed coordinate system is fully defined by movement about and along the IHA.

Finite helical axis. At discrete intervals, for a rigid body moving in space, there is a line in the body or its hypothetical extension that does not move. This is the finite helical axis (FHA). Spatial motion of a rigid body relative to another body or a fixed coordinate system is fully defined by movement about and along the FHA.

Coupling. Coupling refers to motion in which the rotation or translation of a body about or along one axis is consistently associated with simultaneous rotation or translation about or along another axis. The associated motions of axial rotation and lateral bending of the spine is an example of coupling. Coupled motion is the motion produced by the phenomenon of coupling. An example is the turning of a screw, which causes the coupled motion of axial translation.

Somatotypes (body types). A particular category of body build, determined on the basis of certain physical characteristics. There are three fundamental body types: endomorphic, ectomorphic, and mesomorphic. An endomorphic type is characterized by excessive fatness, softness and roundness of the body, ectomorphic by linearity, fragility and delicacy of structure, and mesomorphic by prominent musculature with broad shoulders and narrow hips. Most individuals have a combination of somatotype features and could then be described by compound terminology. For example, a person with an ectomorphic-mesomorphic descriptor would be an individual with some features of each with dominant features of the mesomorph.

Chapter 1

INTRODUCTION

A back injury will affect eight of ten people at some point in their lifetime. Additionally, between 20% and 30% of the general population are suffering from low back pain at any given time. Research on the natural history of spinal injuries suggests that approximately 90% of those affected will recover, without residual problems, within 2-3 months (Frymoyer, 1996). However, the cost of spinal disorders, in terms of sick leave, lost productivity, medical/surgical management, etc. has been estimated at over $20 billion annually (Cats-Baril & Frymoyer, 1991). Further analysis of the costs of low back pain indicate that a small majority of cases (10-25%) account for as much as 85-90% of the total costs (Bigos & Battie, 1991; Frymoyer & Cats-Baril, 1987).

Reducing society's costs related to spinal injury therefore seems necessary. This will likely occur secondary to changes in the medical/surgical management of these patients, which is being forced by the recent trends in healthcare, e.g. managed care. Although some of the changes, i.e., serving as the gatekeeper, reduction in treatment time, inspired by third party payers have been necessary, it would be better if changes in low back pain management could be attained by healthcare practitioners through additional bench and clinical research. For example, the continued development of accurate and reliable measurement tools and methodologies could contribute to a better understanding of normal spinal function. Furthermore, if the measurement protocols were efficient, clinically useful, and cost effective, more effective treatment strategies and assessment of treatment outcomes could be realized. Despite the enormous amount of spine research produced to date, additional research that examines spinal kinematics and kinetics using asymptomatic individuals appears warranted. This additional mechanical information on normal persons could provide stereotypical patterns that could be used as references for evaluating persons with spinal pathology.

Spinal injury mechanisms generally fall into two categories: traumatic and non-traumatic. Most injuries are non-traumatic related to repetitive microtrauma to bone and soft tissue (muscles, ligaments and fasciae). Many of these non-traumatic injuries have been attributed to postures related to prolonged sitting. For example, it has been demonstrated that intradiscal pressures in sitting exceed those in standing by up to 100%, depending on the sitting posture (Nachemson, 1966; Nachemson & Morris, 1964). Relatively high intradiscal pressures sustained over prolonged periods of time (a type of microtrauma) could result in annular fissuring and predispose individuals to disc injury.

Research on spinal mechanics has been conducted on cadaveric functional units (two vertebrae and intervening disc, with and without soft tissues removed), whole cadavers, and living subjects, as well as through the use of spinal models and analytical methods. In vivo measurements have been made with subjects performing functional tasks while standing, performing simulated functional tasks, walking and sitting. Many studies have focused on measuring cardinal plane movements, i.e., flexion/extension, sidebending, and axial rotation, and a few studies have examined coupled movements (out-of-plane) in the erect spine (neutral). However, there is a paucity of literature describing coupled movement patterns of the head, neck, thorax, and lumbar spine in various seated postures (extended, neutral and flexed).

Interest in spine function dates back to Hippocrates. In this century, Lovett (1902; 1905), with the aid of models and living subjects, described both cardinal plane and coupled movement patterns (sidebending and rotation) of the spine. In general, Lovett found that intersegmental coupling patterns varied from one region of the spine to the other (cervical, thoracic or dorsal, and lumbar). At about the same time, Fryette (1918), using both an "articulated" spine and living subjects, described results that were at odds with Lovett's.

Fryette took his research further by studying spinal movement patterns in normal subjects and applied this knowledge to developing corrective exercises and manipulations for those with "different types" of spinal curvatures. Fryette's concepts of spinal movement formed the basis for manual medicine evaluation and treatment techniques used by osteopathic and allopathic physicians, and physical therapists. Researchers have hypothesized that two dominating factors control or modify the mechanical behavior of the spine: the articulating facets and the bodies of the vertebrae. Fryette found that in the thoracic and lumbar regions each vertebrae acted very much the same as the others under the same physiological condition; that is, when any area was in "easy" physiological flexion (neutral) and side-bent, the anterior side of the bodies rotated toward the convexity (rotated away [or contralateral] from the direction of the sidebending). If any area was in hyperextension, or to a lesser degree in hyperflexion, and also side-bent, axial rotation occurred toward the concavity. He also found that if spinal motion was introduced in any one plane, mobility of the vertebra was reduced in the other planes. The cervical spine, in comparison to the thoracic or lumbar spines, had anatomical features that contributed to other unique motion characteristics.

Since Fryette, much research has been produced, some of which has supported and some which has refuted his work. Many studied cadavers under non-physiological conditions (Lysell, 1969; Markolf, 1972; Moroney, Schultz, Miller, & Andersson, 1988; Panjabi, 1977; Panjabi, Brand, & White, 1976b; Panjabi et al., 1986; Rolander, 1966; Schultz, Warwick, Berkson, & Nachemson, 1979; Tencer & Ahmed, 1981; White, 1969), whereas others used living subjects under conditions that were not clinically practical, i.e., invasive, laboratory conditions and radiographic techniques (Frymoyer, Frymoyer, Wilder, & Pope, 1979; Gregerson & Lucus, 1967; Pearcy, Portek, & Shepherd, 1984). Some measurement devices are not able to assess three-dimensional (functional) movement patterns, only cardinal motions, such as flexion and extension or lateral bending (Buck, Dameron, Dow, & Skowlund, 1959; Loebl, 1967; Macrae & Wright, 1969; Mellin, 1986; Schober, 1937; Youdas et al., 1992). Additionally,clinicians have generally relied on subjective palpation techniques, which are often not reliable. A few have begun to use high speed optoelectronic or video-based motion analysis systems and reported results on functional spinal movements (Bechtold, Ridl, Hubbard, & Vorro, 1983; Cheng, 1993; Farahpour, Allard, Labelle, Rivard, & Duhaime, 1995; Gracovetsky et al.,1995; Winters et al., 1993; Woltring, Long, Osterbauer, & Fuhr, 1994). No one has attempted to use video-based motion analysis systems to systematically examine the concepts of spinal motion expressed by Fryette. It is not possible to measure intersegmental vertebral motions directly (although Gracovetsky et al. (1995) have suggested that it can be done indirectly with the use of a correction algorithm for skin movement) using optoelectronic motion analysis and skin-mounted markers, but it is possible to measure the three dimensional motion of larger segments, i.e., head, thorax/ribs, and pelvis, relative to one another or to a global reference system. In light of much research that is discrepant with Fryette's concepts with regard to coupled motion in the thoracic and lumbar regions, there is a need to further investigate coupled motion and its relationship to joint assessment (Gibbons, 1997)

The purpose of this research is to use a video-based motion analysis system to measure three-dimensional kinematics of the thoracic spine/cage relative to the lumbar region and pelvis, according to the tenets of Fryette. Healthy subjects with normal spinal alignment will be recruited to participate. This research will examine Fryette's concepts of spinal motion by measuring the motion of these larger segments. More specifically, this research will attempt to answer the following questions: (1) When spinal motion is introduced in one plane (sagittal), will mobility be reduced in the other planes (frontal and transverse)? (2) When either sidebending (or axial rotation) is introduced when the spine is in neutral, will axial rotation (or sidebending) be coupled to the opposite side? (3) When sidebending (or axial rotation) is introduced when the spine is flexed or extended, will axial rotation (or sidebending) be coupled to the same side? These are clinically relevant questions because patient evaluations, treatment strategies and outcome assessments are based on their answers. The goal of this project will be to investigate whether stereotypical movement patterns of the thoracic spine/cage in normal subjects exist, as described by Fryette. If signature patterns of thoracic spine/cage movement exist, they can be used as a standard for examination and treatment of individuals with spinal pain and dysfunction. Additionally an effective tool will be developed to measure treatment outcomes.

Chapter 2

LITERATURE REVIEW

Introduction

Structure dictates function and function dictates structure. Anatomists and biomechanists often use this adage as they examine the human machine and attempt to understand how and why it works the way it does. Therefore, prior to discussing past research pertaining to spinal kinematics, this chapter will begin with a review of the most salient features of spinal anatomy, including the bony, cartilaginous and soft tissue structures.

Anatomy

Bony Configuration

Taken as a whole, the vertebral column (Figure 2.1) consists of four major regions (cervical, thoracic, lumbar and sacral) composed of 29 segments, with the last five segments fused as the sacrum. The coccyx, which consists of three or four fused rudimentary vertebral bodies, articulates with the sacrum, but is usually not included in discussions pertaining to spinal kinematics. Most of the vertebral elements are separated by cartilaginous, or intervertebral, discs (IVD). These function to facilitate movement and act as shock absorbers. In standing, the bony elements, supported by the ligamentous and myofascial soft tissues, are positioned to optimize attenuation of compressive and shear stresses and minimize energy expenditure. The spinal column functions to support the superincumbent body weight, attenuate the ground reaction forces produced during activities such as walking (or may actually be the "engine" that drives locomotion), provide a base for the large proximal muscles of the upper and lower limbs, and protect the spinal cord.

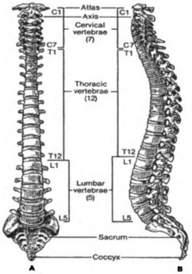

Figure 2.1 Whole vertebral column. From Clinical Musculoskeletal Anatomy (p. 22), by N. E. Pratt, 1991, Philadelphia: J. B. Lippincott Company. Copyright 1991 by J. B. Lippincott Company. Reprinted with permission.

At birth, the spinal column consists of only one curve, a posterior convexity, when viewed laterally. This single curve in the sagittal plane changes as the child develops, however. There are no lateral curves of the normal child or adult spine when viewing it posteriorly (frontal or coronal view). However, a sagittal view of the erect adult spine reveals four anteroposterior curves: posterior concavities in the cervical and lumbar (lordosis) regions and posterior convexities in the thoracic and sacral regions (kyphosis). The sagittal plane curvatures in the cervical and lumbar regions represent the normal development of the spinal column beginning from infancy as the child becomes a bipedal ambulator and adapts to the forces of gravity.

A typical vertebra (Figure 2.2) consists of several named parts fused together to form a single bone. Anteriorly, the heavy cylindrical body forms the base of the vertebra. The body is composed primarily of spongy bone surrounded by a thin layer of cortical or dense bone. The superior and inferior ends of the body are covered by a hyaline cartilage plate, which is attached to the IVD and forms the intervertebral joint. Pillars projecting posteriorly from the lateral aspect of the body form the pedicles, which in turn support the paired laminae. Together the pedicles and lamina create the vertebral or neural arch and, with the posterior aspect of the body, form the vertebral foramen. Each pedicle is notched superiorly and inferiorly close to its junction to the body. The inferior and superior notches of adjacent vertebrae form the respective inferior and superior boundaries of an intervertebral foramen, through which a spinal nerve exits the vertebral canal. Approximately at the junction of the pedicle and lamina there are articular processes or zygapophyses bilaterally that project superiorly and inferiorly. Each process bears a smooth surface, or facet. Facets of the inferior processes of the superior vertebra articulate with the facets of the superior processes of the vertebra below it and are called zygapophyseal joints, which are true diarthrodial or synovial joints. The planes of zygapophyseal articulations vary in the cervical, thoracic and lumbar regions and will be discussed in detail later. There are paired transverse processes that project laterally from the junction of the pedicle and lamina. These serve as sites of attachment for muscles and ligaments. Dorsally or posteriorly the lamina join in the midline to form a spinous process, which also serves as a lever for muscles and ligaments.

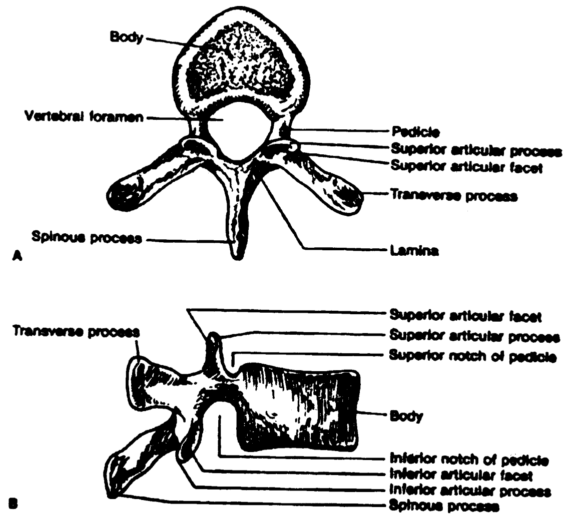

Figure 2.2 Superior (A) and lateral (B) views of a typical vertebra.From Clinical Musculoskeletal Anatomy (p. 24), by N. E. Pratt, 1991, Philadelphia: J. B. Lippincott Company. Copyright 1991 by J. B. Lippincott Company. Reprinted with permission.

Functionally, the cervical spine can be separated into two units. The upper cervical spine includes the axis (C2), atlas (C1) and the occipital condyles (C0). The lower cervical region or typical cervical segments include the inferior aspect of C2 through C7 (Figure 2.3). In the lower cervical region the vertebral bodies are smaller than in the thoracic and lumbar regions and are uniquely characterized by uncinate processes superolaterally, which create a slight concavity superiorly. Articulation with the inferolateral aspect of the vertebral body superiorly forms the uncovertebral joints or joints of von Luschka (some authorities do not consider these joints true articulations). Thus, in the typical cervical segments, there is a five-joint complex: one intervertebral, two zygapophyseal and two uncovertebral joints. The cervical pedicles are short, as are most spinous processes, which are also bifid. The spinous process of C7 (vertebra prominens), which is much longer, is more typical of a thoracic spinous process. Transverse processes from C1 to C6 are perforated by the transverse foramina, through which pass the vertebral artery and vein. Distally, the transverse processes are enlarged into anterior and posterior tubercles. The articulating facets are short, with the superior facets facing upward and backward and inferior ones facing forward and downward, and are oriented approximately 45° in the frontal plane. This facet orientation and the uncovertebral joints are the primary features that contribute to the unique movement characteristics of the lower cervical spine.

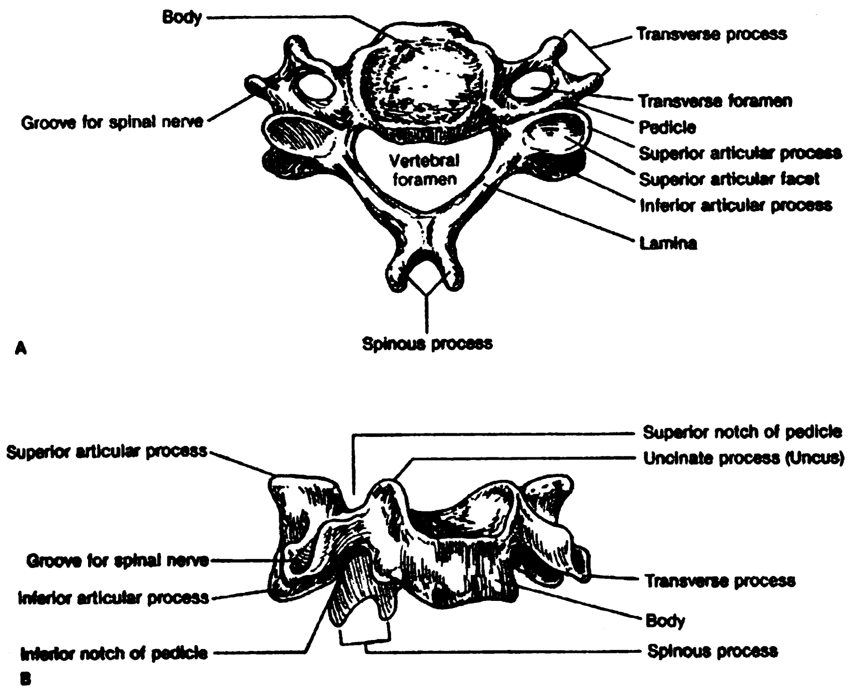

Figure 2.3. Superior (A) and anterolateral (B) views of cervical vertebra C4. From Clinical Musculoskeletal Anatomy (p. 25), by N. E. Pratt, 1991, Philadelphia: J. B. Lippincott Company. Copyright 1991 by J. B. Lippincott Company. Reprinted with permission.

The atlas and axis are markedly different structurally and functionally from the vertebrae in the lower cervical region. There are no intervertebral discs between the occiput (C0) and C1 or between C1 and C2. The atlas (Figure 2.4) has no body and consists of two lateral masses that are bridged by anterior and posterior arches. The superior articular facets sit on the lateral masses, are concave anterior to posterior, housing the reciprocally shaped occipital condyles, and are oriented approximately 30° medial, anterior to posterior, to a sagittal axis. Inferiorly, the zygapophyseal joints of C1 and C2 have a bi-convex relationship, sloping inferiorly from medial to lateral. The mid-posterior aspect of the anterior arch contains a small facet that articulates with the anterior aspect of the ondontoid process or dens of the axis. The transverse processes of C1 are long, making them effective levers for the short cervical muscles. There is no true spinous process, but only a small protuberance posteriorly. Superiorly, C2 is atypical, but inferiorly C2 resembles the typical cervical vertebrae (Figure 2.4). The transverse

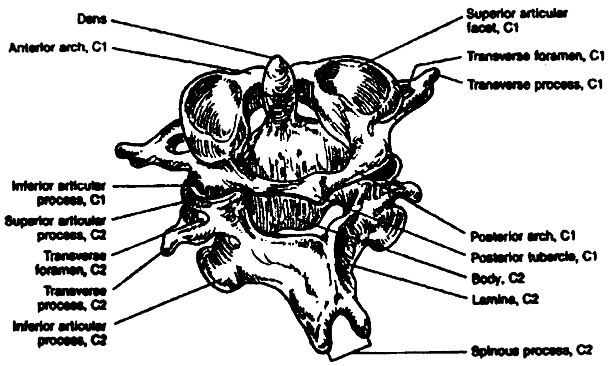

Figure 2.4. Posterolateral and superior views of atlas (C1) and axis (C2). From Clinical Musculoskeletal Anatomy (p. 26), by N. E. Pratt, 1991, Philadelphia: J. B. Lippincott Company. Copyright 1991 by J. B. Lippincott Company. Reprinted with permission.

processes are shorter, but the spinous process is significantly longer, than the corresponding structures of C1. The size of the C2 spinous process makes it an ideal muscle lever arm. Developmentally, the dens is a remnant of the body of C1, which was separated and fused to the axis. The dens articulates with the anterior arch of C1, to which it is securely fastened by the transverse ligament in such a way that it acts like a pivot around which C1 and the occiput rotates. The geometry and orientation of the C0/C1 and C1/C2 zygapophyseal joints, as well as the dens/C1 articulation, appear to dictate the type and amount of motion available.

Progressing cephalad to caudad the vertebral bodies increase in size and mass. Therefore, the thoracic vertebrae (Figure 2.5) are larger than the cervical vertebrae,

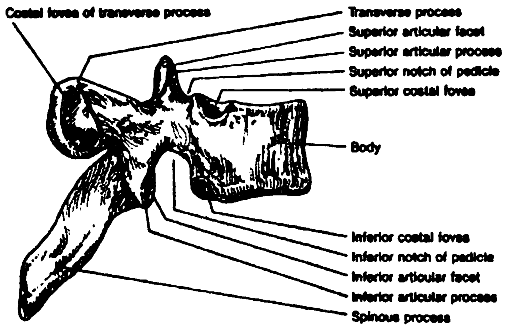

Figure 2.5. Lateral view of thoracic vertebra T7. From Clinical Musculoskeletal Anatomy (p. 27), by N. E. Pratt, 1991, Philadelphia: J. B. Lippincott Company. Copyright 1991 by J. B. Lippincott Company. Reprinted with permission.

but generally have the same general features. However, the thoracic vertebrae have unique articulations with the ribs. Posterolaterally, the first, tenth, eleventh and twelfth thoracic body segments have costal pits or unifacets for articulation with rib heads, whereas the remaining vertebrae have demifacets superiorly and inferiorly so that each rib articulates with two adjacent vertebrae and intervening disc. The transverse foramina are no longer present in the thoracic spine, but each transverse process articulates with the tubercle of a rib. The tip-to-tip width of the transverse processes progressively narrows from T1 to T12. The spinous processes remain long and slender, sloping down and back, and overlap the vertebral body inferiorly to approximately T10 or T11, where a transition then takes place so that the spinous processes of T11 or T12 resemble those of the lumbar spine. The zygapophyseal joints are nearly vertical in the frontal plane with the superior joint surface of the inferior segment facing backward and laterally. Were it not for the rib articulations this facet orientation would facilitate a large range of movement in the frontal and transverse planes.

Whereas the cervical spine sacrifices stability for mobility, the lumbar spine is designed for stability, but lacks global mobility. The lumbar vertebral bodies (Figure 2.6) are massive with short thick pedicles, short posteriorly-directed and large spinous processes, but long slender transverse processes. In contrast to the cervical and thoracic

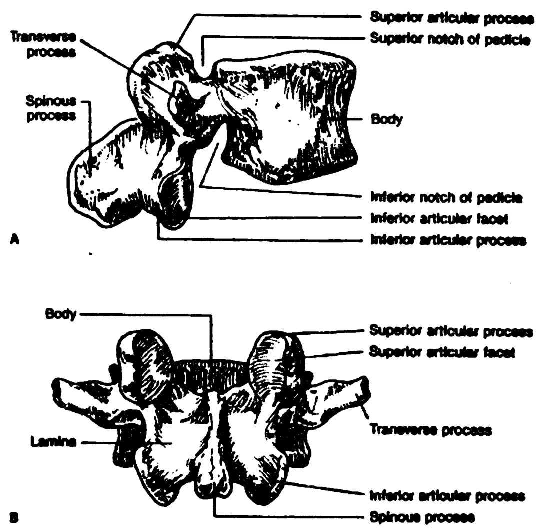

Figure 2.6. Lateral (A) and posterior (B) views of lumbar vertebra L4. From Clinical Musculoskeletal Anatomy (p. 28), by N. E. Pratt, 1991, Philadelphia: J. B. Lippincott Company. Copyright 1991 by J. B. Lippincott Company. Reprinted with permission.

lamina, those in the lumbar spine have less height than the bodies creating considerable space between adjacent laminae. From L1 to L4 the facets of the superior articular processes face up, back and medially, and those of the inferior processes down, forward and laterally, or primarily in the sagittal plane. The articulation between L5 and the sacrum (S1) has a facet orientation that lies more in the coronal plane. On the superior articular processes there are large bony protuberances, called mammilary bodies that serve as additional sites for muscle attachments.

The sacrum (Figure 2.7) is formed by the fusion of five vertebral segments. This triangular bone has a posterior convexity, which is wedge-shaped

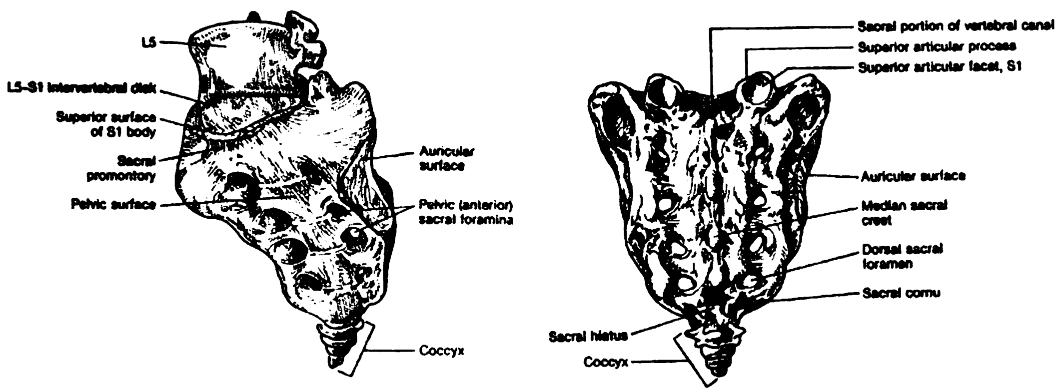

Figure 2.7. Anterior and posterior views of L5, sacrum, and coccyx. From Clinical Musculoskeletal Anatomy (p. 28-29), by N. E. Pratt, 1991, Philadelphia: J. B. Lippincott Company. Copyright 1991 by J. B. Lippincott Company. Reprinted with permission.

superior-to-inferior and anterior-to-posterior. The dorsal surface of the sacrum contains irregular posterior projections that represent rudimentary spinous processes that make good attachment sites for muscles. Four pairs of dorsal and ventral sacral foramina that provide exits for the four sacral nerve roots replace the intervertebral foramina. Superiorly, articular processes, from its broad base, articulate with L5 above and the auricular, inverted L-shaped lateral surfaces articulate with the paired inominate bones. The auricular surface is covered with hyaline cartilage, has cranial and caudal elevations and an intervening central depression, all of which makes motion at the sacro-iliac joint small and complex. The blunted apex inferiorly articulates, or may fuse, with the coccyx.

Intervertebral Disc

An intervertebral disc (Figure 2.8) can be found between every vertebra except in the upper cervical region (C0-C1-C2). Disc height varies by region so that, relative to vertebral body height, disc height is greatest in the lumbar region, smallest in the thoracic spine and intermediate in the cervical spine. Disc structure, however, is consistent at all levels. Each disc has a strong fibrocartilaginous cylindrical shell, with ligamentous characteristics, that surrounds a semigelatinous core. Superiorly and inferiorly,

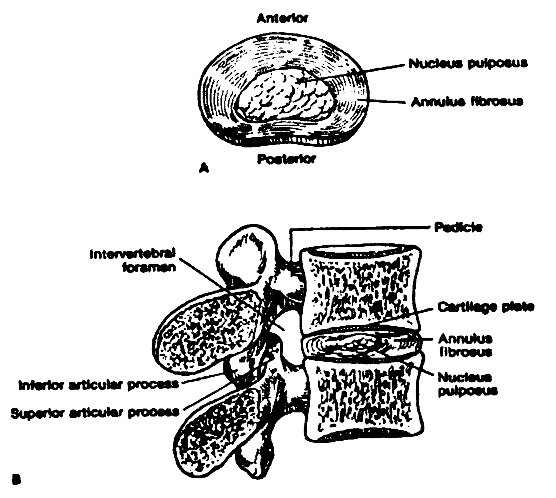

Figure 2.8. Transverse and sagittal sections of the intervertebral disc. From Clinical Musculoskeletal Anatomy (p. 31), by N. E. Pratt, 1991, Philadelphia: J. B. Lippincott Company. Copyright 1991 by J. B. Lippincott Company. Reprinted with permission.

a hyaline plate separates the semigelatinous core from the vertebral bodies. The fibrocartilaginous shell, or annulus fibrosis, consists of concentric layers of fibrocartilage, which attach superficially to the periosteum of the compact bone of the vertebral body and deeply to the hyaline cartilage endplate. The collagen fiber content of the annulus is dense, with adjacent layers arranged at right angles and obliquely to the long axis of the vertebral column.

Functionally, the annulus provides resistance to tensile loads in multiple directions. The nucleus pulposus is the core of the IVD, is mucoid and hydrophylic in nature, comprised of 80% water and contains only a few irregularly arranged collagen and reticular fibers. The nucleus is eccentrically placed posteriorly, more so in the lumbar region, so that annular reinforcement is greater anteriorly and laterally. In general, it is the water content of the nucleus and closed, fluid-elastic nature of the IVD that allows the vertebral column, as a whole, to move freely, distribute stresses evenly and tolerate high torsional and compression loads.

Ligaments

Some ligaments of the spinal column extend the entire length, whereas others are segmental. Therefore, while there are ligaments that are common to all regions of the spinal column, there are others, with highly specialized functions, that are specific to one region. In general, they all serve to hold the vertebrae together, provide stability, limit motion, and, in some cases, contribute as active and reactive moment generators.

The anterior longitudinal ligament (ALL) is a single structure that extends from the atlas (there, referred to as the anterior atlantoaxial ligament) to the sacrum. The ALL attaches firmly to the vertebral bodies and the IVD (except at C0-C1-C2) and covers the anterior and lateral aspect of the column. It serves to reinforce the anterior annulus fibrosis, limit forward and backward sliding movements of the vertebrae and limit extension of the spinal column. The posterior longitudinal ligament (PLL) runs the length of the column posteriorly, attaching to the vertebral body and flaring laterally slightly where it attaches to the IVD, but it is insufficient laterally in comparison to the ALL. It is believed that PLL insufficiency posterolaterally is one reason that posterolateral disc herniations are more common in the lumbar spine. This ligament continues in the upper cervical region as the tectorial membrane. The PLL primarily limits flexion of the spinal column. Intertransverse and interspinous ligaments connect the transverse and spinous processes of adjacent vertebrae, respectively (Figure 2.9). All of these ligaments, and their specialized analogs in the upper cervical region, limit flexion of vertebral segments; acting unilaterally the intertransverse ligaments also limit sidebending to the contralateral side. The supraspinous ligament, a posterior extension of

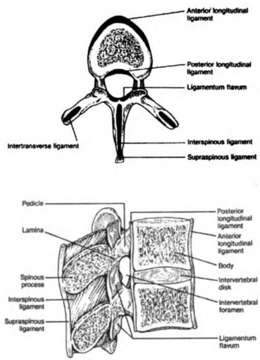

Figure 2.9. Superior and sagittal views of typical ligaments of the vertebral column. From Clinical Musculoskeletal Anatomy (p. 32-33), by N. E. Pratt, 1991, Philadelphia: J. B. Lippincott Company. Copyright 1991 by J. B. Lippincott Company. Reprinted with permission.

the interspinous ligament, and the ligamentum nuchae (cervical region only) run between the tips of spinous processes and limit flexion of the spine. In the lumbar region this ligament merges with the insertion of the lumbar muscles.

The ligamentum flavum (Figure 2.9) is a short, thick ligament that joins laminae of consecutive vertebrae, with some fibers extending laterally to cover the capsules of the zygapophyseal joints. This ligament is paired, symmetrical and runs the length of the spinal column within the spinal canal from C2 to the sacrum. The unique histological structure of the ligamentum flavum (80% elastin and 20% collagen) makes it unlikely that this ligament is able to prevent excessive spinal flexion or produce a significant extension moment. However, its elastic nature prevents this ligament from buckling when the laminae of adjacent vertebra are approximated, thus eliminating encroachment of the spinal cord or spinal nerves.

In the lumbar region there are specialized iliolumbar ligaments that may be vestiges of the quadratus lumborum muscle (Figure 2.10). These ligaments are present bilaterally and, according to most anatomists, run from the tip of the transverse process of the fifth lumbar vertebra to the anteromedial surface of the inominates (ilium)

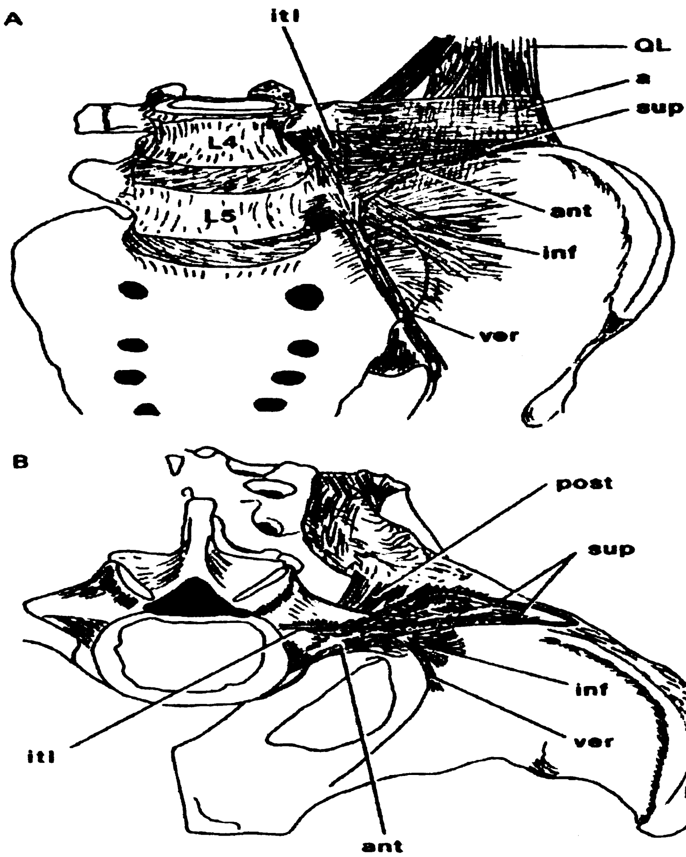

Figure 2.10. Front (A) and top (B) view of the left iliolumbar ligament. Note. Sup – superior iliolumbar ligament; ant – anterior iliolumbar ligament; inf – inferior iliolumbar ligament; ver – vertical iliolumbar ligament; post – posterior iliolumbar ligament; itl – intertransverse ligament; a – anterior layer of thoracolumbar fascia. QL – quadratus lumborum muscle. From Clinical Anatomy of the Lumbar Spine (2nd ed.), (p. 41), by N. Bogduk and L. T. Twomey, 1991, Melbourne: Churchill Livingstone. Copyright 1991 by Churchill Livingstone. Reprinted with permission.

and inner lip of the iliac crest. Some authorities have found this ligament to consist of five parts: anterior iliolumbar, superior iliolumbar, posterior iliolumbar, inferior iliolumbar, and vertical iliolumbar. These parts are listed to emphasize the complexity of the relationship between L5, the ilium and sacrum. In general, these ligaments serve to control movements of L5 in the frontal and coronal planes and limit forward sliding of L5.

Maximum stability has been sacrificed in favor of mobility in the upper cervical region secondary to bony geometry and the absence of intervertebral discs. As a result, many specialized ligaments are required in this region (Figure 2.11). The deep ligaments are the apical ligament of the dens, the two alar ligaments of the dens and cruciate (consisting of transverse, transverso-occipital and transverso-axial parts) ligaments. The alar ligaments are interesting because, in addition to their role as stabilizers, they have been shown to contribute to coupled side bending and contralateral axial rotation that occur in the upper cervical spine. The transverse portion of the cruciate ligaments is also unique. Anteriorly it has a fibrocartilaginous articulation with the dens of C2 and is involved, then, in C1/C2 rotation. In the intermediate plane there are capsular ligaments of the occipital-atlantal joint, which is reinforced laterally by the lateral atlanto-occipital ligament, and the capsular ligaments of the atlanto-axial joint. The superficial ligaments include the median occipital-axial ligament, continuations of the anterior and posterior longitudinal ligaments and other anterior, posterior and lateral ligaments that connect C0-C1, C0-C2 and C1-C2.

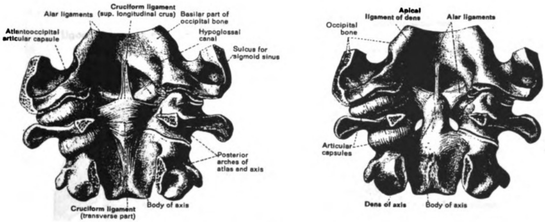

Figure 2.11. Posterior views of suboccipital ligaments. From Anatomy, A Regional Atlas of the Human Body (Figs. 469-472), by C. D. Clemente, 1981, Baltimore: Urban & Schwarzenberg, Inc. Copyright 1981 by Urban & Schwarzenberg, Inc. Reprinted with permission.

Muscles

The posterior muscles of the trunk can be separated into three layers: superficial, intermediate, and deep. Superficially, muscles that have attachments to the spine and pelvis, but are usually considered muscles of the upper extremities, include the trapezius, rhomboid major and minor, levator scapulae and latissimus dorsi (Figure 2.12). Of these, the latissimus dorsi likely has the most influence on trunk and pelvic function. With its broad expansion over the back muscles proper, interdigitation with the thoracolumbar fascia and origin from the sixth thoracic spinous process to sacral four and crest of the ilium, the latissimus dorsi muscle is a powerful back extensor.

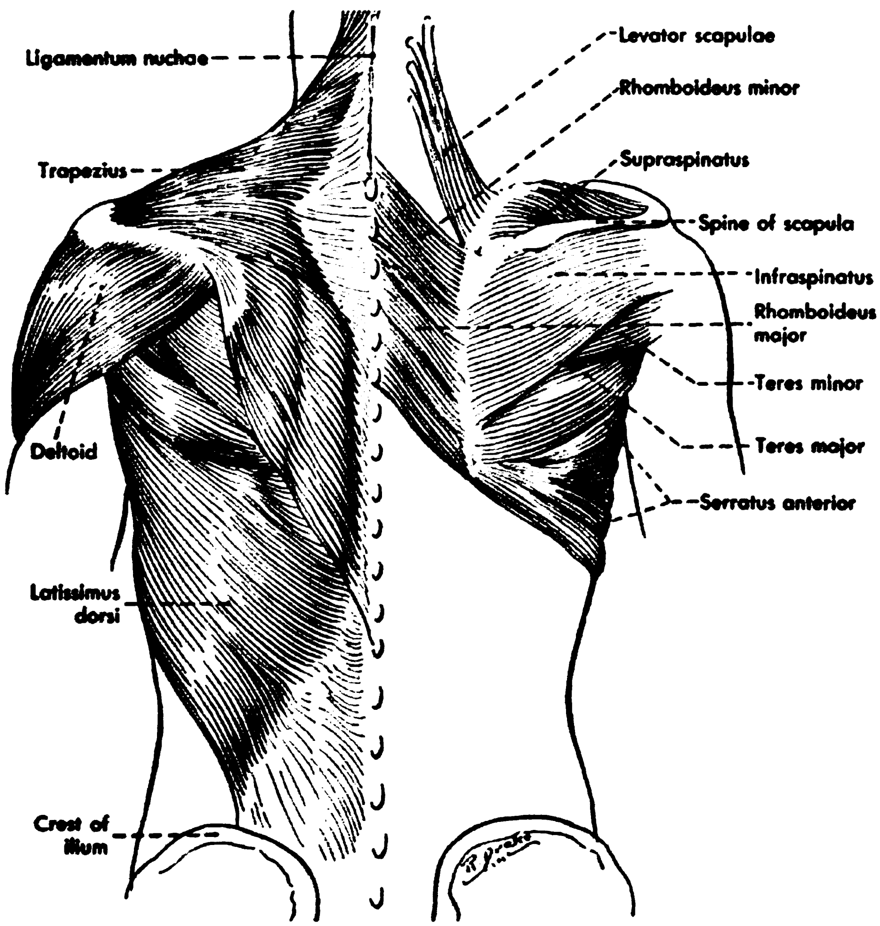

Figure 2.12. Superficial posterior trunk muscles. From Functional Anatomy of the Limbs and Back (5th ed.), (p. 91), by W. H. Hollinshead and D. B. Jenkins, 1981, Philadelphia: W. B. Saunders Company. Copyright 1981 by W. B. Saunders Company.

The thoracolumbar fascia consists of three layers: anterior, middle, and posterior. Historically, the thoracolumbar fascia has been assigned no greater function than investing the back muscles and providing an attachment for the transversus abdominis and internal oblique muscles. However, recently it has been suggested that the posterior portion of this strong fascial layer plays an important mechanical role in lumbar stabilization, particularly while lifting from a flexed posture. The intermediate plane muscles include the serratus posterior superior and serratus posterior inferior. The serratus muscles are primarily involved with respiration.

The true back muscles comprise the deep plane, are also layered superficial to deep, and present a complicated picture of fascicles that are converging and diverging from origin to insertion. The large musculotendinous mass beginning in the sacral and lower lumbar region are known collectively as the erector spinae (ES) (Figure 2.13). The ES generally span several vertebral segments. Proximal to the sacrum the ES divide into three relatively distinct muscle groups (from lateral to medial): the iliocostalis group (lumborum, thoracis and cervicis), longissimus group (lumborum, thoracis, cervicis and capitis) and spinalis group (thoracis). Of these, the spinalis group is least well developed.

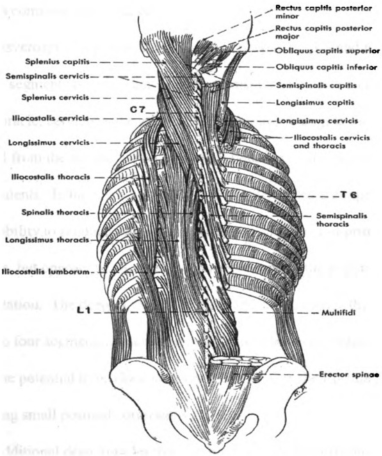

Figure 2.13. Intermediate and deep plane posterior spine muscles. From <u>Functional Anatomy of the Limbs and Back</u> (5th ed.), (p. 211), by W. H. Hollinshead and D. B. Jenkins, 1981, Philadelphia: W. B. Saunders Company. Copyright 1981 by W. B. Saunders Company. Reprinted with permission.

Acting bilaterally, the ES extend the spine. Because of their orientation, the iliocostalis and longissimus lumborum (primarily fourth and fifth lumbar segments) can also resist anterior translation. Acting unilaterally, the iliocostalis and longissimus laterally flex the trunk, but their leverage for axial rotation is minimal. Both the iliocostalis and longissimus thoracis act to increase the lumbar lordosis when acting bilaterally, and they laterally flex the trunk when acting unilaterally. The iliocostalis thoracis cannot cause axial rotation of the trunk from a neutral position, but can derotate the trunk from a contralaterally rotated position.

The transverospinalis group (Figure 2.13) is deep to the ES and has fascicles that span only a few segments or one segment. The semispinalis muscle consists of groups of fibers called thoracic, cervicis and capitus. The multifidi are deep to the semispinalis muscles, extend from the middle cervical levels to the sacrum and generally span only two to four segments. In the lumbo-sacral region these muscles are especially large and strong in their ability to produce segmental extension. They are not prime movers in the horizontal plane, but oppose the flexion moment produced by the abdominal obliques during trunk rotation. The deepest muscle layer of muscles contains the rotators (some of which may span four segments), interspinalis and intertransversaii muscles. These muscles have the potential to produce segmental motion, but their primary role is likely related to making small postural corrections.

Three additional deep muscles that can have a powerful influence on lumbar function, but are usually not considered spinal muscles, include the psoas major, psoas minor and quadratus lumborum (Figure 2.14). These muscles can sidebend the lumbar spine when acting unilaterally, while the psoas major can also produce axial rotation to the contralateral side. Acting bilaterally, the psoas can flex the thigh if the trunk is fixed, but flex the trunk and accentuate the lumbar lordosis if the thigh is fixed.

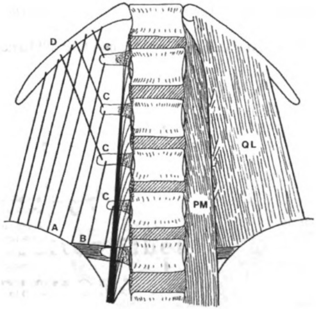

Figure 2.14. Psoas major (PM) and quadratus lumborum (QL). Note. (A) is the iliac crest, (B) represents the iliolumbar ligament and its attachment to the transverse process of L5, (C) are transverse processes, and (D) is the 12th rib. From Clinical Anatomy of the Lumbar Spine (2nd ed.), (p. 84), by N. Bogduk and L. T. Twomey, 1991, Melbourne: Churchill Livingstone. Copyright 1991 by Churchill Livingstone. Reprinted with permission.

In the cervical region, deep to the trapezius and rhomboids, the splenius cervicis and capitus are somewhat unique because the direction of their fibers is oblique from medial to their lateral insertion points. There are four posterior suboccipital muscles that lie deep to the splenii and extend from the occiput to C2: obliquus capitis superior, obliquus capitis inferior, rectus capitus posterior major and rectus capitus posterior minor. Acting bilaterally, these muscles extend the head and neck. Unilateral action produces axial rotation and sidebending of the head and cervical spine (Figure 2.15).

Anteriorly, muscle action generally produces flexion. Beginning in the cervical region these muscles include the sternocleidomastoid (SCM) and scalenes (Figure 2.16) superficially, and the deeper prevertebral (Figure 2.17) and supra- and infrahyoid muscles (Figure 2.18). The SCM forms a large muscular band on the anterolateral aspect of the neck. Unilateral action of the SCM produces a combination of contralateral axial

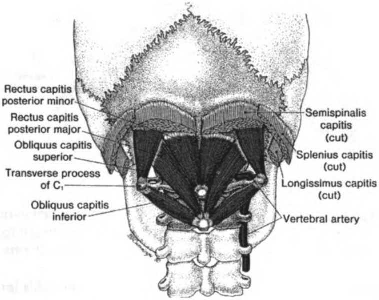

Figure 2.15. Suboccipital muscles. From Myofascial Pain and Dysfunction. The Trigger Point Manual (p. 323), by J. G. Travell and D. G. Simons, 1983, Baltimore: Williams & Wilkins. Copyright 1983 by Williams & Wilkins. Reprinted with permission.

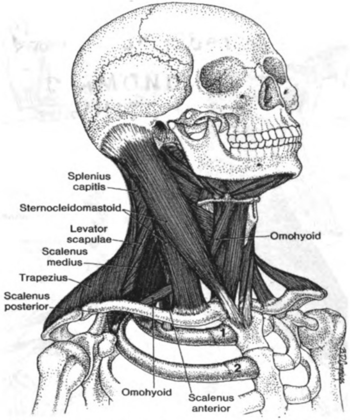

Figure 2.16. Sternocleidomastoid and scalenius muscles. From Myofascial Pain and Dysfunction. TheTrigger Point Manual (p. 354), by J. G. Travell and D. G. Simons, 1983, Baltimore: Williams & Wilkins. Copyright 1983 by Williams & Wilkins. Reprinted with permission.

rotation, ipsilateral sidebending and extension. When the prevertebral muscles are co-acting, bilateral action of the SCM causes flexion of the cervical spine. However, if the deep prevertebral muscles are relaxed or weak, bilateral contraction of the SCM results in an accentuation of the cervical lordosis, extension of the head and flexion of the cervical column relative to the thoracic column. The scalenes have three parts: anterior, medius and posterior. Acting symmetrically they flex the cervical spine, but will accentuate the cervical lordosis if the deep prevertebral muscles are not co-acting. Unilaterally, the scalenes sidebend or laterally flex and axially rotate towards the side of contraction. Because of their attachments to the first two ribs these muscles can also influence rib and upper thoracic mobility.

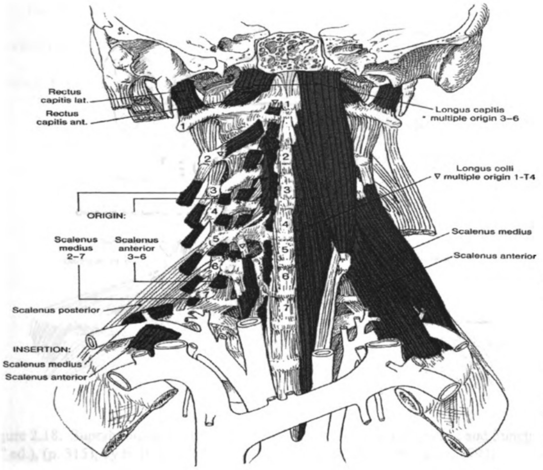

Figure 2.17. Anterior and lateral cerv`ical muscles. From Muscles, Testing and Function (4^{th} ed.), (p. 314), by F. P. Kendall, E. K. McCreary and P. G. Provance, 1993, Baltimore: Williams & Wilkins. Copyright 1993 by Williams & Wilkins. Reprinted with permission.

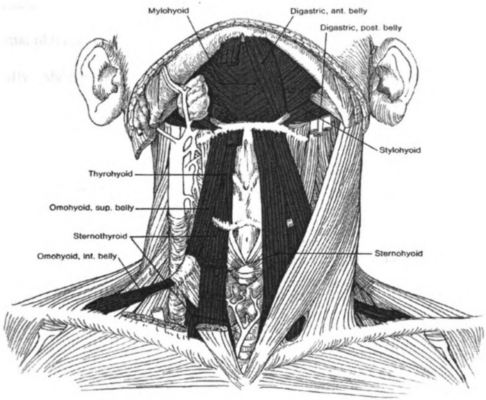

Figure 2.18. Suprahyoid and infrahyoid muscles. From Muscles, Testing and Function (4th ed.), (p. 315), by F. P. Kendall, E. .K. McCreary and P. G. Provance, 1993, Baltimore: Williams & Wilkins. Copyright 1993 by Williams & Wilkins. Reprinted with permission.

The deep prevertebral muscles include the longus cervicis, rectus capitis anterior (superficial and deep fibers), rectus capitus lateralis and anterior intertransverse muscles (Figure 2.17). The longus cervicis flatten the cervical lordosis, flex the neck and stabilize the cervical column at rest when acting symmetrically. Unilateral contraction will produce lateral flexion of the neck to the same side. The actions of the rectus capitus anterior and lateralis occur only at the atlanto-occipital joint. When the mandible is fixed by the muscles of mastication, the suprahyoid (mylohyoid and anterior belly of the digastric) and infrahyoid (thyrohyoid, sternohyoid, sternothyroid and omohyoid) muscles flex the head and neck and flatten the cervical lordosis (Figure 2.18).

The abdominal muscles include the transversus and rectus abdominis and internal and external obliques (Figure 2.19). The transversus abdominis' muscle fibers run horizontally. Shortening of this muscle reduces the diameter of the abdomen, increases

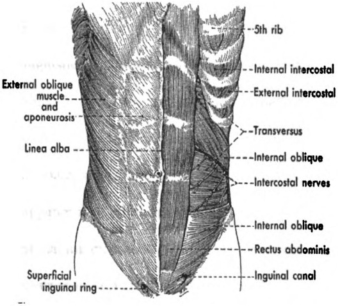

Figure 2.19. Musculature of the anterolateral abdominal wall. From Functional Anatomy of the Limbs and Back (5^{th} ed.), (p. 373), by W. H. Hollinshead and D. B. Jenkins, 1981, Philadelphia: W. B. Saunders Company. Copyright 1981 by W. B. Saunders Company. Reprinted with permission.

the lumbar lordosis and can cause an increase in the intra-abdominal pressure. The rectus abdominis has fibers that run vertically, so that action of this muscle will produce trunk flexion. The oblique muscles will produce trunk flexion when acting bilaterally. Working unilaterally the obliques work synergistically to produce axial rotation, e.g. right external oblique/left internal oblique produce left rotation, and ipsilateral sidebending.

In summary, a study of the complexity of spinal movement would be incomplete without a review of the bony and soft tissue anatomy. Spinal movement is dependent on bony geometry, ligamentous support and muscle action. In the sections that follow, methods of spinal motion measurement will be described.

Clinical Measures of Spinal Mobility

Scientists and clinicians have quantitatively measured spinal motion, in an attempt to document and understand spine function and aberrant movement development and movement patterns, since the early 19th century. Generally, the motivation for these inquiries has been distinguished by the orientation of the investigators. For example, some researchers examined fundamental mechanical (kinematic and kinetic) and material properties of the various tissues of the spinal column (i.e., bone, ligament, intervertebral disc, etc.) under specific loading conditions, whereas other investigators used tools that could document motion patterns of the spinal column. In this section, clinically oriented, noninvasive methods of making measurements of spinal movement will be discussed.

Use of a tape measure to provide a one-dimensional or linear measure of spinal mobility has been promoted by many investigators (Balogun, Abereoje, Olaogun, & Obajuluwa, 1989; Battie, Bigos, Sheehy, & Wortley, 1987; Beattie, Rothstein, & Lamb, 1987; Brodin, Nordgren, & Beije, 1977; Burdett, Brown, & Fall, 1986; Einauf, Gohdes, Jensen, & Jewell, 1987; Fitzgerald, Wynveen, Rheault, & Rothschild, 1983; Gill & Callaghan, 1988; Hsieh & Young, 1986; Macrae & Wright, 1969; Mellin, 1986b; Merritt, McLean, Erickson, & Offord, 1986; Moll, Liyanage, & Wright, 1972a, 1972b; Moll & Wright, 1971; Reynolds, 1975; Salminen, Maki, Olsaned, & Pentti, 1992; Schober, 1937; Sward, Ericksson, & Peterson, 1990; van Adrichem & van der Korst, 1973). The simplest technique to assess standing trunk mobility in either the sagittal or coronal plane was to measure from the finger-tips to the floor (Mellin, 1986b; Gill & Callaghan, 1988; Salminen et al., 1992). Schober (1937), later modified by Macrae and Wright (1969), simply measured the distance between two points on the skin of the lower back and compared that distance in erect standing and maximum forward flexion. Using a radiographic technique, Macrae and Wright validated their modification of Schober's method for measuring forward flexion by finding a product-moment correlation coefficient of 0.97 between skin distraction and forward rotation of the lumbar spine. However, Burdett et al. (1986) were not able to establish reliability for the modified Schober's in a sample of healthy adults. Moll et al. (1972a, 1972b) determined that measuring skin attraction during lumbar extension and skin distraction, or approximation, during thoracolumbar lateral flexion was valid measures. Moll et al. and others (Beattie et al., 1987) have also established the tape measure's reliability as a clinical tool. Portek, Pearcy, Reader, and Mowat (1983) and Merritt et al. (1986), however, have shown that the tape measure technique was prone to large interobserver differences, did not relate to lumbar radiographic measures, and, therefore, concluded that a tape measure assessed some other index of back mobility. Despite the findings of Portek et al. and Merritt et al., the tape measure technique has been recommended as a reasonable clinical measure of lumbar mobility because of its simplicity and ease of use and was shown to differentiate normal and low back pain individuals (Sward et al., 1990; Salminen et al., 1992). Phillippens, Snijders, and Nordin (1987) reported on their use of strain transducers placed on the back to measure skin distraction and a single electronic inclinometer to measure trunk angulation. Their devices could be used to measure spinal curvature and back inclination continuously during working hours. Methods to assess cervical function using a tape measure have also been described (Hsieh & Young, 1986; Balogun et al., 1989).

Two-dimensional measurements usually imply assessment of both translation and rotation in a plane. For practical purposes in a clinical setting, however, usually only rotation in one plane is measured. Application of a draftman's flexicurve has been used to assess standing, sitting or prone sagittal plane postures (Anderson & Sweetman, 1975; Bethune, Broekhoven, Kung, & Snewing, 1986; Burton, 1986; Burton, Battie, Gibbons, Videman, & Tillotson, 1996; Burton & Tillotson, 1988; Hart & Rose, 1986; Israel, 1959; Lovell, Rothstein, & Personius, 1989; Salminem et al., 1992; Stokes, Bevins, & Lunn, 1987; Tillotson & Burton, 1991; Youdas, Suman, & Garrett, 1995;), although it can be applied to measure the spinal configuration in the coronal plane as well. Lumbar regional measurements have been validated with plane radiographs (Hart & Rose, 1986; Stokes, Bevins, et al., 1987), were shown to have good inter-tester reliability (Hart & Rose, 1986; Stokes, Bevins, et al., 1987; Lovell et at., 1989) and intertester parallel forms reliability (Youdas et al., 1995), and were sensitive to detect differences between normal and low back pain patients (Salminen et al., 1992). Burton and Tillotson (1988) established normal upper and lower lumbar regional flexion and extension values using a flexicurve in normal males and females ranging in age from 10 to 84 years. In 1991 Tillotson and Burton suggested that the flexicurve was less biased than the inclinometric technique. Burton et al. (1996) subsequently showed that there was a relationship between loss of lumbar flexibility, as measured with the flexicurve, and loss of disc height secondary to degeneration. Although the flexicurve is valid for regional sagittal plane measures, Stokes, Bevins, et al. (1987) demonstrated a poor correlation between segmental motion measured radiographically and at the surface. Instrumenting a flexible ruler with strain gauges, Reinecke, Hazard, and Coleman (1994) monitored changes in the lumbar lordosis angle while subjects were seated using a lumbar continuous passive motion (CPM) device in an automobile simulation. Compared to not using the CPM device, the authors found that with the CPM in place there was a greater excursion of the lumbar lordosis angle during a 2-hour test period.

Hand-held gravity and electronic inclinometers and a variety of goniometric devices have been employed to assess **cervical** motion (Buck, Dameron, Dow, & Skowlund, 1959; Bennett, Bergmanis, Carpenter, & Skowlund, 1963; Defibaugh, 1964; Ferlic, 1962; Israel, 1959; Kadir, Grayson, Goldberg, & Swain, 1981; Leighton, 1966; Lind, Sihlbom, Nordwall, & Malchau, 1989; Mayer, Brady, Bovasso, Pope, & Gatchel, 1993; O'Driscoll & Tomenson, 1982; Rheault et al., 1992; Schoening & Hannan, 1964; Youdas, Carey, & Garrett, 1991; Youdas et al., 1992), **thoraco-lumbar** motion (Israel, 1959; Mellin, 1986a, 1987; Mellin, Hardonen, & Poussa, 1988; Murrell, Coonrad, Moorman, & Fitch, 1993; Ohlen, Aaro, & Bylund, 1988; Ohlen, Spangfort, & Tingvall, 1989; Ohlen, Wredmark, & Spangfort, 1989; Poussa, Harkonen, & Mellin, 1989; Poussa & Mellin, 1992; Snijders, van Riel, & Nordin, 1987; Tsai & Wredmark, 1993), and **lumbo-pelvic** motion (Brodin et al., 1977; Burdett et al., 1986; Dolan, Adams, & Hutton, 1988; Einauf et al., 1987; Fitzgerald et al., 1983; Gill et al., 1988; Hasten, Lea, & Johnston, 1996; Israel, 1959; Keeley et al., 1986; Lindahl, 1966; Loebl, 1967, 1973; Lowery, Horn, Boden, & Wiesel, 1992; Mayer, Tencer, Kristoferson, & Mooney, 1984; Mayer, Chen, Lavender, Trafimow, & Andersson, 1995; Mayer, Kondraske, Beals, & Gatchel, 1997; Mellin, 1986, 1987; Mellin et al., 1988; Merritt et al., 1986; Ohlen, Spangfort, et al., 1989; Ohlen, Wredmark, et al., 1989; Paquet, Malouin, Richards, Dionne, & Comeau, 1991; Portek et al., 1983; Rondinelli, Murphy, Esler, Marciano, & Cholmakjian, 1992; Shirley, O'Connor, Robinson, & MacMillan, 1994; Sturrock, Wojtulewski, & Hart, 1973; Sullivan, Dickinson, & Troup, 1994; Taylor & Twomey, 1980; Troup, Hood, & Chapman, 1968; Tsai & Wredmark, 1993; Twomey & Taylor, 1979). Using plane radiographs in normal individuals and low back pain patients, Mayer et al. (1984), Pearcy, Portek, and Shepherd (1985), and Keeley and co-workers (1986) have demonstrated the validity of using the single or double inclinometric technique for sagittal plane measurements of the lumbar spine. Portek et al. (1983) found large errors with use of an inclinometer and suggested that an inclinometer could be used reliably if the technique was monitored carefully. Burdett et al. (1986) were not able to show high validity using three different inclinometric/goniometric techniques. Intertester and intratester reliability studies using inclinometers/goniometers for measuring sagittal plane motion in the cervical region (Balgogun et al., 1989; Rheault et al., 1992; Youdas et al, 1991; Youdas, et al., 1992), thoracic region (Murrell et al., 1993), and lumbo-pelvic region (Burdett et al., 1986; Gill et al., 1988; Keeley et al., 1986; Lowery et al., 1992; Mayer et al., 1995; Ohlen et al., 1989; Rondinelli et al., 1992) have shown that, in general, intraobserver repeatability was high, but interobserver reliability was quite variable and generally lower. Gill and co-workers, in comparing four methods of sagittal lumbar measurement techniques, found the modified Schober to be more reliable between testers than the inclinometric method. However, Burdett et al. found good intertester reliability for the three different inclinometric/goniometric techniques they tested. The modified Schober method was less reliable than the other techniques. Rondinelli et al. studied the intrarater and interrater reliability of the single- and double-inclinometer techniques, the back range of motion device, and B200 (a dynamometer that can measure three-dimensional trunk motion and torque). They found that intrarater reliability was high for the back range of motion device and single inclinometer techniques and concluded that there was considerable measurement variability, low interrater reliabilities for each method and poor cross-validity. Mayer and his co-investigators (1995,1997), using a fluid-filled inclinometer, digital (electronic) inclinometer and kyphometer for lumbar measurements, concluded that their poor intertester (14 examiners) reliability was not due to the instrumentation but to the examiner's lack of familiarity with the instruments and variable expertise in location of bony landmarks.

Although most of the spinal motion data collected and published, using hand-held inclinometers/goniometers, have been in the sagittal plane, a few investigators have reported on their attempts to measure coronal and transverse plane spinal motion. Defibaugh (1964) using a modified goniometer and Youdas et al. (1991, 1992) and Rheault et al. (1992), using the cervical range of motion device (an inclinometer), documented cervical motion in all three planes for normal subjects and established the reliability of their respective instruments. Recently, Ordway et al. (1997) have shown that the cervical range of motion (CROM) device gave flexion/extension results that were similar to cervical radiographs. However, they found that the CROM gave different measurements than radiographs and the 3SPACE (an electromagnetic device that can track rigid body position in three-dimensions) for protrusion and retrusion of the cervical spine. Ordway et al. concluded that the CROM was reliable for flexion, extension, protrusion, and retrusion as long as patient thoracic positioning was standardized to minimize thoracic contribution. Mayer et al. (1993) established normal three plane cervical range of motion values for men and women, and their validity, using a two-inclinometer (digital) technique. One interesting finding in their study was that rigidity in one plane did not necessarily predict rigidity in another.

Other studies have supported the use of inclinometers to look at coronal and transverse rotation in the thoracic region (Mellin, 1986a, 1987; Mellin et al., 1988) and lumbar region (Brodin et at., 1977; Lowery et al., 1992; Taylor & Twomey, 1980). Brodin et al., using a goniometer, looked at sidebending of lumbar segments by measuring the angle between a line connecting two lumbar spinous processes with a vertical line that had its origin at the spinous process of S1. They concluded that their method could be used to study the longitudinal progress of patients, but was too variable between individuals to establish normal values. Mellin et al. (1988) studied triplanar thoracic and lumbar mobility and thoracic posture in developing male and female adolescents. Compared to males, females had decreased and more asymmetrical motion. The authors suggested that reduced mobility and the asymmetries could be factors that predisposed girls to scoliosis. Others (Bunnell, 1984; Ohlen et al., 1988; Poussa et al., 1989; Poussa & Mellin, 1992) have also looked at thoracic and lumbar mobility in more than one plane, comparing persons with normal spines to those with scoliotic spines and assessing the outcome of Harrington rod placement (Aaro & Ohlen, 1983). Ohlen et al. (1988) found that lateral bending of the thoracic curves was significantly reduced and that lateral bending and rotation ability were impaired with descending apex of the minor curve in the lumbar spine in subjects with scoliosis. Poussa et al. (1989) and Poussa and Mellin (1992) recorded less axial rotation and sidebending in the thoracic spines of those with scoliosis. They found a slight increase in axial rotation in the lumbar spine and suggested that it was due either to the decreased lumbar lordosis, which open the facets, or to reduced rotation in the thoracic spine. Schenkman, Hughes, Bowden, and Studenski (1995) looked at total axial rotation using a functional axial rotation measuring device.

They measured total trunk rotation in degrees with subjects sitting. Their goal was to design a method that was easy to use and one that provided the clinician with information regarding the patient's ability to move the spine in an integrated fashion and see toward the posterior.

Electronic potientiometers/goniometers have been developed to measure either planar trunk motion (Adams, Dolon, Marx, & Hutton, 1986; Marrus & Wongsam, 1986; Murphy, Rankin, Jones, & Jayson, 1984; Otun & Anderson, 1988; Paquet et al., 1991; Paquet, Malouin, & Richards, 1994) or three-dimensional trunk motion (Alund & Larsson, 1990; Dvorak, Panjabi, Grob, Novotny, & Antinnes, 1993; Hsieh & Pringle, 1994; Marrus, Fathallah, Miller, Davis, & Mirka, 1992; Marrus et al., 1993; Marrus et al., 1994; Marrus et al., 1995; McGregor, McCarthy, & Hughes, 1995; Peterson, Johnson, Schuit, & Hayes, 1994; Snijders et al., 1987). Paquet et al. (1991, 1994) demonstrated the validity and reliability of their device on normal subjects and its usefulness in distinguishing sagittal plane spinal motion between normal and low back pain subjects. Marrus and Wongsam (1986) looked at sagittal plane motion and angular velocity in normal volunteers and subjects with low back dysfunction, and concluded that velocity could be used to quantitate low back disorders and monitor the rehabilitative process. McGregor et al. (1995) tested 203 normal subjects (103 males, 100 females) with the CA-6000 Spinal Motion Analyser™ in order to establish normal three-dimensional motion and velocity characteristics of the thoracolumbar region. McGregor's group and Peterson et al. (1994) found that intraobserver and interobserver repeatability using the CA-6000 was sufficiently high for research and clinical purposes.

Marrus et al. (1992) showed that the lumbar motion monitor (a three-dimensional system) they designed was more accurate and reliable compared to a two-dimensional motion analysis system. Intratester and intertester reliability of the lumbar motion monitor was recently found be clinically acceptable for three-dimensional motion and angular velocity data (Gill and Callaghan, 1996). Marrus and his co-workers (1993) have used their system to study low back ergonomics in the workplace (1993), trunk task asymmetries related to age and gender in normal individuals (1994), and to classify anatomic- and symptom-based low back disorders (1995). Their device appears to be accurate and easy to apply, allowing it to be useful for occupational, clinical, and research activities. However, their application was limited to thoracolumbar motion so that regional mobility could not be distinguished.

Alund and Larsson (1990) developed a device to measure the three-dimensional motion of the neck and found that there were good correlations between its measurements and measurements made by previously validated inclinometric and radiographic techniques. Dvorak et al. (1992) used the CA-6000 Spine Motion Analyser™ (this device has been adapted and used to also study both the thoracolumbar and cervical regions) in the cervical region to categorize mobility based on age and gender. Details of Dvorak's work will be discussed in a later section of this review.

Dynamometers have been used to measure trunk strength and mobility. Most of these devices are restricted to measuring sagittal planar motions and torques. However, the Isostation B200 Lumbar Dynamometer™ does have the capability to detect three-dimensional motion and torque characteristics. It has been used to establish a normative database (Gomez, Beach, Cooke, Hrudey, & Goyet, 1991) and to examine asymmetric motion patterns in low back pain patients (Gomez, 1994). However, its reliability was good only for measurements of lateral bending and sum of all ranges of motion (Rytokoski, Karppi, Soini, & Ronnemaa, 1994).

In many studies inclinometers and goniometers were used to distinguish movement patterns in normal subjects and those with low back pain (Brodin et al., 1977; Keeley et al., 1986; Mayer et al., 1984; Ohlen, Wredmark, et al., 1989). With subjects flexed approximately 90° and using a single pendulum inclinometer placed at T12-L1, Keeley and her co-workers measured lumbar axial rotation in a small sample of normal and back pain individuals. Axial rotation was symmetrical to the right and left for normal subjects, but asymmetrical in patients. For both groups, interobserver reliability was variable, but generally higher in patients. Ohlen, Wredmark, et al. found a correlation between increased lordosis and low back pain in female gymnasts. They suggested that their method of sagittal plane measurements of lumbar motion and lordosis could be used to predict gymnasts who might be predisposed to low back pain. Lowery et al. (1992) cautioned clinicians about making judgments regarding impairments in individuals with back pain using the double inclinometer method based on their results testing individuals without low back pain symptoms. Basing judgments on the American Medical Association (AMA) Guides to the Evaluation of Permanent impairment, they found that all of the normal subjects they tested had some degree of "impairment" (which increased with age) in the cervical and lumbar spines, as defined by the AMA. They found that impairment may be overestimated by as much as 38% and suggested that new guidelines be established based on individual movement characteristics and age.

Photography has been utilized to assess sagittal plane motion of the trunk (Burdett et al., 1986; Davis, Troup, & Burnard, 1965; Gill et al., 1988; Troup et al., 1968). This method involves photographing markers that are placed on key anatomic landmarks and determining angular motions of body segments, e.g., trunk relative to the pelvis, by measuring the angles between vectors drawn from one marker to another. The photographic method is time consuming in the clinical setting and has not been shown to be valid (Burdett et al., 1986) or highly reliable (Burdett et al., 1986; Gill et al., 1988). More sophisticated photographic, optical scanning, or electromagnetic systems have also been used to study planar spinal motion characteristics (D'Amico, D'Amico, & Roncoletta, 1995; D'Amico, Grillet, Mariotti, & Roncoletta, 1995; Esola, McClure, Fitzgerald, & Siegler, 1996; Gracovetsky, 1988; Gracovetsky et al., 1995; Jayaraman, Nazre, McCann, & Redford, 1994; Leskinen, Takala, & Stalhammar, 1987; Pearson & Walmsley, 1995; Robinson, O'Connor, Shirley, & MacMillan, 1993; Rudy, Boston, Lieber, Kuminski, & Delitto, 1995; Shirley et al., 1994) and three-dimensional spinal motion characteristics (Adams, Tregidga, Driver-Jowitt, Selby, & Wynchank, 1994; Bechtold et al., 1983; Buchalter, Parnianpour, Viola, Nordin, & Kahanovitz, 1989; Farahpour, Allard, Labelle, Rivard, & Duhaime, 1995; Hindle & Pearcy, 1989; Hindle, Pearcy, Gill, & Johnson, 1989; Hindle, Pearcy, Cross, & Miller, 1990; Osterbauer et al., 1996; Pearcy, Gill, Hindle, & Johnson, 1987; Pearcy, Gill, Whittle, & Johnson 1987; Pearcy & Hindle, 1989; Thurston, 1982; Thurston, 1985; Trott, Pearcy, Ruston, Fulton, & Brien, 1996; Walmsley, Kimber, & Culham, 1996; Willems, Jull, & Ng, 1996; Winters et al., 1993; Woltring et al., 1994). Elaboration of the studies cited above is provided in a later section of this review.

Other non-optical measurement devices have also been used to assess postures and spinal positions in two or three dimensions. In 1979, Grew and Harris measured the back shape and position of a subject standing still and standing axially rotated using both a two-string and three-string 'vector stereograph'. The vector stereograph was found be highly inaccurate and has not provided significant mechanical or clinical information regarding spinal function. Gross, Neuwith, Graham, and Pugh (1982) and Smidt et al. (1994) described the use of hand-held digitizing devices to assess the three-dimensional position of the lumbar and thoracic spines, respectively. Goel, Clark, McGowan and Goyal (1984) used a sonic digitizer to study the three-dimensional kinematics of whole cervical spine specimens that were intact or with partial removal of ligaments and capsules. Hand-held and sonic digitizers have been found to be valid and reliable.

In summary, useful clinical methods have been devised to measure sagittal, coronal, and transverse plane motion of the cervical, thoracic, and lumbar regions. There is some question regarding the validity of many of these methods, but in general, their intratester and intertester reliability has often been shown to be acceptable. Normal values for all regions of the spine have been initiated, and these can be used to compare to patients with spinal pathology or to monitor treatment progress. In many of the studies cited, however, only planar spinal mobility was measured and these results have not, by design, offered insights into the three-dimensional kinematic nature of the spine. Three-dimensional measurements using electronic potentiometers/goniometers, motion analysis or other optical and electromagnetic measurement systems, or dynamometers, have provided some insights into spinal behavior and have shown promise as clinical tools. A more detailed discussion of the findings related to three-dimensional studies of the spine will be presented in forthcoming sections.

Physiological Movements of the Spine

In this section an historical overview will primarily focus on the work of two physicians, Robert W. Lovett, an allopathic physician, and Harrison H. Fryette, an osteopathic physician, both of who practiced in the late 19th and early 20th centuries. Lovett's findings (1902, 1905) on spinal function seemed to have served as a springboard for Fryette's work and subsequent writings (1954, 1918). After examining Lovett's work in some detail, Fryette's concepts of spinal function will be thoroughly explored. Understanding the basis for Fryette's concepts is important since osteopathic manual medicine practice today is founded on those concepts. The general objective of the proposed research will be to examine Fryette's concepts in living subjects.

In the introduction to his description of the radiographic study of the lumbar and dorsal spine he performed on a flexible 16 year-old female, Elward (1939) gave a brief history of the research related to the physiological motions of the spine. As cited in Elward, Jakob Benignus Winslow, a Danish professor, published in 1730 detailed descriptions of the vertebral apophyseal facets and their intercontact during movements of the head and other regions of the spine. Weber, in 1827, performed measurements of spinal movements using two male cadavers and one female cadaver. He also studies spinal movements of young male living subjects. He found that the cervical vertebrae were most mobile, thoracic vertebrae could be rotated but not flexed, and the lumbar vertebrae could be flexed anteriorly, posteriorly and laterally, but not rotated about a longitudinal axis. In 1859, Bishop, an English geometrician and physician, discussed normal spinal movements in an effort to promote knowledge and treatment of scoliosis. Volkman, a German physiologist, reported in 1872 the results of his work on the spine that contradicted Weber's earlier work. In 1877 a French savant revealed the existence of four centers of lateral rotation of the spine; namely atlanto-occipital, cervical-dorsal, dorsolumbar and lumbosacral. Lohr (1890) was presumably the first to systematically measure forward and backward bending of the spine in living subjects. He projected shadows on a screen and measured the angular motion in 47 subjects ranging in age from seven to 57 years.

Robert Lovett (1902, 1905), a Boston MD physician, developed a spinal model using a flexible rod and tested cadaver and living subjects in an effort to understand cardinal plane and coupled (sidebending and rotation) spinal motions. As reviewed by Lovett (1902), Bradford (1899), Meyer (1865) and Albert (1899) had previously investigated the relationship between rotation and sidebending that occurred in scoliosis. Albert proposed that axial rotation (AR) accompanied sidebending (SB; or lateral bending, LB) because the human spine consisted of two columns, a column of bodies and a column of posterior arches. He suggested that differing degrees of elasticity of the two columns caused rotation to occur as a "lagging behind" of one column during lateral bending.

Lovett attempted to ascertain whether the spine followed certain general laws of mechanics. Along with Harvard Professors T. Dwight and I. N. Hollis, Lovett formulated two laws governing flexible rods:

(A) Although a straight flexible rod (e.g., a quadrilateral rod of rubber or lead) may be bent in one plane without twisting, if such a rod is already bent in one plane it cannot be bent in another plane without twisting.

(B) Although a straight flexible rod may be twisted without acquiring a sidebend, a flexible rod already bent in one plane cannot be twisted without acquiring a sidebend.

Lovett and his colleagues tested these laws using flexible rods of rubber and lead, the backbone of a fish and cat, a human cadaver spinal column, with ribs attached but no sternum, and a living model. They found that, with the rod or spine fixed at the base, when flexion was combined with left sidebending, axial rotation to the right was also produced. When they introduced an axial rotation to the left first, they found that lateral bending also occurred in the opposite direction. To test Albert's two-column theory, Lovett replicated his previous experiments, but with the vertebral bodies (adult whole spine) separated from the laminae and posterior (neural) arches. His findings were unchanged and he concluded that the articular processes did not cause the torsion of the spine in sidebending, but the column of vertebral bodies (like the flexible rod) was the determining factor in the association of lateral bend and twist.

In 1905 Lovett reported details of additional studies on the movement behavior of each spinal region, and the spine as a whole. With the pelvis fixed, manual forces were applied to whole cadavers, spinal columns stripped of muscle and connective tissue and separate spinal regions. With pins inserted into each spinous process, vertebral displacements and rotations in four specimens were measured or observed. In one cadaver a heavy brass rod was thrust down through the vertebral canal through the 12^{th}

thoracic segment to stiffen the dorsal spine so that the lumbar spine could be studied in isolation. To isolate the thoracic region of another specimen, the lumbar vertebrae were nailed together. A third cadaver had the cervical, thoracic and lumbar regions separated by cutting so each could be studied in isolation. Finally, active and passive movements in standing and sitting (pelvis free and fixed) were quantified in a living female subject by marking and photographing the spinous processes.

In the spine as a whole, flexion and hyperextension (backward bending) appeared to be pure antero-posterior movements, with most motion occurring in the lumbar spine. Flexion in the cervical and lumbar regions did not result in a posterior convexity, but flexion in the thoracic spine increased the posterior convexity. Lovett suggested that most flexion in the cervical spine came from the occipital-atlantal joint. Hyperextension in the dorsal (thoracic) spine was extremely limited and changed the kyphotic curve only to a small degree. In the living model the degree of maximum hyperextension was not affected by whether the pelvis was free or fixed.

Lovett noted that the character and distribution of sidebending varied widely according to the degree of sagittal plane positioning. With the spine flexed, sidebending was more evident in the dorsal spine. With an increased degree of flexion, which appeared to lock the lumbar spine, there was a cephalic or proximal progression of the freedom of sidebending. In the erect (neutral) and hyperextended positions sidebending occurred primarily in the thoraco-lumbar junction and lumbar regions, respectively. Hyperextension locked the dorsal spine, essentially preventing sidebending and rotation. In flexion, axial rotation of the vertebral bodies, coupled with sidebending, occurred toward the convexity of the curve, i.e., flexion-left sidebending-right rotation. This pattern occurred chiefly in the dorsal spine, since the lumbar spine appeared to be locked by flexion. With the spine in a neutral and hyperextended position axial rotation occurred toward the concavity of the sidebending curve, i.e., coupled in the same direction. Sidebending was uniformly distributed in the cervical spine and was coupled to axial rotation in the same direction, regardless whether the vertebrae were flexed or hyperextended.

Lovett also found that axial rotation was most free in the erect posture, occurring primarily in the cervical and dorsal spines, but extending to the first and second lumbar segments with forceful manual rotations applied to the cadaver. Axial rotation was most free in the cervical spine between C1 and C2, and more limited in the rest of the cervical region. In the thoracic vertebrae, axial rotation was found to be freer than sidebending. Axial rotation was accompanied by a sidebend of the rotated region away from the side to which the bodies of the vertebrae turned. If axial rotation was to the right, a bend occurred which was convex left; in other words, axial rotation and sidebending were coupled to the same side. This pattern was also true with the spine hyperextended, occurring in the cervical spine and primarily in the thoracolumbar region, rather than the upper or middle dorsal spine. Axial rotation in the flexed spine occurred chiefly in the cervical and upper dorsal spines, with the lower dorsal and lumbar spines restricted because of their locked positions.

Fryette (1954, 1918) disagreed with Lovett's conclusions regarding the physiological movements of the spine and the terminology that he used in describing "flexion (and extension) of the trunk." Fryette preferred to speak of flexion and extension of the spine rather than flexion and extension of the trunk. He defined flexion as an increase in the normal existing curve in any area of the spine and extension as a decrease in the physiological curve. For example, if the trunk is flexed on the thighs the lumbar lordosis will be decreased and, thus, the lumbar vertebra will have extended. Because of these semantic differences (at least as perceived by the present author) it is somewhat difficult to interpret Fryette's writings. For the purpose of this review, Fryette's operational definitions of flexion and extension, as applied to the cervical and lumbar regions, will be discarded in favor of the more traditional concepts. That is, flexion will be associated with forward bending and extension will be associated with backward bending for all spinal regions.

Fryette (1954) defined neutral as "the position of any area of the spine in which the facets are idling, in the position between the beginning of flexion and the beginning of extension." He noted that each area of the spine possessed an antero-posterior curve and that, as a rule, these curves did not become completely obliterated when that area was extended, i.e. flexion in the cervical and lumbar regions and extension in the dorsal spine. In general, according to Fryette, movements of all areas of the spine (except the C0-C1-C2 complex) were either simple (flexion and extension) or compound (extension-rotation-sidebending or flexion-rotation-sidebending). He graded motion, starting from neutral, as flexion or first degree (extension or one of the compound motions), marked or second-degree flexion (extension, etc.), and extreme or third flexion (extension, etc). Fryette based his concepts of spinal movement on manipulations he made to an articulated spine mounted in soft rubber and on observations of living models. He preferred studying living models in the upright position where the weight was superincumbent on the spine.

Dr. Lovett observed that when the vertebral column was sidebent, under load, it tended to collapse toward the convexity (like a pile of blocks would do). Fryette (1954) observed similar behavior and also found that the column of facets "behaved like a flexible ruler or a blade of grass; rotation was necessary before it could be sidebent." Fryette concluded that two dominant factors controlled or modified the mechanical behavior of the spine: the vertebral bodies (in agreement with Lovett) and the articulating facets (which controlled axial rotation). Fryette (1954) summarized Lovett's findings as follows:

1. Lumbar Region

   "The rotation accompanying sidebending in the lumbar is *always* with the bodies turning to the concavity of the lateral curve."

2. Thoracic Region

   "The rotation of the vertebrae in sidebending in the thoracic region is *always* toward the convexity of the lateral curve."

3. Cervical Region

   In the cervical region, "sidebending is accompanied by rotation of the bodies of the vertebrae to the concavity of the lateral curve, as in the lumbar."

He stated that Lovette's conclusions were true for the specific areas of the spine that were tested and for the positions that they were placed in, but were not true in the lumbar area when that area was in neutral or moderate *extension* (italics indicating where this author is making changes to account for differences in operational definitions of flexion and extension, as described previously); or in the thoracic spine when it was sidebent from a position of moderate extension.

According to Fryette (1954), the lumbar spine participated in four simple movements (*flexion*, *extension*, sidebending of ~10° and slight axial rotation) and three compound movements (*flexion*-rotation-sidebending, *extension*-sidebending-rotation, extreme *extension*-rotation-sidebending). In forward bending of the lumbar region, he found that the normal antero-posterior curve was not quite obliterated, although nearly so in pathological cases. In increasing degrees of *flexion* the load was transferred from the facets to the vertebral bodies and intervertebral discs, but the facets were locked in the extreme position. In backward bending the normal existing curve was greatly increased, with very little to limit the movement. A pure sidebending was possible, but seldom found in practice and there was slight axial rotation, which was limited primarily by soft tissues (intervertebral discs, ligaments and muscles). When sidebending was introduced with the region in a position of *flexion* or extreme *extension* the bodies were forced into the concavity, i.e., axial rotation occurred to the same side; Fryette, however, noted that extreme extension-rotation-sidebending had no practical value. With the lumbar spine in neutral, first- or second-degree extension, the bodies rotated away from the concavity (Fryette, 1954, 1918). Fryette (1954) considered lumbar movement in this position to be "free" where the facets were "idling", and therefore not in control of the movement.

Fryette (1954, 1918) suggested that the thoracic cage was not meant to be as flexible as our lifestyles dictated and that thoracic articulations were the weakest area of the spine; however the rib attachments served as good splints and yet modified vertebral movement, especially in axial rotation and sidebending. He believed that sidebending was the dominant movement in the thoracic region, with physiological rotation extremely limited at all times. He also suggested that since vertebral joints tended to collapse in neutral and extension, increasing the load onto the body and disc, the thoracic spine was predisposed to scoliosis. For kinematic purposes, Fryette divided the thoracic spine into two parts: segments T1-T9, and 10th, 11th and 12th segments. The first nine vertebrae were very limited in extension by the character of their articulating ribs, and favored flexion because of the angle of the facets. The lower three segments functioned more like lumbar vertebra in extension, despite their costal attachments, because of the freer movement they demonstrated. With the thoracic spine in hyperextension or hyperflexion (second or third degree) axial rotation occurred toward the concavity of the sidebending curve. In the compound movement of extension-rotation-sidebending the coupled patterns did not seem to be different whether sidebending or rotation was introduced first. When the spine was in neutral or first degree flexion and sidebent, the vertebral bodies rotated away from sidebending (toward the convexity). Fryette (1954) considered physiological flexion-sidebending-rotation to be very limited, and if maintained for a length of time to result in scoliosis.

Fryette (1954) considered studying the two divisions of the cervical region separately since they differed markedly in structure and function: (1) the second, third, fourth, fifth, sixth and seventh vertebrae; and (2) the occiput, atlas and axis. He described anatomical differences in the facet planes between the second-third and third-fourth segments and the ones below. Dr. Fryette believed that these differences made axial rotation the more free movement at C2-C3 and C3-C4, and sidebending the dominant movement from C4 downward. The simple movement of *flexion* favored sidebending, but when in the extreme position facet locking did not occur to the same extent as in the lumbar and thoracic regions. The compound movements (*flexion*-sidebending-rotation and *extension*-rotation-sidebending) were opposite of those in the other two spinal regions; AR always occurred toward the side of sidebending. Fryette found excessive axial rotation at the atlanto-axial joint, some forward and backward bending, but only slight sidebending. Forward/backward rocking of the occiput was found to be the dominant motion at the occipital-atlantal joint; axial rotation and sidebending were found to exist but their compound relationship was not delineated. See Table 2.1 for a summary of the key concepts presented by Drs. Lovett and Fryette.

The foregoing discussion provides an excellent backdrop for the review that will follow. Lovett (1905) and Fryette (1918, and later more fully developed in 1954) had provided, in their day, the most thorough discussion of the physiological movements of the spine. However, their experiments using rubber rods, whole vertebral columns without muscles, whole cadavers and living models were fraught with limitations and subject to significant error. Spinal research has steadily increased since the time of the aforementioned pioneers, but it was not until the late 1940's and early 1950's that there seemed to be an explosion of work in this area. Back pain continues to interest and confound scientists and health care providers today. However, it does not appear that anyone, to date, has systematically examined Dr. Fryette's concepts. The remainder of the literature review will describe the work that has been published in the last 50 years with regard to spinal kinematics.

Table 2.1 Spinal Coupling: Sidebending (SB) and Axial Rotation (AR)

	Cervical		Thoracic		Lumbar	
	Lovett	Fryette	Lovett	Fryette	Lovett	Fryette
Flexed[a]	SB/AR same	SB/AR same	SB/AR opposite[b]	SB/AR same	SB/AR same	SB/AR same
Neutral	SB/AR same	SB/AR same	SB/AR same	SB/AR opposite	SB/AR prevented	SB/AR same
Extended	SB/AR same	SB/AR same	SB/AR same	SB/AR same	SB/AR same	SB/AR opposite[c]

Note. [a]Denotes the position of the spinal column. [b]Indicates if AR is introduced first SB is coupled to the same side. [c]Indicates if the lumbar spine is in extreme hyperextension (which usually does not occur) SB/AR are coupled to the same side.

Radiographic and Invasive Measures of Spinal Kinematics

In this section two- and three-dimensional in vitro and in vivo research models using radiographic and invasive techniques of measurement will be discussed relative to the cervical, thoracic and lumbar spines. Although the focus of this research will be to examine functional movements of the thoracic spine, all three distinct spinal regions will be presented in order to understand their unique characteristics and to show their interdependence. The final portion of this section will discuss geometrical and analytical models of the spine that have been used in conjunction with experimental data in order to understand normal and pathological spinal loading and movement patterns.

Two-Dimensional Kinematics

The Cervical Spine

Several have used intact cadaveric cervical spines to radiographically investigate the two-dimensional kinematics of the upper cervical spine (Dankmeijer & Rethmeier, 1943; Hohl & Baker, 1964; Selecki, 1969) and lower cervical spine (Ball & Meijers, 1964; Beal & Beckwith, 1963; Bhalla & Simmons, 1969; Panjabi, White, Keller, Southwick, & Friedlaender, 1978; Ten Have & Eulderink, 1980). Others have studied conjoined craniovertebral joints (Dvorak, Panjabi, Gerber, & Wickmann, 1987; Werne, 1957) or individual motion segments (Gomez, Moore, & Silver, 1991; Panjabi, White, & Johnson, 1975; White, Johnson, Panjabi, & Southwick, 1975;) to delineate cervical kinematic patterns and ligamentous function.

Ten Have and Eulderink (1980) provided data on sagittal plane (flexion and extension) movement from C0-C1 to C7-T1 using 86 specimens, whereas Ball and Meijers (1964) only looked at segments C2-C3 to C7-T1 from 21 specimens. However, both groups used similar loading devices (~4 kg load) and studied segmental motion by measuring the angles between pins that were inserted into vertebral bodies devoid of muscles, but with ligaments intact. In general, Ball and Meijers' measurements, on a segmental basis, exceeded those of Ten Have and Eulderink, with the former group also noting some horizontal displacements of vertebra with flexion and extension. Both research groups found that the C5-C6 (~15-20°) segment was the most mobile, while the C2-C3 segment was the least mobile (~9°), and that mobility decreased with spinal element degeneration. Panjabi et al. (1975) and White et al. (1975) studied sagittal plane rotations and translations in 17 cervical motion segments including the C3-C4, C4-C5, and C6-C7 units from eight cadavers. Flexion or extension moments were produced by a dacron cord/pulley system. Loads applied to the dacron, which had been threaded through the upper half of the superior vertebrae, were perpendicular to the axis of the spine. Maximum rotations and horizontal displacements of 11° and 3 mm, respectively, were measured. The authors of these independent investigations concluded that for clinical instability to exist displacements exceeding 3-4 mm and rotations exceeding 11° must be evident. Gomez, Moore and Silver (1991) found an average displacement of 2 ± 1 mm and angulation of $15 \pm 5^\circ$ in their flexion/extension tests of the C2-C3, C4-C5 and C6-C7 motion segments. Gomez's group suggested that measurements were dependent on how moments were applied, implying that clinicians needed to be cautious in their interpretation of clinical radiographic studies that attempted to quantify cervical instability. In this regard, Ball and Meijers noted a marked variation in mobility among cadaver specimens (total flexion/extension ranged from 66° to 111°).

Beal and Beckwith (1963) used a Halladay spine (pelvis, lumbar, thoracic and cervical segments, ribs and attached ligaments) to study straight plane and complex (e.g., flexion (extension) and lateral flexion (rotation), etc.) spinal motions that were induced manually. Using cineradiography, they were able to quantify gross motion of spinal regions in the sagittal and frontal planes but were able to provide only qualitative information on axial rotation and complex motion patterns. Their conclusions were limited by having tested only one specimen, inability to control the loading conditions, and their measurement technique. However, their findings provided support for one of Fryette's concepts (1954), namely, "when motion is introduced in the vertebral column in one direction, motion in all other directions is reduced". For example, when flexion or extension was introduced first, lateral flexion and rotation were restricted. Likewise, when lateral flexion or rotation was the first motion produced, flexion and extension were limited.

Using just the upper three cervical segments of ten specimens, Werne (1957) investigated rotations and translations in the three cardinal planes. He noted that only flexion and extension and lateral flexion occurred at the occipito-atlantal joint (C0-C1) and rotation and some flexion/extension occurred at the atlanto-axial (C1-C2) joint. Werne found that sagittal plane motion in the craniovertebral joints (C0-C1-C2) averaged a total of 31°. Ten Have and Eulderink (1980) reported an average of 23° of flexion and extension at C0-C1 and 16° at C1-C2. Werne reported that lateral flexion averaged 13° and was accompanied by a rotation, whereas Dunkmeijer and Rethmeier (1943), using radiographs to study cadavers and living subjects, found approximately 5° of sidebending at C1-C2. According to Werne, axial rotation in the craniovertebral region only occurred at the atlanto-axial joint, was accompanied by a vertical translation, which accounted for its "screw-like" action, and averaged 47° (to one side). Selecki (1969) reported a maximum of 30° C1-C2 rotation, and stated that rotation of the atlas to 45° resulted in movement of the other vertebrae. Selecki found no more that 3 to 5° of axial rotation in any one of the other lower cervical segments. More recently, Dvorak, Panjabi, et al. (1987) used computerized tomography (CT) to study axial rotation in 12 cadaveric C0-C1-C2-C3 segments. Using craniovertebral bony landmarks, angular measurements were made with the aid of a protractor. They found approximately 4 to5° of axial rotation at C0-C1 and 31 to33° at C1-C2.

In summary: (1) Flexion and extension were shown to be the primary motions at C0-C1, although some sagittal plane motion also occurs at C1-C2; (2) Sidebending exists in both of the upper cervical segments and appears to be coupled with rotation; (3) Although rotation predominates at C1-C2, some rotation also occurs at C0-C1. See Table 2.2 for a summary of sagittal plane segmental cervical motion, based on cadaver studies.

In vitro studies are criticized because true physiological motion may not occur due to unrealistic loading conditions or because the motors of movement, i.e., muscle, are dissected under the assumption that they do not contribute to the kinematic patterns of the spinal column. Therefore, many researchers have used radiography (plane, cineradiography, and computed tomography) and magnetic resonance imaging with samples of living normal or patient populations to study the two-dimensional gross and segmental motions of the cervical spine.

Table 2.3 summarizes sagittal plane interverbral angular motion of the cervical spine from radiographic studies. To measure sagittal plane cervical motion, most investigators used some variation of the superposition method where a lateral radiograph taken in extreme flexion (and extension is placed over a radiograph of the spine in a neutral, or "starting" position. The lower vertebra of each radiograph is superimposed and the range of movement is found by measuring the angular displacement of the upper vertebra. Colachis and Strohm (1965) are not included in the summary table because they reported segmental data in terms of linear displacements, which are not often used clinicallally. Inspection of Table 2.3 reveals obvious discrepancies in the magnitudes of segmental motion among the various researchers. These discrepancies can be partially accounted for by the differences in methodology. For example, differences in posture (standing versus sitting) or starting positions of the head and neck could significantly influence final results. Jones (1960), using cineradiography to qualitatively study the cervical spine, found differences in flexion and extension mobility between the standing and sitting positions. In standing, extension and the magnitude of vertebral gliding was reduced and flexion appeared to occur at a lower level. Furthermore, when subjects were asked to tuck their chins and maximally flex their neck the head appeared to extend, and there was a straightening of the mid-cervical lordosis and early flexion at the cervico-thoracic junction. Jirout (1974) found changes in "tilt" of the lower cervical segments when the head was put in a flexed or extended position. When the head was extended, the lower cervical vertebra had a ventral tilt, conversely when the head was flexed there was a dorsal tilt of the lower cervical segments.

Table 2.2. Mean Flexion and Extension (degrees) of Cervical Spine Segments

Author	Year	n	Age	C0 C1	C1 C2	C2 C3	C3 C4	C4 C5	C5 C6	C6 C7	C7 T1
Ball & Meijers	1964	9	21-70	-	-	9.5	15.1	18.1	20.2	17.6	10.4
Ten Have & Eulderink	1980	86	18-90	22.8	16	9.3	14.6	15.8	15.8	13.3	9.7

Note. A dash indicates that no data were available.

Table 2.3. Mean Flexion and Extension (degrees) of Cervical Spine Segments

Author	Year	n	Age	C0 C1	C1 C2	C2 C3	C3 C4	C4 C5	C5 C6	C6 C7	C7 T1
Bakke	1931	15	13-61	-	11.4	12.9	15.8	17.3	20.2	18.2	-
Aho et al.	1955	15	16-30	-	13.6	12.7	16.1	21.8	27.6	15.7	-
Fielding	1957	-	-	~35	~15	-	-	-	-	-	-
Werne	1957	104	10-62	13.4	10	-	-	-	-	-	-
Kottke & Mundale	1959	78	Young	0-22	11	11	16	18	21	18	-
Hohl	1964	-	-	15	15	-	-	-	-	-	-
Bhalla & Simmons	1969	20	18-23	-	-	9	14	22	18	19	-
Mestdagh	1975	33	-	-	-	11	11.5	18	19.5	16	-
Johnson et al.	1977	44	20-36	18.8	13.7	12	17.6	20.1	21.9	20.7	11.7
Dunsker et al.	1978	25	-	-	9	10	13	13	20	11.5	-
Penning	1978	20	Young adult	30	30	12	18	20	20	15	-
Dvorak et al.	1988	28	22-47	-	12	10	15	19	20	19	-
Lind et al.	1989	70	12-79	14	13	10	14	16	15	11	-
Dvorak et al.	1991	44	23-49	-	13.5	12	17.5	21.5	23.5	21.5	-

Note. The statistical range of reported values for most studies was large.

Data from Table 2.3 also suggest that within specific studies there were large ranges about the means, suggesting that inter-individual variation was great. van Mameren, Drukker, Sanches, and Beursgens (1990), using X-ray cinematography and a more sophisticated method for angular and displacement measurements, found that segmental range of motion was larger when frames of intermediate, instead of extreme positions, of the film were considered. Furthermore, even intra-individual segmental and total range of motion measures were too variable suggesting that they were unsuitable to be used as parameters of cervical mobility and therapy assessment. van Mameran et al. concluded that their methodology could be used to determine instantaneous centers of rotation (ICR) and sequences in which segments contribute to motion of the entire cervical spine, both of which may be more useful that segmental range of motion in distinguishing between normal and abnormal functioning of the cervical spine.

Motion in the coronal and transverse planes for the upper and lower cervical spine has been investigated extensively (Bakke, 1931; Dunsker, Colley, & Mayfield, 1978; Fielding, 1957; Fielding, 1964; Hohl, 1964; Hohl & Baker, 1964; Jirout, 1971; Jirout, 1972a, 1972b; Jirout, 1973; Kapandji, 1974; Mestdagh, 1975; Penning, 1978; Reich & Dvorak, 1986; Werne, 1957; Werne, 1959). However, planar radiography, as opposed to biplanar or stereoradiography, does not easily lend itself to quantification of these other motions, particularly axial rotation. Based on their earlier work with cadavers, Dvorak, Hayek, and Zehnder (1987) used functional CT to study axial rotation in nine healthy and 43 subjects with cervical dysfunction. Table 2.4 provides a summary of studies that have documented movements in the upper cervical region.

In addition to the findings summarized in Table 2.4, other interesting motion patterns in the craniovertebral joints have been discussed. Most investigators agree that the majority of axial rotation in the cervical spine occurs at the C1-C2 segment. Two researchers (Fielding, 1957; Hohl, 1964) found simultaneous vertical approximation at the atlanto-axial joint with axial rotation. They related this motion coupling to the geometry of the facet surfaces of C1 and C2. Fielding (1957) discovered that, with lateral flexion of the head with the chin "tucked" in the sagittal plane, more atlanto-axial rotation occurred than with axial rotation alone. Jirout (1979) suggested that maximum forced forward bending at the craniocervical junction would restrict atlanto-axial rotation; therefore, from a clinical perspective, examination of rotation in this position would stress the C2-C3 segment and not the C1-C2 segment. Mestdagh (1975) also alluded to the importance of the C2-C3 segment. He suggested that it was a transitional area situated between the upper cervical spine, where most axial rotation of the neck and little flexion and extension occurred, and the lower cervical spine spaces where motion in the sagittal plane, and some rotation, chiefly occurred. Jirout (1973) and Reich and Dvorak (1986) found that lateral displacement of the atlas occurred toward the side of sidebending. This coupled motion has been attributed to tension in the alar ligaments (Werne, 1957, 1959; Reich & Dvorak, 1986) and traction of the craniocervical muscles on the spinous process of C2 (Jirout, 1973). Simultaneous atlanto-axial rotation (the body of C2 rotates in the same direction as the sidebending) occurred with this sidebending (Fielding, 1957; Hohl & Baker, 1964; Jirout, 1973; Kapandji, 1974; Mestdagh, 1975; Penning, 1978). For example, when the C0-C1-C2 complex was

Table 2.4. Mean Range (degrees, one direction only) for Frontal and Transverse Plane Motion for Upper Cervical Spine Segments

Author	Year	n	Age	Frontal Plane			Transverse Plane		
				C0-1	C1-2	C2-3	C0-1	C1-2	C2-3
Fielding	1957	-	-	0	Exists	-	0	~45	-
Werne	1957, 1959	13	13-42	8[a]	0	-	0	47	-
Hohl; Hohl & Baker	1964	10	19-55	-	4 mm	-	-	~45	-
Mestdagh	1975	33	Adol.	-	-	7	-	-	12
Dunsker et al.	1978	25	Mixed	5	-	-	-	~30	-
Penning	1978	-	-	Exists[a]	-	-	0	~35	-
Jirout	1979	-	-	-	-	-	Exists[b]	-	Exists[c]
Dvorak, Hayek, & Zehnder	1987	9	17-49	-	-	-	~4	~43	-
Penning & Wilmink	1987	26	20-26	-	-	-	1	40.5	3

Note. [a]Indicates that motion is always accompanied by simultaneous atlanto-axial rotation. [b]Indicates that motion was observed occasionally when there was maximum forward bending of the head. [c]Indicates that motion was observed in 50% of cases (n=30) only when the head was "forced" into maximum forward bending. A dash indicates that no data were available.

laterally bent to the right there was axial rotation of C1 on C2 to the left. Kapandji (1974) provided a reasonable rationale for the kinematic behavior of the C1-C2 complex. When the head is laterally bent to the right the left alar ligament becomes taut pulling the occiput (and C1) into left axial rotation. Conversely, when the left alar ligament is placed under tension with right lateral bending of the head, right axial rotation of the body of C2 occurs.

Bakke (1931) found the greatest lateral flexibility in the lower cervical spine, on a segmental basis, from C3 to C5, where it was about 6° to one side. He found that total lateral flexion of the entire cervical spine was about 23°. Penning and Wilmink (1987) calculated total lateral flexion from the axis with respect to T1 to be 25° (range 18-30°). Mestdagh (1975) indicated that there was slight lateral mobility at C2-C3 (~ 7° to each side), which increased to 11° at C5-C6, but he did not give a total range of motion. Dunsker et al. (1978) reported that lateral mobility at C4-C5 (12-14°), C5-C6 (10-20°), C6-C7 (9-18°) and C7-T1 (10-18°) amounted to a total of about 30° to each side, whereas Penning (1978) found about 35° of sidebending to one side, but included the segments from C2-C7. Kapandji (1974) found about 45° of lateral flexion to one side. There is no dispute in the literature that lateral bending is coupled with axial rotation to the same side (Dunsker et al., 1978; Fielding, 1964; Kapandji, 1974; Mestdagh, 1975; Penning, 1978). During frontal plane motion or rotation, translation of the cervical vertebral body occurs to the opposite side of the direction of lateral bending (Bakke, 1931; Penning & Wilmink, 1987). It has been suggested that this coupled rotation and opposite translation is a consequence of the orientation of the apophyseal joints (Penning, 1978) and the posteriorly placed uncinate processes in the lower cervical segments (Penning &

Wilmink, 1987). Jirout (1971, 1972a) noted that with sidebending, ventral (C2-C6 segments) and dorsal (C6-T1) tilting occurred; patterns that changed, however, depending on whether individuals were radiographed sitting or supine.

Fielding (1964) suggested that since 50% of cervical rotation took place at C1-C2 simultaneous lateral bending occurred to a lesser extent. Only Mestdagh (1975) and Penning and Wilmink (1987) have attempted to document segmental axial rotation in the cervical spine using radiographic techniques (Table 2.5). Skalli, Lavaste, and Descrimes (1995) noted large inaccuracies in segmental axial rotation using CT scans if rotations in the other planes were concomitantly large. Total axial rotation has been reported to range from 70° (Penning, 1978; Dvorak, Hayek, et al., 1987) to 90° (Fielding, 1957; Kapandji, 1974).

One of the motivations for attempting to establish normal range and patterns of movement in the cervical spine (and the other regions as well) was to use this knowledge to diagnose and understand spinal pathology. Therefore, a number of studies have used both static and dynamic radiographic techniques to study individuals with cervical spine pathologies.

Aho, Vartiainen, and Salo (1955b) compared segmental motion using functional flexion/extension radiographs between three groups: Group 1 (n = 15) showed no signs (physical or radiographic) of cervical dysfunction; Group 2 (n = 18) were asymptomatic, but had radiographic evidence of intervertebral chondrosis; and Group 3 (n = 15) had both clinical symptoms and morphological changes on radiographs. In general, they found that morphological changes at one segment resulted in reduced mobility at that segment, which was compensated by more mobility in an adjacent segment(s). Dvorak and co-workers (1988), using Penning's superposition technique to measure segmental mobility in 28 healthy individuals and 31 patients who had suffered soft tissue injuries, found that using functional flexion and extension radiographs with passive, rather than active range of motion, provided more consistent information. They detected more hypermobile and fewer hypomobile segments with passive range of motion testing in their patient sample, suggesting that passive testing was a more sensitive test for the detection of dysfunctional cervical segments. In a follow-up study, segmental rotations and translations in 64 patients, who were separated into three groups according to degenerative changes, radicular symptoms, and whiplash trauma, were obtained (Dvorak, Panjabi, Grob, Novotny, & Antinnes, 1993). There was a trend for hypomobile segments in those who were in the degenerative and radicular groups, usually at the C6-C7 segment. The trauma groups showed trends toward hypermobility, particularly in the upper and middle cervical levels. These authors determined a translation to rotation ratio, but concluded that it could not discriminate between the normal and patient groups.

Jones (1961) used cineradiography to examine 201 patients with cervical symptoms. He found that the incidence of degenerative disc disease, as detected by cineradiographs, was slightly greater than detected on plain films. In those segments in which the disc had thinned there was reduced sagittal plane mobility, with the fulcrum of motion fixed at the posterior margin of the vertebral body. The C5-C6 disc was most frequently involved, but the C4-C5 and C6-C7 segments were common sites of degeneration. According to Jones, translatory motion between segments was influenced by condition of both the apophyseal joints (facets) and vertebral body. Translation was

Table 2.5. Mean (degrees, one direction only) Axial Rotation for Cervical Spine Segments

Author	Year	n	Age	C0-2	C1-2	C2-3	C3-4	C4-5	C5-6	C6-7	C7-T1	C2-T1
Fielding	1957	-	-	45	-	-	-	-	-	-	-	45
Kapandji	1974	-	-	12	12	-	-	-	-	-	-	56
Mestdagh	1975	33	Adol.	-	-	12	9	6	3	0	0	-
Dunsker et al.	1978	-	Mix	~30	-	-	-	-	-	-	-	45
Penning	1978	-	-	35[a]	-	-	-	-	-	-	-	35
Penning & Wilmink	1987	26	21-26	41.5	40.5	3	6.5	6.8	6.9	5.4	2.1	30.7

Note. [a]Indicates that no rotation is contributed by the C0-C1 segment. A dash indicates that no data were available.

evident even in the most degenerative segments. With spurring near the inferior aspect of the articular surface of facets, Jones determined that with extension the next superior vertebra had an unusual rocking and twisting motion and it tended to rotate to the unaffected side. Ebara et al. (1990) compared the kinematics (trajectories of vertebral body centers, velocities and accelerations) of cervical segments during rapid flexion-extension movements in four normal subjects and six individuals with athetoid cerebral palsy. They found that velocity and acceleration were greater in patients, particularly in the upper cervical segments and speculated that these kinematic abnormalities could predispose individuals to disc degeneration.

Concerned that cineradiography resulted in too much radiation exposure to patients Dimnet, Pasquet, Krag, and Panjabi (1982) examined segmental motion at the end range of flexion and extension and three intermediate steps using plain radiography. They believed that their method would give them more detailed information compared to the traditional radiographic approach (taking radiographs at only the extremes of motion) and would be safer that cineradiography. Segmental rotations, centers of rotation and overall patterns of curvature were determined in six normal subjects and six patients. With patients less overall mobility and more variability in the trajectory of the centers of rotation were recorded. Pareta (1975) acknowledged the potential usefulness of functional radiographs in the cervical spine. He was the first to use the technique to examine the relationship between functional data (axes and range of movement) and morphology (shape of the vertebral body, articular processes and costo-transverse components in relation to the body) in 300 cases. His assessments resulted in the formulation of a segmental Morphologic-Functional Pattern (MFP), which distinguished individuals with specific cervical syndromes from normal. For example, in patients with vestibular symptoms there was a finding of hyperextension at the C2-C3 and C4-C5 segments. Yoshii and Nakahara (1988) found sagittal plane hypermobility in segments adjacent to segments that had been fused.

Based on two cases, Weisel and Rothman (1979) suggested that translation of more than 1 mm between the basion of the occiput and the tip of the odontoid during flexion/extension constituted occipital-atlantal (OA) hypermobility. In 1987 Dvorak and his co-workers evaluated 43 subjects with suspected rotatory instability of the upper cervical spine. They found that functional CT evidence of unilateral motion greater than 8° axial rotation at the OA joint (or right/left differences of greater than 5°) or greater than 56° axial rotation at the atlanto-axial joint (or right/left differences of greater than 8°) constituted hypermobility. They also gave guidelines for defining upper cervical hypomobility and concluded that functional CT was useful in making clinical diagnoses. Dvorak et al. (1989) used functional magnetic resonance imaging (MRI) to study the effects of flexion and extension on spinal cord compromise in 34 patients with upper cervical spine instability secondary to rheumatoid arthritis. With cervical flexion, nine of the 34 subjects exhibited cranial migration of the axis and the spinal canal diameter was significantly reduced in all subjects.

Planar kinematics of the cervical spine has also been studied by locating the path of the centers of rotation for flexion and extension (Amevo, Macintosh, Worth, & Bogduk, 1991; Amevo, Worth, & Bogduk, 1991a; Amevo, Worth, & Bogduk, 1991b; Amevo, Aprill, & Bogduk, 1992; Dunsker et al., 1978; Dvorak, Panjabi, Novotny, et al., 1991; Dvorak, et al., 1993; Penning, 1978) and in rotation and sidebending (Penning &

Wilmink, 1987). Penning (1978) used functional radiographs at the extreme of motion and constructed segmental axes for flexion and extension using the following method: identical landmarks of the "moving" (superior) vertebra were connected by lines; perpendicular lines from their midpoints were drawn, which converged on the axes of movement. Alternatively, with the lower vertebra presumed fixed and the upper segment "moving," the contours of the intervertebral joints were parts of circles with the axis of movement as the center. Penning (1978) and Dunsker et al. (1978) found the flexion and extension axes to lie in the posterior half of the subjacent vertebral body. In the upper cervical spine axes were more caudally located, whereas in the lower region they were located cranially. In general, IARs situated more caudally corresponded with segments that exhibited more glide than tilt (van Mameren, Sanches, Beursgens, & Drukker, 1992). Consequently, the lower cervical segments would tend to tilt more than glide, which was particularly true of the C6-C7 segment. However, Amevo, Macintosh, et al. (1991) found high interobserver measurement differences using the standard technique described by Penning, and they concluded that poor reliability precluded using centers of rotation for diagnostic purposes. Amevo et al. (1991a) modified the former technique by using stricter criteria for recognizing and tracing vertebral landmarks and demonstrated acceptable intra- and inter-rater reliability in a subsequent study of 40 normal subjects (Amevo et al., 1991b). van Mameren et al. (1992) hypothesized that determining IARs on the basis of extreme positions from two static radiographic films would be subject to large random measuring errors. They showed that "averaged" IARs or aIARs (mean of a cluster of IARs) that were deduced from segments of pairs of nonadjacent frames of cineradiographic film were less variable than IARs using the method described by

Penning. The aIARs for any given individual were tightly clustered. At the C0-C1 level aIARs were less tightly clustered and tended to lie cranial to the occipital condyles. At C1-C2 aIARs were found in the middle third of the dens axis, which was different than Dvorak, Panjabi, Novotny, et al. (1991b), who located the axis near the position of the transverse portion of the cruciate ligament. Below C2 the IARs determined by Dvorak, et al. and van Mameren and co-workers generally corresponded to the locations described by Penning (1978). van Mameren's group concluded that their method could be used for diagnostic purposes, i.e. determining hypermobile segments and monitoring rehabilitation.

Using computed tomography, Penning and Wilmink (1987) determined IARs for coupled axial rotation/lateral bending from C0 to T1. In the lower cervical segments IARs for axial rotation were found to be perpendicular to the intervertebral joint plane and were considered to correspond to the center of circles drawn through the uncovertebral joints (axial view), as formed by the uncinate processes. Generally, axes of rotation for typical cervical segments were located in the cranial part of the vertebral body. Results showed that lateral bending of the lower cervical vertebra was coupled with contralateral translation, but ipsilateral rotation. The authors hypothesized that this movement pattern occurred because of the posterior location of the uncinate processes. Thus, during lateral flexion (or tilt) the anterior aspect of the vertebral body will translate slightly in the same direction as the tilt, but posteriorly the vertebral body must translate in the opposite direction as the tilt in order to avoid abutting against the uncinate process of the vertebra below.

In 1992, Amevo, Aprill and Bogduk compared IAR locations from the C2-C3 to C6-C7 segments of 109 patients, with uncomplicated neck pain, to 40 normal subjects. Based on earlier research (Amevo et al., 1991a, 1991b), average position of segmental IARs were determined and marked by a dot, surrounded by an ellipse which represented the 95% confidence limit of the two standard deviation range of distribution of IARs for that segment. An outer ellipse was then created which represented the 95% confidence limit of technical errors for points plotted on the boundary of the inner ellipse. IARs that fell outside the technical error limit (outer ellipse) were classified as abnormal and those that fell outside the biological distribution (inner ellipse) were classified as marginal. Unequivocally and marginally abnormal IARs were found in 46% and 26% of the patients, respectively. Abnormal IARs significantly correlated with the presence of neck pain, but their locations did not correlate with the segmental source of pain as determined by provocation discography or zygapophyseal joint blocks. Dvorak et al. (1993) examined the range of motion and location of the IARs for flexion and extension in 64 adults with cervical dysfunction. For the trauma group the location of IARs were shifted in an anterior direction when compared to normal subjects.

The Thoracic Spine

Perhaps because fewer acute and chronic dysfunctions are associated with the thoracic spine and rib cage there have been fewer investigative studies involving this region. White (1969) and White and Hirsch (1971) provided two-dimensional kinematic data on T1-T2, T3-T4, T5-T6, T7-T8, T9-T10, and T11-T12 functional units, without attached ribs or muscles, from 10 cadavers aged 16 to 83 years. The forces and moments applied to the motion segments generally exceeded normal physiological loads. Motion segment rotation and instantaneous axes of rotation were determined using geometrical principles, anthropometric measures of vertebra, and data taken from linear displacement gauges placed anteriorly and posteriorly on the vertebra. Maximum error of rotation was determined to be in the range of 3% to 4%. In general, the lower portions of the thoracic spine exhibited more sagittal plane, but less horizontal plane, motion than the upper thoracic segments. No distinct regional patterns of lateral bending were noted. The vertebrae in the central portion tended to behave as a homogeneous group. Axes of rotation (IARs) for extension were located in the anterior body of the superior segment, whereas for flexion they were located more posterior, just below the intervertebral disc. For left lateral bending, IARs clustered on the superior aspect of the inferior segment just to the right of the midline, and vice versa for right lateral bending. IARs for axial rotation tended to be in the midline, but were variable in their ventral/dorsal location. See Table 2.6 for details regarding mobility of the thoracic functional units tested by White (1969).

Table 2.6. Mean Thoracic Segmental Motion (degrees)

	Sagittal Plane		Frontal Plane		Transverse Plane
Spinal Segments	Flexion	Extension	Right LB[a]	Left LB	Total AR[b]
T1-2	4.3	0.7	4.7	1.9	14
T3-4	3.4	1.2	4	3.2	11
T5-6	3.2	1.1	3.2	2.2	10.5
T7-8	5.6	2.6	3.9	3.3	10.4
T9-10	5.9	2.3	3.8	3	4.6
T11-12	12.2	7.1	7.2	6.2	3.4

Note. These data are based on two-dimensional measurements. [a]LB denotes lateral bending. [b]AR denotes axial rotation.

Markolf (1972) performed moment-rotation (flexion, extension, lateral bending, and torsion), axial tension and compression, and shear tests on 20 thoracic functional units to characterize their load-displacement properties. Two long pins were inserted into the vertebral bodies. Dial indicators recorded the linear displacement of these pins, which was proportional to vertebral translation and rotation. Load-displacement curves were shown to be nonlinear. A maximum applied moment of 5 ft-lb produced approximately 1.8° (0.8-3°), 1.2° (0.6-2.6°), 2° (0.7-3.0°), and 2.1° (1.2-3°) of flexion, extension, sidebending and axial rotation, respectively, for the T7-T10 segments. The lower thoracic segments (T10-L1) generally exhibited slightly less flexion and extension mobility, and greater stiffness was noted with axial rotation. With posterior elements (articular processes and ligaments) removed extension stiffness was significantly reduced.

Panjabi, Hausfeld, and White (1981) studied the in vitro planar behavior of 19 thoracic functional spinal units (FSU) that consisted of two vertebrae, interconnecting soft tissue, and about 3 centimeters of ribs on either side. FSUs representing segments from T1-T2 to T12-L1 with varying levels of degeneration (from normal to degenerated nucleus and annulus) were used. They tested the FSUs intact and after sequential sectioning (anterior to posterior and posterior to anterior) ligaments, disc annuli and joint capsules, including connective tissues of the costo-vertebral and costo-transverse joints. Flexion and extension loads, beginning at 12 newtons and incremented so as to obtain loads of 11, 21, 32 and 43 percent body weight for each specimen, were applied; the final load was considered a close estimate of physiological loading. The measurement jig consisted of two spherical balls mounted on a plate on the superior vertebral segment and three mechanical displacement gages that had flat plates which contacted the spherical balls. Overall accuracy of the measurement apparatus was determined to be ± 0.08 mm for horizontal translation and ± 0.07 degrees for rotation. Lateral X-rays were taken of the FSU and the measuring jig to provide coordinates of the centers of the spherical balls and allow for the complete description of planar motion of the upper vertebra at its loading point with respect to the lower vertebra. Intact spines exhibited more rotary motion in flexion 1.4 (0.9) degrees compared to extension 1.0 (0.4) degrees, in agreement with White's earlier work (1969). Horizontal translation during flexion and extension approximated 1.0 (0.4) mm. Based on sequential soft tissue sectioning, the authors concluded that thresholds of mechanical instability were 2.5 mm of horizontal translation and 5 degrees of rotation on one vertebra with respect to the other. However, they conceded that spinal neuromuscular control and the thoracic cage normally enhanced stability; thus, their conclusions need to be tested clinically. In a follow up study, Panjabi, Krag, Dimnet, Walter, and Brand (1984) applied physiological tension and compression loads, anterior and posterior shear, and flexion/extension moments to thoracic FSUs. They located the average position of the centers of rotation (CR) to be 15-45 mm directly below the geometric center of the moving vertebrae. With anterior shear and flexion/extension moments CRs were closer to the moving vertebra, which is slightly different than White (1969) reported. Panjabi, Krag, Dimnet, et al. (1984) hypothesized that CR locations were likely due to the influence of facet guidance. CRs associated with the application of extension moments were less variable and appeared to be related to increased stability, whereas CRs associated with posterior shear were more variable and related to decreased facet guidance and rotation.

Bakke (1931) used radiographs to determine segmental mobility in the thoracic spine and found total sagittal plane motion to be 68°, 22° from dorsal flexion (extension) and 46° from ventral flexion (flexion). He noted that greatest flexibility occurred at the T1-T2 segment (10° total; 5° dorsal flexion; 5° ventral flexion) which decreased to approximately 5° in the more caudal segments, but increased again in the thoracolumbar region. Dorsal flexion was markedly limited in the upper and middle vertebra, but progressively increased in the lower regions. Lateral flexibility was evenly distributed (2-3° per segment) throughout the whole region.

Following a series of investigations using cadavers with normal spines and scoliosis, Feiss (1907) concluded that vertebra moved toward the side of the convexity of the sidebending curve, e.g., rotation was coupled with lateral bending in the opposite direction. Roaf (1958) qualitatively studied the rotation and lateral flexion characteristics of stillborn children, verifying his observations with radiographs on normal children. He concluded that: (1) the axis of axial rotation was in the region of the posterior longitudinal ligament, (2) lateral flexion and rotation normally occurred independently (no coupling) in the thoracic and lumbar spines, and (3) scoliosis could be explained solely on abnormal rotatory vertebral relationships.

Gregersen and Lucus (1967) screwed Steinmann pins into the spinous processes of seven healthy male subjects 20-26 years old and tested axial rotation of segments T1 through L5 over eighteen sessions. Subjects were tested in standing, sitting, and during locomotion. Displacement of the pin (axial rotation) was transmitted through a flexible extension arm to a relative-rotation transducer, which was accurate to ± 0.1 degree. Axial rotation during standing and sitting was measured relative to a sacral belt rod with subjects well secured in pelvic fixation device. During walking rotation was synchronized with heel strike. An average of 74 degrees axial rotation occurred between T1 and T12 in standing and sitting, which is considerably greater than Bakke (1931) reported. In general, axial rotation was somewhat less in the lower thoracic region in sitting. During walking, the pelvis and lumbar spine rotated as a functional unit. Moreover, maximum axial rotation occurred in the T6-T8 segments (1.4° to 2.4° per segment) suggesting that the greatest compliance occurred in the mid-thoracic region. In standing, lateral bending and coupled axial rotation of primarily the mid-thorax (T6 to sacrum) and thoracolumbar (L1 to sacrum) was assessed in three subjects. Axial rotation was coupled with lateral bending to the same side in all subjects that were tested, which supports Lovett's (1905) findings for the erect spine. Based on the morphology and orientation of the apophyseal joints in the thoracic spine, Gregersen and Lucus hypothesized that the axis of axial rotation for thoracic segments would fall within or anterior to the intervertebral disc, in which case considerable rotation would be possible.

Arkin (1950) examined coupling patterns in five subjects, aged twenty-seven, twenty-six, fifteen, eleven, and ten years, who had straight spines. Standard anteroposterior roentgenograms were taken in active and passive lateral deviation in (1) neutral, (2) flexion, and (3) hyperextension with subjects seated, standing, or recumbent, and with hips flexed or extended. Axial rotation was assessed by position of the spinous processes, and was only considered valid if the segment above and below the segments of interest were rotated in an opposite direction. Children showed less of a tendency towards coupled motion, although there was some evidence of it, which differs with what Roaf (1958) concluded. In adults, convex-side rotation coupled with lateral flexion, e.g.

right lateral flexion produced right axial rotation, occurred whether the spine was neutral, flexed, or hyperextended. Arkin concluded that this behavior primarily reflected tension in soft tissue, rather than the arrangements of the articular facets. These findings contradict those previously presented by Lovett (1902, 1905), Fryette (1954, 1918), Feiss (1907), and Gregerson and Lucus (1967). Others (Frymoyer, Frymoyer, Wilder, & Pope, 1979; Pope, Wilder, Matteri, & Frymoyer, 1977; Vicenzino & Twomey, 1993) have also shown that coupling occurs independently of muscular activity.

Cobb (as reported by Drerup, 1984) provided a radiographic technique to quantify the lateral flexion deformity in individuals with scoliosis. Cobb's method is still used today to determine the severity of scoliosis and monitor the progression of the disease. However, it has been suggested that Cobb's method did not account for the concomitant rotational deformities, which also needed to be treated. Nash and Moe (1969) developed a radiographic technique (frontal projection) to estimate vertebral axial rotation using pedicle-shadow offset measurements. Benson, Schultz, and Dewald (1976) examined the accuracy of this technique and found it to be lacking due to individual variations of vertebra, differences between the radiological and real geometrical projection of the pedicles, and the influence of sagittal and frontal inclinations of the vertebra. Improvements in measuring vertebral axial rotation using frontal projection radiographs (Coetsier, Vergauteren, & Moerman, 1977; Drerup, 1984, 1985; Drerup & Hierholzer, 1992a, 1992b; Koreska, Seebacher, & Moseley, 1985; Stokes, Bigalow, & Moreland, 1986), biplanar roentgenographs (Matteri, Pope, & Frymoyer, 1976), and computed tomography (Aaro & Dahlborn, 1981; Ho, Upadhyay, Chan, Hsu, & Leong, 1993; Krismer, Sterzinger, Haid, Frischhut, & Bauer, 1996) have been forwarded. However, Skalli, Lavaste, and Descrimes (1995) found that axial rotation measured on transverse projections was misleading for vertebrae rotated in space. Koreska and his group noted that rotation occurred in the same direction as sidebending in the thoracic region, but did not specify in which spinal posture this was observed.

When the spinal column or spinal segments are placed in particular postures prior to motion testing one must consider how these segments are pre-loaded and how these loads affect stiffness and/or mobility. Goodwin and co-workers (1994) performed torsional stiffness experiments on whole spines (T2-S1) and 25 thoracic and lumbar FSUs under increasing distraction and compression preloads. For the whole spine and thoracic segments (3° of axial rotation was introduced) torsional stiffness significantly increased under both types of axial preloads. This suggests that preloading the spine, such as might occur in the sitting posture in living subjects, would increase the stiffness of the spine to torsional movements and could decrease mobility in spinal segments.

In summary, two-dimensional in vitro and in vivo radiographic studies related to the thoracic spine are limited in quantity, compared to the cervical and lumbar spines. Bakke's (1931) early radiographic studies suggest that extension is limited in the thoracic spine, especially in the middle region. Although Markolf (1972) and Panjabi, Hausfeld, et al. (1981) agreed that extension was limited compared to flexion, they generally did not find as much segmental motion as reported by Bakke. Techniques to measure segmental axial rotation in the thoracic spine using frontal plane radiographic projections have been developed, but they have not been used to quantify segmental motion in subjects without scoliosis. Based on only five subjects, Arkin (1950) concluded that lateral flexion and axial rotation were coupled in the opposite direction regardless of the spinal posture, which contradicts the findings offered by many others, including Lovett (1902, 1905) and Fryette (1954, 1918). Gregersen and Lucus (1967) used an invasive technique to demonstrate axial rotation in static sitting and standing postures, locomotion, and found that axial rotation was coupled with sidebending to the same side. It has been demonstrated that distraction and compression pre-loads increase the stiffness of the spine in general and the thoracic segments in particular.

The Lumbar Spine

Rolander (1966) conducted loading experiments (up to total body weight) on 71 samples of intact and fused lumbar spine segments aged 4-76 years. He determined the following ranges of motion for the intact segments: forward bending 1-8°, backward bending 2-6°, right lateral bending 1-8°, and left lateral bending 1-7°. Nachemson, Schultz, and Berkson (1979) studied 42 motion segments using a 400 N compression preload and found: flexion 5-6°, extension 2-3°, lateral bending 5-6°, and axial rotation 1-2°. Horizontal displacement generally followed the direction of rotation and did not exceed 2 mm (Rolander, 1966; Nachemson et al., 1979).

Instantaneous centers (IC) of rotation for flexion and extension were found in the dorsal and ventral part of the discs, respectively (Rolander, 1966). Twomey and Taylor (1983), testing whole lumbar cadaveric specimens, also located the center of rotation for flexion and extension in the posterior annulus. Seligman, Gertzbein, Tile, and Kapasouri (1984) used L4-L5 motion segments from 47 cadaveric spines under the age of 60 years and determined that ICs were located in the posterior half of disc when the superior vertebra moved from maximum extension to flexion. However, by taking radiographs every 3°, rather than just at the extremes of flexion and extension, they found loci of ICs, which they termed the centrode. In degenerated segments the centrode lengths increased significantly, regardless of the range of motion in the involved segments. The technique used by Seligman et al. was highly sensitive, detecting 94% of the abnormal spines, as compared with only 25% sensitivity when only the range of flexion and extension, as measured radiographically, was used to determine abnormality.

Markolf (1972), using specimens from cadavers aged 21-55 years, recorded segmental displacement and stiffness under axial compression and tension, shear, and moment-rotation loading conditions. Using applied moments up to five foot-pounds, he found that segments did not exceed 3° for lateral bending and forward flexion, 3° for extension, and 2° for axial rotation. Torsional stiffness showed a discontinuity at the T11-T12 region, suggesting that this region may be susceptible to torsional injuries. Markolf concluded that articular processes and related ligaments contributed to mechanical stability, particularly with extension in the thoracic spine and axial rotation in the lumbar region. Rolander (1966) determined that axial rotation mobility ranged from 0° to 1° in four functional units (2 each of L3-L4 and L5-S1). He located the IC through the center of the disc, whereas Haher, et al. (1992) found it to be posterior to the annulus. Cossette, Farfan, Robertson, and Wells (1971) located the IC for the L3-L4 functional unit anterior to the facet joints and in the region of the posterior part of the nucleus. They also noted that the IC tended to move towards the side to which rotation was forced, suggesting that a "free play" in the joint existed and that motion tended to be limited on the side of tension rather than the side of compression.

Posner, White, Edwards, and Hayes (1982), using preloads of 70% (simulated reclining) and 140% (simulated standing) body weight, applied normal and maximum physiological flexion and extension forces to 18 lumbar FSUs for the purpose of defining clinical stability. They determined segmental load-displacement characteristics during flexion with ligaments intact and after serial sectioning from posterior to anterior and during extension with ligaments intact and sectioned from anterior to posterior. A greater preload limited the flexion response at L5-S1 ($5 \pm 7^\circ$ vs $8 \pm 7^\circ$), but did not affect the upper lumbar segments in flexion or any of the segments with extension. With maximum bending loads (no preload) flexion ranged from 3° to 10° (most at L5-S1) and extension averaged 16°; horizontal translations approximated 2 mm for all segments tested. Edwards and co-workers (1987) performed a follow up study to determine FSU stiffness response to combined load states that simulated in-vivo conditions (reclining vs standing). Although they did not report segmental angular mobility, they concluded that FSU specimens were stiffer in flexion than in extension, and that the specimens were also stiffer with flexion at high preloads. These results have implications related to how changes in posture may affect mobility of spinal units and the spine as a whole.

Twomey (1979) applied forces of 3.5 kg to specimens attached to a vice and used a protractor to measure lumbar spine (T12-S1) mobility in 200 cadavers aged 1-97 years. In general, there was decreasing mobility with increasing age and females were more mobile than males. Combined mobility from the T12-S1 segments in the 36-59 age category (males and females) were: flexion 29°, extension 11°, right/left sidebending 15°-17°, and right/left rotation 12°-14°; with segmental axial rotation ranging from 2° to 4°. Hilton, Ball, and Benn (1979) used radiography to measure total and segmental sagittal plane motion in 111 lumbar cadaveric specimens ranging from 13-96 years. A superposition technique was used in which angular displacements were measured relative to pins placed in the anterior bodies of the vertebral segments. They found no gender differences in mobility and at all ages there were marked variations in total mobility. Total sagittal plane mobility decreased with age, declining from 50° to 40° between 30 and 70 years. Segmentally, mean mobility progressively decreased from L5 (12-16°) to T10 (~1°).

In 1986, Adams and Hutton, using a servo-controlled materials testing machine, tested lumbar flexion mobility. See Table 2.7 for detailed summary of their data. After correcting for standing lumbar lordosis, they compared their in vitro data to flexion angles radiographically measured in vivo. Results showed that when people adopted the static, fully flexed posture, the spine was flexed about 10° short of its elastic limit, suggesting that the back muscles provided a margin of safety. Adams, Dolan, and Hutton (1988) found that, in 29 FSUs aged 20-58 years, segmental extension approximated 5°. Interestingly, segments (n=6) from specimens less than twenty years of age showed less mobility (~3°). In testing segments to failure they found that extension was restricted primarily by the disc and spinous processes.

Several researchers have shown that axial rotation in the lumbar spine is limited to 1-4° (Abumi et al., 1990; Markolf, 1971; Nachemson et al., 1979; Rolander, 1966; Twomey, 1979; Yamamoto, Panjabi, Oxland, & Crisco, 1990). Rolander had shown that removal of the intervertebral facets increased axial rotation slightly, suggesting that facet morphology was one of the limiting elements of lumbar axial rotation. McFadden and Taylor (1990) applied manual axial torsions to L3-S1 segments and used a weight and pulley system with forces of 1.5 and 3.0 kg to L3-L4 and L4-L5 segments to determine axial rotation in the lumbar spine. Using a calibrated wheel to measure the rotation of the

4-segment specimens, a mean total (right + left rotation) of approximately 11° was found. They observed that some flexion and sidebending were coupled with axial rotation. With the 2-segment specimens they measured angular movement of pins inserted into the anterior body and transverse processes and reported averages of 1.5° and 3.0° of axial rotation. Gunzburg and co-workers (1991, 1992) used 13 whole lumbar spines (T12-S1), aged 19-58 years without a history of spinal pathology or evidence of disc degeneration, to investigate the role that each of the lumbar capsulo-ligamentous structures played in axial rotation with the spine in neutral and flexion. Kirschner wires were inserted into the spinous processes and axial rotation measurements were made with a protractor that could be aligned with each wire. Segmental axial rotation for the intact spine in neutral for all specimens ranged from 1° to 3°, with rotation progressively decreasing from L1 to L5. There was much variation in axial rotation between vertebrae within the same spine

Table 2.7. Mean (± SD) Range of Flexion Angles for 122 Lumbar Motion Segments

	Limit of Flexion					
Age Range	L5-S1	L4-L5	L3-L4	L2-L3	L1-L2	Total
15-29	11.1 ± 2.0	11.7 ± 1.4	10.3 ± 3.9	11.0 ± 2.1	9.0 ± 2.8	53.1
30-49	12.1 ± 2.2	11.2 ± 1.5	8.3 ± 1.5	7.9 ± 0.7	7.8 ± 1.8	47.3
50-71	10.1 ± 3.4	9.5 ± 2.2	9.1 ± 1.7	7.0 ± 1.3	6.0 ± 1.0	41.7

and across different spines. The apophyseal joint capsules were found to limit axial rotation when the lumbar spine was in neutral or flexed. At the lumbosacral junction axial rotation also appears to be controlled by the iliolumbar ligaments (Yamamoto et al., 1990). Gunzburg et al. (1991, 1992) found that flexion reduced axial rotation, but they did not specify how far the lumbar spine was flexed. The posterior annulus and posterior longitudinal ligament were thought to be primarily responsible for limiting axial rotation during lumbar flexion. The magnitude of segmental axial rotation reported by Gunzburg et al. was high compared to previous in vitro studies, suggesting that the torsional loads and measurement device were not well controlled. Pearcy and Hindle (1991) hypothesized that forward flexion would move the zygapophyseal joints apart, thus permitting more axial rotation. They tested five FSU (3 L4-L5 and 2 L3-L4 segments) in neutral, 5° of flexion, and 10° of flexion with a preload that simulated the superincumbent body weight. They found (with some variability) that submaximal flexion increased axial rotation mobility of the FSU's, but full flexion limited axial rotation. There is disagreement between Pearcy and Hindle and Gunzburg et al. but their loading and measurement techniques differed significantly, therefore, no firm conclusions can be drawn regarding the relationship between axial rotation and a flexed posture. However, these findings lend some support for one of Fyrette's concepts, namely that motion introduced in one plane will reduce motion in the other planes.

Some investigators used invasive in vivo methods to study spinal kinematics (Gregersen & Lucus, 1967; Gunzburg, Hutton, & Fraser, 1991; Lumsden & Morris, 1968; Kaigle, Pope, Fleming, & Hansson, 1992; Kaigle, Wessberg, & Hansson, 1998). Gregersen and Lucus (1967) found 11° of axial rotation at the T12-L1 junction, but only tested one subject. A total of only 9° of rotation between L1 and L5 were measured, which corroborates previous work. Gregersen and Lucus speculated that axial rotation in lumbar segments was limited because of facet orientation and the axes of rotation were located posterior to the disc. Lumsden and Morris (1968) suggested that a more accurate measurement of lumbosacral axial rotation could be obtained if a sacral belt were not used. Therefore, they measured the displacement of pins inserted into spinous processes of L4 (n=2) and L5 (n=9) relative to ones inserted into the posterior superior iliac spines of the sacrum in normal male subjects aged 21-32 years. Average axial rotation at L5-S1 was 6° (4-8°). During walking rotation at L5-S1 increased from 1° to 2° as speed of locomotion increased. Gunzberg et al. (1991) studied the effects of posture on axial rotation in eight male volunteers. In flexed postures, in both standing and sitting positions, it was noted that axial rotation decreased compared to the neutral posture (2° to 0°). These authors concluded that muscle played a dominant role in limiting axial rotation in the flexed posture in vivo.

Standard radiography, cineradiography and videofluoroscopy have been used to document gross and segmental sagittal and coronal plane mobility in healthy individuals and in patients with a variety of low back pain syndromes. The most common approach was to take lateral radiographs of individuals who statically held fully flexed and extended positions. Intersegmental kinematics was then determined using some variation of the superposition technique described earlier. Bakke (1931) reported sagittal plane flexibility totaled 71°, (54° dorsal flexion and 16° ventral flexion), with most motion occurring between L4 and L5. Wiles (1935), measuring flexion and extension from the top of L1 to the bottom of the sixth dorsal vertebra (sacrum) in four individuals, found an average of 63° and 41° of flexion and extension, respectively, an average of approximately 21° per vertebral function unit. Since 1935 many additional studies have been conducted to determine normal mobility in the lumbar spine. See Table 2.8 for a summary of these studies. There appears to be significant variability among studies, which may be attributed to gender, age, cultural, and study methodological differences.

For example, if subjects are tested in standing versus sitting there might be differences in the amount of segmental flexion or extension. In a recent radiographic study by Lord, Small, Dinsay, and Watkins (1997) it was shown that lumbar lordosis while standing was 50% greater on average than sitting lumbar lordosis. This difference could mean that segmental extension, as measured in standing, would be less than in sitting since in standing the segments are relatively more extended to begin with. Furthermore, the amount and pattern of coupled motion could be affected by changes in lordosis in going from standing to sitting. Finally, errors in measurement due to systematic issues, poor film quality, out-of-plane rotation, magnification of the radiographs, and interobserver differences have been cited by several investigators (Dvorak, Panjabi, Chang, Thieler, & Grob, 1991; Panjabi, Chang, & Dvorak, 1992; Harvey & Hukins, 1997).

Radiographic studies have shown that ventral, horizontal displacement of vertebra occur during flexion, and dorsal translation with extension (Boden & Wiesel, 1990; Dvorak, Panjabi, Chang, et al., 1991; Gianturco, 1944; Hoag, Kosok, & Moser, 1960a; Kanayama, Abumi, Kaneda, Tadano, & Ukai, 1996; Tallworth, Alaranta, & Soukka, 1992; Wiles, 1935; Yoshioka, Tsuji, Hirano, & Sainoh, 1990). Yoshioka et al. (1990) concluded that L4 showed a translation-predominant motion characteristic; whereas the L5 vertebra had a rotation-predominant one, with translation limited by tension in the iliolumbar ligaments. See Table 2.9 for a summary of these data. The reader can see that large inter-study differences exist, which can be attributed primarily to methodological differences. For example, Dvorak, Panjabi, Chang, et al. (1991) found that use of superior vertebral body points had three to six times the translation of the inferior body points. Boden and Wiesel (1990) concluded that normal lumbar vertebral levels should had less than 3 mm (or < 8% of vertebral body width) of "dynamic" anteroposterior translation. They believed that their "dynamic" measurement was superior to ones used by other investigators since it represented the relative movement between two vertebrae that occurred in the time interval between maximum flexion and extension. It has been reported that a small amount of axial translation, ranging from 1 to 3 mm, also occurs during flexion-extension (Yoshioka et al., 1990; Dvorak, Panjabi, Chang, et al., 1991).

Location of the instantaneous axes of rotation for flexion and extension in healthy individuals has been demonstrated in vivo (Dimnet, Fischer, Gonnon, & Carret, 1978; Gianturco, 1944; Hoag, Kosok, & Moser, 1960a, 1960b; Keessen, During, Beeker, Goudfrooij, & Crowe, 1984; Ogston et al., 1986; Pearcy & Bogduk, 1988; Pennal, Conn, McDonald, Dale, & Garside, 1972; Rosenberg, 1955; Wiles, 1935; Yoshioka et al., 1990). Wiles (1935) deduced that the axes of motion were movable during lumbar flexion and extension. In full extension they were posterior to the articular processes and in full flexion they were near the median plane of the bodies. Gianturco (1944) located the fulcra on the caudal segments, which was also been shown by others (Ogston et al., 1986; Pearcy & Bogduk, 1988; Yoshioka et al., 1990). Gianturco (1944) corraborated

Table 2.8. Mean Flexion and Extension (degrees) of Lumbar Segment Motion

Author	Year	n	Age	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1
Tanz	1953	10	2-13	10.4	13.1	14.8	16.7	24.2
		14	34-49	5.6	7.6	8.6	12.2	8.2
		22	50-64	3.9	5	8.1	8	7.8
		9	65-77	2.2	4.8	3.3	7.1	7.1
Aho et al.	1955	26	17-39	5.3	6.1	8.8	10.8	8.8
Allbrook	1957	20	16-50	6	8	13	19	18
Jonck & van Niekerk[a]	1961	20	4-10	11.1	16.5	19.5	26.7	30
		40	20-30	12	15	15.5	21.3	23
		27	30-40	11.2	12.8	15.5	19.5	21.4
		5	40-60	11	12.5	14.5	16.5	20.6
Clayton	1962	26	College	12.6	15.8	15.9	17.7	18.7
Froning & Frohman	1968	30	20-70	9	11	13	16	17
Ogston et al.	1986	12	19-31	-	-	-	18.9	19.6
Hayes et al.	1989	59	19-59	7	9	10	13	14
Boden & Wiesel	1990	40	19-43	8.2	7.7	7.7	9.4	9.4
Yoshioka et al.	1990	61	15-18	12.7	16.6	16.7	18.3	19.6
Dvorak et al.	1991	41	22-50	11.9	14.5	15.3	18.2	17
Tallworth et al.	1992	56	35-54	-	-	13.1	16.1	16.8
Lin et al.	1994	89	24-81	6.9	8.7	12.6	14.4	11.8
Kanayama et al.[b]	1996	8	18-27	-	-	11.4	15.9	21

Note. [a]Indicates measurements taken from the Bantu of South Africa. [b]Indicates that cineradiography was used to measure lumbar segment mobility continuously. A dash indicates that no data were available.

Wiles' work, noting that the fulcrum for extension was posterior to the fulcrum for flexion, but he found that the fulcra lay within narrow limits (separated by a mean distance of 5 mm) at about the center of the nucleus. Centrode patterns (loci of ICs) of the L4-L5 and L5-S1 segments in 12 healthy men (Ogston et al., 1986) were similar to those reported by Seligman et al. (1984), suggesting that centrode lengths might be a useful clinical test. Although instantaneous axes of rotation for flexion (from a position of extension) fell within a small range, large errors occurred when movement of the joints was less than 5° (Pearcy & Bogduk, 1988). Therefore, Pearcy and Bogduk cautioned against an indiscriminate use of IARs, but concluded that a single extension to flexion axis may be of value clinically.

Using anterior-posterior radiographs, in vivo segmental mobility in the coronal plane has been reported by only a few (Bakke, 1931; Dvorak, Panjabi, Chang, et al., 1991; Jonck & van Niekerk, 1961; Miles & Sullivan, 1961; Tanz, 1953). Bakke (1931) concluded that most lateral flexibility occurred between L2 and L5, where it totaled 7-8° per segment, and that total flexibility was approximately 24°. A summary of the research cited can be found in Table 2.10. When comparing mobility of comparable age groups it can be seen that the Bantu have highly mobile lumbar spines, suggesting differences in functional demands or morphology. Dvorak, Panjabi, Chang, et al. (1991) hypothesized that their subjects manifested increased mobility because they measured passive motion, whereas other investigators only measured active range of motion. They believed that passive motion measurements were more clinically relevant and concluded that two-dimensional (rotation and translation) measurements accurately represented spinal

Table 2.9. Mean (± SD) Anterior and Posterior Translation (mm) During Lumbar Flexion and Extension

Author	Year	n	Age	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1
Hayes et al.	1989	59	19-59	1.9	2.4	2.5	3	1.3
Boden & Wiesel	1990	40	19-43	1.4	1.3	1.2	1.2	1
Yoshioka et al.	1990	61	15-18	6.8 ± 1.5	8.7 ± 1.4	8.9 ± 1.4	9.7 ± 1.9	7.5 ± 2.7
Dvorak et al.	1991	41	22-50	10.7 ± 2.1	12.2 ± 2.2	12.3 ± 2.4	12.3 ± 2.7	6.5 ± 2.9
Tallroth et al.	1992	56	35-54	-	-	(0-6)	(0-6)	(0-7)
Lin et al.	1994	89	24-81	1.4 ± 0.9	1.5 ± 1.4	2.2 ± 1.2	2.0 ± 1.3	0.4 ± 1.7
Kanayama et al.[a]	1996	8	18-27	-	-	3.9	3.6	2.4

Note. [a]Indicates that cineradiography was used to measure lumbar segmental mobility continously. A dash indicates that no data were available.

function as long as radiographs were of high quality, and if random errors (human factor) and out-of-plane motions (> 5°) were minimized. Two independent research groups qualitatively noted that lateral bending was coupled with rotation to the opposite side, e.g. left side bending occurred with right rotation (Miles & Sullivan, 1961; Koreska, Seebacker, & Moseley, 1985).

Any of the kinematic parameters (angular motion, linear displacement, and IC location) described above have potential clinical relevance, as alluded to by several authors. Gianturco (1944) found that 20 of 35 patients complaining of low back pain showed deviations in normal segmental mobility and location of the flexion/extension fulcra. For example, in some cases the spread of the fulcra were greater than normal, whereas in other cases the fulcra were more posterior or location of the extension fulcrum was anterior to the flexion fulcrum, i.e. they were reversed.

Most investigators have studied the angular changes associated with lumbar pathology (Aho, Vartiainen, & Salo, 1955a; Begg & Falconer, 1949; Dupuis, Yong-Hing, Cassidy, & Kirkaldy-Willis, 1985; Dvorak, Panjabi, Chang, et al., 1991; Dvorak, Panjabi, Novotny, Chang, and Grob, 1991; Froning & Frohman, 1968; Hanley, Matteri, & Frymoyer, 1976; Hasner, Schalimtzek, & Snorrason, 1952; Kaigle et al., 1998; Knutsson, 1944; Poussa, Korpi, & Helvioaara, 1991; Putto & Tallroth, 1990; Quinnell & Stockdale, 1983; Soini et al., 1991; Stokes & Frymoyer, 1987; Wood, Kos, Schendel, & Persson, 1996). Decreased and increased segmental motion involving degenerative segments (Aho et al., 1955a; Begg & Falconer, 1949; Froning & Frohman, 1968; Knutsson, 1944; Kaigle et al., 1998), hypermobility at segments adjacent to hypomobile ones (Froning & Frohman, 1968), and segmental instability (Dupuis et al., 1985) have been demonstrated.

Table 2.10. Total Sidebending to the Right and Left in Lumbar Spine (degrees)

Author	Year	n	Age	T12-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1
Tanz	1953	10	2-13	-	11.6	11.7	15.8	14.	7.
					(3.7)	(3.4)	(4.4)	(4.4)	(2.0)
		14	34-49	-	5.4	7.8	8.0	8.2	2.3
					(2.5)	(3.2)	(4.1)	(4.4)	(2.8)
		22	50-64	-	5.6	5.8	7.5	6.8	0.9
					(2.3)	(3.1)	(1.7)	(3.0)	(1.6)
		9	65-77	-	4.1	6.8	6.1	5.4	0.3
					(1.7)	(3.2)	(2.0)	(3.0)	(0.9)
Jonck & van Niekerk[a]	1961	20	4-10	-	17.5	20.9	17.6	12.7	4.6
		40	20-30	-	12.3	15.9	17	15.5	5.5
		27	30-40	-	13.5	15	14	14	4
		5	40-60	-	9.4	13	12	9.5	4.8
Miles & Sullivan	1961	49	19-45	-	5.3	5.7	4.7	3.7	1.7
Dvorak et al.	1991	41	22-50	7.9	10.4	12.4	12.4	9.5	5.1

Note. [a]Indicates that measurements were taken from the Bantu in South Africa. Some data are mean (± SD).A dash indicates that no data were available.

Kaigle and co-workers (1998) demonstrated that chronic pain patients, with suspected lumbar segmental instability, had decreased intervertebral motion that was likely secondary to persistent erector spinae myoelectrical activity. However, because of large inter-subject and day-to-day measurement variability, several researchers concluded that measuring segmental flexion-extension did not have diagnostic value (Begg & Falconer, 1949; Dvorak, Panjabi, Chang, et al., 1991; Dvorak, Panjabi, Novotny, Chang, et al., 1991; Sioni et al., 1991; Stokes & Frymoyer, 1987). However, the technique may play a role in studying the progression of pathology in individuals. There is also disagreement in the literature regarding how segmental translation changes with pathology. Several have reported that this kinematic parameter effectively differentiates normal and abnormal (Keessen et al., 1984; Knutsson, 1944; Quinnell & Stockdale, 1983; Putto & Tallroth, 1990; Sihvonen, Lindgren, Airaksinen, & Manninen, 1997). Others found that it was an invalid indicator of instability (Stokes & Frymoyer, 1987), unless the translations were large (> 5 mm) on radiographs that were relatively clear, with little obliquity, and when concomitant motions were minimal (Shaffer, Spratt, Weinstein, Lehmann, & Goel, 1990). Because radiation exposure is potentially high when performing functional radiographs, clinicians must weigh the questionable diagnostic benefit relative to iatrogenic injury when assessing the low back pain patient.

In summary, it is not possible to list definitive values of quantitative motion parameters (both angular and linear) for specific lumbar segments based on this literature review. Differences in in vitro and in vivo data are apparent and likely related to inherent differences in cadaveric and living tissues, loading conditions, and other methodological issues. Likewise, data from the in vivo studies suggest that there is a large range of "normality", something that clinicians must be aware of when making diagnostic and treatment decisions. The following conclusions about the lumbar spine can be made with certainty: (1) Flexion and extension are the predominate segmental motions; (2) Lateral bending is less than flexion/extension, but is greater that axial rotation which is quite limited; (3) Axes of rotation for flexion and extension are located approximately in the posterior disc of the caudal segment, e.g., on L5 when L4 is flexing on L5; and 4) Linear displacement of the vertebral body accompanies rotation in the same direction.

Three-Dimensional Kinematics

The Cervical Spine

Prior to Lysell (1966) it was intuitively known that cervical motion occurred in more than one plane simultaneously. Aware of the limitations of plane radiography for accurately assessing spinal mobility, Lysell designed a biplanar radiographic method to study cervical kinematics with the following objectives: linear errors in measurement must be small, synchronous recording of a motion in space of at least 24 points (7 vertebrae each with three points), the method could not restrict motion, and measurement points must be reproducible. Lysell inserted four 0.8-mm steel balls (spinous process, anterior body, and right and left inferior intervertebral joint processes) into 28 cadaver cervical spines (freed of muscle, but with ligaments and joint capsules intact) from C2 to T1. Cadaver specimens ranged in age from 11 to 67 years and had varying degrees of degeneration. Maximum flexion, extension, right and left sidebending, and right and left axial rotation were introduced manually by means of thin metal wires. Location of the markers from the stereoradiographs was made with a "coordinatograph" for each "step" of radiographs that were taken; for example, sagittal plane motion was divided into 19 steps, coronal plane motion in 13 steps, and transverse plane motion in seven steps. Three-dimensional angular and positional data were determined using geometrical methods, with error estimates given as 0.5° and 0.15 mm for angular and linear measurements, respectively. Vertebral rotation was given relative to the neutral position of the vertebra. Lysell located the axis for flexion/extension in or below the moving vertebra, which is in agreement with several two-dimensional studies previously discussed; whereas for lateral bending and axial rotation the axis of movement was situated in the anterior contour of the vertebral body. Vertebral bodies translated anterior during flexion and posterior during extension, which is also in agreement with previous studies. Lateral bending was coupled with axial rotation (and vice versa). Rotation decreased in magnitude from C2 to C7, so that at C2-C3 the rotation/lateral bending ratio was 3:2, but at C7-T1 lateral bending was 7.5 times larger that axial rotation. Total range of motion in three planes follows: sagittal 64° (extension 24°, flexion 40°), frontal 49° to one side was combined with 28° axial rotation, and horizontal 45° to one side was combined with 24° of lateral bending. See Table 2.11 for a summary of three-dimensional segmental motion, as reported by Lysell. Lysell did not find a decrease in range of motion with an increase in vertebral degeneration.

Since Lysell others have documented three-dimensional cervical motion using whole cervical spine specimens (Goel, Clark, McGowan, & Goyal, 1984; Goel, Clark, Harris, & Schulte, 1988; Nowinski, Visarius, Nolte, & Herkowitz, 1993; Pintar et al., 1990; Yoganandan, Pintar, Sances, & Maiman, 1991; Yoganandan, Pintar, Sances, Reinartz, & Larson, 1991; Yoganandan et al., 1994). Yoganandan (1991, 1991, 1994) and Pintar's (1990) groups studied linear displacement of the cervical spine segments in response to complex high impact loads. Goel and co-workers (1984, 1988) reported relative intervertebral rotations (primary and coupled) which resulted from the

Table 2.11. Mean (± SD) Segmental Motion (degrees) for the Lower Cervical Spine

Spinal Segments	Sagittal Plane	Frontal Plane	Transverse Plane
C2	4.9 ± 2.2	7.9 ± 2.9 (6.4)[a]	6.0 ± 3.4 (5.4)[b]
C3	10.2 ± 2.7	9.8 ± 3.4 (6.8)	9.8 ± 4.9 (6.8)
C4	13.0 ± 3.5	9.1 ± 2.9 (6.1)	10.3 ± 4.4 (5.7)
C5	14.5 ± 3.2	9.0 ± 2.7 (4.7)	8.0 ± 3.9 (4.5)
C6	13.5 ± 4.4	8.4 ± 3.4 (3.4)	5.7 ± 4.3 (3.7)
C7	8.0 ± 2.6	6.3 ± 2.2 (2.0)	4.7 ± 1.9 (2.0)

Note. Values in the frontal and transverse planes reflect total motion to the right and left. [a]Values in () represent mean axial rotation coupled with lateral bending. [b]Values in () represent mean lateral bending coupled with axial rotation.

application of 0.3 Nm moments. Three-dimensional kinematics was determined using sound waves (1984) and optoelectronic devices (1988). During sagittal plane motion a small amount (generally less than 1° per segment) of axial rotation and lateral bending coupling was found. In agreement with Lysell, simultaneous rotation in the frontal and horizontal planes occurred to the same side. However, the magnitude of segmental rotations in all planes was considerably less than what Lysell reported. For example, in the 1988 study (Goel et al.), average sagittal plane motion for all segments was approximately 5°, compared to Lysell's 11°. Nowinski et al. (1993) also used an optoelectrical measurement system to study the kinematic behavior of nine intact and injured specimens. They only reported total motion: sagittal plane 53°; frontal plane 36° (with 17° axial rotation); and horizontal plane 47° (with 17° lateral bending), which are also generally less than the totals reported by Lysell. A total of 3° lateral bending and 1° axial rotation was coupled with flexion/extension. Additionally, there was approximately 2° and 8° of sagittal plane motion coupled with axial torsion and lateral bending, respectively. Laminectomy with facetectomy tended to increase primary and coupled motion in all planes (Goel, Clark, Harris, et al., 1988). Discrepancies between the more recent studies and Lysell could be due to differences in how the specimens were loaded and in the kinematic measurement and processing methods.

Corroborating evidence, and additional information regarding load-displacement behavior, primary and coupled motions, and three-dimensional axes in the cervical spine, has been provided by those who tested functional spinal units rather than whole cervical spines (Moroney, Schultz, Miller, & Andersson, 1988; Onan, Heggeness, & Hipp, 1998; Panjabi, Summers, & Southwick, 1983; Panjabi et al, 1986; Peles, Crawford, Sonntag, Dickman, & Yamaguchi, 1997; Raynor, Moskovich, Zidal, & Pugh, 1987; Wen, Lavaste, Santin, & Lassau, 1993; Zidel, Nagai, Raynor, Hobs, & Pugh, 1985). With anterior and posterior shear loads it was found that translation occurred in the same direction (~2 mm), and the main coupled motions were flexion (~4°) and extension (~6°), respectively (Panjabi et al., 1986). Lateral shear loads resulted in translations of approximately 1.5 mm and were coupled with axial rotation (1-2°), but not lateral bending. Compression (~1 mm) was associated with flexion (2-3°) and lateral bending (1-2°), while distraction (~1 mm) was coupled with extension (3-4°) and lateral bending (~2°). It is difficult to compare Panjabi's data to the other studies cited because of differences in the loads (maximum of 50 N) that were applied. Onan et al. (1998) reported that axial rotation and lateral bending (C3-C4 and C5-C6) were coupled to the same side, but the coupling ratio changed caudally as the incline of the zygapophyseal joints changed. Their findings were in agreement with Lysell's and they concluded that both the intact vertebral ring and combination of the two zygapophyseal joints were responsible for producing the coupled motions in the lower cervical spine. Milne (1991) suggested that interfacet angle was responsible for controlling how strictly lateral flexion and axial rotation were coupled in the cervical spine.

Panjabi and co-workers (1986) defined the neutral zone (NZ) as the zone (region) within the range of motion in which the spine can be displaced with the application of a very small force or moment. Neutral zones for anterior and posterior shear forces were ~2 mm of translation and ~6° of rotation, for lateral shear forces 1-2 mm and ~2°, and for compression/distraction ~1 mm and 3°. Panjabi et al. suggested that the NZ was related to inherent stability of the spinal column. For example, an increase in NZ mobility may be an indicator of segmental instability. Wen et al. (1993) also defined NZ and range of motion for 56 cervical FSU's (C2-C7) in three dimensions. They found that the NZ correlated well with the range of motion (neutral zone ratio = NZR) and determined ratios in the sagittal, frontal, and horizontal planes ranging from 0.50 to 0.78. NZs tended to vary from segment to segment and ranged from 7° to 8° in the sagittal, frontal, and horizontal planes, respectively. In addition to determining intervertebral range of motion, the authors noted that lateral bending and axial rotation were coupled considerably, regardless of which motion was introduced first. The mean ratio of coupled motion for axial rotation/lateral bending when the specimen was lateroflexed was 0.32 while the mean for lateral bending/axial rotation was 0.49 when the specimen was rotated. Lateral bending provoked by axial rotation was greater than the axial rotation provoked by lateral bending, and the ratios were significantly different at different spinal levels.

Moroney et al. (1988) reported sagittal plane shear displacements (less than 4 mm) that were significantly less than Panjabi et al. (1986), likely due to differences in loading conditions. They found lateral translation to be in the same direction as the lateral bending moment, which is contrary to what Bakke (1931) found in vivo. Combined principal motions of flexion/extension (10°) corresponded to 91% of the mean intersegmental sagittal range of motion reported by Lysell (1969). Additionally, lateral bending corresponded to 112% of the mean intersegmental frontal range of motion and axial rotation corresponded to 51% of the mean intersegmental horizontal range of motion reported by Lysell. Raynor et al. (1987) found the magnitude of normal coupling patterns were decreased in FSUs following facetectomy.

The finite helical axis (FHA) patterns over 0.5° increments for six C5-C6 FSU specimens, intact and following ligament dissection were determined following the application of flexion, extension, lateral bending and axial rotation moments (Peles et al., 1997). For intact specimens, FHAs were clustered in the posterior half of the C6 vertebra for flexion/extension, which was consistent with the two-dimensional studies previously cited. During axial rotation, the FHA originated in the anterior portion of the vertebral bodies and migrated posteriorly with movement. With lateral bending FHAs began in the superior vertebral segment and moved inferiorly during motion. With both frontal and horizontal plane movements the FHAs were angled in the sagittal plane reflecting the coupled motion. Measurements following ligamentous dissection resulted in variations of placement and movement of FHAs.

Mimura et al. (1987) took biplanar roentgenograms on 20 normal male subjects (aged 25-31 years) with the head and neck in neutral and maximally rotated to the right and left. Mean total (right + left) axial rotation was 105°, with 75° occurring in the CO-C1-C2 complex. In the lower cervical segments, lateral bending occurred to the same side as axial rotation. Minimal (2-3°) flexion was coupled with axial rotation below the C5-C6 level, and extension above the C4-C5 level. See Table 2.12 for a comparison of Mimura's data to that from previous studies.

Table 2.12. Mean (degrees) Total Axial Rotation for Cervical Segments

	In Vitro		In Vivo		
Spinal Segments	Lysell	White & Panjabi	Penning	Dvorak	Mimura
C0-C1	-	0	2	8	75.2
C1-C2	-	47	81	86.2	-
C2-C3	6	9	6	-	7.2
C3-C4	9.8	11	13	-	5.8
C4-C5	10.3	12	13.6	56.6[a]	4.2
C5-C6	8	10	13.8	-	5.4
C6-C7	5.7	9	10.8	-	6.4
C7-T1	4.7	8	4.2	-	-

Note. A dash indicates that no data were available. Lysett (1969), White & Panjabi (1990), Penning (1987), Dvorak (1987), and Mimura (1989). [a]Represents mobility of lower four segments combined.

Three-dimensional kinematic studies of the upper cervical spine (C0-C1-C2) have primarily been conducted in vitro (Goel, Clark, Galles, & Liu, 1988; Oda, Panjabi, & Crisco III, 1991; Panjabi et al., 1988; Panjabi, Dvorak, Crisco III, Oda, Wang, et al., 1991; Panjabi, Dvorak, Crisco III, Oda, Hilibrand, et al., 1991; Panjabi, Oda, Crisco, Dvorak, & Grob, 1993; Worth & Selvik, 1986). See Table 2.13 for a summary of these studies. Comparing range of motion in the sagittal plane among the three- and two-dimensional studies (see Table 2.2 and Table 2.3), including both in vivo and in vitro studies, it is evident that total flexion-extension at C0-C1 ranges from 18-30° and at C1-C2 from 10-30°. Only the three-dimensional studies have consistently documented frontal plane range of motion in the upper cervical spine, where it is seen to average approximately 5° and 7° at C0-C1 and C1-C2, respectively. Up through the 1970s most believed that axial rotation was nonexistent at the atlanto-occipital joint, but more recently (from two- and three-dimensional studies) it has been demonstrated that approximately 4-5° of total axial rotation occurs at this joint. It appears that total axial rotation at C1-C2 ranges from approximately 46° to 94°, which is consistent with data collected from two-dimensional studies.

Prior studies (Fielding, 1957; Hohl & Baker, 1964; Jirout, 1973; Kapandji, 1974; Mestdagh, 1975; Penning, 1978) reported that axial rotation and lateral bending were coupled to the opposite side, e.g., left axial rotation produces right lateral bending. These coupling patterns were verified by three-dimensional studies (Worth & Selvik, 1986, Goel, Clark, Galles, et al., 1988; Panjabi, Dvorak, Crisco III, Oda, Wang, et al., 1991; Panjabi, Dvorak, Crisco III, Oda, Hillibrand, et al., 1991). Control of this coupling pattern is provided primarily by the alar ligaments, and secondarily by the tectorial membrane (Panjabi, Dvorak, Crisco III, Oda, Wang, et al., 1991; Panjabi, Dvorak, Crisco III, Oda, Hillibrand, et al., 1991), as was suggested by previous two-dimensional studies (Werne, 1957, 1959; Reich & Dvorak, 1986). However, when lateral bending was introduced first axial rotation was coupled to the same side at C0-C1 (Panjabi, Dvorak, Crisco III, Oda, Wang, et al., 1991; Panjabi et al., 1993). Extension at C0-C1 and flexion at C1-C2 were found to be secondary motions during lateral bending/axial rotation (Panjabi, Dvorak, Crisco III, Oda, Wang, et al., 1991; Panjabi et al., 1993). Panjabi and co–workers (1993) concluded that the spinal level was more important than the type of load applied when the magnitude of primary and secondary motions were concerned. For

Table 2.13. Mean (± SD) Joint Angles (degrees) for Upper Cervical Segments

				Sagittal		Frontal		Transverse	
Author	Year	n	Age	C0-1	C1-2	C0-1	C1-2	C0-1	C1-2
Worth & Selvik[a]	1986	13	-	18.6 (0.7)	13.3(0.9)	3.9(0.6)	4.1(0.8)	3.4(0.4)	35.2(2.8)
Goel et al.	1988	8	63-86	F6.5(2.5)	F4.9(2)	L3.4(2.8)	L4.2(2.8)	L2.4(1.2)	L23.3(11.2)
				E16.5(7.6)	E5.2(2.9)	-	-	-	-
Panjabi et al.[b]	1988	10	29-59	F3.5(0.6)	F11.5(2)	L5.6(0.7)	L4(0.8)	L7.9(0.6)	L38.3(1.7)
				E21.0(1.9)	E10.9(1.1)	R5.4(1.0)	R9.4(2)	R6.6(0.8)	R39.5(1.7)
Panjabi et al.	1991	10	35-78	F14.4(3.2)	F12.7(3.2)	L5.6(3)	L12.6(7)	L3.3(2.3)	L37.4(9)
				E14.4(3.2)	E10.5(5)	R5.1(2.5)	L8.3(4.5)	R6(4.5)	R34(9.8)

Note. [a]Indicates that sagittal plane motion was reported as full flexion from full extension; frontal plane motion as moving from left to right lateral; transverse plane motion as moving from right left axial rotation. [b]Indicates that the values in () are standard error of the mean. F = flexion; E = extension; LLB = left lateral bending; RLB = right lateral bending; LAR = left axial rotation; RAR = right axial rotation. A dash indicates that no data were available.

example, at C0-C1 axial torque produced greater main motions, while lateral bending produced greater sagittal plane motions, and at C1-C2 coupled axial rotation was significantly larger than the main motion of lateral bending.

When C0-C1-C2 specimens were placed in different sagittal plane postures (neutral, flexion, and extension) three-dimensional motion of the segments were affected in a complex manner (Panjabi et al., 1993). Maximal flexion consistently reduced the magnitude of the primary motions, whereas the extended posture had varying effects. At both craniovertebral segments the extended posture resulted in coupled extension and the flexed posture resulted in coupled flexion during the application of either lateral bending or axial rotation moments. Therefore, there appeared to be a reversal of the normal sagittal plane coupling pattern, as compared to what was seen when the spine was in a neutral posture. There were no changes in axial rotation/lateral bending or lateral bending/axial rotation coupling patterns with changes in posture at C0-C1, but the flexed posture reversed the normal coupled axial rotation with a lateral bending moment at C1-C2, e.g., left axial rotation/right lateral bending changed to left axial rotation/left lateral bending. The authors concluded that their findings would improve the interpretation of three-dimensional kinematic studies performed clinically and in the understanding of whiplash injuries, and benefit those who perform manual medicine.

During flexion the occipital condyles generally translate posteriorly and, conversely, anterior with extension (Kapandji, 1974; Oda et al., 1991; Worth & Selvik, 1986). Oda et al. (1991), using two anatomical landmarks on the occiput, however, found the anterior point translated, during flexion for example, posteroinferiorly while the posterior point translated anterosuperiorly; and vice versa during extension. Total translation at C0-C1 ranged from 1.5 mm to 5.5 mm (Oda et al., 1991; Worth & Selvik, 1986). Worth and Selvik (1986) suggested that this normal posteroinferior translation of C1 relative to the occiput during extension must be taken into account by clinicians during examination and treatment of the upper cervical spine. At C0-C1 during axial rotation, translation of the occiput occurred in the same direction, but during lateral bending translation occurred in the opposite direction (Oda et al., 1991; Worth & Selvik, 1986).

During flexion and extension at C1-C2, C1 translated posteroinferiorly and anterosuperiorly, respectively (Oda et al., 1991; Worth & Selvik, 1986). From maximum flexion to extension, linear displacement ranged from 0.4 mm (Worth & Selvik, 1986) to 2.6 mm (Oda et al., 1991), whereas the magnitude of longitudinal translation ranged from 4.1-9.3 mm (Oda et al., 1991). Oda and co-workers (1991) determined that the posterior point translated laterally three times as far as the anterior point during axial rotation, e.g., left axial rotation the posterior point shifted to the right and the anterior point shifted to the left. This suggested that the center of rotation for C1 was closer to the anterior point. Since lateral bending in the craniovertebral joints is coupled with axial rotation to the opposite side, lateral displacement of C1 during lateral bending occurs to the same side (Fielding, 1957; Hohl & Baker, 1964; Jirout, 1973; Kapandji, 1974; Mestdagh, 1975; Penning, 1978; Worth & Selvik, 1986; Goel, Clark, Galles, et al., 1988; Panjabi, Dvorak, Crisco III, Oda, Wang, et al., 1991; Panjabi, Dvorak, Crisco III, Oda, Hilibrand, et al., 1991). For example, right lateral bending of C1 would result in left axial rotation and a posterior point on C1 would translate to the right, following the movement pattern for axial rotation described above, as noted by Oda et al. (1991). Vertical approximation of

C1 on C2 during axial rotation has been suggested (Fielding, 1957; Hohl, 1964; Kapandji, 1974), however Oda et al. found that longitudinal translation occurred in two phases, a superior displacement followed by an inferior one.

Lee, Harris, Nassif, Goel, and Clark (1993) developed a three-dimensional roentgen stereophotogrammetric technique using metallic markers, with linear and angular accuracies of 0.07 mm and 0.08-0.14°, respectively. With selected patients (Lee, Harris, Goel, & Clark, 1993; Lee et al., 1994), this method was able to detect small abnormal motions in patients before they were detected clinically using standard physical examination and radiographic procedures. Although their technique holds some promise for the longitudinal study of patients and to establish the efficacy of treatments related to the cervical spine, the invasive nature of the procedures may preclude widespread use.

The Thoracic Spine

Applying a stereophotogrammetric technique identical to the one used by Lysell (1969), White (1969,1971) determined the three-dimensional motion characteristics of thoracic segments, T1-T11, from 17 cadavers aged 5-83 years. As described in his two-dimensional study, White found mean segmental extension to be less than mean flexion or approximately 42% of the full sagittal motion. Below T10 sagittal plane motion was increased. Mean (flexion and extension) sagittal plane motion was approximately 34°, which was considerably less than recorded in his two-dimensional study, and that reported by Bakke (1931). A small amount of anterior translation occurred with flexion and posterior translation with extension (Panjabi, Brand, & White, 1976a, 1976b; Oxland, Lin, & Panjabi, 1992), as well as some axial translation.

White (1969) found no particular cephalocaudal pattern with lateral bending, recording a mean of 52° combined right and left lateral bending (3-6° at each intespace), which is comparable to results from other studies (Bakke, 1931; Oxland, Lin, & Panjabi, 1992; Panjabi, Brand, & White, 1976a, 1976b). Linear displacement occurred in the same direction as the lateral bending (White, 1969), but it was found to be less than 0.5 mm (Oxland, Lin, et al., 1992), which is less than that reported by Panjabi, Hausfeld, and White (1981). Penning and Wilmink (1987) theorized that the heads of the ribs functioned like the uncinate processes in the cervical region and forced the posterior aspect of the vertebral bodies to translate into a direction contralateral to that of lateral flexion; which would, at the same time, produce ipsilateral axial rotation. Lateral flexion coupled with axial rotation ipsilaterally (Oxland, Lin, et al., 1992; White, 1969); however, for some middle thoracic segments the opposite pattern was found (White, 1969). With functional segments that included intact costovertebral (CVJ) and costotransverse joints (CTJ), Panjabi et al. (1976a, 1976b) also found that lateral bending and axial rotation were coupled to the opposite side. Lee (1993, 1994) theorized that this pattern was not due to zygapophyseal orientation (as in the cervical and lumbar regions), but due to interaction of the vertebral elements with the ribs. For example, during right lateral bending the ribs are displaced inferiorly on the right side, and superiorly on the left. At some point during thoracic cage motions rib movement is constrained. As the vertebra continues to side bend to the right, there is a superior glide of the right rib at the CTJ and an inferior glide of the left rib at its CTJ. Since the CTJ is saddle shaped (concavoconvex) in a craniocaudal plane, the superior glide of the right rib produces an anterior roll or anterior rotation of the neck of the rib. The inferior glide of the left rib results in a posterior rotation of the rib neck. The result of these two actions is to produce left (contralateral) axial rotation of the vertebra. Since ribs 1 and 2 are atypical they do not influence coupling in the upper thoracic region (C7-T1 and T1-T2), therefore lateral bending and axial rotation are coupled to the same side. The sidebending/axial rotation coupling characteristics of segments T8-T12 are dependent on the location of the apex of the sidebending curve and less dependent on rib rotations. Lee suggested that the T11-T12 region was capable of pure sidebending secondary to the unique rib articulations.

Axial rotation ranged from 2-6° (Oxland, Lin, et al., 1992; Panjabi et al., 1976a, 1976b; White, 1969) and totaled 41° for 11 segments (White, 1969), with decreasing segmental motion from T9 to T11, a pattern similarly noted in White's two-dimensional study. With axial rotation as the primary motion, lateral bending was coupled in the same direction (Panjabi et al., 1976a, 1976b). With right axial rotation the vertebral body translated to the left (Panjabi et al., 1976a, 1976b) and it was suggested that the right rib rotated posteriorly and the left rib rolled anterior (Lee, 1993. 1994). Lee hypothesized that left lateral translation of the superior vertebral segment pushes the left rib away and causes a posterolateral translation of the rib at the left CTJ. Conversely, the right rib is pulled towards the vertebra, which causes an anteromedial translation of the rib at the right CTJ. The ligaments of the CV and CT joints become taut when the limit of horizontal translation is reached, so that further right rotation of the superior vertebral segment is possible only if it tilts (side bends to the right) up and over the left superior CVJ. Cropper (1996) suggests that a passive elastic moment is created in the posterior layer of the superior costotransverse ligament which literally pulls the right transverse process of the superior vertebral segment downward producing right side flexion. At the same time, the corresponding ligament on the left side becomes lax, allowing a right-sided tilt to occur. Because the anatomy of the rib articulations with vertebra and sternum change below T7 Lee hypothesized that rib influence on coupling is decreased. Therefore, with side flexion or axial rotation, the secondary motion may be coupled ipsi- or contralaterally (Lee, 1993, 1994). Additionally, pure axial rotation can be produced at the T11-T12 segment since rib articulations are less constraining.

White (1969) also determined instantaneous helical axes (IHA), which constitutes a complete and precise three-dimensional analysis of the motion of the segments studied. For extension, IHAs were clustered above the disc, for flexion below. During lateral bending axes were at or near the disc, slightly away from the midline contralateral to the direction of side flexion. For axial rotation, they tended to cluster at points along a line from the anterior middle portion of the vertebra to the region of the spinal canal. Location of the IHAs was similar to locations of the ICRs described previously.

The reader is reminded that the results reported above originate from in vitro experiments in which all soft tissue, muscle, and rib cage elements have been removed. Additionally, theories of coupled movement were based on in vitro studies of functional segment units, without rib elements, and clinical intuition (Lee, 1993). The costovertebral joints and rib cage have been shown to significantly stiffen functional unit mobility, particularly lateral bending and axial rotation (Oda, Abumi, Shone, & Kaneda, 1996). Furthermore, loading conditions likely differed between studies and may not have simulated physiological conditions. Finally, spinal posture was not controlled for, as it had been in some of the spinal model and in vivo two-dimensional studies. Therefore, it is difficult to make reasonable comparisons between studies and draw strong conclusions.

Using a roentgen stereophotogrammetric system, Reynolds (1994) studied nine male whole, unembalmed cadavers in neutral, maximum erect, and slumped seated postures. Prior to testing, osteopathic physicians examined specimens for joint flexibility and vertebral asymmetries. To maintain a neutral sitting posture, cadavers had straps placed around the forehead, upper thorax, and pelvis, with a dowel placed behind the lower cervical/upper thoracic spine (C7/T1). For the erect postures, a bar was placed between the mid-lumbar spine and seat back and was used to push the mid-lumbar spine forward. Removing the lumbar bar and pelvic strap and pulling the pelvis forward produced slumped postures. To simplify kinematic analysis of the thoracic spine, segments were grouped as follows: T1-T4, T4-T8, and T8-T12. For example, segments T1-T4 were considered to move together. The upper thorax, from C7 through T4, translated anteriorly, relative to the global coordinate system, from maximum erect to maximum slump. There was a posterior linear displacement of segments T8 through the pelvis when cadavers had postures changed from erect to neutral, but an anterior linear displacement when posture changed from neutral to maximum slump. When cadavers went from erect to neutral the T1-T4 and T4-T8 segments extended, whereas the T8-T12 segment flexed. In moving from a neutral to a slumped posture, T1-T4 flexed, but T4-T8 and T8-T12 segments extended. Reynolds concluded that changes in angular position in the lumbar spine and thorax were determined in large part by the location of the pelvis. This is one of the few studies which has looked at the role of posture on spinal kinematics and these data have clinical implications regarding static and dynamic positional testing of lumbar and thoracic vertebral segments. However, Reynolds constrained the cadavers in a fashion that biased the results and detailed segmental and out-of-plane, i.e., sidebending and axial rotation, data are lacking.

Various radiographic techniques to assess the three-dimensional position of thoracic spine vertebral elements have been advanced in an effort to improve methods that used only plane radiographs to assess scoliotic curves (Andre, Dansereau, & Labelle, 1994; Brown, Burstein, Nash, & Schock, 1976; Kanagama, Tadano, Kaneda, Ukai, & Abumi, 1996; Yamagata et al., 1990). Reuben and co-workers (1979, 1982) examined healthy adolescent subjects, while erect, supine, and supine with Cotrel traction, to determine: (1) central vertebral disc height: (2) vertebral endplate solid angle (angle formed between subjacent endplate surfaces: (3) anteroposterior and mediolateral wedge angles: (4) successive intervertebral rotation: (5) vertebral rotation, measured with respect to a particular reference body: and (6) locations of vertebral mass centers. DeSmet et al. (1981, 1984) compared three-dimensional radiographic analysis to the traditional frontal and lateral projections of the spine in individuals with a right thoracic scoliosis. DeSmet's group found that three-dimensional information provided insight into axial rotation deformities that the other methods were unable to provide. Stokes and co-workers (1987, 1988, 1989) conducted a series of studies on scoliosis. In 1987 they examined the relationship between severity of scoliosis and changes in sagittal plane curvature, relationships between curvatures in the coronal plane, sagittal plane, plane of maximum curvature, and the plane of the most axially rotated vertebra. Using raster-stereophotography and stereoradiography in 1988 they determined the relationship between back shape and spine shape. The relationships between the axial rotation of the vertebra, the back surface, rib cage, plane of maximum curvature of the thoracic spine, and magnitude of the scoliosis deformity were examined in 1989. Matsumoto et al. (1997) found, in 31 patients with scoliosis, a significant correlation between the degree of the scoliotic angle in the frontal plane, kyphotic angle in the sagittal plane, and the rotational angle of the apical vertebra. They further noted that hypokyphosis was associated with a scoliotic angle greater than 40° in the frontal plane and increased axial rotation of the apical vertebra. Three-dimensional tomography has also been used (Kojima & Kurokawa, 1992a, 1992b) to document degree of deformity in scoliosis using rotation vectors (Kojima & Kurokawa, 1992b) instead of Euler angles. Biplanar radiography has also been used to assess thoracolumbar segmental stability before and after removal of Harrington rods (Dodd, Fergusson, & Pearcy, 1986).

In summary, stereoradiography has provided more accurate data related to rotational deformities in scoliosis, which has the potential to improve treatment techniques. However, this technology has not been used to corraborate research related to in vitro segmental kinematics in normal subjects. One of the reasons for this could be the risk of high radiation exposure to healthy subjects, which is inevitable with stereoradiography.

<u>The Lumbar Spine</u>

The in vitro mechanical properties and three-dimensional kinematics of "normal" lumbar spine motion segments have been studied extensively. Additionally, investigators have looked at motion segment kinematic behavior as a result of disc injury (Goel, Goyal, Clark, Nashiyama, & Nye, 1985; Panjabi, Krag, & Chung, 1984;), spinal decompression (Goel, Nye, Clark, Nashiyama, & Weinstein, 1987), ligamentous injury (Abumi et al., 1990; Yamamoto, Panjabi, Oxland, & Crisco, 1990), facetectomy (Abumi et al., 1990), and fusion (Esses, Doherty, Crawford, & Dreyzin, 1996).

With three-dimensional kinematic analysis, primary and coupled motions are measured simultaneously. Several researchers found that anterior shear was coupled with flexion, lateral shear with side flexion (to the same side), and posterior shear with extension (Berkson, Nachemson, & Schultz, 1979; Panjabi, Oxland, Yamamoto, & Crisco, 1994). Some investigators found no rotatory coupled motions with lateral bending (Goel et al., 1985; Schultz, Warwick, Berkson, & Nachemson, 1979; Tencer, Ahmed, & Burke, 1982), but Panjabi et al. (1977, 1981, 1989, 1994) and others have provided significant details on coupling patterns in the frontal and transverse planes (Cholewicki, 1996; Frymoyer, Frymoyer, Wilder, & Pope, 1979; Pope, Wilder, Stokes, & Frymoyer, 1977). When axial rotation was the primary motion lateral bending was coupled in the opposite direction for the upper three lumbar segments, but coupled in the same direction for L4-L5 and L5-S1. With lateral bending, there was pronounced flexion (more so than with axial rotation), lateral translation in the same direction, and for the lower four segments opposite side axial rotation. The limitations of in vitro studies have been previously cited but these findings suggest that clinicians may not be able to regard physiological movements in the lumbar spine as homogeneous. A predisposing posture of the lumbar spine had not been considered in the aforementioned studies, so caution must be exercised in comparing these results with those of Fryette's. Discussion of the effects of posture on lumbar segment mobility will be presented below.

Simulating intradiscal pressures that were consistent with living subjects in a recumbent position, Tencer and Ahmed (1981) and Tencer et al. (1982) corraborated

Berksons' work (1979) and determined that posterior shear and extension moments resulted in segmental motions that were approximately 50% to 60% of those produced by anterior shear and flexion moments. At L5-S1 anterior and posterior linear displacements were approximately the same (McGlashen, Miller, Schultz, & Anderson, 1987). Displacements due to shear loads did not exceed 2.5 mm, which is consistent with what Rolander (1966) found in his two-dimensional study. Lateral bending moments produced angular motions that were intermediate between flexion and extension. Axial rotation is most limited in the lumbar spine (McGlashen et al., 1987; Panjabi, 1977; Panjabi, Yamamoto, Oxland, & Crisco, 1989; Panjabi, Oxland, Yamamoto, & Crisco, 1994; Patwardhan, 1980; Schendel, Wood, Buttermann, Lewis, & Ogilivie, 1993; Schultz, et al., 1979; Soni, Sullivan, Patwardhan, Gudavalli, & Chitwood, 1982; Tencer et al., 1982). Although the L5-S1 segment appeared to be less stiff in torsion than the more cranial lumbar segments (McGlashen et al., 1987), the iliolumbar ligaments had been resected. Tencer et al. determined that intervertebral discs were the major load-bearing elements during lateral and anterior shear, axial compression, and flexion loads, whereas the apophyseal joints provided the major load-bearing surface in posterior shear and axial torque (Ahmed et al., 1990; Duncan & Ahmed, 1989; Oxland, Crisco, Panjabi, & Yamamoto, 1992). When the posterior elements were removed linear and angular displacements increased (Berkson et al., 1979; McGlashen et al., 1987; Schultz et al., 1979; Tencer et al., 1982). When action of the intersegmental muscles, e.g., rotatores, multifidi, and interspinali, was simulated instability was reduced (Panjabi, Abumi, Duranceau, & Oxland, 1989; Wilke, Wolf, Claes, Arand, & Wiesend, 1995), suggesting that the muscular system can play an important role in controlling excessive intervertebral motion.

In comparing the magnitude of segmental displacements and rotations among studies one must be cognizant of where displacements are measured from (Panjabi, 1977), how segments are constrained (Grassmann, Gerich, & Oxland, 1997), and pre-load conditions (Panjabi, Krag, White, & Southwick, 1977) since these factors can affect experimental results. For example, spinal segments became more flexible in the presence of preloads (that approximated in vivo loads) when the physiologic forces were directed anteriorly (flexion), but less flexible under axial tension or torsion (Panjabi et al., 1977). The effect of pre-load on lateral shear was variable (McGlashen et al., 1987; Panjabi et al., 1977). These findings have clinical implications regarding how posture might affect results of static and dynamic segmental testing. When large loads (those that may be associated with excessive motion or large internal moments) were applied to lumbar segments linear and angular displacements concomitantly increased (Miller, Schultz, Warwick, & Spencer, 1986), but when large compressive pre-loads were applied motion decreased (Janevic, Ashton-Miller, & Schultz, 1991). See Table 2.14 for a summary of segmental range of motion data derived from in vitro studies.

Reynolds (1994) studied thoracic and lumbar segments and the pelvis in whole cadavers that were placed in erect, neutral and slumped postures. He did not report movements out of the sagittal plane, but determined that lumbar motion segments were controlled by the location of the pelvis and thorax. Panjabi et al. (1989) used intact lumbar specimens (L1-sacrum) to re-examine the question of coupling and relate it to different postures. In neutral, axial rotation and lateral bending were coupled opposite in the upper and to the same side in the lower lumbar segments. Whereas, when lateral bending was introduced first axial rotation was always coupled to the opposite side (except for the L1-L2 functional unit) (Cholewicki et al., 1996; Panjabi et al., 1989). However, Vicenzino and Twomey (1993) reported that L5-S1 always demonstrated same side coupling and that coupled motion in the fully extended and flexed postures did not change. However, there was more variability at L5-S1 in extension when axial rotation was the primary motion. In the upper levels, flexion allowed greater lateral bending, while at the lower levels full extension tended to completely limit axial rotation. Flexion was always coupled with axial rotation and lateral bending, except when the spine was flexed segments tended to extend (Panjabi et al., 1989). Vicenzino and Twomey also looked at the influence of posture on physiological motions of the lumbar spine, but did not put the spine in extreme positions since that tended to reduce the magnitude of sideflexion. They concluded that lumbar posture and intervertebral level affected the direction of coupling, but zygapophyseal geometry and stage of degeneration did not. Their results were inconsistent with Panjabi's (1989) findings. For example, conjunct rotation (which is assumed to mean axial rotation) was generally coupled in the same direction when the spine was flexed, coupled opposite when the spine was extended, and always in the same direction as sideflexion at L5-S1. Additional research on how altered posture effects lumbar motion and coupling patterns, using an in vitro model, is needed.

Using the concepts described by Brown et al. (1976) for the three-dimensional study of the thoracic spine in living subjects, Pope et al. (1977) and Frymoyer et al. (1979) applied biplanar orthogonal radiography to study intersegmental motion of the lumbar spine in subjects without a history of back pain. With subjects lying supine on a specially designed apparatus they were able to passively introduce flexion, extension, lateral bending and axial rotation. Results of their preliminary work showed that segments exhibited coupled motions and that instantaneous centers of rotation varied in location depending on the properties of the motion segment, magnitude of load, and muscle activity. They concluded that biplanar radiography could be a useful research and clinical tool if there was adequate control of roentgen sources, subject positioning, proper selection of vertebral body landmarks, and, most importantly, reliable location of vertebral landmarks. Additional quantitative three-dimensional lumbar motion data were subsequently published in the 1980's (Pearcy, 1985; Pearcy & Tibrewal, 1984; Pearcy & Whittle, 1982; Pearcy, Portek, & Shepherd, 1985, 1984; Plamondon, Gagnon, & Maurais, 1988; Stokes, Wilder, Frymoyer, & Pope, 1981). However, motion and loads were not imposed and subjects were tested in the standing position (neutral posture) with the pelvis constrained, rather than supine. Table 2.15 summarizes these data. The data in Table 2.15 are comparable to the in vitro data presented in Table 2.14, considering the major limitations associated with in vitro experiments and differences between researchers in how displacements and rotations were determined.

Linear displacements generally followed the direction of rotation and did not exceed 2 mm (Pearcy, 1985; Plamondon et al., 1988). With regard to coupled rotations, Pearcy et al (1984) found that it did not make a difference whether axial rotation or lateral bending was introduced first. In the upper three lumbar segments axial rotation and lateral bending were coupled in the opposite direction. The L4-L5 segment appeared to be transitional and L5-S1 consistently showed same side coupling. Plamondon et al. (1988) reported opposite side coupling when axial rotation was introduced first, except at

Table 2.14. Mean Lumbar Segmental Motion (degrees) in Sagittal, Frontal, and Transverse Planes Based on In Vitro Studies

Author	Year	n	Age	Sagittal[a]					Frontal[b]					Transverse[c]				
				L1	L2	L3	L4	L5	L1	L2	L3	L4	L5	L1	L2	L3	L4	L5
Schultz et al.	1979	42	21-60	8.5	8.5	8.5	8.5	-	5.3	5.3	5.3	5.3	-	1.5	1.5	1.5	1.5	-
Tencer et al.	1982	8	16-57	-	12.5	2.5	12.5	-	-	5.5	5.5	5.5	-	-	2	2	2	-
Goel et al.	1985	8	42-90	5.8	5.8	5.8	5.8	5.8	2.6	2.6	2.6	2.6	2.6	1	1	1	1	1
Miller et al.	1986	9	18-41	22	22	22	22	22	14	14	14	14	14	6.4	6.4	6.4	6.4	6.4
Panjabi et al.	1989	6	-	-	-	-	-	-	4.4	5.8	5.4	5.3	4.7	1.2	2.7	2.7	2.1	1.1
Schendel et al.	1993	5	38-70	12	-	-	-	-	4.8	-	-	-	-	1.3	-	-	-	-
Panjabi et al.	1994	9	35-62	9	10	11	13	15	4.2	6	5.8	5	4.9	1.1	2	2	1.5	1

Note. Maximum applied moments were: Schultz et al., 10.6 Newton-meters (Nm); Tencer et al., 11.2 Nm; Goel et al., 3 Nm; Miller et al., 70 Nm; Panjabi et al. (1989, 1994), 10 Nm; Schendel et al., 4 Nm. [a]Indicates flexion plus extension range of motion (ROM). [b]Indicates lateral bending ROM to one side. [c]Indicates axial rotation ROM to one side. L1 implies the L1-L2 motion segment, L2 the L2-L3 motion segment, etc. A dash indicates that no data were available.

L4-L5 (L5-S1 was not tested). However, there was ipsilateral coupling from L1-L3 and contralateral coupling at L4-L5 when lateral bending was introduced first. Extension was coupled with lateral bending from L1-L3 (the L4-L5 segment demonstrated variable coupling patterns) but L5-S1 flexed (Pearcy, 1985), whereas Plamondon et al. (1988) generally found that lateral bending was coupled with flexion.

Recently, Steffen et al. (1997) have reported a new technique to measure lumbar intersegmental motion in vivo. They inserted 2.5-mm diameter Kirschner wires into the spinous processes of L3 and L4 of 16 healthy males (mean age 31.6 years). The wires had electromagnetic sensors (FASTRAK™, Polhemus, Colchester, VT) attached to them for the purpose of tracking three-dimensional intervertebral motion. The source of the electromagnetic tracking system was harnessed to the mid-thoracic region. Biplane radiography was used to calibrate the setup. Accuracy and reliability of an earlier generation of FASTRAK™ had previously been established (An, Jacobsen, Berglund, & Chao, 1988), and the authors reported RMS errors for rotation and translation ranging from approximately 0.1° and 0.4 mm, respectively. Motion testing in all planes was performed with subjects standing. The following mean motions were recorded: flexion-extension 16.9°, one-side lateral bending 6.3°, and one-side axial rotation 1.1°. During sidebending there was concomitant contralateral axial rotation and flexion. However, when axial rotation was the primary motion, 10 subjects exhibited contralateral sidebending and four exhibited ipsilateral sidebending; coupled flexion was evident in 9 of 11 subjects. Range of motion values appear to be consistent with those already presented (Tables 15 and 16), but coupling patterns show mild differences from those presented by Pearcy (1985) and Plamondon et al. (1988). This method has an advantage

Table 2.15. Mean Lumbar Segmental Motion (degrees) in Sagittal, Frontal, and Transverse Planes

Author	Year	n	Age	Sagittal[a]					Frontal[b]					Transverse[c]				
				L1	L2	L3	L4	L5	L1	L2	L3	L4	L5	L1	L2	L3	L4	L5
Pearcy	1985	31	21-37	13	14	13	16	14	5	5	5	3	0	1	1	1	1	1
Plamondon et al	1988	16	25	8.1	12.7	13.7	14.3	-	4.9	5.7	4.5	4.9	-	0.6	1.3	0.6	1.6	-

Note. In Pearcy there were three groups of subjects: flexion/extension 11 subjects; axial rotation 10 subjects; lateral bending 10 subjects. [a]Indicates range of motion (ROM) for flexion plus extension. [b]Indicates ROM for lateral bending to the right side. [c]Indicates ROM for axial rotation to the right side. L1 implies the L1-L2 motion segment, L2 the L2-L3 motion segment, etc. A dash indicates that no data were available.

over stereoradiographic techniques in terms of less gamma ray exposure, while maintaining accuracy, and it has the ability to measure motion continuously rather than at the extremes. Skin motion related errors associated with optoelectric methodologies are not a factor in Steffens' method, and pin motion did not appear to result in significant errors. The disadvantages of the method lie in the sensitivity of the electromagnetic devices to interference from electrical noise (McGill, Cholewicki, & Peach, 1997) and the invasiveness of inserting wires into vertebral spinous processes.

Stereoradiography has been used to assess three-dimensional intervertebral lumbar motion in patients following spinal fusion (Morris, Chafetz, Baumrind, Genant, & Korn, 1985; Olsson, Selvik, & Willner, 1976, 1977). They were able to detect small intervertebral motions (pseudoarthroses), which correlated to poor clinical results in some cases. Their technique was invasive since it entailed placing tantalum spheres percutaneously on spinous processes, neural arches or transverse processes. Tantalum spheres (as opposed to anatomical landmarks) are more readily visualized and are not prone to radiographic distortion. Therefore, the advantage this technique offered over the method described by Pearcy and others is improved accuracy, i.e. 0.2° for rotations and 30-120 μm for translations (Olsson et al., 1976). Other investigators have also used biplanar radiography on patients post-fusion and have noted non-union, paradoxical patterns of motion, and hypermobility at adjacent segments (Pearcy & Burrough, 1982; Pearcy, Portek, Shepherd, Burrough, & Wadsworth, 1985; Stokes et al., 1981). Additional applications of the technique have found asymmetrical intervertebral movements (Stokes, Medilicott, & Wilder, 1980; Stokes et al., 1981), decreased primary movements, and increased coupled movement in vertebra above (Tibrewal, Pearcy, Portek, & Spivey, 1985) segments with a herniated disc or spondylolisthesis (Pearcy, Portek, Shepherd, Burrough, et al., 1985). Patients with mechanical low back pain and with no nerve tension signs, i.e., pain secondary to segmental dysfunction and not due to herniated nucleus pulposus, were similar in that they exhibited restricted primary motions and increased coupling. Those with nerve tension signs did not have increased coupled movements (Pearcy, Portek, & Shepherd, 1985). Patients with a herniated nucleus pulposus that were treated surgically did not demonstrate increased sagittal plane motion, but had a reduction the magnitude of coupled movements, while those who received medical and exercise treatments for ankylosing spondylitis demonstrated improvements in mobility (Tibrewal et al., 1985).

Geometrical and Analytical Models of the Spine

This section will examine two- and three-dimensional models of the spine that have been used to provide further insight regarding spinal function. Where possible experimental data will be presented to verify spinal models. These models will be compared to data previously discussed.

Mathematical models of the spine are of two kinds, the continuum and discrete-parameter types (Agrawal & Li, 1992; Dietrich, Kedzior, & Zagrajek, 1991; Panjabi, 1973; Panjabi & White, 1971). Continuum models (as discussed by Panjabi, 1973 and Scholten, 1986) have had limited success in realistically representing the complex three-dimensional nature of the spine. However, a variety of discrete-parameter models representing the spine with three degrees-of-freedom (Agrawal & Li, 1992) or six degrees-of-freedom, using computer-generated (Belytschko, Andriacchi, Schultz, &

Galante, 1973; Merrill, Goldsmith, & Deng, 1984) or finite element methods (Dietrich et al., 1991), have been more successful in describing spinal kinematics and kinetics.

The Cervical Spine

Schultz and Galante (1970) used a realistic, yet simple, discrete-parameter type model to study the various regions of the spinal column. The vertebral column was idealized as a three-dimensional collection of rigid bodies inter-connected by deformable (springs) or fixed length elements. Vertebral body geometry was obtained from an educational spinal model and intervertebral disc heights were adopted from cadaver measurements. In their geometrical configuration model (where the rigid bodies were interconnected by fixed length elements) adjacent vertebral bodies (VB) and spinous processes (SP) were each connected at one point, and articular facets (AF) and transverse processes (TP) were connected on the right and left sides, respectively. Altering VB and SP, and TP lengths simulated vertebral movements in the sagittal and frontal planes, respectively. Deleting the TP constraints and adding short rotator constraints obtained axial rotation. A result for cervical spine simulated movements showed that segmental range of motion in all planes was exaggerated since the limiting action of soft tissues was not considered. However, it was shown that lateral flexion and axial rotation were coupled to the same side, which is consistent with experimental results presented previously. Maurel, Lavaste, and Skalli (1997) used a three-dimensional parameterized finite element model of the lower cervical spine to study functional units, the lower cervical spine as a whole, and the influence of zygapophyseal geometry on the mechanical behavior of this region. Segmental range of motion in all planes and coupled motion patterns agreed with experimental data previously presented. Orientation of facets in the horizontal plane was shown to be particularly influential with regard to axial rotation and the ratio of "coupled rotation to principal rotation". For example, when the facets were oriented more vertically, sagittal rotation increased in extension and axial rotation and lateral bending decreased (see Figure 3 for review of normal cervical facet orientation).

Snijders, Hoek van Dijke, and Roosch (1991) employed a static biomechanical representation of the cervical spine. They included the occiptal-atlantal and atlanto-axial joints in their model. The upper cervical segments were combined with the intervertebral joints of C3-C7 (since they were assumed to function as a unit) and employed an optimizing algorithm (minimize joint reaction forces with a static model that was over-determined) to estimate the forces acting on the cervical spine. Input parameters for their model were the weight of the head, and, if required, acceleration forces and the weight of the helmet. Axes of rotation were assumed to be located in the middle of the respective joints. Muscles that were assumed to make the greatest contribution to the stabilization of the head and neck were incorporated into the model. Snijder's purpose was to concentrate on joint forces relative to various positions of the head and neck in an effort to provide insight that could be used in flight situations. Joint reaction forces were large during flexion (especially at C7-T1), lateral flexion beyond 16°, axial rotation beyond 35°, and minimal during extension. The estimates Snijder's group made were conservative and not accurate. They were not able to verify their model, but concluded that the order of magnitude of forces was correct.

Crisco, Panjabi, and Dvorak (1991) developed a geometrical and mathematical model to examine the function of the alar ligament relative to upper cervical kinematics.

Their model was supported by experimental evidence and predicted that a significant percentage of C1-C2 axial rotation occurred freely, without ligamentous resistance. Additionally, both the right and left alar ligaments must be intact to prevent axial rotation, although the authors conceded there were several ligamentous structures that influenced upper cervical rotation.

Winters, Liang, and Daru (1988) designed an anthropomorphic model of the head/neck and compared and contrasted different methods for planar and spatial estimates of axes of rotation. They concluded that accurate methods of estimating marker locations were critical to determining the location of "joint" axes of rotation and that best results could be obtained if the markers were located far from each other and along the same arc relative to the centrode. Their findings showed that for sagittal loading, the screw axis was perpendicular to the plane, but changed as the applied load changed. They also showed that the head axially rotated when it was loaded in the direction of lateral flexion, which is consistent with experimental data. To gain further insight into the role of neck muscles in head movement organization, Winters and Peles (1990) later extended their model, tested human subjects, and used computer simulations with a three-dimensional neuromusculoskeletal model.

More recently, a fully three-dimensional finite element model of the C5-C6 motion segment of the human spine was developed and validated (Clausen, Goel, Traynelis, & Seifert, 1997) for the purpose of quantifying the role of the Luschka joints and uncinate processes. Recall that Penning and Wilmink (1987) suggested that coupled motion (sidebending and axial rotation) in the lower cervical spine was not influenced solely by the orientation of the apophyseal joints, but also by the presence of the uncinate processes. Results of Clausen's simulation indicated that the apophyseal and Luschka joints were the major contributors to coupled motion in the lower cervical spine. The presence of Luschka joints appeared to increase primary cervical motion. The uncinate processes effectively reduced motion coupling and primary cervical motion, especially in response to axial rotation and lateral bending loads, thereby showing an effect opposite to that of the Luschka joints.

The Thoracic Spine

Using the discrete-parameter model described earlier, Schultz and Galante (1970) found that thoracic segments exhibited less flexion and extension, but an intermediate amount of lateral bending and axial rotation range of motion compared to their lumbar and cervical counterparts. Lateral bending was coupled with ipsilateral axial rotation in the upper thoracic region in the normal (Schultz & Galante, 1970), but coupled contralaterally in the simulated scoliotic spine (Schultz, Larocca, Galante, & Andriacchi, 1972). Extending the model, where vertebrae were idealized as rigid bodies and discs, ligaments, and connective tissues were represented by deformable elements, nonlinearities due to large deformations were taken into account (Belytschko et al., 1973; Schultz, Belytschko, Andriacchi, & Galante, 1973). Frontal plane segmental range of motion, ranging from approximately 8° (T12-L1) to 10° (T2-T3), was comparable to data from the literature (Belytschko et al., 1973). With the longitudinal axis of the segment in the anatomical position (neutral), T8-T9 exhibited ipsilateral axial rotation with lateral bending, regardless of which motion was introduced first (Schultz et al., 1973). Schultz et al. (1973) suggested that both inherent kinematics and orientation of the motion segment played a role in coupled motion.

Scholten and Velhuizen (1985) and Scholten (1986) studied the spine: (1) as a homogeneous (and herterogeneous), torsionally stiff cylindrical rod with sagittal lordotic and kyphotic curvature, and (2) using a discrete three-dimensional, nonlinear geometrical mathematical model, as described by Belytschko et al. (1973), but modified, to characterize segmental motion behaviors. For example, Scholten modeled facet joints with only compression elements, whereas Belytschko et al. modeled them as tension and compression elements, and Scholten used an incremental stiffness method so that large rotations and displacements could be permitted. Scholten's model consisted of 17 rigid bodies each corresponding to a thoracic or lumbar vertebra, intervertebral discs represented by deformable beam elements, and three linear springs representing the ligaments between the spinous and transverse processes. To test the behavior of the intervertebral disc model loads were applied at the geometric center of the inferior surface of the body of the superior vertebra (T8). Model responses of 9.5° axial rotation, 4.7° of flexion, extension, and lateral bending, and translations less than 1 mm are comparable to experimental data. Motion segment behavior (T8-T9), as distinguished from disc behavior, was assessed by loading the geometric center of the superior surface of the superior vertebral segment. Segmental range of motion of approximately 3° for flexion, 3° extension, 5° lateral bending, and 3° axial rotation was found. Segmental extension and axial rotation values were different than what Schultz et al. (1973) reported. The compression stiffness for the facet joint elements used in Scholten's model was higher than what Schultz used, which may explain the differences in mobility. Otherwise, the reduced extension and axial rotation motion suggest that the facet joints have an importance influence on motion segment behavior. Additionally, it was shown that flexion was coupled with anterior translation, extension was coupled with posterior translation, sidebending was coupled with translation to the same side, flexion was coupled with sidebending, and sidebending was coupled with axial rotation to the same side. When sidebending was introduced first axial rotation was also coupled to the same side.

Scholten modeled the whole spine as a homogeneous and then as a herterogeneous cylindrical bar, without influence of the zygapophyseal joints (1986). With the spinal column modeled as a homogeneous cylinder, Scholten showed that sidebending and axial rotation were coupled in the same direction in the upper thoracic spine (to T6), but coupled in the opposite direction from T7 to L2. However, according to Scholten, the spinal column functioned more like a heterogeneous (morphological variability) cylinder, with spinal regions uniquely distinguished as follows: segments C5-T8 and L3-L5 as proclive (ventrally tilted) and segments C2-C4 and T9-L2 as declive (dorsally tilted) (Scholten, 1986; Veldhuizen & Scholten, 1987). Scholten suggested that tilt of vertebra, as well as the initial position (neutral, flexed or extended) of the spine, could influence kinematic coupling. In neutral, for example, proclive vertebra exhibited ipsilateral coupling of sidebending and axial rotation and declive segments exhibited the opposite pattern (Figure 2.20).

Scholten (1985; 1986; 1996) extended his findings, as described above, by investigating the influence of zygapophyseal geometry on kinematic coupling. He systematically altered the orientation of the zygapophyseal joints relative to the transverse (0°-90°) and frontal (45° to -45°) planes and determined the magnitude and

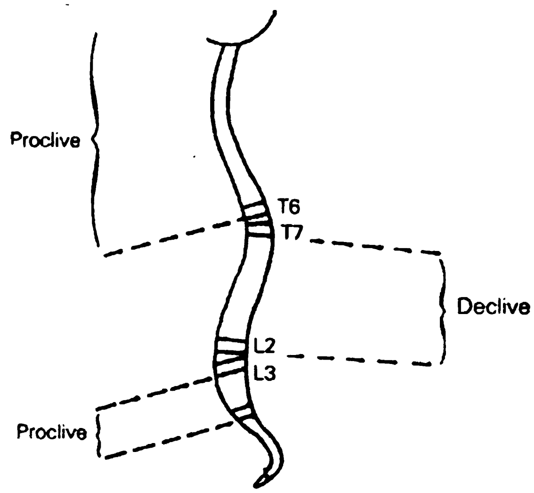

Figure 2.20. Classification of spinal curves according to the inclination of the vertebrae. From Diagnosis and Treatment of the Spine (p. 784), by D. Winkel, 1996, Gaithersburg, MD: Publisher. Copyright 1996 by Aspen Publishers. Reprinted with permission.

direction of axial rotation that followed application of a 10 Nm pure lateral moment (Figure 2.21). Results showed that generally frontal plane inclination of the facet joints was the main influence on coupling between lateral bending and axial rotation. As the angle of the facet, in relation to the transverse plane, increased from 0° to 90°, the magnitude of sidebending mobility increased and became maximal at 90°, whereas axial rotation mobility increased up to 45° and then progressively decreased. This pattern was consistent with in vivo findings, where axial rotation was shown to decrease caudally (moving from thoracic to lumbar segments). Scholten found that segment proclivity reinforced ipsilateral axial rotation in the upper thoracic region. Facet orientation and declive position of lower thoracic segments, with the spine neutral or slightly flexed, tended to counter ipsilateral axial rotation during sidebending. Results suggested that extension in the thoracolumbar region prevented axial rotation altogether or at least

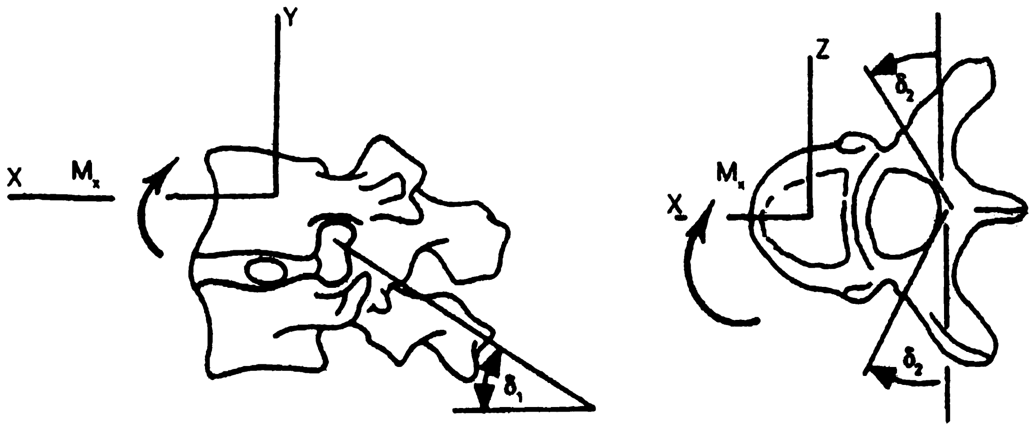

Figure 2.21. Position of the joint facet of the zygapophyseal joints, as illustrated by parameter δ_1 (left) in relation to the transverse plane and by parameter δ_2 (right) in relation to the frontal plane. From Diagnosis and Treatment of the Spine (p. 788), by D. Winkel, 1996, Gaithersburg, MD: Publisher. Copyright 1996 by Aspen Publishers. Reprinted with permission.

reversed the coupling pattern, i.e., contralateral sidebending and axial rotation. Moderate to maximum flexion of the lower thoracic segments caused the vertebra to become ventrally tilted, which enhanced ipsilateral sidebending and axial rotation. Studies on scoliotic spines showed the same coupling patterns as in the non-pathological (Velhuizen & Scholten, 1987), which differs from Schultz's findings described earlier.

In summary, Scholten (1986, 1996) found that both spinal form (posture) and zygapophyseal orientation influenced kinematic coupling. Generally, ipsilateral sidebending and axial rotation was favored in the upper, middle and lower thoracic regions in neutral and flexion, and vertebra tilt in the middle and lower thoracic region predisposed motion segments to contralateral axial rotation when the spine was extended. If axial rotation was introduced first, sidebending was still a coupled motion along with ventral flexion, albeit diminished; however, maximal axial rotation, prevented sidebending, was associated with ventral flexion. Scholten's model can be criticized for not accounting for the affects of the thoracic cage or muscle; however, previous investigators (Frymoyer et al., 1979, Pope et al., 1977; Vicenzino & Twomey, 1993) have shown that coupled movements occur independent of muscular activity.

The presence of ribs (costovertebral and costotransverse joints), costal cartilage (costochondral junction), and sternum (sternocostal joints) adds to the complexity of the thoracic region, as compared to the cervical and lumbar regions. Only Panjabi, Brand, and White (1976a) and Oda and co-workers (1996) have studied the in vitro kinematic behavior of thoracic functional motion segments taking into account the ribs and their attachments. However, Panjabi et al. left only the costovertebral and costotransverse joints intact, whereas Oda's group included the whole cage, but used canine specimens. Therefore, kinematic and kinetic data are lacking with regard to the whole thoracic cage. Roberts and Chen (1970) used a two degree-of-freedom finite element model of thoracic skeleton (sternum, costal cartilage, ribs 1-10, and vertebral column from T1-sacrum) and showed that an anterior-to-posterior load (100 lb) resulted in posterior displacement of the sternum. Since 1970, others (Andriacchi et al., 1974; Sundaram & Feng, 1977) have also concluded that the sternum could be modeled as a rigid body under conditions of sagittal plane symmetrical loading. However, this conclusion is relative to how the sternum was modeled, that is, without mobility at the manubrial-sternal and xiphi-sternal junctions, which is not consistent with functional anatomy. Andriacchi et al. (1974) expanded on a previous model of the thoracolumbar spine (Schultz et al., 1973) by adding rib pairs 1-10 and the sternum. Vertebra, ribs, calcified portions of the ribs, and the sternum were modeled as rigid bodies, while intervertebral discs, joint capsules, costal cartilages, and ligaments were modeled as spring-type or beam-type deformable elements. An anterior-to-posterior load on the sternum resulted in posterior displacement, and was associated with a dorsal displacement and rotation of the rib heads. The rib cage and sternum were shown to increase the stiffness behavior of thoracic segments under all moment loading conditions, i.e., flexion, extension, lateral bending, and axial torsion. For example, Andriacchi et al. (1974) showed that the rib cage increased the bending stiffness of the spine by a factor 1.5 for flexion and 2.5 for extension. Scholten (1986) suggested that the skin, elastic properties of the back and abdominal muscles, and the internal organs increased the bending stiffness of the trunk in flexion three times.

Closkey and Schultz (1988) and Closkey, Schultz, and Luchies (1992) further expanded the rib cage model described Andriacchi et al. (1974) by dividing ribs into five segments (rather than one rigid segment) to allow for rib deformability. Simulating a scoliotic spine, axial rotation was coupled to sidebending contralaterally (Closkey et al., 1992). Furthermore, results showed that on the convex side of the curve the thoracic cage was narrowed, with the ribs pushed posteriorly, whereas the ribs were pushed antero-laterally on the concave side of the curve. Rib cage maximum axial rotation was highly correlated to vertebral body axial rotation and both vertebral lateral displacements and tilts correlated highly with rib cage maximum lateral offset. However, axial vertebral rotations and rib lateral offsets correlated poorly. The authors concluded that the rib hump seen with scoliosis was due to axial rotation of the vertebral bodies (Closkey & Schultz, 1988). Saumarez (1986) showed, on the other hand, considerable independent movement of the sternum and the spine, suggesting that spine mobility could occur without forcing concomitant movements of the rib cage.

The lumbar spine

A two-dimensional sagittal plane geometric model, using skin profiles, lateral radiographs, and five anthropometric measurements (Sicard & Gagnon, 1993), was found to be useful for evaluating the linear and angular displacements (absolute and relative) of the lumbar vertebra. However, their model was only valid for angular motions in flexion of the pelvis, the entire lumbar spine (L1-S1), and for intervertebral movement of L4-L5. The authors suggested that their model could also be used with models designed for the evaluation of spinal loadings for specific occupational tasks. One of the benefits of the Sicard and Gagnon model is that it accounts for the neuromuscular control of spinal movement. However, it is limited in diagnosis or assessment of treatment outcomes because of its inability to document frontal and transverse plane movements.

Early three-dimensional mathematical models of the lumbar spine (Belytschko et al., 1973; Schultz et al., 1973; Schultz & Galante, 1970) approximated mobility of the L3-L4 segment in flexion (6°), extension (4°), lateral bending (7°) and axial rotation (6°). These values are comparable to in vivo and in vitro studies (Table 2.14 and Table 2.15) except for axial rotation, which is excessive. Patwardhan (1980) sought to improve on earlier models by more exact accounting of the geometric and kinematic constraints imposed by the facet joints. His model predicted cardinal plane as well as coupled motions, but tended to underestimate the degree of mobility compared to previous experimental data.

Three-dimensional finite element models (Lavaste et al., 1992; Robin, Skalli, & Lavaste, 1994; Shirazi-Adl, 1994a, 1994b; Shirazi-Adl, Ahmed, & Shrivastava, 1986a; 1986b; Shirazi-Adl & Parnianpour, 1996) have further enabled scientists to study static and dynamic intervertebral mechanics, albeit without neuromuscular elements. Shirazi-Adl et al. (1986a, 1986b) incrementally applied flexion and extension loads to a maximum of 60 Nm to a simulated L2-L3 motion segment. Results were consistent with previous in vitro studies and showed that flexion mobility (12°) was limited by the posterior ligaments and disc fibers, whereas extension mobility (10°) was limited by contact of the facet joints. In a follow-up study, Shirazi-Adl (1994b) applied sagittal and lateral moments (10 Nm) to a whole lumbar spine. Results showed that segments responded in a nonlinear fashion to loading, were more flexible in flexion than extension (except at L5-S1), and demonstrated a range of motion for flexion, extension and lateral bending similar to previous studies. Robin et al. (1994), however, found the L1-L2, L2-L3, and L3-L4 segments to be stiffer in flexion (mean = 2.9°) than extension (mean = 3.0°) with application of 10 Nm moments. In general, Robin et al. found that mobility decreased in the more caudal segments, whereas Shirazi-Adl (1994b) found a significant increase in stiffness only at L5-S1, especially with lateral bending. Segmental mobility, with application of 8-10 Nm lateral bending and torsion moments, ranged from 2.1° to 6° (Lavaste et al., 1992; Shirazi-Adl, 1994b; Robin et al., 1994) and 1.3° to 2.5° (Shirazi-Adl et al., 1986; Ueno & Liu, 1987; Lavaste et al., 1992; Shirazi-Adl, 1994a, 1994b; Robin et al., 1994), respectively. The disc annulus and facet capsules were found to be the primary restraint to torsional strains below axial rotations of 6°.

The axis of rotation, under torsional loads, was located in the disc nucleus (Shirazi-Adl et al., 1986b), but migrated towards the compression facet when maximum moments (60 Nm) were applied. This result suggests that in vitro studies, in which axes of rotation were fixed, could have produced findings that were erroneous. Under torque alone there was only upward axial displacement (Shirazi-Adl et al., 1986b), but with compression lateral rotations/displacements and flexion occurred concomitantly (Shirazi-Adl et al., 1986b; Lavaste et al., 1992; Shirazi-Adl, 1994a, 1994b).

Lavaste et al. (1992), applying maximum moments of 8 Nm, found posteroanterior displacement and sagittal plane rotation coupled with compression, anterior displacement coupled with flexion, lateral bending and sagittal plane rotation coupled with torsion, and lateral displacement and torsion coupled with lateral bending. Shirazi-Adl et al. (1986b), however, found no coupled lateral bending with application of small axial loads. With application of 10-15 Nm moments, however, left axial torque generated left lateral rotations at all levels, and right axial torque produced right lateral rotations at the lower lumbar levels, but smaller left lateral rotations at the upper levels (Shirazi-Adl, 1994a, 1994b). Schultz et al. (1973) found that left lateral bending was accompanied by counterclockwise torsion and counterclockwise torsion produced left lateral bending and extension for a simulated L3-L4 segment which was in neutral. When the segment was flexed and laterally bent, axial rotation occurred contralaterally, but when axial rotation was introduced first lateral bending occurred ipsilaterally. In extension lateral bending and axial rotation were coupled ipsilaterally, but opposite when axial rotation was introduced first. Scholten (1986) found that, generally, lateral bending and axial rotation were coupled ipsilaterally in all lumbar segments, except for perhaps the upper lumbar segments when the spine was extended. Few finite element studies took posture into account during simulations. Several researchers have concluded, based on the above analytical results, that both intrinsic segmental kinematics and lumbar posture must be considered when interpreting analytical and experimental results

(Cholewicki et al., 1996; Scholten, 1986; Schultz et al., 1973; Shirazi-Adl & Parnianpour, 1996). Cholewicki et al. hypothesized that the neuromuscular control system worked in such a way as to guide the spine motion along its natural physiological coupling characteristics and suggested that more clinical studies were necessary to increase the diagnostic utility of examining abnormal couple motions.

Summary of Experimental and Analytical Research on Spinal Kinematics

This section will include a summary of the findings that were common to both two- and three-dimensional studies of spinal sagittal plane kinematics. Kinematics out of the sagittal plane have been described qualitatively based on two-dimensional studies (Arkin, 1950; Beal & Beckwith, 1963; Feiss, 1907; Gregerson & Lucus, 1967; Reich & Dvorak, 1986; Roaf, 1958; Werne, 1957, 1959;). However, only three-dimensional in vivo and in vitro studies were able to quantify the more complex movement patterns (Berkson et al., 1979; Cholewicki et al., 1996; Goel, 1984; Goel et al., 1985, 1988; Lysell, 1966; Moroney et al., 1988; Oda et al., 1991; Panjabi et al., 1976a, 1976b, 1983, 1986, 1988, 1994; Pearcy, 1984, 1985; Schultz et al., 1979; Steffan et al., 1997; Tencer et al., 1982; White, 1969, 1971). Studies incorporating mathematical models have provided corroborating three-dimensional data (Belytschko et al., 1973; Maurel et al., 1997; Schultz et al., 1973; Schultz & Galante, 1970; Scholten, 1986; Shirazi-Adl, 1994a, 1994b; Shirazi-Adl et al., 1986a, 1986b; Winters et al., 1988).

The cervical spine can be functionally divided into two regions: (1) The upper cervical spine comprised of the occiput (C0), C1, and C2; and (2) The lower cervical spine, comprised of the segments C2 through C7. Many studies documented two- and three-dimensional segmental and total range of motion in both upper and lower cervical regions, but large intra- and inter-individual variations were found to exist (Goel et al., 1984, 1986; Lysell, 1966; Moroney et al., 1988; Oda et al., 1991; Panjabi et al., 1983, 1986, 1988, 1993; Panjabi, Dvorak, Crisco III, Oda, Wang, et al., 1991; Panjabi, Dvorak, Crisco III, Oda, Hilibrand, 1991). In general, when motion was introduced in one plane, motion in the other planes was reduced significantly. The primary motion at C0-C1 occurs in the sagittal plane. With rotation in the sagittal or frontal plane there is a concomitant glide in the opposite direction, e.g., with flexion the occipital condyles glide posterior with the center of rotation located somewhere in the occiput. Early research was not able to document axial rotation at C0-C1 (Werne, 1957), but subsequent three-dimensional studies showed that transverse plane motion did exist, albeit limited (Oda et al., 1991; Panjabi et al., 1988; Panjabi, Dvorak, Crisco III, Oda, Wang, et al., 1991; Panjabi, Dvorak, Crisco III, Oda, Hilibrand, et al., 1991; Worth & Selvik, 1986). Axial rotation, coupled with a vertical translation, is the primary motion at C1-C2 (Fielding, 1957; Hohl, 1964; Kapandji, 1974; Oda et al., 1991). There is posterior translation of C1 on C2 during flexion, vice versa with extension, and with lateral bending translation occurs to the same side as the direction of the bending (Oda et al., 1991; Worth & Selvik, 1986). The C2-C3 functional unit appears to be an important transitional region between the upper and lower cervical spine. In the lower cervical spine sagittal plane motion is most free, followed by lateral bending and axial rotation (Goel et al., 1984; Lysell, 1966; Moroney et al., 1988; Panjabi et al., 1983, 1986). In the sagittal plane translation generally occurs to the same side as the rotation. However, with lateral bending some authorities found that translation occurred to the opposite side secondary to influence of the uncinate processes (Penning & Wilmink, 1987). Sidebending and axial rotation are always coupled to the same side regardless of the positional attitude of the cervical spine (Goel et al., 1984; Lysell, 1966; Moroney et al., 1988; Panjabi et al., 1983, 1986). The direction of sagittal plane motion (flexion or extension) associated with sidebending is region dependent. Instantaneous (IAR) and finite helical (FHA) axes of rotation for primary sagittal plane motion are located in the posterior half of the vertebral bodies. For sidebending and axial rotation IARs are located in the anterior portion of the body. FHAs migrate superior to inferior during lateral bending and anterior to posterior during axial rotation (Amevo et al., 1992; Amevo, Macintosh, et al., 1991; Amevo, Worth, et al., 1991a, 1991b; Dunsker et al., 1978; Dvorak et al., 1991, 1993; Peles et al., 1997; Penning, 1978; Penning & Wilmink, 1987).

Most referenced information on thoracic cage kinematics is based on in vitro research (Oxland et al., 1992; Panjabi et al., 1976a, 1976b; White, 1971) and mathematical modeling (Andriacchi et al., 1974; Belyschko et al., 1973; Roberts & Chen, 1970; Schultz et al., 1973; Schultz & Galante, 1970; Schultz et al., 1972). Inherent segmental geometry/facet orientation, posture (kyphosis and lordosis), and rib cage (ribs and sternum) dictate range of motion in the cardinal planes and coupled movement patterns in the thoracic region. Coronal and transverse plane rotations are favored in the upper and middle regions of the thoracic spine, but sagittal plane mobility is greater in the lower region (White, 1969). Segmental flexion range of motion is generally greater than extension and lateral bending motion remains nearly constant for all thoracic segments (White, 1969). With flexion and extension there is anterior and posterior vertebral gliding, respectively, as well as some axial translation (Oxland et al., 1992; Panjabi et al., 1976a, 1976b). Lateral translation of the vertebral body occurs in the same direction as lateral bending (White, 1969), although it has been suggested that rib heads function like cervical uncinate processes which thereby forces contralateral translation (Penning & Wilmink, 1987). Flexion is always coupled with lateral bending (Schultz et al., 1973), but there are disagreements in the literature regarding how axial rotation is coupled with lateral bending and how lateral bending is coupled with axial rotation. Some concluded that when lateral bending was introduced axial rotation was always coupled opposite regardless of spinal posture (Arkin, 1950; Panjabi et al., 1976a, 1976b). Panjabi and co-workers (1976a, 1976b) also reported that when axial rotation was introduced first lateral bending was coupled in the same direction. However, Gregersen and Lucus (1967) found lateral bending and axial rotation always to be coupled to the same side. It's likely, as suggested by Fryette (1954, 1918), that the relationship between side bending and axial rotation is region and posture dependent. For example, when the spine is in neutral (normal standing position), sidebending and axial rotation are coupled ipsilaterally in the upper region (White, 1969; Oxland et al., 1992), with variable patterns in the middle and lower sections (White, 1969; Scholten, 1986). While in flexion, all segments tend to exhibit same side coupling patterns, whereas when the thoracic spine is extended segments tend to demonstrate opposite side coupling, e.g., left lateral bending results in right axial rotation (Scholten, 1986). Individuals with idiopathic scoliosis present with lateral deviations of the spine (sidebending curves), rib humps on the convex side of the curve, and segments that are axially rotated toward the convexity, suggesting that rib deformities are dictated by axial rotation of the vertebra (Closkey & Schultz, 1988; Closkey et al., 1992).

The IARs for thoracic flexion and extension are located slightly posterior and anterior, respectively, in the inferior segment (White, 1969). The instantaneous helical axis (IHA) for extension is found above the disc and for flexion below the disc. IARs and IHAs lie in the inferior segment to the left of midline for right sidebending and vice versa for left sidebending. Axes for axial rotation lie somewhere in the middle of the vertebral body with a vertical or longitudinal orientation. Sitting postures and compression loading tend to increase torsional stiffness, thereby reducing axial rotation (Oda et al., 1996). The ribs and sternum generally increase the stiffness of the entire thoracic region (Andriacchi et al., 1974). A definitive relationship of the thoracic vertebra, rib, and sternal kinematics has not been established, although Saumarez (1986) suggested that the sternum moved independent of the vertebra.

In the lumbar spine orientation of the apophyseal joints rests primarily in the sagittal plane, thus making flexion/extension the predominant motions. Generally, there is a slight increase in segmental mobility from L1 to L5 (Twomey, 1979). Lateral bending mobility is less than flexion/extension (except at L5-S1), but more than axial rotation (Markolf, 1972; Rolander, 1966). Translation occurs in the same direction as the rotation, e.g., during flexion there is an anterior translation of the superior vertebra (Nachemson et al., 1979; Rolander, 1966). Flexion is coupled with sidebending and axial rotation (Cholewicki, 1996; Plamondon et al., 1988), although extension may be coupled with sidebending in the upper lumbar segments (Pearcy, 1985). When the lumbar spine is in a neutral posture, i.e., the position of the lumbar spine in the normal standing position, sidebending and axial rotation are coupled contralaterally in the upper lumbar segments (Cholewicki, 1996; Panjabi et al., 1989), but ipsilaterally at L5-S1 (Cholewicki, 1996; Panjabi et al., 1989; Pearcy, 1984). There is disagreement on the nature of sidebending/axial rotation coupling when the lumbar spine is in a flexed posture. Some (Schultz et al., 1973; Vicenzino & Twomey, 1993) found that the pattern remained the same as in neutral spine mechanics; whereas others (Plamondon et al., 1988; Steffan, 1997) found that the coupling patterns depended on which motion was introduced first. For example, if sidebending is initiated axial rotation is coupled opposite, but if axial rotation is initiated first sidebending is coupled in the same direction. Scholten (1986) noted that sidebending and axial rotation were coupled ipsilaterally when the lumbar spine was flexed. When the lumbar spine was extended coupling patterns seemed to vary considerably among studies (Schultz et al., 1973; Scholten, 1986; Vicenzino & Twomey, 1993). Location of IARs for flexion and extension are variable based on in vitro and in vivo radiographic research. The IAR for flexion is in the median plane of the vertebral body or posterior annulus (Rolander, 1966; Twomey & Taylor, 1983). During extension, the IAR is located near the posterior articular processes, posterior disc, or anterior disc (Rolander, 1966; Twomey & Taylor; Seligman et al., 1984). IARs for right and left sidebending are located to the left and right of the midline, respectively (Rolander, 1966). For axial rotation the IAR is in the center of the disc (Rolander, 1966), tending to migrate towards the side of rotation at the end range (Cossette et al., 1971). Increasing axial loads on lumbar segments tend to decrease flexion and axial rotation mobility (Edwards et al., 1987; Posner et al., 1982). Full lumbar flexion decreases axial rotation (Gunzburg et al., 1991, 1992), but submaximal flexion increases axial rotation range of motion (Pearcy & Hindle, 1991).

Videographic and Non-Invasive Measures of Spinal Kinematics

This section of the literature review will focus on more recent research that describes the use of video, optoelectric or multi-dimensional electrogoniometric devices to document regional two- and three-dimensional spinal kinematics. Although these devices/methodologies have been questioned with regard to how well they track rigid body (bone) motion and they cannot provide information on vertebral segmental mobility, they offer the advantages of being reliable and clinically practical. The studies reviewed to this point include those that used in vitro methodologies and in vivo invasive or radiographic techniques. Analytical methods were also examined and found to be useful, especially when sufficiently accurate anatomical and mechanical data were available as input. Mathematical tools have the advantage of being useful to manipulate several variables in order to test different kinematic and kinetic scenarios. Disadvantages of in vitro, invasive, and radiographic research include: (1) use of cadaver specimens, which cannot account for normal neuromuscular control mechanisms; (2) impractical (non-clinical) laboratory test conditions; (3) limited subject participation (secondary to invasive techniques); and (4) gamma ray exposure, to name a few. Although mathematical and experimental results were reasonably consistent, most of the analytical methods were also limited by not accounting for the neuromusculoskeletal system in total. For example, Wilke, Wolf, Claes, Arand, and Wiesend (1995) showed that simulating muscle forces during in vitro loading studies affected load-deformation characteristics and range of motion of vertebral segments. The use of television based motion measurement systems also have the advantage of accounting for neuromuscular control mechanisms.

The Cervical Spine

Motion measurement detection devices and kinematic analyses have ranged from simple to complex. Because the cervical region is difficult to isolate most studies have attempted to study its function by tracking movement of the head relative to the fixed thorax. Murphy and co-workers (1984) developed a one-degree-of-freedom electronic device that could measure occipito-cervical axial rotations continuously over prolonged periods of time. Normal population subjects demonstrated smooth movement patterns, a total range of motion of approximately 90°, and Gaussian distribution of neck positions/movements recorded over a long period of time. Patients with ankylosing spondylitis moved in less predictable patterns and within a much narrower range of motion over a prolonged period of time. The device used by Murphy et al. (1984) has some clinical promise, however, it is limited by its accuracy (6-9°) and one-dimensional nature.

Alund and Larsson (1990) used a test apparatus that had five high-precision electrogoniometers simultaneously which recorded primary and coupled motions of the head/neck complex relative to a manually constrained thorax. Subjects performed active test motions while in a comfortably seated position. Total range of motion measurements in the sagittal and frontal planes was validated by radiographic studies on a sample of 19 patients with neck pain. Measurement repeatability was high in all planes of movement ($R \geq 0.90$). Mean (± SD) range of motion in all three cardinal planes for 10 normal subjects were as follows: flexion/extension - 140° ± 18°, lateral bending - 91° ± 12°, and axial rotation - 153° ± 16°, which are comparable to previous studies that used gravity goniometric or radiographic analyses. Whether lateral bending or axial rotation was introduced first lateral bending was coupled with ipsilateral axial rotation, and vice versa. However, there was more axial rotation associated with lateral bending than lateral rotation with axial rotation. Coupled sagittal plane motion occurred with frontal and transverse plane movements, but was inconsistent. Alund and Larsson's device had an upper and lower goniometer that recorded sagittal plane motion, and it appeared to differentiate between upper and lower cervical flexion-extension patterns, a feature that could be extremely useful clinically.

Dvorak, Antinnes, Panjabi, Loustalot, and Bonomo (1992) used the CA 6000 Spine Motion Analyzer™ (a six high-precision electronic potentiometer device) to assess age and gender related three-dimensional cervical motion. Active and passive motion of the head-neck complex was measured in 150 asymptomatic individuals, who were tested in a seated position. The device was attached to the head via a headband and to a specially designed chair that also stabilized the thorax. In addition to the usual cardinal plane motions, rotation with the neck in maximum flexion and extension was measured. Intra-observer and inter-observer repeatability analysis was clinically acceptable, with more variability for measuring the sagittal plane and rotation from flexion motions. Passive range of motion was found to be greater than active range of motion. In general within particular age groups, females had greater motion than males. There was a decrease in range with increased age, except for rotation in maximum flexion, suggesting that rotation of the atlanto-axial joint did not diminish with age. Table 2.16 shows that axial rotation with flexion is significantly less than axial rotation in neutral and comparable to the in vitro values for rotation reported earlier in this review. These data support the clinical assumption that C1-C2 rotation can be isolated by first placing the neck (lower cervical spine) in full flexion. Axial rotation from the extended neck position was not significantly different from axial rotation alone, suggesting that lower cervical extension did not close-pack or constrain the zygapophyseal joints.

Adams' group (1994) tracked the movement of the head-neck complex, but they used a stereometric video technique. A pair of digital video cameras followed the movement of a reflective target that was placed on the glabella (relative to the thorax that was fixed and targeted). For the experiment subjects (n = 6) performed maximum flexion, extension, lateral flexion bilaterally, axial rotation, protraction (anterior translation of the head), and retraction (posterior translation of the head). Three- dimensional position data showed that marker movement very closely approximated an elliptical paraboloid (with tendency to a hemisphere). Anatomical dissections (n = 6 cadavers) and measurement of the shapes of the articular facets of C0, C1, and C2 revealed that their geometry also approximated elliptical paraboloids. The technique used by Adam et al. (1994) was able to provide gross motion (flexion/extension and axial rotation) data, but it cannot provide true three-dimensional movement data of the head since only one target was used. The clinical usefulness of Adams' device and methodology may reside in its ability to detect abnormal movement patterns that would produce geometrical inconsistencies in comparison to normal individuals.

Refshauge, Goodsell, and Lee (1994) attempted to establish a relationship between surface contours and vertebral alignment in the cervical and upper thoracic spine. They taped 40 mm long metal markers on the skin overlying the spinous processes of C2, C4, and C6-T6 and measured cervical tilt (sagittal plane position of C2 relative to C7), cervical lordosis, and cervico-thoracic kyphosis from the surface markers and lateral radiographs. A computer-linked digitizer was used to digitize the geometric centers and surface points of the respective vertebral bodies, the vertical reference, and a horizontal reference perpendicular to the vertical. Cervical inclination was calculated as the angle made with the horizontal and a line drawn between C2 and C7. Cervical lordosis was represented by the angle subtended by lines drawn through C2 and C4 and through C4 and C7 and the cervico-thoracic angle was represented by the angle subtended by lines drawn through C4 and C7 and through C7 and T4. A weak relationship between surface and vertebral measurements was found, prompting the authors to conclude that caution is needed when attempting to make inferences regarding vertebral alignment from observed surface contours.

Another group (Bechtold, Ridl, Hubbard, & Vorro, 1983; Johnston, Vorro, & Hubbard, 1985; Vorro, Johnson, & Hubbard, 1991) conducted a series of tests to compare primary total range of motion, secondary movement patterns, and cervical myoelectrical activity among asymptomatic individuals with and without asymmetrical cervical movements. Three osteopathic physicians who were skilled in manual examination of vertebral motion asymmetry assessed gross and segmental movements. Head motions were recorded with a standard video camera that tracked movement of an orthogonal targeting system (four rods attached to a plexiglass cube and athletic mouth guard) that was held in the mouth of the subjects. Therefore, triplane motion could be recorded, but true three-dimensional motion could not since only one camera was used. System accuracy and precision, near the middle of the visual field, was 3° and 1°, respectively. Subjects, seated in a position of comfort, voluntarily restrained shoulder and trunk movements while performing two active range of motion sets; an examiner later

Table 2.16. Mean Passive Motion (degrees) for the Cervical Spine

Age	n	Flex./Ext.		Lat. Bend		AR		AR from Flex.		AR from Ext.	
		M	F	M	F	M	F	M	F	M	F
20-29	24M[a],15F[b]	152.7	149.3	101.1	100.0	183.8	182.4	75.5	72.6	161.8	171.5
30-39	29M,12F	141.1	155.9	94.7	106.3	175.1	186.0	66.0	74.6	158.4	165.8
40-49	16M,12F	131.1	139.8	83.7	88.2	157.4	168.2	71.5	85.2	146.2	153.9
50-59	10M,14F	136.3	126.9	88.3	76.1	166.2	151.9	77.7	85.6	145.8	132.4
> 60	7M,11F	116.3	133.2	74.2	79.6	145.6	154.2	79.4	81.3	130.9	154.5

Note. M = Male; F = Female; AR = Axial rotation; Lat. Bend = lateral bending; Flex. = flexion; Ext. = extension; Standard deviations ranged from 13° to 20°, with males generally demonstrating greater variation.

performed two passive range of motion sets. Each subject performed maximum forward and backward bending, sidebending to the right and left, and axial rotation to the right and left. Geometrical relationships were used to define three-dimensional head position at the termination of the range. Secondary motions (those motions that occurred about the other two defined axes) were interpreted as if they occurred separately, and were determined relative to a target system that had undergone the primary rotation. Subjects with asymmetrical movements exhibited limited primary and secondary range of motion compared to subjects with normal cervical motion. However, the paths of the more minor secondary deviations, within the limited range, did not differ significantly between the groups suggesting that asymptomatic (but asymmetrical) individuals had the capacity to self-correct. The authors recommended that additional studies on asymptomatic individuals needed to be conducted to determine whether they had the capacity to self-correct with secondary motions.

Roozmon, Gracovetsky, Gouw, and Newman (1993) used a customized version of the WATSMART™ motion analysis system to document straight and out-of-plane cervical spine motion. Others (Houck, Yack, & Mulhausen, 1997; Osterbauer et al., 1992; Osterbauer et al., 1996; Ribaudo, 1993; Winters & Peles, 1990; Winters et al., 1993; Woltring, Long, Osterbauer, & Fuhr, 1994) have used passive marker motion analysis systems to capture head/neck range of motion and to determine finite (Osterbauer et al., 1992; Osterbauer et al., 1996; Ribaudo, 1993; Winters & Peles, 1990; Winters et al., 1993) or instantaneous (Woltring et al., 1994) helical axes in normal subjects and persons with acute and chronic neck pain. In Winters and Peles' (1993) study, the "natural" cervical range of motion was tested by having subjects (9 normal; 18

patients) track targets that were placed on a grid. Position of the head in three-dimensional space was determined by a motion analysis system that tracked five targets placed on a helmet worn by subjects. Average marker positions were used to calculate finite screw (helical) axis parameters (FSAPs). For normal subjects, consistent trends demonstrated that: (1) vertical movements (sagittal plane) had a laterally-directed axis with a midsagittal plane crossing position that was a function of the head orientation, (2) oblique movements had a diagonally-directed axis, and (3) horizontal movements had a vertical axis that was modified near extremes of motion and was influenced by upward and downward bias orientations. Woltring et al. (1994) found a similar pattern for location of the instantaneous helical axis for sagittal plane movement in one subject. Patients tended to exhibit a variety of abnormal screw axis patterns (Osterbauer et al., 1992; Osterbauer et al., 1996; Ribaudo, 1993; Winters et al., 1993; Woltring et al., 1994;), reduced range of motion (Osterbauer et al., 1996; Ribaudo, 1993; Woltring et al., 1994), and reduced angular velocity (Osterbauer et al., 1996). These biomechanical parameters (location of screw axis, range of motion, and angular velocity) were found to be useful to objectively detect cervical abnormalities, but did not correlate with subjective indicators of pain and disability (Ribaudo, 1993; Osterbauer et al., 1996).

Polhemus' 3SPACE Isotrak System™ has been used by several to investigate cervical spine motion (Buchalter, Parnianpour, Viola, Nordin & Kahanovitz, 1989; Ordway et al., 1997; Pearson & Walmsley, 1995; Trott, Pearcy, Ruston, Fulton, & Brien, 1996). The 3SPACE system consists of the following components: (1) a System Electronics Unit (SEU), (2) a source, and (3) a sensor. The source emits and the sensor detects low-frequency magnetic fields, so that position and orientation are determined by a process of updating the previous values by the difference in the magnetic fields detected by the sensor transformed to changes in position and orientation. The SEU contains all the analog circuitry to genenerate and sense the magnetic fields. It also contains the hardware and software to control the intensity of the magnetic signal (relative to the speed of movement and change in distance between the source and the sensor), digitize the signals, and perform the calculations to compute the position and orientation of the sensor. The system is affected by the presence of metallic conductors, limited to 60 Hz movements (An, Jacobsen, Berglund, & Chao, 1988), and tends to contaminate EMG signals (if these are collected simultaneously during motion testing) (McGill, Cholewicki, & Peach, 1997). According to the manufacturer, the device has a static positional accuracy of 0.25 in. root mean square (RMS) and an angular accuracy of 1.5° RMS, provided the sensor to source separation is between 4 and 28 in. (separation distance up to 60 in. is allowed with reduced accuracy). The orientation angle ranges are yaw ± 180°, pitch ± 90°, and roll ± 180°. An et al. (1988) have demonstrated the 3SPACE Isotrak to be accurate and reliable and potentially useful for kinesiological studies, but suggested that measured data be filtered and smoothed to eliminate noise and increase the frequency of subsequent calculations.

Ordway et al. (1997) compared the 3SPACE to radiographic and inclinometric measures of cervical flexion, extension, protraction, and retraction in 20 asymptomatic individuals. Protraction and retraction were reliably measured by all three methods, but without measurement consistency between devices. In contrast to the goniometer, the internally referenced radiographic and 3SPACE methods were well correlated and able to isolate cervical segments. The authors cautioned that subject positioning should be standardized to control and minimize thoracic contributions to the cervical motion measured.

Buchalter et al. (1989) studied cervical, thoracic, and lumbar motion in 60 asymptomatic individuals (27 males and 33 females) aged 31.7 years. With subjects standing erect, motions of the cranial-cervical complex were deduced from sensors placed on the inion and spinous process of C7. Results showed approximately 45° flexion and 55° of extension, with minimal out-of-plane motion. There was approximately 45° of lateral bending to each side and inconsistent coupled axial rotation. Ipsilateral lateral bending consistently occurred when axial rotation (65-70° rotation to one side) was the primary movement. Trott et al. (1996) tested, in a seated position, 120 asymptomatic individuals stratified by gender and age. They found more flexion and extension range of motion than Buchalter et al., but similar degrees of lateral bending and axial rotation. In contrast to Buchalter et al., axial rotation was consistently coupled to the same side as lateral bending. Gender did not seem to affect mobility, but mobility decreased with age (Buchalter et al., 1988; Trott et al., 1996). See Table 2.17 for a summary of Trott et al. data. It is noteworthy that these data are comparable to data from radiographic studies previously summarized.

Table 2.17. Mean Range (degrees) of Active Cervical Movements

Age	Flexion	Extension	Left AR[a]	Right AR	Left LB[b]	Right LB
20-29	57.5	76.1	71.7	78.0	45.5	47.6
30-39	46.8	64.8	71.7	77.5	40.3	44.8
40-49	47.4	61.2	64.2	73.9	38.8	39.4
50-59	45.1	60.0	63.4	70.4	32.4	35.4

Note. Thirty subjects per age group. [a]AR = Axial Rotation; [b]LB = Lateral Bending.

Fryette (1954, 1918) found that the introduction of spinal motion in one plane reduced motion in the other planes. Prior in vitro studies (Beal & Beckwith, 1963;

Panjabi et al., 1993) have shown this motion concept to be true and Dvorak et al. (1992) also demonstrated this phenomenon when they tested axial rotation in full flexion.

Dvorak et al. did not find axial rotation to be decreased from full extension, whereas Walmsley, Kimber and Culham (1996), using the 3SPACE, found that axial rotation was reduced when it was initiated from full flexion, extension, protraction and retraction. Postural changes affecting the pelvis (Hoeberlein-Miller, Katz, & Balogun, 1997), lumbar (Black, McClure, & Polansky, 1996), and thoracic spine (Raine & Twomey, 1994) may also influence cervical position and mobility. Hoeberlein-Miller and co-workers found significant inter-subject variability (n = 26), but no differences in cervical flexion mobility whether the pelvis was in neutral, or anteriorly and posteriorly tilted. They concluded that lumbar and thoracic adaptations could have attenuated the effect of pelvic tilt. Black's group (1996) used the Metrecom™ to measure upper and lower cervical position and an electronic digital inclinometer to monitor lumbar lordosis and pelvic tilt. In contrast to the work just cited, Black et al. found that different extreme sitting postures tended to produce predictable changes in the head-neck complex, lumbar spine and pelvis. As the lumbar spine moved toward extension, the cervical spine moved toward flexion and vice versa. Whether the compensation occurred in the upper or lower cervical spine was uncertain, but the inclination of the cervical base (vector formed between the body of T1 and episternal notch) appeared to be an important component in head and neck posture (Black et al., 1996; Raine & Twomey, 1994).

<u>The Thoracic Spine/Cage</u>

A number of studies employing two-dimensional measures of the trunk and thoracic cage have been conducted. In 1979, Pope, Wilder, Stokes, and Frymoyer described a device that could quantify flexion, extension, lateral bending and circumduction mobility of the trunk. Standing with their pelvis secured, subjects had a harness placed around the trunk at the level of the xiphoid process, which in turn was attached to a string in turn connected to a two-dimensional potentiometer such that movement could be recorded on a chart recorder. Differences in mobility between normal subjects and patients were documented using this method. Dawson et al. (1993) used an optoelectric device to measure the three-dimensional shape of trunk deformity in scoliosis. They found a correlation between the calculated lateral trunk displacement, as determined from the optoelectric measurement, and the Cobb angle, and concluded that changes in curvature could be monitored using their measurement device. Rudy, Boston, Lieber, Kumbinski, and Delitto (1995) described two-dimensional trunk and pelvic motions in normal and symptomatic individuals and found that symptomatic persons exhibited less upper torso and pelvic motion, upper torso axial rotation, and lateral trunk flexion. Using a 27-marker set to define the position of the head, thorax, and pelvis, D'Amico, D'Amico, and Roncoletta (1995) developed an algorithm to automatically quantify scoliotic curves in the frontal and sagittal planes (Cobb angles). Because markers were placed on the skin over every other spinous process from C7 through S3, segmental and intersegmental angles could also be determined during a lateral bending test (D'Amico, Grillet, Mariotti, & Roncoletta, 1995). Automatic reconstruction of a spinal model, based on marker position during the lateral bending movements, allowed investigators to identify regions of motion restriction in patients with scoliosis. Although the methods described above would appear to have some clinical usefulness, they are not able to provide insight into three-dimensional movements and more complex coupled motion patterns.

Several research groups have examined three-dimensional movement patterns of the trunk during ambulation (Crosbie, Vachalathiti, & Smith, 1997; Elders, Greenwald, & Sartor, 1997; Gracovetsky, 1988). Although evidence of the specific nature of coupled lateral bending and axial rotation was not the focus of these studies, consistent three-dimensional trunk motions patterns were demonstrated relative to subphases of the gait cycle. What is most interesting and relevant to this review are the marker sets used to define trunk and pelvic segments and their motions. Both Crobie et al. and Elders et al. used Grood and Suntay's (1983) method to determine three-dimensional Euler angles of the trunk and pelvis. Crosbie's group divided the trunk into discrete segments using reflective marker coordinates to define a series of rigid bodies. An upper trunk segment was defined using markers located over the spinous process of T1, the spinous process of T6, and two paravertebral markers (over rib angles) at the T6 level. A skin-mounted marker on the spinous process of T12 and two paravertebral markers (exact location not specified) defined the lower trunk segment. Markers apparently placed on the skin over the spinous process of L5 and three pelvic sites defined the pelvis. The upper trunk, lower trunk, lumbar, and pelvis segments were treated as rigid bodies and movement was defined in terms of relative motion between the rigid body above and the one below the region of interest. For example, motion of the lumbar spine was defined as the relative motion of the lower trunk segment with respect to the pelvic segment and the relative motion of the lumbar and upper trunk segments defined the lower thoracic region. The relative attitude of the "rigid bodies" representing the trunk segments with respect to the laboratory coordinate system was also investigated. Crosbie and co-workers recognized that the marker set they used was likely subject to significant marker movement error due to placement on paravertebral soft tissues. They presumed that this error would be especially evident with axial rotation of the trunk, but did not quantify it. The assumption that Crosbie et al. made regarding the spine segments (as defined by them) as rigid is flawed, especially in the thoracic region due to the presence of the rib cage. It might be better to assume that in normal subjects smooth, rhythmic movement of a specific spinal region is a consequence of smooth, rhythmic movement of a superior vertebral segment on the one below it, and so on.

Elders et al. (1997) pilot-tested three trunk targeting protocols to be used during a full-body gait analysis: (1) bilateral mid-clavicles and spinous process of T4; (2) sternal notch, xiphoid process, and spinous process of T4; and (3) sternal notch and spinous processes of T4 and T9. The pelvis was marked at bilateral anterior superior iliac spines (ASIS) and spinous process of S2. Protocol one was discarded because extraneous motion of the clavicles due to shoulder girdle movements resulted in erroneous thoracic cage motion, compared to the other two methods. Protocol two was discarded because the xiphoid target was often lost from camera views when full-figured women were tested. Using protocol three, results showed an intra-subject coefficient of variation ranging from 52-76% for trunk angles determined relative to the laboratory coordinate system. Elder's marker set would seem to be less prone to marker movement error with axial rotation of the trunk and may more accurately and reliably represent thoracic cage movement. However, any marker placed on the sternum may not reflect "true" thoracic spine movements because of sternal and rib movements.

Haideri et al. (1997) also used a passive marker motion analysis system to measure trunk, lumbar and pelvic motion during ambulation and trunk range of motion testing. Their objective was to create a model that could be used to study functional impairments associated with a given pathology, such as scoliosis, and evaluate changes following surgical intervention. They placed markers on the skin over the following anatomical landmarks: right and left ears, spinous process of C7, right and left acromion processes, right and left 11th rib costal angles, right and left lateral pelvic crests, sacrum, and right and left ASIS. Embedded local coordinate systems were constructed within the thoracic spine, lumbar spine, and pelvis and used to compute Euler rotation angles for each of the segments. The pelvis was considered the root segment and its motion was measured relative to a global or laboratory coordinate system, while the lumbar spine was measured relative to the pelvis, and thoracic segment relative to the lumbar spine. During ambulation the thoracic and lumbar segments tended to move in opposition to one another in the sagittal and frontal planes, but synchronously in the transverse plane. With trunk motion testing (flexion/extension, lateral bending, and axial rotation) significant out-of-plane movements were detected when the primary movements were in the frontal and transverse planes. The thoracic and lumbar segments demonstrated opposing movements, but within specific segments, lateral bending and axial rotation coupling patterns were not reported. Shared markers were used to define the lumbar segment (markers placed over the 11th ribs were used to define both the thoracic and lumbar segments) and this may have caused an underestimation of this segment's perceived mobility. Beyond that, it is highly doubtful whether markers placed on the soft tissue of a floating rib could represent movement of the lumbar region. Similarly, use of markers on the acromion processes to define the thoracic segment may have resulted in an overestimation of thoracic cage mobility.

Ployon et al. (1997) developed a 14-target marker set (forehead, chin, both temples, bilateral acromions, bilateral ASIS, sacrum, spinous process of C7, and four others over spinous processes chosen in relation with the pathology) which allowed them to identify global posture and spinal kinematic characteristics of individuals with scoliosis. Axis systems were attributed to the head, spine (from C7 to the sacrum), shoulders, and pelvis. Four projected angles on the frontal plane (head, shoulders, spinal axis, and pelvis), two on the sagittal (head and spinal axis), and two on the transverse plane (head and shoulders) defined the posture. Three-dimensional angular positions of the various axis systems were made relative to a global axis system. Postures and main motions were useful to characterize changes following treatment. Coupled motions were measured, but were found to be clinically insignificant (less that 5°). In contrast, Farahpour, Allard, Labelle, Rivard, and Duhaime (1995) examined spinal mobility in five female individuals with idiopathic scoliosis (right thoracic deformity of $37^{\circ} \pm 7.5^{\circ}$, left lumbar compensatory curve of $31^{\circ} \pm 5.7^{\circ}$) and five females without pathology and noted significant coupling patterns in both groups. They used two sets of markers. One marker set consisted of a V-shape triad having a reflective marker at its base, and two others at the extremity of a thin and rigid 3-cm mesh placed over the T1, T3, T6, T8, T10, T11, T12, L1, L3, L5, and sacrum spinous processes. The other set had single 1.25-cm markers placed over each acromion to identify the shoulder and others on the iliac crests and sacroiliac spine to control for pelvic motion. Subjects performed a flexion movement, right and left lateral bending, and axial rotations. Rotations between any two triads were estimated by Euler angles; however, only whole spine (T1-L5), thoracic (T1-T12), and lumbar (L1-L5) motions were reported for right lateral bending. Although scoliosis resulted in a relatively "rigid" (compared to normal) thoracic segment, the coupling patterns were the same as in the normal subjects: right axial rotation and extension for the whole spine, left axial rotation and extension for the thoracic segment, and right axial rotation and flexion for the lumbar segment.

Cheng (1993), also motivated by finding a non-invasive method to analyze spinal motions in patients, developed spinal models using Grood and Suntay's joint coordinate system method to describe: gross motion of the cervical spine, orientation of the thoracic cage relative to the pelvis, gross motion of the whole thoracic and lumbar spines, and orientation of each point on the spinal curve relative to the pelvis. Thoracic cage movement was measured as relative motion between an embedded coordinate axis system on the thorax, formed by markers on the sternal notch, xiphoid, and spinous process of T1, and a pelvic axis system (as described by Elders et al., 1997). Gross motion of the thoracic spine was determined by calculating relative motion between coordinate axes on the upper (marker set described above) and lower thorax (markers placed at xiphoid and spinous processes of T10 and T12), while lumbar spine motion was determined from the lower thoracic and pelvic defined segments. Cheng assumed that since the thoracic spine was less mobile than the lumbar spine, movement of the thoracic cage, relative to the pelvis, was a good approximation of gross motion of the lumbar spine. One subject, free of pathology, performed a lateral bending, flexion, and axial rotation movement from the standing position. For the thoracic cage and spine, there did not appear to be significant axial rotation coupled with lateral bending, but lateral bending was coupled contralaterally when axial rotation was performed.

Cheng also ran a series of static test conditions: standing erect, standing in maximum right lateral bending, standing in forward flexion, and standing in maximum right axial rotation. Target linkages (base and distal markers) located perpendicular to the skin over the spinous processes of T1, T3, T5, T7, T9, T11, L1, L3, L5, and S1 were tracked in each of the static test conditions for four seconds. Using a quintic spline to curve fit the upper and lower markers and differential geometrical methods, in combination with a joint coordinate system to create a trihedron at each point, the orientation of each point on the spinal curve relative to the pelvis was determined. The spinal curves were projected onto three orthogonal planes, which allowed for the evaluation of standing posture and the change in spinal posture with movement. Space curvature and torsion were found to be useful qualitatively to distinquish different curve conditions. Cheng's method holds some promise for clinical application, especially as it pertains to measuring scoliotic curves non-invasively.

Buchalter et al. (1989) used the 3SPACE to measure three-dimensional kinematics of the whole thoracic spine, whereas Willems, Jull, and Ng (1996), using a similar device, divided the thorax into upper (T1-T4), middle (T4-T8), and lower (T8-T12) segments. Both groups tested 60 normal subjects, with an equal number of males and females. Buchalter's group found about an equal amount of extension mobility in the thoracic and lumbar spines, but significantly more flexion in the lumbar region. Flexion and extension were relatively pure movements, but perceptible frontal and transverse plane motions (on the order of 1°-5°) were consistently found (Buchalter et al., 1989;

Willems et al., 1996). Buchalter et al. found that lateral bending and axial rotation were always coupled contralaterally, regardless of which motion was introduced first, which is similar to Cheng's and Farahpour's (whole thoracic spine) results. However, Willems et al. found that when lateral flexion was introduced first, axial rotation was coupled ipsilaterally 47%, 83%, and 68% of the time in the upper, middle, and lower thoracic regions, respectively. When axial rotation was the primary motion, ipsilateral lateral bending occurred 18%, 99%, and 93% of the time in the respective thoracic segments. The upper thoracic coupling patterns reported by Willems et al. are not consistent with the coupling patterns reported earlier (Veldhuizen & Scholten, 1987), where the upper thoracic vertebrae were found to function similarly to cervical vertebra, i.e., sidebending and axial rotation always coupled to the same side. The patterns in the middle and lower thoracic regions also seem to demonstrate more variability than what was reported from in vitro studies and may be a reflection of the neurological control that is absent when cadaver studies are performed. See Table 2.18 for details of regional primary motions as found by Willem et al. (1996).

How can one justify the differences in results presented by Cheng, Buchalter, and Willems? Could they be due to methodological differences? For example, Cheng (1993) and Buchalter et al. (1989) tested subjects in standing, whereas Willems' group (1996) performed measurements with subjects sitting. In the study by Willems et al. subjects sat on a wooden bench with feet flat on the floor, with a lumbar support adjusted to fit into the back and pelvis and thighs secured. In Buchalter's study subjects stood in an upright position and performed the thoracic movements with arms folded across their chest. For

Table 2.18. Mean (± SD) Primary Motion (degrees) in Specified Thoracic Regions

Movement	T1-T4		T4-T8		T8-T12	
	Male	Female	Male	Female	Male	Female
Flexion	7.8(5.0)	9.5(4.9)	10.0(3.3)	11.4(4.3)	12.5(2.8)	12.8(3.9)
Extension	9.0(6.4)	7.1(7.8)	9.9(5.8)	7.9(4.6)	7.8(4.6)	9.7(5.2)
Lateral Flexion (R)	6.2(2.7)	6.2(2.1)	7.7(2.3)	8.5(2.3)	12.4(2.9)	11.9(2.3)
Lateral Flexion (L)	5.6(2.5)	6.1(2.9)	8.1(2.5)	7.9(2.1)	13.2(2.4)	12.0(2.3)
Axial Rotation (R)	15.9(4.9)	14.4(4.6)	25.3(6.7)	24.3(6.7)	8.3(6.1)	7.9(5.5)
Axial Rotation (L)	12.1(5.1)	11.8(4.4)	22.1(6.3)	21.5(4.6)	11.8(4.9)	8.3(4.2)

flexion they curled the trunk forward with emphasis on movement throughout the thoracic spine rather than the lumbar spine. Extension was initiated with a chin retraction, then followed by cervical spine extension action and thoracic extension. For axial rotation and lateral flexion subjects were instructed to allow their heads to follow the respective thoracic action, which was based on preliminary testing that showed how upper thoracic axial rotation and lateral bending could be influenced by the position of the head/neck. Nachemson and Morris (1964) demonstrated changes in intradiscal pressure in standing and sitting suggesting differences in spinal loading, which could then influence spinal movement behavior. Normal healthy subjects, as determined by prior screening, were used in the studies just reviewed, but individuals whom have asymmetrical movements (as determined by a skilled manual medicine practitioner) and are asymptomatic could present with a large variety of secondary movement patterns. Additionally, it appeared that Willems et al. included some subjects with minor rib humps (an indication of scoliosis), which may have also contributed to inter-subject variability.

The Lumbar Spine

A number of non-invasive methodologies have been used to measure two-dimensional gross and segmental lumbar motion. Electronic goniometers (Adams, Dolan, Marx, & Hutton, 1986; Otun & Anderson, 1988) and wire potentiometers (Marrus & Wongsam, 1986) have been developed to measure sagittal plane motion during dynamic activities in clinical or work settings. Ranges of motion and angular velocities were both found to be reliable quantitative measures that were different among normal subjects and patients with low back pain (Marrus & Wongsam, 1986).

Robinson et al. (1993) used a video-based motion analysis system to measure flexion, extension, sidebending, and axial rotation of the thoraco-pelvic, thoracolumbar, and lumbar spinal regions in a group of patients with chronic back pain. Reproducibility for range of motion measurements (Intraclass Correlation Coefficients (ICC)) ranged from 0.77-0.96) and for angular velocity (ICC ranged from 0.75-0.97) was good. Shirley et al. (1994), in comparing a video-based motion analysis system to an inclinometer technique and the MedX™ lumbar extension testing machine, found that motion analysis tended to yield significantly lower range of motion values in the lumbar spine. However, they concluded that motion analysis was potentially more useful because it could record dynamic motion patterns, whereas the other two devices recorded motion only at the extremes of motion. Smidt et al. (1994) described a device that recorded coordinates of external body landmarks in three-dimensional space, which were used to obtain sagittal and frontal plane angles for the lumbar spine in various seated postures. They found that all seated postures were well within the extreme passive ranges of motion established by sidebending left and right, flexion, and extension. In comparing individuals with and without scoliosis, Smidt et al. noted that ranges of motion were similar, seated postures decreased the lumbar lordosis similarly in both groups of subjects and seated postures increased the lateral curvature in persons with scoliosis.

Jayaraman et al. (1994) employed a video-based motion analysis system and a force platform to analyze lateral bending behavior of subjects with normal (n = 12) and painful (n = 10) spines. Individuals, with markers placed on the spinous processes of C7, T7, L1, L3, and S1, stood symmetrically on a force platform. Motion and force data were synchronously collected with subjects standing erect, maximally sidebent to either side, and while performing sidebending movements to both sides at normal and maximum speeds. The following parameters were analyzed: (1) angular velocity and maximum angle of sidebending (from vertical) for four spinal segments, e.g., segment one was comprised of the region spanning C7-T7, segment two the region from T7 to L1, etc.; (2) center of pressure and ground reaction moments; and (3) "compliance", defined as a measure of the angle of rotation per unit ground reaction moment, and "transfer mobility" or measure of the angular speed per unit ground reaction moment. Results showed that range of motion and angular velocity were markedly reduced in patients with low back pain, particularly in the lower segments. Decreased "compliance" and altered "transfer mobility" in patients suggested that quality of sidebending was just as important, if not more important, as maximum range of motion in characterization of patient movement profiles.

Chen and Lee (1997) sought to develop a non-invasive method to predict the lumbosacral vertebral angles. They placed external markers on the skin overlying the spinous processes of L1, L3, L5, and S1, with additional markers attached at the shoulder, caudal-most point on the iliac crest, greater trochanter, lateral femoral condyle, and lateral malleolus. With subjects holding their torsos upright and then at 90°, 120°, 150°, and 180° flexion, marker positions were captured with an optoelectronic system, while vertebral positions were radiographed. Despite the fact that videographic data of the externally measured marker angles demonstrated virtually no agreement with the radiographically measured vertebral angles, linear regression models for calculating vertebral angles at L1, L3, L5, and S1 were validated.

Gracovetsky (1990, 1988) and Gracovetsky et al. (1995) used the Spinoscope™ (a specially designed optoelectronic system with a resolution 64 times better than television-based video systems) to measure sagittal and frontal plane motion of the lumbar spine and pelvis. He placed 12 light-emitting diode markers on the skin overlying the spinous processes from C7 to S2, with markers 1 and 9 (positioned over the spinous processes of C7 and L4, respectively) placed to provide references for locating the position of the remaining 10 spinal markers. Subjects were tested in the standing position. Using the information collected on the position of the markers 1 and 9, Gracovetsky et al. (1995) used an algorithm that calculated the position of the other vertebra according to a method proposed by Bryant et al. (1989). Forty (20 men, 20 women) aged 19-64 years were then tested standing still, during flexion/recovery from flexion (unloaded and with loads of 11 kg, 23 kg and 45 kg), and during right and left lateral bending (unloaded and with a 4.6 kg load). Many parameters were determined: (1) Thoracolumbar flexion and recovery from flexion were determined as the angle of the 'best fit' line through markers 1-12 projected in the sagittal plane, and measured from the vertical; (2) Thoracolumbar lateral bending to the right and left were determined as the best fit line projected in the frontal plane, and measured from the vertical; (3) Pelvic contribution to total trunk motion in the sagittal (flexion) and frontal (lateral bend) planes was determined by projection of a vector perpendicular to the horizontal plane of the pelvis and the vertical; (4) Lumbar lordosis was estimated as the angle between two lines perpendicular to the tangents at the estimated levels of T12-L1 and L5-S1; and (5) Lumbar elongation was the percentage increase in arc distance between estimated levels T12-L1 and L5-S1 during flexion. Gracovetsky hypothesized that skin motion contained recognizable, specific, and consistent patterns that were accessible to measurement. Therefore, using position data from three lumbar markers (5, 6, and 7) he also estimated lumbar intersegmental mobility (ESIM) for flexion, recovery from flexion, and lateral bend to the right and left. Average error between true and ESIM ranged from 0.71° to 3.65°. Gracovetsky concluded that non-invasive measurements should be considered as an acceptable source of information during dynamic response of the un-restrained spine. See Table 2.19 and Table 2.20 for a comparison of ESIMs to values based on cadaver and radiographic studies presented previously. With regard to the different loading conditions that Gracovetsky used: (1) There were no differences in ESIM during flexion or lateral bending, and (2) There was an increase in ESIM in the lower lumbar levels during recovery from flexion.

Several investigators examined kinematic coordination of the lumbar spine and pelvis during trunk flexion and extension (Esola, McClure, Fitzgerald, & Siegler, 1996; Gracovetsky et al., 1995; Leskinen, Takala, & Stalhammar, 1987; McClure, Esola, Schreier, & Siegler, 1997; Nelson, Walmsley, & Stevenson, 1995; Paquet, Malouin & Richards, 1994; Porter & Wilkinson, 1997). Gracovetsky et al. (1995) also looked at frontal plane coordinated motion of the thoracolumbar spine and pelvis. During extension from a stooped, or knees extended, position (lifting) pelvic rotation (relative to the thigh or lab) preceded extension of the lumbar spine throughout the movement (Leskinen et al., 1987; McClure et al, 1997; Nelson et al., 1995). When stooping down or when bending forward with knees extended lumbar flexion preceded pelvic tilt (Esola et al., 1996; Leskinen et al., 1987). Gracovetsky et al. found an approximate 50/50 division between the lumbar spine and pelvic contributions during forward, backward, and sidebending tasks, whereas Nelson et al. noted that lumbar and pelvic motion occurred simultaneously during flexion, but during extension the movements were more sequential. Esola et al. divided the flexion phase into three parts, early (0-30°), middle (30-60°) and late (60-90°), and found that the lumbar spine contributed more to early forward flexion and the hips (pelvis) contributed more to the later stage. During the extension phase the hips contributed more in the early phase and the lumbar spine more in the later stages (McClure et al., 1994). Although inter-subject variability was high (Leskinen et al., 1987; Nelson et al., 1995), assessment of lumbar spine, pelvic, and hip motion holds promise with regard to longitudinal clinical assessment of individuals who have low back pain (Esola et al., 1996; McClure et al., 1997; Paquet et al., 1994). For example, Porter and Wilkinson (1997) found a significant reduction in maximum lumbar mobility and changes in hip contribution to total trunk flexion in a group of individuals with chronic low back pain.

The relationship between the pelvis and lumbar spine has also been investigated with regard to standing posture (Levine & Whittle, 1996) and walking (Rowe & White, 1996; Whittle & Levine, 1997; Whittle & Levine, 1998). Using the Isotrak device, Rowe and White (1996) determined the three dimensional motion of the lumbar spine relative to the pelvis during ambulation (during the gait cycle the lumbar spine is operating under neutral mechanics). They found that axial rotation and sidebending were coupled to the same side. Whittle and Levine (1997) determined pelvic motion in the sagittal, coronal, and transverse planes from the relative positions of one marker on each ASIS and one on the spinous process of S2. However, for these studies only sagittal plane (the angle between the horizontal plane and the line joining the sacral marker to the midpoint between the two ASIS markers) angles were reported. Measurement of lumbar lordosis

Table 2.19. Mean (±SD) Degrees of EI Flexion Mobility of Lumbar Spine Segments

Author	Year	n	T12-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1
Clayson et al.	1962	26	-	3.0(1.8)	3.7(1.9)	3.9(2.6)	2.8(3)	0.6(5.5)
Pearcy & Tibrewal	1984	11	-	8.0(5)	10.0(2)	12.0(1)	13.0(4)	9.0(6)
Yamamoto et al.	1989	10	-	5.8(0.6)	6.5(0.3)	7.5(0.8)	8.9(0.7)	10.0(1)
Gracovetsky et al.	1995	40	4.5(2.3)	8.1(2)	10.9(2.8)	12.0(3)	11.3(2.6)	11.2(2.9)

Note. A dash indicates that no data were available. EI = estimated intersegmental.

Table 2.20. Mean Degrees of EI Lumbar Mobility in LB Left and Right

Author	Year	n	T12-L1	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1
Tanz	1953	14	-	5.4	7.8	8	8.2	2.3
Pearcy et al.	1984	10	-	10	11	10	6	3
Yamamoto et al.	1989	10	-	9.9	14	16.5	11.4	11.4
Gracovetsky et al.	1995	40	4.6	7.7	9.9	10.3	9	9

Note. A dash indicates that no data were available. LB = lateral bend.

involved the use of two measurement rigs, each of which consisted of a flat plastic plate that was taped to the skin over the sacrum (S2) and the upper lumber (T12-L1) spine. Each rig covered approximately two spinal levels and was small and light enough so as not to interfere with subjects' posture or gait. Rigs had one marker placed directly on the flat plate and one on the end of a light metal rod (center-to-center distance ~117 mm). The rod on the upper rig pointed backward and upward; the rod on the lower rig back and downward, so that angles were formed (lumbar wand angle and sacral wand angle) between the surfaces of the rigs and the line joining the two markers. To measure the lumbar and sacral wand angles, the rigs were placed on the floor, with the skin-contact surface horizontal. The angle between the skin surfaces in the lumbar and sacral regions was determined from positions of the two markers on each rig and the known lumbar wand and sacral wand angles. The angles between the skin surfaces in the two regions were subtracted, giving the lumbar lordosis angle. Based on preliminary studies, where either four (L1, L3, L5, and S2) or three (L1, L4, and S2) skin-mounted markers were used to measure lumbar lordosis, Whittle and Levine (1997) concluded that: (1) A 4-marker set would not work for smaller individuals; and (2) A 3-marker set could work, but resulted in more noise and larger coefficient of variation (24%) compared to the rig method (2%). Reliability showed good test-retest agreement (ICC and r values exceeded 0.90) for measuring pelvic tilt and lumbar lordosis for both the standing pelvic tilt tests and during ambulation. Results showed that anterior tilt of the pelvis caused an increase in the lumbar lordosis, and a posterior tilt caused a decrease in the lumbar lordosis. Maximum tilt of the pelvis, however, did not produce maximal amounts of lumbar flexion or extension. During ambulation the pelvis and lumbar spines moved in phase, i.e. when the pelvis increased its anterior tilt the lumbar lordosis increased. Although these preliminary studies presented only two-dimensional data, they are significant because they: (1) confirmed that a significant relationship existed between position and movement of the lumbar spine and pelvis, and (2) demonstrated that using skin-mounted marker rigs may be more accurate than skin-mounted markers when assessing spinal motions. Subsequent studies revealed the three-dimensional relationship between the pelvis and lumbar spine during walking (Whittle & Levine, 1998). In agreement with Rowe and White, axial rotation and lateral bending were coupled ipsilaterally.

The ability to accurately and reliably measure three-dimensional movements of the lumbar spine in normals and patients is motivated by the high incidence of low back pain syndromes. Gomez, Moore, and Silver (1991) used the Isostation B-200 Lumbar Dynamometer™ to establish a normative database (85 men, 83 women; 18-68 years old) for trunk range of motion, strength, velocity, and endurance. The B-200 is a computer-controlled hydraulic apparatus that can three-dimensionally measure position, torque, and velocity in real time and has been shown to be valid and reliable. During standard test procedures subjects stand in an upright neutral position with the pelvis and lower extremities securely fixed. The flexion/extension axis of the B-200 is aligned approximately with the lumbosacral junction. Gomez et al. reported maximum range of motion for flexion, extension, sidebending, and rotation, but out-of-plane motions were not given. In a follow-up study of 120 low back pain patients, Gomex (1994) found a similar pattern of asymmetry in both normal individuals and patients, although patients demonstrated a greater asymmetry and more inter-trial variability. Gomez hypothesized that, because of the large number of interdependent functional units involved in during trunk motions, there would be a great adaptive potential that would allow for normal function even if one or more functional units were impaired. He concluded that the concept of a normal population that possessed ideal structure was unrealistic; therefore, there was a need to first study the asymptomatic population before determining the importance of asymmetries in the symptomatic population.

Marrus, Fathallah, Miller, Davis, and Mirka (1992) described a lumbar motion monitor (LMM) that recorded potentiometer signals, which correlated to trunk angles relative to the pelvis. Recorded signals are subsequently processed to determine the three-dimensional motion and angular velocity and acceleration of the lumbar spine. The LMM is an exoskeleton of the lumbar spine that replicates motion of the "T" segments (spinous process and paired transverse processes) that is attached to the thorax/shoulders and pelvis with a semi-rigid plastic material. It appears to be well suited for use in clinical and work settings because it is lightweight and may not encumber normal motion, ease of application, and ability to measure motion in real time. This device has been shown to be more accurate than a two-dimensional motion analysis system (Marrus et al., 1992) and is highly reliable (Gill & Callaghan, 1996; Marrus et al., 1992; Marrus et al., 1995). Normal ranges of motion of the thoracolumbar spine (subjects usually tested standing), and angular velocities and accelerations have been established (Marrus et al., 1995, 1994) in planes of symmetry (flexion and extension) and asymmetry (flexion and extension with the spine in specific degrees of axial rotation). Marrus and his co-workers hypothesized that trunk motion characteristics, or a "signature", of motion contained a large amount of information about the status of the trunk's neuromusculoskeletal control system. In testing subjects with low back pain of various etiologies the authors found that range of motion, velocity, and acceleration in the sagittal plane decreased with increasing task asymmetry, with most pronounced differences occurring in terms of angular velocity and acceleration (Marrus et al., 1995, 1994). The findings with regard to angular velocity are consistent with those of Jayaraman, Nazre, McCann, and Redford (1994).

The OSI CA 6000 Spine Motion Analyzer™, described earlier, has also been used to measure lumbar spine mobility. Normal values for cardinal plane movements and angular velocities have been established using the CA-6000. Reliability of the CA-6000 was shown to be sufficiently high to warrant its use for clinical and research purposes (Dopf, Mandel, Geiger, & Mayer, 1994; McGregor, McCarthy & Hughes, 1995; Peterson, Johnson, Schuit, & Hayes, 1994). Dopf and co-workers have demonstrated the superiority of the CA-6000 over the double inclinometer and Schober techniques for assessing lumbar mobility. With regard to coupled movements: (1) axial rotation was significantly decreased when the spine was forward flexed and in the neutral erect position (Dopf et al.), (2) lateral bending was coupled with axial rotation to the same side, and (3) when lateral bending was the primary motion axial rotation occurred to the same side approximately 50% of the time (Schuit & Rheault, 1997).

Thurston (1982) was perhaps the first to use computerized three-dimensional video motion analysis to attempt to capture lumbar and pelvic motion during walking. He used two rigs, an upper lumbar rig, bearing four targets, and a lower sacral rig, bearing three targets. Straps secured the upper lumbar and lower sacral rigs around the lower thorax and pelvis, respectively. Using a simulator prior to testing with humans, the least accurate measurements were found to be associated with transverse plane movements. The greatest variability during walking occurred with sagittal plane movements of the pelvis (3.4° ± 0.90°).

Others have since studied motion of the lumbar spine segments relative to the pelvis during walking and trunk motion testing, but used different marker sets (Cheng, 1993; Crosbie, Vachalathiti, & Smith, 1997; Haideri et al., 1997). Crosbie and co-workers created an embedded coordinate system on the lower trunk using skin-mounted targets on the spinous process of T12 and two paravertebral targets. The local pelvic coordinate system was developed using four skin-mounted targets (spinous processes of L5 and S3 and bilateral posterior superior iliac spines). Haideri et al., acknowledging the difficulty in locating reliable marker locations in the lumbar region, used a shared marker approach to define a "lumbar" coordinate system. Markers placed on the skin overlying the spinous process of C7 and 11th rib costal angles were used to define a lower trunk coordinate system, while markers on the right/left lateral pelvic crests, sacrum, and right/left ASIS were used to define a pelvic coordinate system. Cheng assessed lumbar spine motion by measuring relative motion between a lower thoracic coordinate system, created by skin-mounted markers on the spinous processes of T10 and T12 and one on the xiphoid, and a pelvic coordinate system (bilateral ASISs and sacrum). None of these investigators assessed the accuracy or repeatability of their targeting schemes, so it is difficult to know which technique may be most appropriate for clinical use.

Using the trunk and pelvic rigs described by Thurston (1982), Pearcy, Gill, Whittle, and Johnson (1987) reported standing lumbar straight plane and coupled range of motion patterns for six healthy subjects. Results showed that flexion mobility was greater than extension. Sagittal plane motion occurred with minimal coupled side flexion or axial rotation. Cheng (1993) and Haideri et al. (1997) likewise found insignificant out-of-plane movements during sagittal plane motion tests. Axial rotation and sidebending were coupled contralaterally (Pearcy, Gill, Whittle, et al., 1987), although Cheng found this be negligible. When axial rotation was the primary motion, secondary sidebending occurred in the opposite (Pearcy, Gill, Whittle, et al., 1987) or same (Cheng, 1993) direction. Coupled sagittal plane motion occurred with both axial rotation and sidebending: (1) Pearcy et al. found some flexion with axial rotation and extension with sidebending, whereas (2) Haideri noted that the lumbar spine tended to move anterior during lateral bending. These data suggest that secondary motions may not be "determined" or consistent, but may be highly individualized and variable.

Pearcy, Gill, Hindle, and Johnson (1987) compared the results of trunk motion testing using a video-based motion analysis system and a CODA-3™ scanner. The CODA-3 is an optical scanning device that sends out three fan-shaped beams of light, producing a rectangular cone shaped field of view, to retro-reflective prisms attached to a subject (in this case, one rig taped to the spinous process of L1 and the other strapped to the sacrum). The light is sent out via three octagonal, synchronized rotating mirrors (two vertical and one horizontal). The three-dimensional position of the prisms is determined when sensors in the rotating mirrors detect reflected light. This device was initially limited (compared to the video system) by crossover conflict (Pearcy, Gill, Hindle, et al., 1987), where loss of information occurred when any two markers came within approximately 25 mm of each other in a horizontal or vertical plane. Hindle, Pearcy, Gill, and Johnson (1989) were able to overcome the crossover conflict when they tested the sagittal and transverse plane lumbar motion of 16 normal subjects in standing and two sitting postures. In standing, more maximum flexion was recorded than maximum extension, with both values being comparable to values obtained from bi-planar radiography. CODA-3 measurements of axial rotation measurements were significantly more than those recorded radiographically, likely due to excess sliding of the thoracic rig. More axial rotation was found in the two sitting postures, where the lumbar spine was flexed to approximately 40% and 65% of its maximum, compared to standing. Coupled contralateral sidebending during axial rotation was recorded, but it was not consistent.

The 3SPACE has also been used to measure lumbar mobility in three dimensions (Hindle & Pearcy, 1989; Hindle, Pearcy, Cross, & Miller, 1990; Mulvein & Jull, 1995; Peach, Sutarno, & McGill, 1998; Pearcy, 1993; Pearcy & Hindle, 1989; Russell, Weld, Pearcy, Hogg, & Unsworth, 1992; Russell, Pearcy, & Unsworth, 1993). True lumbar spinal motion tended to be overestimated (Pearcy & Hindle, 1989), but the 3SPACE demonstrated the ability to reliably quantify whole kinematic patterns. In agreement with previous studies using the CODA-3, axial rotation tended to increase with subjects seated with the lumbar spine submaximally flexed (Hindle & Pearcy, 1989; Pearcy, 1993). Standing flexion tended to tighten posterior soft tissues resulting in less axial rotation. In addition, regardless of the position of the lumbar spine (neutral or flexed), axial rotation and sidebending were always coupled to the opposite side. Subsequent research (Peach et al., 1998) demonstrated that lateral bending and axial rotation were coupled to the same side. Flexion seemed to be consistently coupled with lateral bending, but inconsistently coupled with axial rotation (Peach et al., 1998; Hindle & Pearcy, 1989; Pearcy, 1993). Recently, Mulvein and Jull (1995) examined upper (L1-L4) and lower (L4-S1) mobility during lateral bending and lateral shifting maneuvers. They observed that the lateral shift resulted in more movement in the lower lumbar region, suggesting that this may be an important adjunctive mobility test procedure for low back pain patients. Furthermore, they found that both lateral bending and lateral shift were coupled with flexion in the upper lumbar region, but extension in the lower segments. With regard to coupled transverse plane motion the following results were reported: (1) In the upper lumbar region contralateral axial rotation was found 48% and 81% of the time with sidebending and lateral shifting, respectively, and (2) In the lower region contralateral axial rotation was found 88% and 66% of the time for the respective movements.

Summary of in vivo Research on Cervical, Thoracic, and Lumbar Kinematics

This section will provide a summary of cervical, thoracic, and lumbar kinematics as just reviewed. Where possible, comparisons will be made to data from in vitro and radiographic studies.

When external measurement systems were used to study the cervical spine, the head and neck were studied as one unit (Adams et al., 1994; Alund & Larsson, 1990; Bechtold et al., 1983; Buchalter et al., 1989; Dvorak et al., 1992; Murphy et al., 1984; Winters & Peles, 1990; Woltring et al., 1994). Therefore, the reader must be careful when interpreting the research findings just presented since it is has been established that the cervical spine has two distinct functional units, i.e. C0-C1-C2 and C2-C7. In vivo studies have shown that the head/neck complex (heretofore referred to as the cervical spine) moves freely in all planes nearly equally, with passive mobility exceeding active mobility (Dvorak et al., 1992). With regard to coupled motion patterns: (1) axial rotation was always coupled to the same side as sidebending, and vice versa (Alund & Larsson, 1990; Buchalter et al., 1989; Trott et al., 1996), and (2) extension was occasionally coupled with sidebending. When maximum forward bending was introduced, axial rotation was significantly reduced. The motion that remained corresponded to the range of motion that was available at the atlanto-axial joint, suggesting that axial rotation with full flexion could be used clinically to isolate the C1-C2 segment (Dvorak et al., 1992). Cervical extension, protraction, and retraction also reduced axial rotation, but not to the same degree as maximum flexion (Walmsley et al., 1996). These findings support one of Fryette's (1954, 1918) concepts, namely, that motion introduced in one plane will result in a concomitant reduction in motion in the other planes. Altering the posture of the pelvis, and lumbar and thoracic spines were shown to affect cervical posture and kinematics, but additional research is needed to more consistently define these changes (Black et al., 1996; Hoeberlein-Millet et al., 1997; Raine & Twomey, 1994). Asymptomatic individuals with asymmetrical cervical mobility showed decreased motion in primary and secondary planes compared to normals, but seemed to have compensated in subtle ways (Johnson et al., 1985; Vorro et al., 1991). Further analysis of this phenomenon is needed. Analysis of the cervical spine, during straight- and oblique-plane movements in healthy subjects and patients, demonstrated altered location of screw axes, suggesting that this biomechanical parameter could be used in a clinical setting (Osterbauer et al., 1992; Osterbauer et al., 1996; Ribaudo, 1993; Winters et al., 1993; Woltring et al., 1994).

Thoracic spine motion in the transverse plane was greater in the upper and middle regions (T1-T8) and significantly less in the more caudal segments (Buchalter et al., 1989; Willems et al., 1996). Flexion, extension and lateral bending were found to increase in the more caudal (inferior) segments, with flexion range of motion generally exceeding extension range of motion in the lumbar region (Buchalter et al., 1989). These findings are similar to results from in vitro studies discussed previously. With in vitro testing of vertebral segments flexion was consistently coupled with sidebending, but in vivo sagittal plane movements were inconsistently coupled with frontal and transverse plane motions (Buchalter et al., 1989; Willems et al., 1996).

When the sidebending/axial rotation coupling patterns were assessed for the thoracic spine as a whole, some researchers found that these motions were always coupled to the opposite side (Buchalter et al., 1989; Cheng, 1993; Farahpour et al., 1995). When the thoracic spine was segmented into upper (T1-T4), middle (T4-T8), and lower (T8-T12) sections axial rotation was ipsilaterally coupled with sidebending approximately 50%, 80%, and 70% of the time in the respective regions (Willems et al., 1996. When axial rotation was the primary motion sidebending occurred to the same side greater than 90% of the time in the middle and lower regions, but only 20% of the time in the upper thorax (Willems et al., 1996).

These findings on normal healthy subjects are not consistent with the findings based on in vitro, in vivo radiographic, and mathematical modeling studies. Several investigators have suggested that transverse plane rotation seemed to have the highest signal to noise ratio secondary to marker sets that were placed on the skin overlying spinous processes and/or paravertebral soft tissue (Crosbie et al., 1997). Therefore, differences in findings could be related to measurement error. Secondly, methodological differences could explain result variances. For example, some subjects were tested standing while others were tested sitting. In sitting, individuals often assume a posture that puts the pelvis in posterior rotation, which can result in decreased lumbar lordosis and affect changes to the kinematic chain proximally. Furthermore, differences in axial loading between standing and sitting postures are likely which could affect spinal mechanics. White (1969) showed that when the thoracic spine was in neutral (segments were in a state that simulated a normal standing posture), sidebending and axial rotation were coupled ipsilaterally in the upper region, with variable patterns in the middle and lower regions. Scholten's model demonstrated that when the spine was in flexion all segments exhibited ipsilateral coupling, but when extended there was tendency for contralateral coupling (Scholten, 1986). When individuals with scoliosis were studied lateral bending and axial rotation was always coupled to the opposite side (Closkey & Schultz, 1988; Closkey et al., 1992) that is an example of neutral spine mechanics (Fryette, 1954, 1918). Much more research is needed before a full understanding of thoracic spine/cage will be realized. According to Scholten, Veldhuizen and Grootenboer (1988) "if analysis of mechanical instability can help in the understanding of the mechanism of scoliosis more attention has to be paid to the coupling behavior between bending and torsion" (p. 32). The primary objective of this dissertation will be to define a methodology that will accurately and reliably measure thoracic spine kinematics in vivo. This methodology can then be applied clinically and may contribute to understanding of the relationship between axial rotation and lateral bending.

In the lumbar spine, gross sagittal plane mobility is greater than frontal plane mobility, with very little axial rotation available (Dopf et al., 1994; McGregor et al., 1995; Peterson et al., 1994). Generally from a standing position, there is more flexion range of motion than extension. Whittle and Levine (1997) demonstrated that use of skin-mounted markers on lumbar spinous processes resulted in more noise, i.e., error in determination of lumbar motion, than when markers were placed on rigs that were attached to the lumbar spine. Gracovetsky et al. (1995) showed that marker/skin movement was related to segmental movement by producing intersegmental ranges of motion that were comparable to in vitro and radiographic results. Many investigators have shown that sagittal plane motion of the lumbar spine is significantly related to motion of the pelvis (Esola et al., 1996; Gracovetsky et al., 1995; Leskinen et al., 1987; McClure et al., 1994; Nelson et al., 1995; Paquet et al., 1994; Porter & Wilkinson, 1997). For example, forward trunk flexion was initiated by superior segments (thoracic followed by lumbar), with the pelvis contributing to the later stages (Esola et al., 1996; Leskinen et al., 1987). A posterior pelvic tilt initiated recovery from a forward bent or stooped position, while lumbar spine extension completed the recovery phase (McClure et al., 1994). Marrus et al. (1992, 1994, 1995) showed that symmetrical lumbar flexion angular velocity and acceleration and asymmetrical (flexion plus variable degrees of axial rotation) forward lumbar flexion movements were sensitive biomechanical parameters that could distinguish normal subjects from those with low back pain.

There is disagreement about the coupling patterns between the frontal and sagittal planes. Some have found that extension was coupled with sidebending (Pearcy et al., 1987), whereas others reported that flexion was coupled with sidebending in the upper lumbar region, but extension and sidebending were coupled in the lower segments (Mulvein & Jull, 1995). Coupling of sidebending (SB) and axial rotation (AR) in the lumbar spine were found to be variable: (1) SB and AR were always found to be coupled to the same side by Cheng, 1993, (2) SB and AR were coupled to the opposite side when the lumbar spine was in neutral or a flexed position (Hindle & Pearcy, 1989; Pearcy, 1993), (3) SB and AR were coupled to the same side 50% of the time (Schuit & Rheault, 1997), (3) Coupling patterns depended on which motion were introduced first (Dopt et al., 1994; Schuit & Rheault, 1997), and (4) SB and AR were coupled contralaterally 50% of the time in the upper segments and 90% of the time in the lower segments (Mulvein & Jull, 1995). In agreement with earlier studies, submaximal flexion of the lumbar spine was found to increase the amount of axial rotation mobility, presumbly due to relaxation/opening of the zygapophyseal joints (Hindle & Pearcy, 1989; Pearcy, 1993).

Implications of Literature Review and Statement of Purpose

In vitro, in vivo radiographic, video- and optoelectric-based motion analysis, and analytical kinematic studies have been reviewed for the cervical, thoracic, and lumbar spinal regions. Understanding of cervical kinematics has come largely from in vitro and radiographic research, and little controversy exists regarding cervical spine function, despite the complex nature of the upper and lower functional units. Significant attention has been paid to lumbar spine investigations, largely because of the higher incidence and cost of disabling injuries to this region. In vitro and stereoradiographic research and finite element models have contributed to understanding of lumbar kinematics; however, there seems to be significant disagreement among this body of literature. If more comprehensive finite element models, i.e., those that include the muscular system, can be developed, their application to further our knowledge of normal and pathological lumbar spinal function appears promising. Although Gracovetsky et al. (1995) claim that motion of the skin is related to vertebral motion, the use of noninvasive tools, e.g., video and electromagnetic devices, to measure three-dimensional kinematics of the cervical and lumbar spines has been limited primarily to examining larger segments, such as the head/neck complex. However, noninvasive tools have been shown to be accurate and reliable, and may be more practical to use in clinical settings.

Compared to the cervical and lumbar spines, far less research has been conducted relative to thoracic spine and rib cage kinematics. Although limited by their use of cadaveric functional spinal units without an intact thoracic cage, the research by White (1969) and Panjabi et al. (1976b) has been referred to often. Scholten (1986) reported some interesting concepts related to three-dimensional thoracic spine function using a complex analytical model. However, Scholten did not include the musculoskeletal system in his model. More recently, others have used electromagnetic (Buchalter et al., 1989; Willems et al., 1996) and video-based motion analysis systems (Cheng, 1993; Crosbie et al., 1997; Haideri et al., 1997) to explore the three-dimensional nature of thoracic spine/cage, but with disparate results. These methodologies are somewhat limited by placing marker sets on the skin overlying spinous processes, which predisposes to measurement error resulting from skin movement. Additionally, although previous studies used subjects who were healthy and free of back pain, it was not known if these asymptomatic subjects had normal spinal alignment and symmetrical movement patterns. It has been shown that asymptomatic subjects can have asymmetrical movement patterns at the segmental level in the cervical spine (Johnson et al., 1985; Vorro et al., 1991) and regional level in the lumbar spine (Gomez, 1994). These findings suggest that, if not screened closely enough, "normal, healthy" subjects might exhibit a variety of movement patterns when measured with noninvasive devices. Winters et al. (1993) and Woltring et al. (1994) have used motion analysis to find a screw axis related to natural movements of the head/neck complex, but these methods have not been used to find screw axes for the thoracic spine/cage.

Spine research has been motivated primarily by two factors: (1) the need to gain an increased understanding of normal spinal function, which could aid in understanding dysfunction and assist with diagnostic and intervention strategies; and (2) a need to find valid and reliable instruments that can measure complex spinal motions for research and clinical use. This proposed research is also motivated by these two factors, particularly as it applies to the thoracic spine/cage. Fryette (1954, 1918), using whole cadaver specimens and living subjects, provided laws or concepts of spinal behavior that continue to be applied today by practitioners of manual medicine. Fryette noted that when spinal motion was introduced in one plane, it would be reduced in the secondary planes. This concept has been demonstrated by others in the cervical (Beal & Beckwith, 1963; Dvorak et al., 1992; Jirout, 1979), thoracic (Goodwin et al., 1994), and lumbar spine (Pearcy & Hindle, 1991) regions. Dvorak et al. (1992) found that axial rotation with full flexion of the cervical spine was significantly less than axial rotation with the cervical spine in neutral. Axial rotation mobility with full flexion was comparable to that found at the atlanto-axial joint, which supports the manual medicine method used to isolate the atlanto-axial joint.

In the thoracic region in particular, Fryette found that: (1) sidebending was the dominant movement, with axial rotation extremely limited in all cases; (2) for kinematic purposes the thoracic spine could divided into two parts, the first nine vertebra and last three; with flexion favored in the upper part and extension favored in the lower part; (3) regardless of which motion was introduced first, sidebending and axial rotation were coupled to the same side when the spine was in extreme extension or flexion, but coupled to the opposite side when the spine was in neutral. There is much disagreement in the literature regarding movement patterns of the thoracic spine, and yet, the three concepts described above (especially concept 3) are used by physicians and physical therapists to make diagnoses, plan treatments, and assess treatment outcomes. Gibbons (1997) has recently called for more in-vivo research in order to establish the physiological movements of the spine in normal and dysfunctional states. He reasoned that with this information the ability of manual medicine practitioners to verify their palpation findings will be enhanced and the practitioner's ability to impact joint function and mobility could be assessed.

Therefore, the purposes of this research will be to: (1) investigate whether out-of-plane movements are reduced when motion in one plane is already established, (2) examine whether sidebending and axial rotation are coupled ipsilaterally when the thorax is in extreme extension or flexion, (3) examine whether sidebending and axial rotation are coupled contralaterally when the thorax is in neutral (as defined by the natural standing posture of individuals), and (4) describe the location of the helical (screw) axis for natural movements of the thoracic spine. Despite the measurement errors identified previously with using skin-mounted markers, a video-based motion analysis system will be used to capture three-dimensional thoracic spine/cage kinematics. Fryette's concepts are based on intervertebral movement patterns. It is well understood by this researcher that three-dimensional intervertebral motions cannot be detected with marker systems that are placed on the thoracic cage. To achieve the purposes of this study it will be assumed that in healthy subjects, free of asymmetrical intervertebral and rib cage movements, gross motion of the thoracic spine will realistically reflect the underlying thoracic intervertebral motion

Chapter 3

METHODOLOGY

Introduction

In the peripheral joints each respective articulating bony surface has unique geometrical characteristics that are reasonably congruent so that most joints have well-defined centers of rotation. Generally in biomechanics, bones are conceptualized as rigid mechanical links or bodies and joint articulations are modeled as mechanical joints (e.g., hinges, ball-and-socket joints). Thus, the sophisticated human skeletal structure can be represented and understood as a mechanical system that consists of multiple rigid segments connected by joints.

The spine and associated vertebral joints are also modeled as a mechanical linkage system, albeit more complex. Because of spinal column complexity, however, some biomechanists (Hubbard, Haas, Boughner, Canole, & Bush, 1993; Hubbard, Gedraitis, & Bush, 1998) have examined spinal dynamics using models that lump individual intervertebral joints together, i.e., the torso is considered as a single rigid body mechanically linked to the head above and lower extremities below. Despite the overall complexity of the axial skeleton, vertebral bony segments in specific regions (i.e., cervical, thoracic, and lumbar) share common geometrical, joint, and soft tissue characteristics. For example, the thoracic functional unit (two vertebrae plus the intervening disc) is grossly characterized by zygapophyseal joint orientation that favors frontal and transverse plane motion, partially constrained by the rib cage. Furthermore, the thoracic functional units in the vertebrosternal region (T3-T7) are similar with regard to joint geometry and kinematics and have been distinguished from functional units in the vertebromanubrial (T1-T2), vertebrochondral (T8-T10), thoracolumbar (T11-T12) (Lee, 1994), lumbar and sacral regions (Pratt, 1991). Therefore, modeling the torso as a single mechanical or kinematic link is overly simplistic. In this study, although the constraints of a video-based motion analysis system preclude modeling the torso as a 24-link mechanical system, the trunk will be modeled and studied kinematically as a 3-link system. The upper region will be designated thoracic and will span segments T3 to T6, the second region will be designated thoraco-lumbar and will span the T12 to L3 vertebral segments and the third segment will be the pelvis. In the next two sections requisite background in kinematic principles related to the determination of Euler (sometimes referred to as Cardan or Tait-Bryant or Dexter) angles (Goldstein, 1980; Grood & Suntay, 1983) and helical axes (Kinzel, Hall, & Hillberry, 1972; Woltring, Huiskes, & de Lange, 1985; Woltring, de Lange, Kauer, & Huiskes, 1987; Woltring, Long, Osterbauer, & Fuhr, 1994) will be presented in some detail. This author acknowledges that the formulations related to these kinematic principles are well documented in the literature; however, their application in this research is unique.

Determination of Euler Angles

To describe the spatial movement and orientation of body segments, unique reference spaces must be established. A reference space is usually represented by a set of three orthogonal unit vectors, called a Cartesian coordinate system that is attached to a fixed point in laboratory space or a specific rigid segment. For this study, body-fixed position data will be referenced to a laboratory or global coordinate system (GCS) fixed within a calibrated testing volume (see calibration procedures below). Local (body-fixed) reference systems were subsequently established, with respect to the GCS, by measuring the position of markers strategically placed on torso and pelvic segments.

Although the International Society of Biomechanics has made recommendations (Wu, Siegler, Allard, et al., 2002) for the establishment of global and joint coordinate systems for the spine, there is no consensus within the biomechanics community. Therefore, for this study, a right-handed orthogonal triad $\langle \vec{X}_G, \vec{Y}_G, \vec{Z}_G \rangle$ is fixed in the floor, approximately in the center of the calibrated volume. With an individual standing in an anatomically defined, neutral position the axes are defined as:

+ $\vec{X}_G$ axis pointing right

+ $\vec{Y}_G$ axis pointing anteriorly (forward)

+ $\vec{Z}_G$ axis pointing superiorly (upward).

In this system, the sagittal plane is the *Z-Y* plane, the frontal plane is the *X-Z* plane and the horizontal or transverse plane is the *X-Y* plane (Figure 3.1).

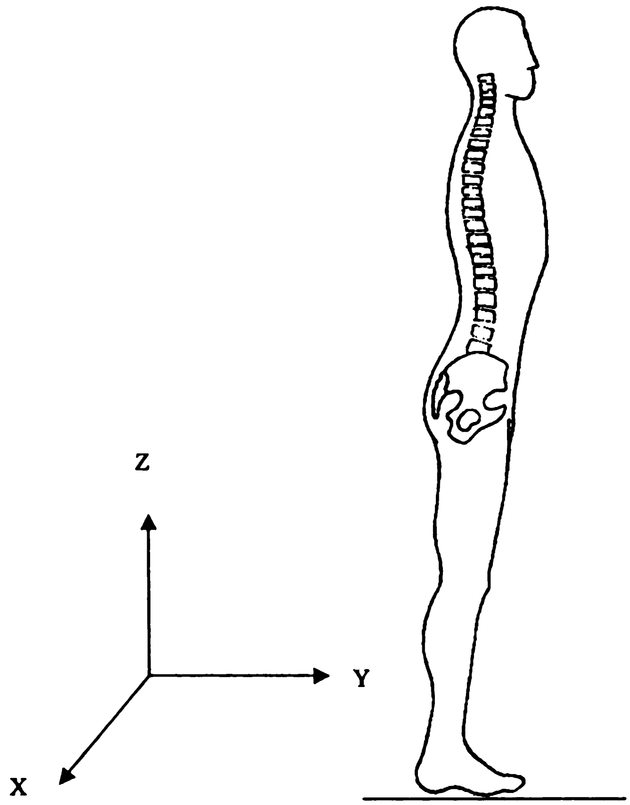

Figure 3.1. Orientation of the body relative to the global (laboratory) coordinate system.

One way to determine the three-dimensional motion of body segments is to first define local, or body-fixed, coordinate systems. The local reference systems, aligned with the GCS, are right-handed, orthogonal coordinate systems that are fixed to, and move with, the body segments. The three axes of the body-fixed reference frame are determined from known positions of three markers strategically placed on the thoracic and thoraco-lumbar segments and pelvis. One rigid array of two markers (Figure 3.2) was secured (taped) to the skin overlying the spinous process of vertebral segments T3/T4 and a third marker was taped to the skin overlying the spinous process of T6 (Figure 3.15 shows the mounting rig and Figure 3.17 shows how the mounting rig is arranged relative to the most distal marker). A similar arrangement of markers spanned the thoraco-lumbar segments from T12 to L3. A third set of individual markers was secured to the skin at four distinct pelvic anatomical sites: the most prominent points of the right and left anterior superior iliac spines (ASIS) and the most prominent points of the right and left posterior superior iliac spines (PSIS). A rigid-array of markers was not used for the pelvis for two reasons: (1) difficulty in securing a rigid array to the pelvis without significant slipping, and (2) satisfaction with reliability (based on the gait analysis protocol used in the Mary Free Bed motion analysis laboratory) of marker placement on skin overlying the anatomical sites described. Movement of the upper thoracic marker triad with respect to the lumbar marker set represents movement of the thoracic spine/cage from T3 to T12. For the purpose of this study, movement of the thorax relative to the pelvis and movement of the lumbar region with respect to the pelvis was not analyzed based on observations during the testing which suggested that the lumbar marker setup did not follow the lumbar spine consistently. Future research on the lumbar spine will depend on development of an improved lumbar marker system.

The pelvic segment was referenced with respect to the GCS by the location of markers placed on the skin overlying the right ASIS ($\mathbf{p}_1$), left ASIS ($\mathbf{p}_2$), right PSIS ($\mathbf{p}_3$), and left PSIS ($\mathbf{p}_4$) (Figure 3.2). Based on these four position vectors ($\mathbf{p}_1$, $\mathbf{p}_2$, $\mathbf{p}_3$, $\mathbf{p}_4$), a local pelvic reference system $\langle \hat{x}_{P,} \hat{y}_{P,} \hat{z}_P \rangle$ was determined. In general, placing more than three markers on a rigid body will ultimately improve the accuracy of transformation matrices (based on the algorithm used in this present research). Note that it was possible to place only three markers on the thoracic and lumbar segments because of the small bony attachment sites.

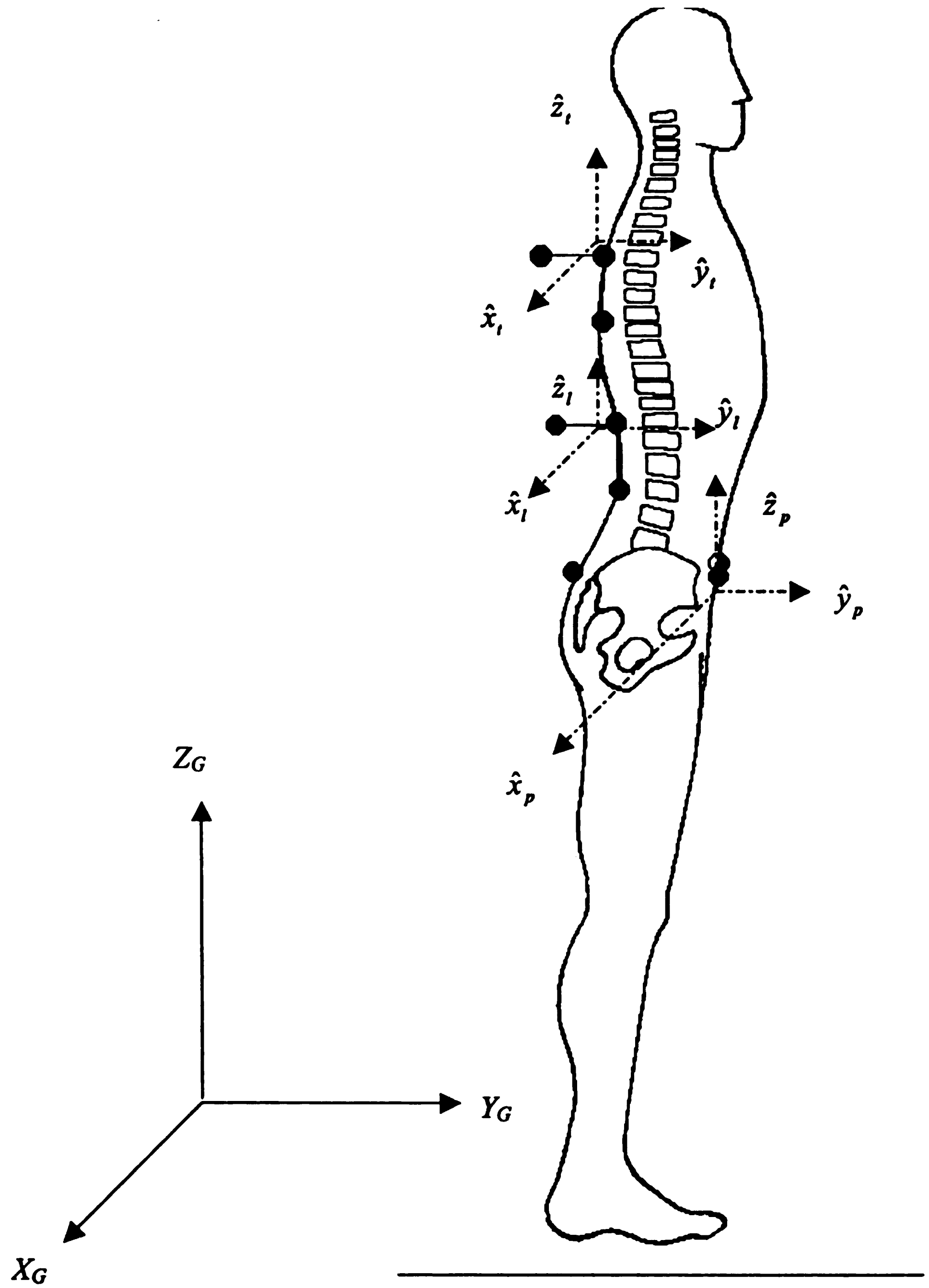

Figure 3.2. Marker arrays with body-fixed coordinate systems for the thoracic, lumbar, and pelvic segments.

The top of the lumbar spine was referenced to the GCS using a rigid array with its proximal end attached on the skin at T12. The markers were labeled distal ($\mathbf{l}_1$), proximal

($\mathbf{l}_2$) and posterior ($\mathbf{l}_3$). The local coordinate system, $\langle \hat{x}_{L,} \hat{y}_{L,} \hat{z}_L \rangle$, of the thoraco-lumbar region was created with the origin fixed at $\mathbf{l}_2$. Likewise, an upper thoracic marker array was secured to the skin overlying segments T3 to T6, with the three markers labeled as distal ($\mathbf{t}_1$), proximal ($\mathbf{t}_2$), and posterior ($\mathbf{t}_3$), and the local reference frame $\langle \hat{x}_{T,} \hat{y}_{T,} \hat{z}_T \rangle$ originating at $\mathbf{t}_2$ (Figure 3.2). The convention for rotations is determined by imagining oneself at the origin of the coordinate system looking in the positive direction of the axis with clockwise rotations designated as positive and counterclockwise rotations as negative (White & Panjabi, 1990). Thus, for this present research, $+\theta_x$ is extension, $+\theta_y$ is right sidebending, and $+\theta_z$ is left axial rotation; movements in the opposite directions are represented by negative values.

The three-dimensional motion of a rigid body is described by six independent coordinates (three translations and three rotations) or degrees of freedom. The orientation of a rigid body based on these parameters is given by an orthogonal matrix transformation, which is most commonly expressed as Euler angles (Goldstein, 1980). Transformation from a given Cartesian coordinate system to another occurs by means of three successive rotations performed in a specific sequence, i.e., sequence-dependency. Euler angles are considered sequence dependent because they are the result of finite rotations about axes of Cartesian systems. Finite rotations cannot be represented by a vector, which results from the fact that such rotations do not commute, so, in general, different results will be obtained depending on the order in which rotations occur. From Goldstein (1980), suppose **A** and **B** are two such "vectors" associated with transformations **A** and **B**. To qualify as vectors they must be commutative in addition: **A** + **B** = **B** + **A**; however, the addition of two finite rotations, i.e., one rotation performed after another corresponds to the product **AB** of the two matrices. However, matrix multiplication is not commutative, that is, **AB** $\neq$ **BA**, thus, **A** and **B** are not commutative in addition and cannot be accepted as vectors.

The choice of rotation sequence is arbitrary (since all rotation conventions are correct from a mathematical point of view) with the stipulation that the initial rotation can be taken about any of the three Cartesian axes, but no two successive rotations can be about the same axis. A common rotation convention is the two-axis convention in which the first and third rotations are taken about a z axis, while the second rotation occurs about an intermediate x axis (Figure 3.3). So, in the sequence employed below, the first rotation, ϕ, occurs counterclockwise about the z axis, with the resultant axis labeled x',y',z'. In the second stage, the intermediate axes, x',y',z, are rotated about the x' axis counterclockwise by an angle θ to produce another intermediate axis system, x'',y'',z''. The x''axis is at the intersection of the xy and $x''y''$ planes and is known as the *line of nodes*. The final counterclockwise rotation (by amount φ) occurs about the z'' axis resulting in the desired x''',y''',z''' system. Euler angles ϕ, θ, and φ completely specify the orientation of the x''',y''',z''' system relative to the x,y,z system and can therefore act as three generalized coordinates. Other common rotation sequences described in the literature include the three axes type x,y,z-convention (*Tait-Bryant* or *Cardan* angles) and the z,x,y-convention or *Dexter* angles (Goldstein, 1980; Grood & Suntay, 1983).

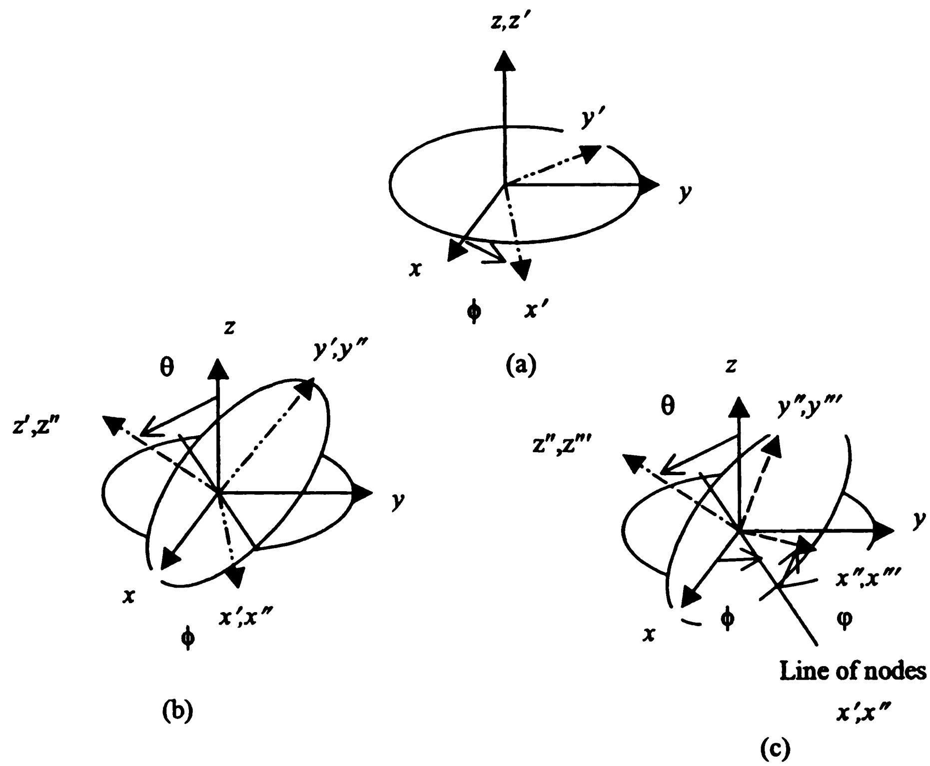

Figure 3.3. Rotations defining the Eulerian angles using the *z,x,z*-convention.

The joint coordinate system (JCS) formulation described by Grood and Suntay (1983) offered a definition of Euler angles (three axes type) that was sequence independent and eliminated much of the confusion relative to nomenclature. The relation between the conventional Euler or Cardan angles and the angles produced by using the JCS is explained by the following:

> For a given set of Euler angles, there exists a unique set of axis corresponding to the joint coordinate system: a body fixed axis in the moving system, a body fixed axis in the stationary system and a common perpendicular to these two body fixed axes. When the conventional definition of Euler angles is used, a change in the order of rotations will produce a different joint coordinate system where the fixed axes have new orientations within their respective bodies. Thus, different sequences of the Euler rotations will produce different motions (Grood & Suntay, 1983).

Thus, there is a relationship between traditional Euler angle calculations and the Grood and Suntay convention. Grood (personal communication, 1990) delineated several advantages for using his method of describing joint angles:

1. Coordinates are real angles and displacements are real rotations about well-defined axes in space,
2. The axes can be selected so that angles correspond to common clinical descriptions of joint position,
3. The angles are valid generalized coordinates that can be used in dynamic analysis of joint motions,
4. The angles are commutative and rotational displacements can be combined by adding and subtracting the angles, and
5. The system provides insight into the nature of joint motion by explaining such phenomena as Codman's paradox.

Woltring (1991, 1994) discussed disadvantages of the Grood and Suntay/Euler convention including the gimbal-lock effect, Codman's paradox, sequence dependency, and the result that joint coordinate axes may not be orthogonal. Although Woltring acknowledged that the results of the Grood and Suntay convention might be more clinically relevant, he suggested that describing spatial movement in terms of helical angles was more reliable and was more appropriate from a mechanical viewpoint. He argued that the attitude vector was well determined from noisy data and allowed direct generalization from other vectorial entities and decomposition along three defined anatomical axes in each of the two segments that comprised a joint (i.e., helical angles' axes are always mutually orthogonal). Finally, when two of the three helical angles are zero, the remaining component could be interpreted as a physical rotation about the relevant coordinate axes. Despite Woltring's arguments, the Cardan convention will be used in this study primarily because spinal angle descriptions, e.g., flexion, extension, side bending, and axial rotation that result from its application are most useful to the clinical community.

The Cardan (*xyz*) convention was used in this study to calculate 'joint' angles (i.e, spinal motion). Rationale for this choice will be discussed in a later section. For visual purposes consider the Cardan convention analog, i.e., the JCS, by Grood & Suntay (1983). The JCS can be formally defined as a right-hand triad $(\hat{e}_1, \hat{e}_2, \hat{e}_3)$ fixed to a point that connects the proximal and distal segments. Then the axes are:

- $\hat{e}_1$ axis representing an axis in the proximal segment reference system (local x)
- $\hat{e}_3$ axis representing an axis in the distal segment reference system (local z)
- $\hat{e}_2$ axis representing a floating axis (local y) that is the cross product of $\hat{e}_3$ and $\hat{e}_1$ (Figure 3.4).

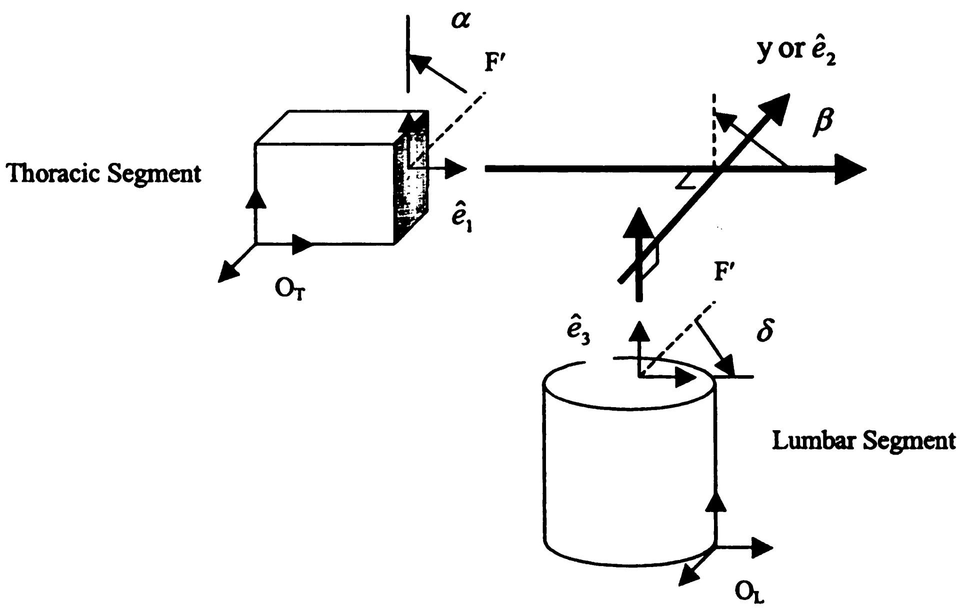

Figure 3.4. The generalized joint coordinate system (JCS) composed of three axes: two embedded (with unit base vectors $\hat{e}_1$ and $\hat{e}_3$) in the two bodies whose relative motion is to be described and the third axis, y, is the common perpendicular to both body-fixed axes. The third axis is not fixed and is referred to as the floating axis with unit base vector $\hat{e}_2$. Posterior frontal view, looking in postive y-direction.

In other words, two body-fixed axes are chosen, one from the proximal segment (e.g., thoracic spine) and one from the distal segment (e.g., lumbar spine). The third rotation axis is the common perpendicular to the two body-fixed axes. The body-fixed axes that correspond to any set of Cardan angles are identified as follows: the first rotation (flexion/extension) is performed about the fixed axis in the stationary body (thoracic spine) when the coordinate systems are coincident; the second rotation (sidebending) is about the floating axis or *line of nodes*; and the third rotation (axial rotation) is about the fixed axis in the moving body (lumbar spine).

For analysis of spinal kinematics in this study, the first axis is the body-fixed x-axis of the thorax. Rotations about this axis correspond to movements in the sagittal plane, described as flexion and extension (FE). The second axis is the z-axis fixed in the distal segment (lumbar or pelvis). Rotations about this axis, as viewed from above, are clockwise (CW) or counterclockwise (CCW), referred to as axial rotation (AR). The common perpendicular axis lies in the local sagittal plane. Rotations about this axis occur in the frontal plane and are referred to as right sidebending (RSB) and left sidebending (LSB).

Rationale for Choice of Cardan Convention

As mentioned previously, for joint angle analysis purposes, there are several Euler or Cardan rotation sequence choices available, all of which are mathematically correct. However, for a given motion, different rotational sequences result in different angle calculations (Baker, 2001; Blankevoort, Huiskes, & de Lange, 1988; Cole, Nigg, Ronsky, & Yeardon, 1993; Crawford, Yamaguchi, & Dickman, 1996; Hof, Koerhuis, & Winters, 2001; Karduna, McClure, & Michener, 2000; McGill, Cholewicki, & Peach, 1997; Skalli, Lavaste, & Descrimes, 1995; Woltring, 1991; Woltring, 1994). For example, Baker (2001) found differences in pelvic orientation during walking when comparing sequences, while Crawford et al. (1996) and Hof et al. (2001) noted discrepancies in cervical spine motion, and McGill et al. (1997) described lumbar angular motion differences.

In general, for a given transformation or attitude matrix, the component values, i.e., rotations (α, β, γ), vary only slightly with changes in sequence if the angles are much less than one radian, and if the "floating angle" does not become too large (if the second Euler angle equals 90° the first and third axes become aligned resulting in a gimbal lock singularity) (McGill et al, 1997; van den Bogert, personal communication; Woltring, 1994). Thus, it appears that sequence choice may depend on the "joints" and the magnitude of the motions being examined. For example, in gait analysis the sequence flexion/extension, ad-abduction, and axial rotation (*xyz*-convention in the Mary Free Bed Motion Analysis Center) are the recommendations for analysis of the hip (Wu et al., 2002), knee (Grood & Suntay, 1983), and ankle (Cole et al., 1993; Wu et al., 2002) joints. These Euler conventions for the study of joints of the lower extremity have been recommended by the ISB and are generally accepted by the biomechanics community.

Presently, there is no standard Euler convention for pelvic and spinal analysis. Baker (2001) makes the case for convention axial rotation (rotation), lateral bending (obliquity), and flexion/extension (tilt) for describing pelvic rotations during gait. For spinal analysis, the order flexion/extension, axial rotation, and lateral bending has been used by several (Goel, Clark, Harris, & Schulte, 1988; Hof et al., 2001; Panjabi & White, 1971; Panjabi, Krag, & Goel, 1981; Panjabi, Oxland, Yamamoto, & Crisco III, 1994), whereas others have used axial rotation, flexion/extension and lateral bending (Feipel, Rondelet, Le Pallec, & Rooze, 1999), lateral bending, flexion/extension and axial rotation

(Cao, 1993), and flexion/extension, lateral bending and axial rotation (Crawford et al., 1996; Hof et al., 2001; Lee & Wong, 2002; McGill, Cholewicki, & Peach, 1997; Schacke, et al., 2001). Still others have used the average of six possible permutations (Oxland et al., 1992; Panjabi et al., 1993). There may be good rationale for using the mean value of all valid Euler or Cardanic representations. It has been shown that this mean value is approximately equal to the helical or attitude vector, a mechanical description of motion that appears to be more 'stable' (Woltring, 1994; Durá, 2003). The answer to the question of which of the Euler sequences best applies to spinal motion has not been firmly established.

For spinal analysis (Crawford et al., 1996; McGill et al., 1997; Wu et al., 2002) the sequence flexion/extension, lateral bending and axial rotation has been recommended. ISB (Wu et al., 2002) justified their recommendation for standardization by suggesting that, in general, the Euler sequence they chose was accepted by the biomechanics community and was consistent with Grood and Suntay's convention (1983). McGill et al. suggested that sequence choice should be based on the following criterion, "match the axis rotations of the joint so that the first axis to experience 90° of rotation is also the first one in the Euler rotation sequence in order to minimize error (i.e., cross-talk) on the other two axes". Hof et al. (2001; 2002 (personal communication)), however, concluded that one presentation that always gave the correct angles did not seem to exist since the order flexion/extension, axial rotation and lateral bending had to be used in order to determine lateral bending angles most accurately. At the least, Hof et al. suggested when reporting three-dimensional rotations the Euler sequence should always be described, and that as long as no solution seemed to be available that could exclude cross-talk effects (discussed in a later section), any discussion of spinal coupling should be interpreted with caution.

To date, Crawford et al. (1996) have provided the most extensive rationale for using the Euler sequence flexion/extension, lateral flexion and axial rotation. In brief, Crawford et al. used symmetry to choose the most appropriate projection vector set (and its corresponding Euler sequence). They made two observations:

1. Since a vertebra has only a single plane of symmetry (mid-sagittal plane), angles should, if possible, describe the deviation from this plane. That is, the y- and z-axis rotations describing the position of a vertebra should have the same magnitude and the opposite sign of the y- and z-axis rotations describing the position of the vertebra's mirror image across the mid-sagittal plane.
2. Lateral bending and flexion/extension are essentially the same type of motion ('bending'), only in different directions whereas both motions are distinctly different in nature from axial rotation ('twisting'). Because of their similarity, flexion/extension and lateral bending should be complementary motion, i.e., bending that is not lateral bending is flexion/extension and bending that is not flexion/extension is lateral bending.

From the first observation, Crawford et al chose the projection vectors best suited for determining the axial rotation and lateral bending angles, and from the second observation, they chose the projection vectors for use in describing flexion/extension. Then, under the assumption that with small Euler angles (≤ 30°) that are approximately the same magnitude, they chose the Euler convention that matched the preferred projection angles. They concluded that when "studying a simple motion of the spine controlled to a single plane, the selection of a particular Euler sequence or projection set was of little importance since variation by different sequences and set permutations would be small. However, in studies of spinal coupling, where the magnitudes of each of the three planar angles described the pattern of movement, selection of the correct technique for angle calculation was crucial." Crawford et al. showed that the 'best' Euler convention followed the flexion/extension, lateral bending and axial rotation sequence. Although he was not studying spinal motion, Durá (2003) compared different Euler rotation sequences with Wolting's attitude vector and found that the convention recommended by Grood and Suntay (1983) for the hip, knee and ankle was the most stable and most similar to the attitude vector. Therefore, based on these findings (Crawford et al, 1996; Durá, 2003; McGill et al., 1997) the Cardan sequence flexion/extension, lateral bending and axial rotation (*xyz*) was chosen for the analysis of three-dimensional thoracic spine motion.

Helical Axis

In the previous section discussion of rigid body kinematics and Euler angle calculations for specific segments of the spine and pelvis was presented. However, a more general and precise description of rigid body motion may be obtained by applying Chasles' theorem (Goldstein, 1980) or helical (screw) axis theory (Kinzel, Hall, & Hillberry, 1972; Woltring, Huiskes, & de Lange, 1985; Woltring, de Lange, Kauer, & Huiskes, 1987; Woltring, Long, Osterbauer, & Fuhr, 1994). Thus, the instantaneous spatial motion of a body, or motion of one body relative to another body, can be given completely by specifying the body's rotation about and translation along a helical axis; as well, the helical axis changes in time. Another objective of this research is to apply helical axis theory to provide an alternative description of three-dimensional thoracic spine motion.

The instantaneous helical axis (IHA), also known as the instantaneous screw axis, twist axis, or axis of rotation may be the most elaborate description of three-dimensional motion. At each moment in time, joint motion is seen as the movement of one body segment with respect to an adjacent segment, with a translation (or shift) component (velocity) along, and a rotation component (velocity) about a directed line in space that is uniquely determined as long as the rotatory component does not vanish (Figure 3.5). The position of the helical axis will generally vary during the movement, and the movement is completely known once the translation and rotation velocities, and the position and direction of the helical axis, are known over time.

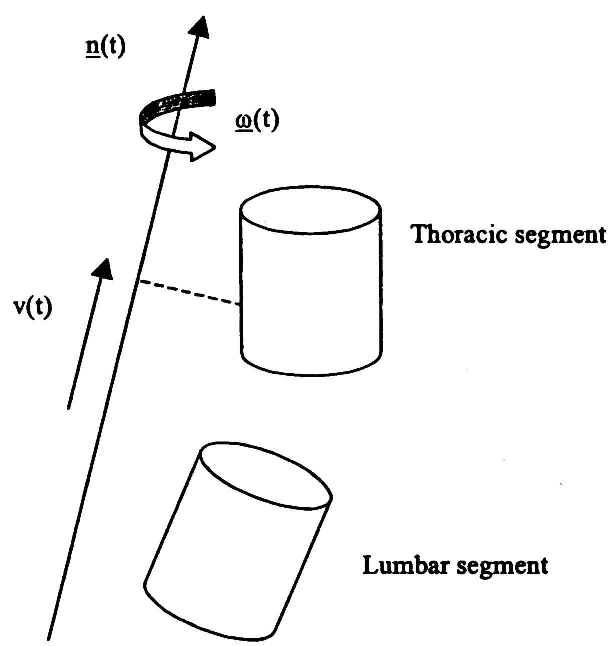

Figure 3.5. Instantaneous helical axis defining relative motion between thoracic and lumbar segments. The total amounts of translation and rotation along the path of motion can be defined as the time integrals of the instantaneous translation and rotation velocities at the IHA from a given reference time.

Many researchers (Winters, Liang, & Daru, 1988; Winters & Peles, 1990; Winters et al., 1993) have approximated the IHA and centroid by means of the finite helical axis (FHA), which are estimated from single, finite displacements (Figure 3.6). It is known that stochastic errors in the position and direction of the finite helical axis and centroid are inversely proportional to the finite rotation magnitude (Woltring et al., 1985). On the other hand, small increments are required in order to reliably approximate the continuous movement by means of a sequence of finite displacements. So, it is necessary to find a practical balance between these deterministic and stochastic, conflicting error sources. For this study, an IHA analysis was used to demonstrate location and movement of the axis that describes motion of the thoracic segment relative to the lumbar segment. Determination of the FHA was then used to quantify the helical parameters: helical angle, point on helical axis, unit vectors with direction of helical axis and amount of translation along the screw axis.

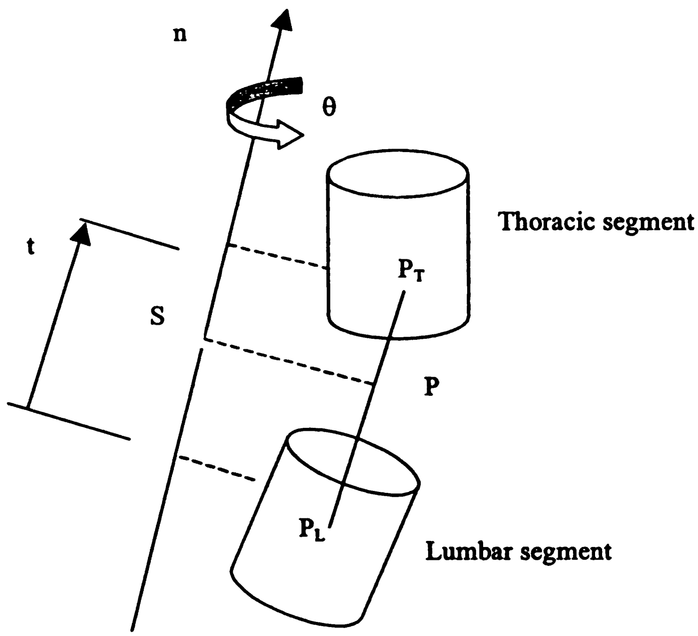

Figure 3.6. Finite helical axis describing relative motion of thoracic segment relative to lumbar segment.

Methods for the Calculation of Rigid Body Kinematics

What follows is a description of the methods that were used to calculate intersegmental "joint" motions. In the standard rigid-body transformation describing

"Eulerian movement", **y** is the position coordinate vector of an arbitrary point in the global (or proximal) coordinate system and **x** the corresponding vector in the local (or distal) coordinate system,

$$\mathbf{y}_{GCS} = \mathbf{Rx} + \mathbf{p}, \qquad (3.1)$$

where $\mathbf{y} = (x_g, y_g, z_g)$, coordinates in a global, Cartesian coordinate system; $\mathbf{x} = (x_l, y_l, z_l)$, coordinates in a local, body-fixed coordinate system; $\mathbf{p} = (p_x, p_y, p_z)^T$ is the position of the local coordinate systems in global coordinates, and $\mathbf{R} = [r_{ij}]$ is a 3*3 orthonormal attitude (orientation) matrix. Important properties of the orthonormal matrix **R** include: all columns are mutually orthogonal and have unit magnitudes, $\mathbf{R}^T\mathbf{R} = \mathbf{R}\mathbf{R}^T = \mathbf{I}$, and determinate, $det(\mathbf{R}) = +1$ means that the matrix is *proper*.

The attitude matrix **R** in (3.1) can be expressed in terms of an ordered matrix product of three elementary attitude matrices:

$$\mathbf{R}_{ijk} = \mathbf{R}_i(\phi_i)\,\mathbf{R}_j(\phi_j)\,\mathbf{R}_k(\phi_k) = \mathbf{R}_{xyz};\ \phi = (\alpha, \beta, \gamma) \qquad (3.2)$$

With the component matrices,

$$\mathbf{r}_x(\alpha) = \begin{bmatrix} 1 & 0 & 0 & Hx \\ 0 & \cos\alpha & -\sin\alpha & 0 \\ 0 & \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (3.3)$$

$$\mathbf{r}_y(\beta) = \begin{bmatrix} \cos\beta & 0 & \sin\beta & 0 \\ 0 & 1 & 0 & Hy \\ -\sin\beta & 0 & \cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (3.4)$$

$$
\mathbf{r}_z(\gamma) = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 & 0 \\ \sin\gamma & \cos\gamma & 0 & 0 \\ 0 & 0 & 1 & Hz \\ 0 & 0 & 0 & 1 \end{bmatrix}. \qquad (3.5)
$$

The full attitude or transformation matrix, **T**, follows:

$$
\mathbf{T} = \begin{bmatrix} \begin{bmatrix} \text{direction} \\ \text{cosine} \\ \text{matrix} \end{bmatrix} & \begin{matrix} Hx \\ Hy \\ Hz \end{matrix} \\ 0 \quad 0 \quad 0 & 1 \end{bmatrix}, \qquad (3.6)
$$

where the direction cosine matrix equals the matrix product $\mathbf{R}_{xyz}$, and Hx, Hy and Hz describe the relative (translational) orientation between two segments, or in general, between two coordinate systems. The attitude matrix is determined under the assumption that body segments, with at least three non-colinear markers well-situated on each segment, can be modeled as "rigid" (distance between points on the moving segments are invariant during the movement) with six degrees of freedom.

Joint movement is usually defined as movement of the distal body segment with respect to the proximal body segment that both comprise the joint. In the present research movement of the thoracic segment (subscript T) with respect to the lumbar segment (subscript L) was determined. Defining proximal and distal orientation parameters as $\mathbf{R}_T$, $\mathbf{p}_T$, $\mathbf{R}_L$ and $\mathbf{p}_L$ in (3.1),

$\mathbf{y} = \mathbf{R}_T\mathbf{x}_T + \mathbf{p}_T$, thoracic with respect to global, (3.7)

and

$\mathbf{y} = \mathbf{R}_L\mathbf{x}_L + \mathbf{p}_L$, lumbar with respect to global. (3.8)

Elimination of the global coordinate vector **y** results in the following,

$$\mathbf{x}_L = \mathbf{R}_{joint}\mathbf{x}_T + \mathbf{p}_{joint} \quad (3.9)$$

$$\mathbf{R}_{joint} = \mathbf{R}^T{}_L\mathbf{R}_T \quad (3.10)$$

$$\mathbf{p}_{joint} = \mathbf{R}^T{}_L(\mathbf{p}_T\text{-}\mathbf{p}_L). \quad (3.11)$$

Now, let $\mathbf{R}_{joint} = \mathbf{T}_{TL}$, the matrix transforming coordinates from the coordinate system "T" to coordinate system "L". $\mathbf{T}_{TL}$ = söderkvist([$\mathbf{x}_T$; $\mathbf{x}_L$]), where söderkvist([x_T1, y_T1, z_T1,...x_Tn, y_Tn, z_Tn; x_L1, y_L1, z_L1,...x_Ln, y_Ln, z_Ln]) calculates $\mathbf{T}_{TL}$ that provides the solution to the following least squares problem (Challis, 1995; Söderkvist & Wedin, 1993):

$$\min\left(\sum_{i=1}^{n}\left\|[T_{TL}]\cdot\vec{r}_{Ti} - \vec{r}_{Li}\right\|^2\right); n \geq 3. \quad (3.12)$$

Note that $\mathbf{T}_{TL}$ contains all information needed to solve for the Cardan angles and helical parameters. Cardan angles for the thoracic segment were determined from $\mathbf{T}_{TL}$ (or T) using the *xyz*- convention, such that,

$$\alpha = \sin^{-1}(\mathbf{T}(2,3)/\cos(\beta)) \quad (3.13)$$

$$\beta = \sin^{-1}(-\mathbf{T}(3,1)) \quad (3.14)$$

$$\gamma = \sin^{-1}(\mathbf{T}(2,1)/\cos(\beta)). \quad (3.15)$$

Finite helical axis parameters: $\mathbf{n}$ = unit vector with direction of helical axis; point = point on helical axis; phi (ϕ) = rotation angle (in degrees); and t = amount of translation along screw axis were also determined, following Spoor and Veldpaus (1980), such that $\mathbf{n}$ and phi (ϕ) are derived from the relations:

$$\cos\phi\,\mathbf{I} + (1-\cos\phi)\mathbf{n}\mathbf{n}^T = \tfrac{1}{2}(\mathbf{T} + \mathbf{T}^T) \quad (3.16)$$

$$\sin\phi\,\mathbf{S}\{\mathbf{n}\} = \tfrac{1}{2}(\mathbf{T} - \mathbf{T}^T) \quad (3.17)$$

with

$$\mathbf{R}_{joint} = \mathbf{R}^T{}_L\mathbf{R}_T = \mathbf{T}_{TL} = \mathbf{T};\ \mathbf{n}^T\mathbf{n} = 1;\ 0 < \phi \leq 180° \tag{3.18}$$

and **I** is the unit matrix of order 3 * 3; **S** {.} the skew-symmetric matrix,

$$\mathbf{S}\ \{s\} = \begin{bmatrix} 0 & -s_z & s_y \\ s_z & 0 & -s_x \\ -s_y & s_x & 0 \end{bmatrix}. \tag{3.19}$$

The translation t along the helical axis and the radius vector s of a point on the axis follow

$$t = \mathbf{n}^T\mathbf{v}, \tag{3.20}$$

where **v** is the translation vector (Hx, Hy, Hz), and

$$\mathbf{s} = -\tfrac{1}{2}\mathbf{n} * (\mathbf{n} * \mathbf{v}) + \frac{\sin\phi}{2(1 - \cos\phi)}\mathbf{n} * \mathbf{v}. \tag{3.21}$$

The helical axis is undefined for $\phi = 0$, i.e, under pure translation, and therefore **n**, **s** and t are not unique. Point is where the helical axis intersects the plane of interest. The IHA analysis refers to the limiting case of a vanishing displacement, as the sampling interval is decreased in the digitized continuous movement (Woltring et al., 1985).

Error Analysis

Instrumentation Error

When using video-based motion analysis passive markers are attached to skin overlying the moving bones or segments of interest, with the assumption that motion of a cluster of markers ($n \geq 3$) represents the three-dimension motion of the underlying bone or segment. The assumption for the present research is that movement of skin-mounted markers overlying the vertebral spinous processes will adequately express the kinematics of the segments of interest, i.e., thoracic segment relative to lumbar segment. However, two types of errors in general affect assessment of variables in joint kinematics: instrumental errors and errors by which a bony landmark location in space can be determined.

The primary instrumental errors that will affect reconstruction of marker trajectories come in two forms: systematic and random. The magnitude of the systematic error depends on the position that the marker(s) assumes in space and is due to optical distortion or other types of instrumental non-linearities. Camera linearization prior to calibration and calibration procedures will minimize systematic errors. In general, random errors are caused by quantization inherent in the digitizing process and to effects occurring within the image processing equipment. These errors were small for an early generation of a Vicon motion capture system, with linear RMS errors ranging from 0.6 to 1.3 mm, and an angular RMS error of 1.4° (Richards, 1999).

For this study instrumental error in determining angular and linear measures was quantified in several ways. First, system accuracy and reliability was assessed through repeated calibration procedures. Briefly, calibration is the process that linearizes each camera, measures each camera position relative to the others and establishes the global coordinate system. Linearization occurs with each new calibration and is the process of correcting for distortions in the camera lenses and variations in the internal mounting of the cameras' sensor plates. Correction factors are calculated as part of the volume calibration. Two calibration parameters, residuals and static reproducibility, can be examined to evaluate the robustness of each calibration. Residuals are the root mean square (RMS) of the distance between two rays; the first ray being that from the center of the camera strobe ring to the centroid of the marker, and the second being the reflected ray from the marker to the camera lens. According to the manufacturer, acceptable residual values should be less than 0.1% of the distance from the camera to the center of the capture volume. For this study camera distance to center of capture volume was approximately 3.7 m. The manufacturer considers residuals from 1-4 mm acceptable. Static reproducibility is the RMS error of the L-frame (described in calibration section) coordinates as calculated compared to a *.cro file scaled to the size of the L-frame (the manufacturer states that static reproducibility should be less than 1%).

For the first system test, ten calibration procedures were conducted. Results of the ten calibrations showed that mean residuals for all 10 calibrations and all six cameras averaged 0.74 (±. 05) mm (range 0.65 - 0.83 mm). These values are better than manufacturers recommendations, i.e., 1- 4 mm. Percent static reproducibility averaged 0.88% (±.09) (range 0.76 - 1.04%), again, below recommended values (see Appendix A for full data set). Also, the mean residual (for all ten calibrations) for each camera was examined relative to its distance to the center of the capture volume. The accepted residuals were, on average for all six cameras, 0.02% of the distance from camera to the center of the capture volume, well below the manufacturer's recommendation of 0.1%. These data demonstrate excellent system accuracy and reliability.

Following the repeated calibrations a "wand trial" was conducted. A "wand trial" is a dynamic test (50 mm marker with a center-to-center distance 250 mm) where the wand is waved randomly throughout the capture volume. Marker images were sampled for a period of 10-20 seconds at a sampling frequency of 30 Hz. After marker images were reconstructed and labeled the system's graphing function was used to determine the mean (and standard deviation or SD) linear distance between the markers (SD can be thought to represent the RMS error (RMSE) of measure). After wand data were collected each of the ten sets of calibration parameters were applied, resulting in ten sets of wand data. Results showed that the mean RMSE for all ten calibrations was 0.72 mm, (range 0.42 - 1.7 mm). Thus, system linear measurement accuracy and repeatability are excellent. It should be noted that system calibrations and wand trials were routinely conducted prior to subject testing. The calibration parameters and wand trial data for these tests will be reported in the calibration section.

System angular and linear accuracy was also determined using a static test. A rigid, steel two-armed ruler was used in a static test with three 14 mm diameter markers mounted to each end and triangle vertex, forming a 30°-60°-90° right triangle. Markers were separated by a constant distance of 242 ± 1, 371 ± 1 and 422 ± 1 mm. The ruler was used in a series of "motion" capture tests that were performed at each corner and at the center of the capture volume while oriented along each of the three axes of the global coordinate system producing a total of twenty-seven data sets. Marker images were sampled for a period of 4 seconds at a sampling frequency of 30 Hz at each position/orientation. Following data collection marker positions were reconstructed and labeled. Then, using the graphing tool of the Vicon system the linear distance between each marker and the 60° angle formed by the three markers was determined. The mean angular difference (± SD or RMSE) between the known and measured value was 0.75° (± 0.12°). Mean linear differences (± RMSE) were also determined and found to be, 0.75 ± 0.44 mm, 0.62 ± 0.28 mm and 1.86 ± 0.68 mm for the arms of the triangle, respectively. Thus, the motion capture system used in this research has an angular accuracy of less than 1° and linear accuracy of less than 1 mm, which is considered excellent (Appendices B and C).

Error Related to Skin Motion

A major source of artifact or error in experimental procedures using optoelectronic systems that use active or passive markers is associated with the relative movement between skin-mounted markers and underlying bone. Skin marker artifacts are usually high with respect to both systematic and random photogrammetric errors and were found to reach 10-15 mm in the longitudinal and mediolateral directions, and up to 30 mm in the posteroanterior direction on the thigh and shank during walking (Cappozzo, Catani, Leardini, Benedett, & Della Croceu, 1996; Cappello, Cappozzo, Della Croce & Leardini, 1997). As a result of skin motion artifacts large differences in knee joint angle calculations were found, when comparing the use of skin-mounted marker arrays and marker arrays mounted on skeletal pins that were screwed directly into bone (Fuller, Liu, Murphy, & Mann, 1997). The magnitude of these artifacts may be uniquely related to the specific bones or joints markers are fixed to, and it seems that with greater joint excursions skin motion artifacts increase in magnitude (Cappello et al., 1997). Finally, it is thought that skin motion artifacts are primarily caused by: 1) stretching of the skin, 2) muscle contraction, 3) inertia phenomena, and 4) stereophotogrammetric noise (Cappozzo et al., 1996).

There is less information in the literature regarding skin motion artifact with spinal motion testing. Lundberg (1996) concluded that the spine was extremely difficult to adequately assess from externally derived data because of three factors: 1) The spine consists of a large number of segments, 2) Only spinous processes (SP) are even moderately close to the skin, the SPs are surrounded by large muscles and the SPs seem to be less rigid that most other parts of the skeletal system and 3) the range of normal variation in the shape and orientation of the vertebral column is fairly large. However, Lundberg went on to state, "...analysis is, to some extent, helped by the fact that the fascia over the spinous processes is relatively rigidly fixed to bone and thus the skin movement will follow bone movement more closely than in many other regions". Additionally, in studies examining segmental lumbar mobility in the sagittal and frontal planes it was shown that spinal kinematics from data collected from the motion of skin markers compared favorably with data obtained from radiographs (Gracovetsky, 1988; Gracovetsky et al., 1995). Gracovetsky concluded, "spine marker motion in normal subjects is a good reflection of lumbar spine motion and function, which suggests that the motion of skin is not random but contains relevant physiologic information". However, more recently, significant differences between external marker-defined inter-segmental motions and corresponding internal vertebral rotations were reported (Zhang & Xiong, 2003). Considering that different conclusions have been drawn regarding correlation between actual vertebral motion and measured vertebral motion some caution needs to be exercised in the analysis and interpretation of results reported in this research.

Since it has been demonstrated that skin motion errors may translate directly into joint angle errors, it is important to attach reference markers to the skin in such a way that they move as accurately as possible with the underlying bone (Lamoreux, 1996). For this present research markers were affixed to the skin overlying the spinous processes using a silicon base that could be molded to the shape of the bone, a spray skin adherent and tape. Observation of marker movement over the thoracic spine using this protocol during pilot testing suggested that the markers followed the thoracic segment movement well. During flexion/extension of the thoracic spine, markers were observed to separate proximally/distally, but this has been shown to correlate well with actual sagittal plane vertebra movement (Gracovetsky, 1988; Gracovetsky et al., 1995). Of particular concern was the potentially excessive mediolateral movement of the distal thoracic marker (approximately at T6) relative to the marker rig secured at T3 that contained the proximal and posterior markers. Excessive abnormal movement of the distal marker could significantly affect the accuracy, as well as reliability, of sidebending and axial rotation angle calculations. As noted above with sagittal plane motion testing, observation of thoracic sidebending and axial rotation during pilot testing suggested that the distal marker followed the two proximal markers and segment motion direction well, a finding that has also been documented in the lumbar spine (Gracovetsky et al., 1995).

An error propagation analysis based on actual error measures was not performed; however, an estimate of the effect of skin motion artifact on the determination of thoracic spine was derived using projection angles. Crawford et al. (1996) mapped projection angle vectors that correspond to the Cardan rotation sequence used in this study. Flexion/extension is determined from projection P_{xk}, which uses k and k′, projected on the mid-sagittal plane (Figure 3.7). If a marker is displaced proximally or distally the sagittal plane angle calculation will not be affected. Likewise, it is not likely that a marker displaced laterally will affect calculation of the flexion/extension angles.

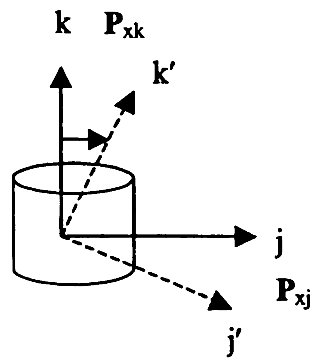

Figure 3.7. Sagittal plane projection vectors with a right-side view of a cylinder representing the thoracic segment.

Sidebending (SB) is determined from projection P_{yk}, which used k and k′, projected on the frontal plane (Figure 3.8). A marker displaced proximally or distally will not affect the SB calculation. However, it is likely that a marker displaced laterally will affect the sidebending calculation as a function of the arctan of the sides of a triangle (Lamoreux, 1996).

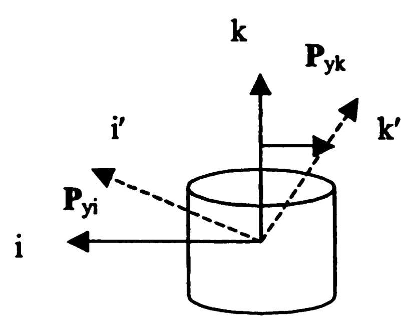

Figure 3.8. Frontal plane projection vectors with a front view of a cylinder representing the thoracic segment.

The distance from T3 to L1 was approximately 30 cm (distance between origins of thoracic and lumbar body-fixed coordinate systems). Assume that marker movement error ranges from 1 cm to 3 cm (Cappozzo et al., 1996; Cappello et al., 1997). Thus,

$$\beta_{minerror} \approx \arctan(1/30) = 1.9° \quad (3.22)$$

$$\beta_{maxerror} \approx \arctan(3/30) = 5.7°. \quad (3.23)$$

Finally, it is shown that axial rotation (AR) is determined from projection P_{ky}, which uses y and y′, deviation from the plane of symmetry (Figure 3.9). A marker displaced proximally or distally will not affect calculation of the AR angle. However, excess,

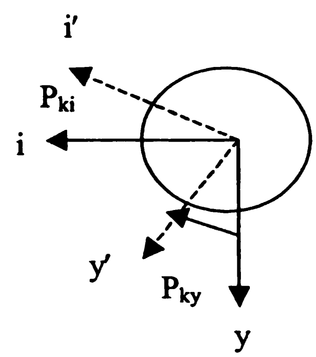

Figure 3.9. Transverse plane projection vectors with a superior view of a cylinder representing the thoracic segment.

uncorrelated movement of the rig markers (proximal and posterior markers) with respect to the distal marker affixed to the skin over the spinous process of T6 could lead to error in the calculation of AR. Assuming the distance from the skin to the posterior marker on the rig is 13 cm and the linear error due to skin motion ranges from 1 to 3 cm, then,

$$\gamma_{minerror} \approx \arctan(1/13) = 4.4° \quad (3.24)$$

$$\gamma_{maxerror} \approx \arctan(3/13) = 12.9°. \quad (3.25)$$

Based on this simple error analysis, clearly, skin motion artifact appears to affect calculation of AR angle most.

Other considerations with regard to marker placement have been discussed in the literature. Distribution of markers in terms of separation distance has been advocated to improve the accuracy of rigid body transformation parameters (Challis, 1995); however, specific marker distribution distances were not pronounced. Challis also determined that if the number of markers placed on a rigid body was greater than three, helical angle accuracy increased, with the improved accuracy most evident when the number of markers was increased from three to four. Unfortunately, for spinal analysis the surface area of the vertebra available for marker attachment is very limited so increasing marker number is difficult. Marker distribution is also a problem because if markers are placed more than an inch laterally off of the spinous processes they will lie over corresponding ribs and movement of the ribs may not correspond to vertebral movement. Distribution was partially solved by placing two markers on a rig with the third marker placed over the spinous process approximately three segments distally. For this study, artifacts could not be eliminated, but since skin motion errors are somewhat random in nature they were minimized by using a rigid array of markers, assuring good marker separation distance, filtering the raw data set, and the application of a least squares approach to determine rigid body transformation matrices. Finally, since the primary objective of this study was to examine coupled motion patterns, and not the magnitude of secondary motion, some error in angle magnitudes were tolerable.

Error Related to Cross-talk

Cross-talk is a phenomenon where rotations about one axis are also visible in the angles of other axes (Chao, 1980; Woltring, 1994). Cross-talk results from the attempt to parameterize a three-dimensional phenomenon using three variables (i.e., α, β, and γ) and from the fact that the instantaneous axis of rotation does not, in general, coincide with one of the local coordinate axes (Hof et al., 2001; Woltring, 1994). Thus, misalignments between the true anatomical system and the calculated one may give rise to correlated and exaggerated rotations around the non-dominant axes (Feipel, et al., 1999; Hof et al., 2001; Koerhuis, Winters, van der Helm, & Hof, 2003; McGill et al., 1997; Ramakrishnan & Kadaba, 1991; Woltring, 1994) that are sensitive to the Cardan sequence chosen (Crawford, 2002; Crawford, et al. 1996; Feipel et al., 1999; Hof et al., 2001; Koerhuis et al., 2003; McGill et al., 1997; Woltring, 1994). Since the Cardan sequence chosen for this research was substantiated in a previous section and shown to minimize cross-talk, any remaining error related to cross-talk is likely due to marker placement (Ramakrishnan & Kadaba, 1991) and skin motion artifact (Lamoreux, 1996).

In an attempt to quantify cross-talk and the error in determination of Cardan angles (using different Cardan sequences) and helical parameters a dummy set-up was created. The 'dummy thorax' consisted of a metal plate attached to a revolving cylinder (simulating the local z-axis) mounted on the base plate of a camera tripod. The marker (i.e., 14 mm diameter markers) arrangement fixed to the metal plate matched the arrangement used on the thorax of test subjects. The base plate of the tripod could be tilted to the right or left to simulate rotation about a local y-axis. The tripod base plate was also part of another cylinder that could be tilted in the sagittal plane to simulate flexion/extension about a local x-axis. Four 25 mm diameter markers (simulating the marker arrangement on the pelvis) were attached to the tripod below all movable cylinders. Thus, movement of the 'dummy thorax' was examined relative to a 'dummy pelvis'. Two additional 25 mm diameter markers were placed on the tripod that mapped the endpoints of the flexion/extension axis (not shown in figure). During 'motion testing' each rotation was completely independent of the other ones. Protractors, with 5°

precision, were attached around the three movable axes so that calculated angles could be compared to the known angles (Figure 3.10).

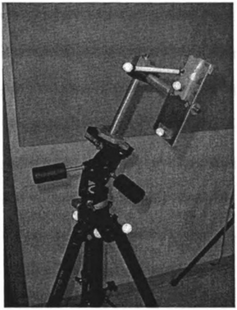

Figure 3.10. Dummy set-up illustrating marker arrangement for thorax and pelvis.

Since it was not possible to design a mechanical linkage that exactly simulated the nature of a human spine the dummy set-up was designed to model the geometrical linkage that modeled the *xyz*-Cardan sequence, as suggested by Crawford (2002; personal communication).

A total of twenty-four motion tests were conducted using the dummy set-up. Motion tests included one-plane motions (i.e., flexion, extension, sidebending and axial rotation, two-plane motions (i.e., flexion + sidebending, sidebending + axial rotation) and three-plane motions (i.e., flexion + sidebending + axial rotation). Flexion/extension angles ranged from 60° to 30° respectively, up to 30° of right and left sidebending and up to 45° of right and left axial rotation were used for these tests to simulate in vivo motion. The most simple test consisted of 60° flexion followed by 30° of extension, whereas the most complicated test consisted of 60° flexion, followed by 15° left axial rotation, followed by 5° right sidebending. To verify choice of the *xyz* sequence for this research Cardan angle calculations were performed and compared for all motions using all six possible sequences (i.e., *xyz*, *xzy*, *yzx*, *yxz*, *zxy*, and *zyx*). A more detailed comparison of angle calculations was made for a subset of twelve motion tests by examining all possible Cardan pairs (fifteen total). Results showed that for one-plane motions all Cardan sequences accurately reflected the true angle. For two-plane and three-plane motions all Cardan sequences accurately reflected the true angle for the primary motion (i.e., first motion introduced), but there was significant deviation among Cardan sequences in accurately determining the secondary and tertiary motions. As expected, since the geometrical linkage of the dummy was designed as described, the *xyz* sequence most accurately determined all motions in all planes. Crawford (2002) suggested that the sequence *xzy* sequence should perform nearly as well as the *xyz* sequence, and this was found to be true as well.

The primary purpose for conducting simple and complex motion tests using a dummy set-up was an attempt to approximate and quantify cross-talk. Analysis revealed that cross-talk existed in the following manner: 1) If flexion was introduced alone, in addition to calculation of the flexion angle, ~ 4° of left sidebending and ~ 4° of right axial rotation were also calculated; 2) If extension was introduced alone, ~ 4° of right sidebending was calculated with the extension angle; 3) If sidebending was introduced alone, ~ 3° of flexion was calculated with right sidebending and ~ 3° of extension was calculated with left sidebending; and 4) If axial rotation was introduced alone, ~ 1° of flexion/extension was also calculated. See Appendix D for details of dummy test Cardan angle and cross-talk data.

A sensitivity analysis was also performed with the dummy spine. This analysis was an additional attempt to quantify the possible effects of skin motion artifact on angle calculation. The dummy thoracic segment was composed of a metal plate with three markers arrange as they were on living subjects. To simulate potential skin motion artifact the distal marker was mathematically moved in the positive x-direction 10 mm and then 30 mm. Thoracic motion (Cardan angles) was determined and graphically compared under the three conditions: no movement of the distal marker, distal marker moved 10 mm, and distal marker moved 30 mm. Joint angle comparisons were done for the following three dummy trials: (1) trial 04 – approximately 60° flexion and 30° extension; (2) trial 07 – approximately 30° of right sidebending and 30° of left sidebending; and (3) trial 11 – approximately 45° of right axial rotation and 45° of left axial rotation. Results are illustrated below. From Figure 3.11 it is evident that lateral movement of the distal thoracic marker has no effect on calculation of flexion/extension angles, as hypothesized above using projection angles.

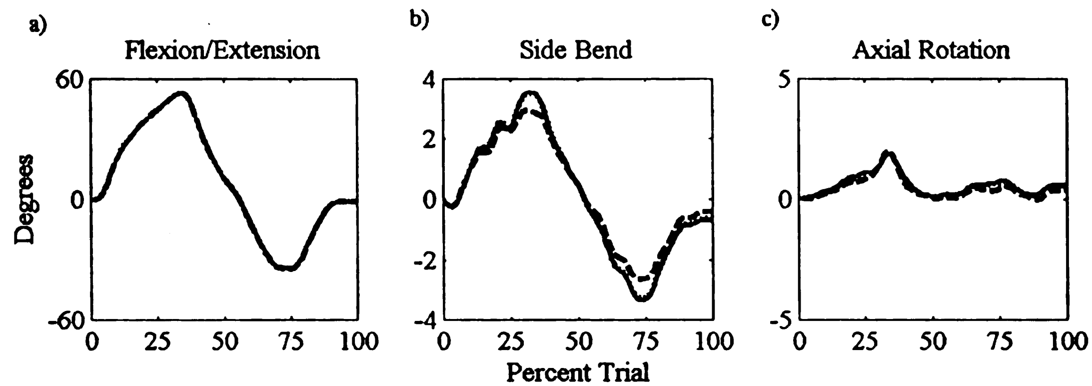

Figure 3.11. Results of trial 04 sensitivity test. Solid line = no error, dotted line = 10 mm error and dashed line = 30 mm error.

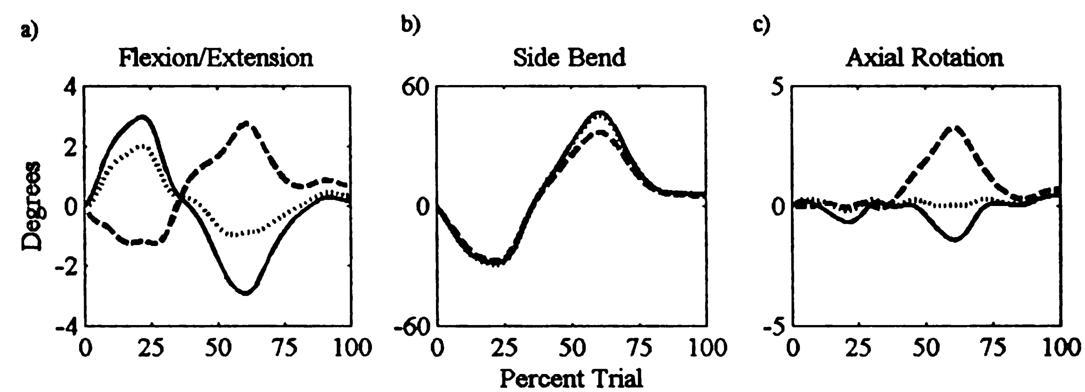

Figure 3.12. Results of trial 07 sensitivity test. Solid line = no error, dotted line = 10 mm error and dashed line = 30 mm error.

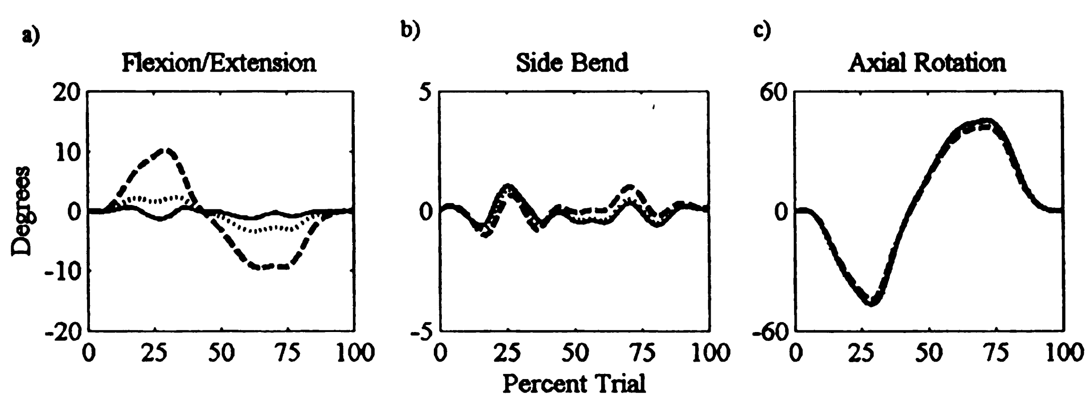

Figure 3.13. Results of trial 11 sensitivity test. Solid line = no error, dotted line = 10 mm error and dashed line = 30 mm error.

Figure 3.12 shows that movement of the distal marker had no appreciable affect on the primary motion of sidebending, but did introduce approximately 3° of transverse and sagittal plane cross talk. Likewise, simulated abnormal movement of the distal marker during dummy spine axial rotation did not affect the primary motion of axial rotation, but did create error angles in the frontal and sagittal planes of approximately 1° to 10°, respectively (Figure 3.13).

Using a dummy cervical spine setup and the same Euler sequence used for this research, Hof and Winters (2002) found ~ 8° of flexion and 12° of sidebending error (i.e., cross-talk) when 120° of axial rotation was introduced. When 120° of axial rotation was added to a flexed dummy (50°) there was 10° flexion and 12° of sidebending cross-talk. When flexion or extension (90°) was the only motion introduced, motion about the secondary axes was less than 2.5°. Hof and Winter's results demonstrated greater cross-talk than this study, but their movement testing involved a non-physiologic 90° flexion/extension plus 120° axial rotation. Maximum dummy flexion, sidebending and axial rotation used in this research was 60°, 30° and 45°, respectively.

Dummy data were also used to test finite and instantaneous helical analyses algorithms. Dummy trial 04 consisted of ~60° flexion followed by ~30° extension.

Table 3.1. Helical Parameters for Dummy Flexion/Extension Test.

	Angle	Unit Vector			Piercing Points			Translation
		U_x	U_y	U_z	P_x	P_y	P_z	
Extension	33.2°	0.9963	0.0847	0.0158	0	461.8	508.4	-2.86
Flexion	50.9°	-0.9964	-0.0843	0.0014	0	465.4	515.3	-1.94

Note. Piercing points and translation in mm.

Flexion/extension in the dummy set-up occurred about a rigid medial-lateral axis so that motion in the frontal and transverse planes could not occur. Cardan angles calculated for this test approximated 53° flexion and 35° extension, values that essentially match the finite helical angles (Table 3.1). The helical unit vector indicates primary motion in the sagittal plane with very small motions in the other planes, which likely represent small errors due to misalignment of the local axis (as discussed above in the cross-talk section).

The instantaneous helical axis analysis for dummy trial 04 was plotted relative to placement of two markers that were placed on the ends of the flexion/extension axis of rotation. Results showed the calculated axis approximated well the known location of the flexion/extension axis (Figure 3.14). See Appendix E for two additional planar views of instantaneous helical axis relative to the fixed flexion/extension axis.

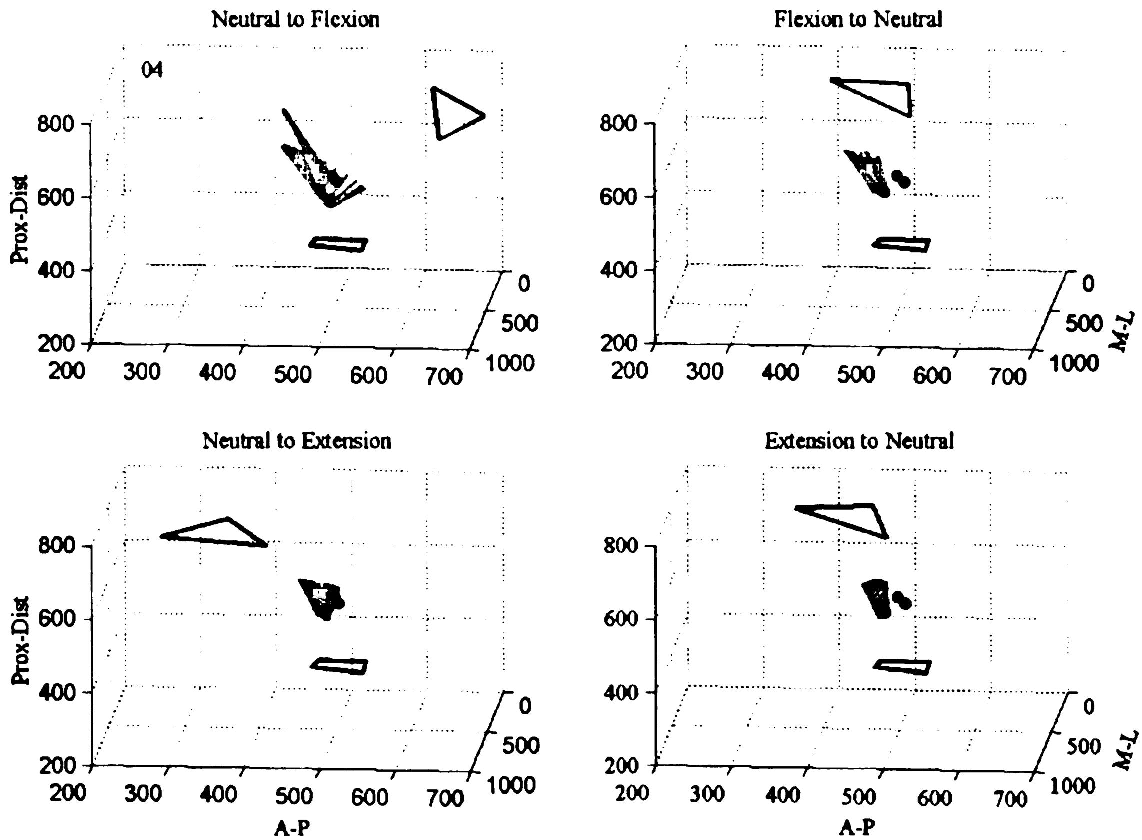

Figure 3.14. Sagittal view of the instantaneous helical axis relative to the fixed flexion/extension axis for dummy trial 04. Blue represents the beginning of the movement and green the end of the movement. The upper triangle represents the "thoracic" segment, the lower quadriangle represents the "lumbar" segment, and the two blacked-filled circles represent the endpoints of the dummy flexion/extension axis.

Reliability

Observed variance in measures (i.e., difference between observation and 'true' values) results from measurement error (systematic + random), as noted previously, and from biological variability (Brinckmann, Frobin & Leivseth, 2002). In an attempt to approximately quantify both biological and statistical measurement error, repeated measures (i.e., reliability) were examined. Using the Flock of Birds electromagnetic device, Koerhuis et al., (2003) reported standard deviations (SD) ranging from 2-4° within a series of eight consecutive measures of human subject cervical motions. Same and between day SD's ranged from 4-12° (Koerhuis et al). Using an electromagnetic device to measure lumbar spine motion, Lee and Wong (2002) reported an intra-day mean coefficient of multiple determination of 0.98 ± 0.01, with mean SD's of 2.1 ± 1.0°. Whittle and Levine (1997) used a lumbar marker array similar to the one used in this study to examine the lumbar spine lordosis during walking. Reliability analysis of their data suggested that test-retest repeatability was high (Pearson values > 0.90) enough to be acceptable with the use of the marker array system. For this study a trial consisted of five repetitions. Within trial repeatability was examined for the middle three repetitions using the coefficient of variation (Winter, 1991). To examine between-day variability the coefficient of multiple correlation (Growney, Meglan, Johnson, Cahalan, & An, 1997; Hershler & Milner, 1978; Kadaba, et al., 1989) was used for a subset of 10 subjects that were re-tested approximately 1-2 weeks following their initial test. Determination of the coefficients of variation and multiple correlation will be described in more detail in the analysis section of this chapter.

Subjects

Ethics approval for this study was obtained from the Michigan State University Office of Research and Ethics and Standards, University Committee on Research Involving Human Subjects (IRB # 99-780), Mary Free Bed Hospital (MFB) & Rehabilitation Center Research Committee and MFB Human Subjects Review Committee. Sixty-three male and female subjects were recruited to participate. Subjects were informed about the experimental procedure and any potential risks prior to the attainment of written consent (see Appendix F).

Once informed consent procedures were accomplished subjects completed a medical history form (Appendix G). Subjects who presented with an ectomorphic-mesomorphic body type and were cleared of any significant past medical and surgical history were considered "normal" and proceeded to the screening examination (Appendix H). A normal gait based on observation analysis, symmetrical posture, normal trunk, upper extremity and lower extremity range of motion, symmetrical respiratory patterns, and leg length differences less than 6 mm were criteria that allowed subjects to participate in the study (Greenman, 1996; Magee, 2002). It should be noted that the criteria for "normalcy" for this study were stricter than any previous research reviewed in the literature. Based on inclusion criteria, 15 male and 15 female individuals between the ages of 18 and 29 years were tested. Study subjects are identified by code only.

Instrumentation and Calibration

Single spherical markers were attached to four pelvic anatomical landmarks and over thoracic and lumbar spinous processes, as described earlier. These 14 mm diameter markers are plastic, covered by gray retro-reflective tape and glued to a 15 mm diameter circular base. Two marker rigs were also used, one placed on the thoracic spine and one placed on the lumbar spine. The marker rigs housed two 14 mm diameter spherical markers, one glued to a ¼-inch polyethylene base (7.5 × 3 × 0.5 cm) and one glued to the end of a 95 × 2 mm, rigid rod (Figure 3.15). The center-to-center distance between the "base" and "posterior" markers was approximately 10.5 cm. The extended rod, at its base, was hinged (base end) to allow for positioning/re-positioning of the "posterior" marker over the "base" marker. The base of the hinged rod was glued to the polyethylene base with epoxy. A silicon gel that could be formed to fit over the bony spinous processes served as the interface between the polyethylene base and the skin.

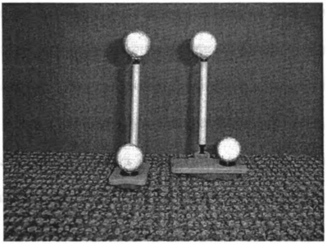

Figure 3.15. Marker rigs used to track motion of the thoracic and thoraco-lumbar vertebral segments. Notice silicon gel attached to underside of polyethylene base.

Six VICON 512™ (Oxford Metrics, LTD., Oxford, England) variable-speed (60 to 240 Hz), high-resolution cameras, placed strategically in a calibrated volume, were be used to capture the position of markers secured on the thoracic and thoraco-lumbar spines, and pelvis of male and female volunteers. Data were collected at 30 Hz. Each camera lens is surrounded by a ring of light emitting diodes (LEDs) that emit visible red light that is reflected back to the camera lens from the anatomically placed markers or rigid marker arrays. The camera shutters are synchronized so that each camera pixel screen simultaneously records an image of the object. Given the marker position from two camera pixel screens, the three-dimensional position of a marker can be reconstructed if the camera positions are known in space. The camera positions and calibration coefficients are determined using static and dynamic calibration tests and a direct linear transformation (DLT) algorithm (Abel-Aziz & Karar, 1971).

A calibration procedure, as prescribed by the manufacturer (VICON Users Manual), was conducted for each test date, but it was not necessary to re-calibrate between each test subject. Calibration is the process that establishes the laboratory coordinate system and linearizes each camera and measures each camera position relative to the others. The calibrated volume was slightly different for each subject, but measured approximately 1 × 1 × 1 m. The approximate camera distance to center of capture volume was: camera 1: 3.730 m, camera 2: 3.900 m, camera 3: 3.740 m, camera 4: 4.040 m, camera 5: 3.480 m, and camera 6: 3.170 m (mean camera distance to volume center was 3.680 m).

Calibration occurred in two steps: static and dynamic. For the static test, approximately 20 frames of video data were collected with an L-frame. The L-frame is a metal right-angle frame that contains four 25 mm diameter markers, three along one pole and a single at the end of the other pole, with known locations. The L-frame was leveled and placed snugly around two edges of rigid metal and tile square that was placed on a wooden stool. The static test calculates the origin of the capture volume and determines the orientation of the three-dimensional workspace. Following collection of static data, the L-frame was removed and dynamic calibration took place. This test consisted of waving a wand, on which two 50 mm markers are mounted at a known separation (250 mm), throughout the anticipated measurement space. The wand was moved in a variety of attitudes and out to each corner of the measurement area. Dynamic position data were captured for approximately 10-15 seconds, or as long as needed in order for the operator to move the wand through the entire measurement volume. During dynamic testing it is important that the two markers on the wand are visible to as many cameras as possible, particularly at the beginning of the dynamic data capture. Dynamic calibration allows the system to calculate the relative positions and orientations of the cameras and linearizes the cameras. As mentioned previously, calibration residuals (mm) are given for each camera following the two-step calibration procedure. Residuals are a measure of the accuracy of a single camera in mm. Residuals above 1 mm generally were not accepted and calibration was repeated. Mean (± SD) residuals for all cameras, over all test dates, ranged from 0.65 to 0.92 (± 0.04-0.25) mm. The manufacturer recommends acceptable residuals ranging from 1-4 mm. Static reproducibility (SR) is the RMSE of the L-frame coordinates as calculated compared to the *.cro file scaled to the size of the L-frame. Manufacturer's SR recommendation is < 1%; mean (± SD) SR for all pre-test calibrations was 0.72 (± 0.16) % (Appendix I). Following the calibration a second "wand" trial was conducted. The wand was waved throughout the calibrated volume in a variety of attitudes for approximately 10-15 seconds while marker position data were captured at 30 Hz. After data capture marker reconstruction and labeling were performed and then the system graphing routine was used to calculate the mean linear distance (± SD) between markers. For all wand trials the mean SD was 0.62 mm, a value that results from good calibration and demonstrates excellent system linear accuracy.

During subject testing the video system is able to "see" a marker as long as its retro-reflective surface is in view of the cameras. The LEDs surrounding the camera lens allow the retro-reflective surface of markers placed in front of the lens to reflect a bright image onto the pixel screen within each video camera. Since the marker image is very bright, the threshold of the video system can be adjusted so that background images are removed and only the marker images remain. A computer data station controls the video image of on-off pixels. Finding the centroid of the pixel image approximates the center of each marker. Once the centroid of the pixel image is found for each marker, the workstation and digitizing software, using a direct linear transformation algorithm, determines the 3D position of every marker. The workstation provides the control interface for the system and includes tools for editing motion data.

Procedures

Screening Examination

After subjects read and signed informed consent and the medical history form, a screening examination (Appendix H) for the entire body was performed. The human neuro-musculoskeletal system can compensate for skeletal mal-alignments and restricted joint motions in areas of the body away from the primary joint dysfunction of decreased mobility or range of motion. For example, decreased mobility of any vertebral segment secondary to tight muscles or zygapophyseal capsular tightness can result in hypermobility of adjacent vertebral segments. The purpose of this study was to examine thoracic spine/cage movement patterns in normal subjects. Therefore, it was important to include only subjects that had normal, "ideal" skeletal alignment and normal/symmetrical joint ranges of motion in the peripheral joints as well as the spine. Abnormal motion of the upper extremities and asymmetrical respiratory patterns may also be indicative of thoracic cage dysfunction. Subjects who did not pass all twelve steps of the screening examination, as determined by a licensed physical therapist skilled in manual orthopaedic examination procedures, were excluded from this study.

Test Preparation

Male subjects were tested with shorts, shoes and socks. In addition to wearing shorts, female subjects were required to wear a top that allowed the placement and visualization of markers on the thoracic cage. Prior to placing markers on the skin in the thoracic and lumbar regions a quick-drying tape adherent (Q.D.A.™, Cramer Products, Inc., Gardner, KS, 66030) was applied. Marker rigs and individual markers were then secured, using hypoallergenic tape, on the subjects' skin over the following areas: spinous processes spanning T3 to T6, spinous processes spanning T12 to L3/4, bilateral anterior and posterior superior iliac spines (Figure 3.16). Six 14 mm diameter markers were also secured to the head (forehead, right and left temples, glabella and just anterior to the right and left ears) to be used for future analysis of head/cervical spine motion.

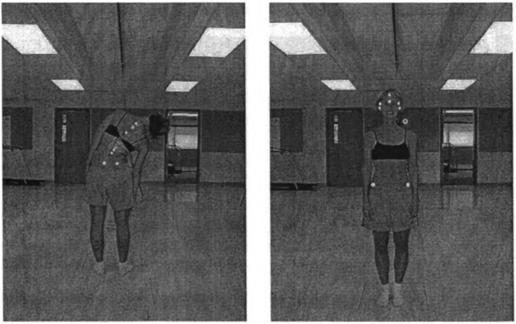

Figure 3.16. Marker placements for head, spine and pelvis.

Testing Protocol

Prior to data collection, subjects were instructed in the test motions and were allowed to warm up. The warm up session allowed the researcher to inspect attachment security of markers and excessive skin motion (Figure 3.17). Common knowledge suggests that a warm up is necessary to allow for sufficient tissue creep, thereby reducing myofascial restrictions to joint motion. One in vitro load-displacement study (Taylor, Dalton, Seaber, & Garrett, 1990) showed that four repeated stretch-elongation cycles of the muscle-tendon unit adequately stretched the muscle. Therefore, subjects were allowed three to five repetitions of trunk/pelvic movement in each plane, i.e., flexion, extension, right and left sidebending, and right and left axial rotation as a warm-up. Before movement tests were performed a static standing trial was collected, after which three of the head markers (glabella and two ear markers) were removed.

Figure 3.17. Motion test to evaluate the fidelity of marker fixation to skin.

Five repetitions of all test movements were collected in both standing and sitting positions. Standing movements were tested first, followed by test movements in sitting. In standing, test movements were conducted in the order trunk flexion/extension, right and left sidebending, and left and right axial rotation. In sitting, test movements consisted of right and left sidebending and left and right axial rotation. In standing, for flexion, extension and axial rotation, and in sitting for sidebending and axial rotation, subjects crossed their arms, resting fingertips on shoulders. During sidebending in standing subjects were asked to keep their arms at their sides letting their hands slide along the lateral aspect of the thighs as motion progressed. For flexion/extension and axial rotation in standing subjects were instructed to attempt to restrict excessive forward/backward pelvic tilting and rotation, respectively; in sitting this was not necessary since the pelvis is stabilized by weightbearing on the ischial tuberosities. During sidebending tests in standing subjects were instructed not to flex or extend as they bent to the side. During trunk extension in standing, and sidebending or axial rotation in sitting with torso "hyperextended" subjects were instructed/reminded to maintain a maximum "chin-tuck" position. A "chin-tuck" required subjects to posteriorly translate their head/neck. For sitting, the order of tests was right and left sidebending then left and right axial rotation, first in the "neutral" posture, followed by testing in the slumped (flexed) and erect (hyperextended) postures. Subjects were seated on a wooden stool with thighs supported and feet flat on the floor (hips and knees were flexed approximately 90°). A gravity inclinometer was used to measure the lumbo-sacral angle in standing, which was considered that individual's characteristic "neutral" spinal angle. Thus, the "neutral" sitting angle was that angle of the lumbo-sacral spine that was the same as in standing. For the "neutral" test subjects were asked to maintain their neutral lumbo-sacral angle during the test movements. Immediately following the motion testing the lumbo-pelvic angle was remeasured. If the lumbo-sacral angle remained within ± 5° the data were kept, if not, the motion test was repeated.

Ten subjects, randomly selected, were asked to return for repeat testing approximately one to two weeks following their first test. Returning individuals were screened subjectively and inspected for changes in status. Re-tested subjects demonstrated no changes in subjective or objective measures. The purpose of the repeated testing was to duplicate the procedures of the first test in order to determine reliability of the testing procedures (i.e., placement and stability of markers and marker rigs) and the impact this had on joint kinematics.

Data Processing and Analysis

Data Processing

Following data collection, the VICON 512 video processor and digitizing software, through a process called reconstruction and labeling, determined three-dimensional marker positions (see Appendix J for data collection/processing sheet). The system editing process was used to refine marker trajectories. After reconstruction and labeling it is not uncommon for markers to disappear for a 'period' whereby the system will have two trajectories with the same name or label. Defragmentation is the editing process undertaken to rejoin these two separate trajectories into one. The defragmenting process doesn't fill the gaps between the joined trajectories. A cubic spline interpolation algorithm was used to fill gaps in trajectories (usually 15-20 frames) by calculating a smooth curve between the broken ends. Other editing features that were used included: deletion of "ghost" or duplicate trajectories; use of an existing marker that was visible to "create" the trajectory of another marker that had been lost for more than 20 frames (called copy pattern); and deleting and filling the gap of marker trajectory data that were visibly poor (called delete and fill). The majority of data files did not require significant editing. Custom-written software was used to convert VICON C3D binary files into standard computer language format (ASCII). MATLAB™ (Mathworks, Natick, MA) programs (both custom and modifications of acquired programs) were written to determine kinematic and reliability parameters, and graphing formats. Raw marker data were filtered at 0.5 Hz using a Butterworth algorithm. Microsoft EXCEL was used to determine sample descriptive statistics.

Data Analysis

Descriptive statistics (mean, standard deviation) were used to summarize subject demographics. Ten subjects were retested to examine differences in spine range of motion and determine coefficients of multiple correlation (CMC). Descriptive statistics were also used to summarize the test-retest data.

Cardan angles were calculated using MATLAB™ software (Reinschmidt & van den Bogert, 1997) previously written, but modified for this research. Movements of the thoracic and lumbar segments were plotted against time. There were five repetitions, e.g., five flexion cycles and five extension cycles during the standing flexion test, of each motion tested. In order to examine the repeatability of measurements of each segments' movement, the angle-time curves had to be normalized with respect to time to a uniform length. The five motion cycles were cut and cycles two, three and four were time normalized and used for subsequent analysis. The three middle cycles only were chosen for data analysis for several reasons: in many subjects the initial part of cycle one was missing (started data collection late or markers were missing), the last cycle also, at times had missing markers, and it was felt that the middle three cycles would best represent the movement.

Prior to averaging the three cycles intra-subject coefficients of variation (CV) were determined (Winter, 1991) to evaluate repetition variability to signal ratios, i.e., signal-to-noise ratio (see Equation 3.26).

$$CV = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\sigma_i^2}}{\frac{1}{N}\sum_{i=1}^{N}|X_i|} \qquad (3.26)$$

where N is the number of intervals over the range of motion, X_i is the mean value of the variable at the ith interval and σ_i is the standard deviation of the variable X about X_i. Intra-subject CVs of 30% or less (Rosner, 1995) for the primary motions was the cutoff for acceptable reproducibility and provided support for describing individual subject data as ensemble averages. The mean CV for all subjects and all primary motions was 14.6% and for secondary motions was 36%. See Figure 3.18 for representative consistency plots for the standing motion tests.

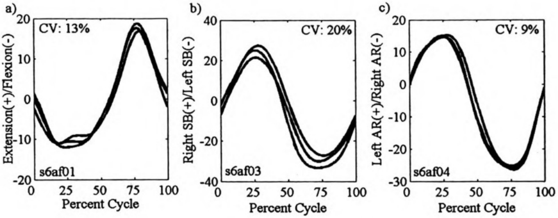

Figure 3.18. Consistency plots for three of the five test motion cycles with CVs for a) standing flexion/extension, b) standing sidebending, and c) standing axial rotation.

The coefficients of multiple correlation (CMC) were calculated using the mean of cycles two, three and four for all tested motions (Growney, Meglan, Johnson, Cahalan, & An, 1997; Hershler & Milner, 1978; Kadaba, et al., 1989; Piotter, Post, & Vanden Berg, 1999). CMCs for both primary and secondary movements were examined. The CMC describes the variance in waveform data that can be explained by the test conditions, in this case the intra-rater, inter-day variability. The ratio in the radical is the variance ratio (VR). 1-CMC describes variance than cannot be explained by the test conditions. The CMC is a ratio of variance statistic with "1" signifying a perfect relationship and "0" signifying no relationship. The equation for the intra-rater, inter-day conditions follow:

$$\mathrm{CMC} = \sqrt{1 - \frac{\sum_{d=1}^{D}\sum_{t=1}^{T}\left(\overline{Y}_{dt} - \overline{Y}_{t}\right)^2 / T(D-1)}{\sum_{d=1}^{D}\sum_{t=1}^{T}\left(\overline{Y}_{dt} - \overline{Y}\right)^2 / (DT-1)}} \tag{3.27}$$

where D represents the day and T represents the number of time points (T = 251). In the equation $\overline{Y}_{dt}$ is the average of all trials within a day, $\overline{Y}_t$ is the average of all trials and all days and $\overline{Y}$ is the overall average of all days, trials and time points. Computation of $\overline{Y}_t$ and $\overline{Y}$ follows as:

$$\overline{Y}_t = \frac{1}{MN} \sum_{m=1}^{M} \sum_{n=1}^{N} Y_{mnt} \tag{3.28}$$

$$\overline{Y} = \frac{1}{MNT} \sum_{m=1}^{M} \sum_{n=1}^{N} \sum_{t=1}^{T} Y_{mnt} \tag{3.29}$$

where M (M = D) is the number of days, N is the number of trials, T is the number of time points and $\overline{Y}_{mnt}$ represents the average of all trials on one day. If average curves are similar the numerator [the variance of the average of all trials on a given day ($\overline{Y}_{dt}$) about the average of all trials on all days ($\overline{Y}_t$)] will be smaller than the denominator [the variance of the average of all trials on a given day ($\overline{Y}_{dt}$) about the grand average of all days, trials and time points ($\overline{Y}$)] and CMC will approach 1 (high repeatability). If the numerator is approximately equal to the denominator, then CMC approaches zero (no waveform similarity). The VR numerator is thought to represent between day variability associated with marker reapplication errors (Growney et al., 1997). The CMC was considered to be analogous to the Pearson Product Moment correlation coefficient or Intraclass Correlation Coefficient so that values greater than 0.75 indicate good and values greater than 0.90 indicate excellent test/retest repeatability (Portney & Watkins, 1993).

Three-dimensional angle-angle plots (Barker, Kelly, & Paul, 1996; Hershler & Milner, 1980; Lee & Wong, 2002; Whittle & Levine, 1999) were used to reveal the trajectory of the movement pattern. The primary angle, e.g., sidebending, was plotted against that of the secondary and tertiary angles, e.g., axial rotation and motion in the sagittal plane, i.e., flexion and extension. The general shape of the curve describes the trajectory of the movement. A straight line in the angle-angle plot of primary vs. secondary motions for example indicates "exact" coordination of the two motions. A deviation from a straight line indicates the relative magnitude of the primary and secondary movements varies at different stages of movement. Similar examination of the primary and tertiary movements gives further insight into the complex three-dimensional nature of spinal motion. The angle-angle plots were used to determine the frequency of coupling patterns of sidebending and axial rotation, as well as other coupling patterns. These frequencies were compared to Fryette's hypotheses which stated that sidebending and axial rotation are coupled to same side 100% of the time when the thoracic spine is flexed or extended and are coupled to the opposite side 100% of the time when the spine is in a neutral posture.

An aperiodic or random waveform (i.e., joint angles) represents a signal that is not repetitive or may not be specified at every instant of time and cannot be represented by a Fourier series so that its future cannot be predicted with certainty on the basis of its past history. It is known that time series signals contain both random and deterministic components so for analysis it is necessary to sort the real signal from artifact (Lynn, 1973). Signal processing using auto-correlation (detecting for the presence of periodic signals buried in noise) or cross-correlation (a time-averaged measure of shared signal properties) functions are useful for determining signal fidelity (Ramirez, 1985; Winter & Patla, 1997). For this research the cross-correlation function was used to detect signals that may be hidden in noise and to examine the potential relationship between primary and secondary motions, e.g., sidebending and axial rotation. The following equation illustrates the theory used to calculate the coefficient of cross correlation (R_{xy}) of the two time series, *x* and *y*, each with N data points.

$$R_{xy}(k) = \frac{c_{xy}(k)}{\sqrt{c_{xx}(0)c_{yy}(0)}} \qquad 3.30$$

$$\text{where } c_{xy}(k) = \begin{cases} \sum^{N-k}{}_{t=1}(x_t - \bar{x})(y_{t+k} - \bar{y}) + \sum^{N}{}_{t=N-k-1}(x_t - \bar{x})(y_{t-N+k} - \bar{y}) \\ \sum^{N}{}_{T=1}(x_t - \bar{x})(y_t - \bar{y}) \end{cases}$$

$$\text{if, } \begin{matrix} k = 1,2,\ldots,N \\ k = 0 \end{matrix}$$

$$c_{xx}(0) = \sum_{t=1}^{N}(x_t - \bar{x})^2 \text{ and } c_{yy}(0) = \sum_{t=1}^{N}(y_t - \bar{y})^2 ,$$

k is a number indicating a time shift of one signal with respect to the other; k = 0 for the original two time series synchronized in time.

Findings from cross-correlation were used to corroborate results from the angle-angle plots. The primary movement of the thoracic spine was used as the reference for establishing the correlation. Using the mean of three cycles a cross-correlation function was determined for all eight of the test movements, examining potential relationships between primary and secondary, and primary and tertiary curves. The correlation $R_{xy}(0)$, calculated from $c_{xy}(0)$, will give an indication of pattern similarity between the two sets of data. The coefficient of determination, or R^2, may be more meaningful since it is indicative of the percentage of the total variance in one variable, e.g., sidebending, that

can be explained by another variable, e.g., axial rotation. Therefore, R^2 is a measure of proportion, indicating the accuracy of prediction based on the primary variable or primary motion. Furthermore, values of R^2 are more meaningful for conceptualizing the extent of an association between variables than values of r alone (Portney & Watkins, 2000). The phase relationships between the primary and secondary motions were also examined by determining the time lag at which the absolute value of the correlation coefficient was maximal.

The instantaneous (IHA) and finite (FHA) helical parameters were calculated using MATLAB™ software (Reinschmidt & van den Bogert, 1997) previously written, but modified for this research. With video motion capture systems marker positions are in fact captured at discrete points in time. Thus, technically continuous three-dimensional marker position data are not realized, but instantaneous positions are approximated. Determination of the best approximations is dependent on the frequency of sampling and/or resampling. For this research data were sampled at 30 Hz since the movements tested were relatively slow. Thus, determining the "finite helical axes" every 33 msec approximated the IHAs. IHAs relative to the thoracic reference frame were projected onto three-dimensional figure plots illustrating the location of the axes relative to thoracic and lumbar markers for the nine motion tests conducted. Because the IHA is undefined when the angular velocity approaches zero, determination of the axis was difficult when the motion approached the end range as subjects reversed the direction of movement. Therefore, to minimize the error in locating the IHA at the end range of motion the test movements were divided into four phases and the IHA was determined up to some critical point, i.e., up to the point where the absolute angle of motion was approximately 5°. For example, for standing flexion/extension, Phase I was initiated from standing neutral posture and completed when the individual came within 5° of end range flexion. Phase II began 5° after the individual reversed the fully flexed position and began the return to the neutral posture. Phase III began 5° after trunk extension was initiated and ended 5° prior to end range extension. Finally, Phase IV began 5° after the initiation of returning from full extension back to the neutral posture. Note that helical motion data were not time normalized. Thus, since the motion tests were not velocity controlled there will not be the same number of helical axes represented during the different phases of motion.

FHA parameters, i.e., helical angle, amount of translation along the helical axis, helical unit vector and piercing points, of the thoracic relative to the lumbar spine were determined with one step size. For example, the finite helical angle for standing flexion was determined from the neutral starting point to the end of the flexion range and the finite helical angle for standing extension was determined from neutral to the end range of extension. Thus, for the standing flexion/extension test there were two phases in which the helical angle and translation were calculated, the flexion phase and the extension phase. Likewise, for the sidebending and axial rotation tests there was a right movement phase and left movement phase. The helical parameters, angle and translation, were computed as an average of the same three cycles (both phases) that were used for Cardan angle analysis. The helical unit vector and piecing points were computed as an average of three cycles but for just one of the phases.

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THREE-DIMENSIONAL KINEMATIC ANALYSIS OF THE THORAX IN STANDING AND SITTING

VOLUME II

By

Gordon J. Alderink

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Mechanical Engineering

2003

Chapter 4

RESULTS

Subjects

Sixty-three subjects (45 males, 18 females) were recruited to participate in this study. Of those, 15 males and 15 females (mean age = 22 ± 3 years, mean mass = 70 ± 14 kg, mean height = 1.74 ± 0.09 m) qualified to complete the experimental testing (Table 4.1). All sixty-three subjects were in good health and reported no back or extremity symptoms that were attributed to back dysfunction within the last six months. However, only 30 subjects passed the screening physical examination, suggesting that there were a high percentage of individuals without back-related symptoms who were functioning with mild vertebral or rib dysfunctions.

Table 4.1. Subject Characteristics

Subjects	Handedness	Age (yrs)	Height (m)	Mass (kg)
Female (n = 15)	12 R/3 L	22.3 (3.2)	1.68 (0.07)	59.9 (8.0)
Male (n = 15)	12 R/1 L 2 R/L*	22.7 (3.0)	1.80 (0.07)	80.2 (11.4)
Total (n = 30)	24 R/4 L 2 R/L*	22.5 (3.0)	1.74 (0.09)	70.0 (13.9)

Note. * denotes number of subjects that were ambidextrous. Age, height and weight are presented as mean (± SD).

Thoracic Spine Range of Motion

Many prior studies, including Fryette's (1918) early work, discussed segmental thoracic spine motion or motion of functional spinal units (superior vertebra + intervening disc + inferior vertebra). The reader needs to be reminded that for technical reasons intervertebral motion was not investigated in this research, but that motion of a lumped group of thoracic segments was studied. However, it was assumed that, motion of a group of vertebra would mimic intervertebral motion, given that the spine was normal (as determined by the screening examination).

Thoracic motion relative to the lumbar spine, and lumbar motion relative to the pelvis, was determined for all motion tests. However, reporting and discussing thoracic kinematics will be the focus of this dissertation. Five repetitions were performed for all nine motion tests, but only the middle three cycles were used for statistical purposes since it was felt that these cycles would be most representative. With regard to spinal motion, the major motion is typically referred to as the primary motion and the coupled motion is referred to as the secondary motion. Several (Buchalter et al., 1989; White, 1969) have shown also that a small amount of sagittal plane motion occurs during sidebending or axial rotation of the spine. Although sagittal plane motion could also be considered coupled motion, flexion/extension is not typically considered the second motion, thus, for this research it will be called the tertiary motion.

Based on thoracic spine/cage anatomy, i.e., orientation of zygapophyseal joints and presence of ribs, it was expected that axial rotation (AR) and sidebending (SB) would generally be the predominant motions, in terms of magnitude. Data support this expectation as mean transverse plane (62.1°) motion exceeded motion in the frontal (45.4°) and sagittal planes (25.3°) (Table 4.2). Although neutral standing and sitting

Table 4.2. Total Thoracic Spine Range of Motion

	Flexion + Extension	Sidebending (R+L)	Axial Rotation (R+L)
Stand FE	25.3 (12.7)[a]	6.4 (3.4)	6.3 (2.5)
Stand SB	5.8 (2.9)[c]	45.4 (13.9)[a]	10.5 (5.8)[b]
Stand AR	11.8 (5.2)[c]	18.9 (7.6)[b]	62.1 (13.7)[a]
Sit Neutral SB	7.9 (5.9)[c]	60.4 (12.2)[a]	22.4 (11.9)[b]
Sit Neutral AR	12.8 (4.6)[c]	18.4 (6.9)[b]	62.9 (11.8)[a]
Sit Slouch SB	4.5 (2.6)[c]	44.6 (9.7)[a]	8.9 (5.4)[b]
Sit Slouch AR	3.7 (1.7)[c]	16.2 (10.8)[b]	31.9 (11.9)[a]
Sit Erect SB	7.1 (4.3)[c]	52.9 (14.3)[a]	14.8 (10.1)[b]
Sit Erect AR	12.4 (6.0)[c]	22.9 (12.4)[b]	59.1 (14.6)[a]

Note. Table data provide magnitude and not direction of motions; FE = flexion/extension, SB = sidebending, AR = axial rotation; [a] = primary, [b] = secondary, [c] = tertiary motions. Data are presented as mean (± SD) angle in degrees.

AR motions were similar in magnitude (62° vs. 63°), neutral SB was quite different in standing (45°) and sitting (60°). Sitting in a slouched position exaggerated subjects' thoracic flexion, whereas sitting erect moved subjects' thoracic spine into hyperextension. The slouched and erect postures had mixed effects on the magnitude of SB and AR. Whereas, the slouched and erect postures did not appear to inhibit subjects' ability to SB, slouch decreased subjects' ability to move in the transverse plane. With axial rotation as the primary motion in standing, sitting neutral and sitting erect coupled sagittal plane motion (~ 12°) was consistently evident. Recall, that sagittal plane cross-talk during axial rotation was previously shown not to exceed 1°. Since sagittal plane cross-talk during sidebending was shown to approximate 4°, the tertiary sagittal plane motion during the sitting sidebending tests is considered minimal and not clinically relevant.

Fryette (1918, 1954) suggested that when motion was introduced in one plane motion in the other planes would be reduced. For example, during the slouch sit tests the thoracic spine is placed in a hyperflexed posture prior to subjects' performance of sidebending and axial rotation. It might be expected then that sidebending and axial rotation would be reduced, but data show that only axial rotation was reduced. Likewise, it was expected that sitting erect would also have reduced sidebending and axial rotation mobility, which was not the case.

Mean total range of motion data for the cohort can be viewed graphically in Figure 4.1through Figure 4.4.

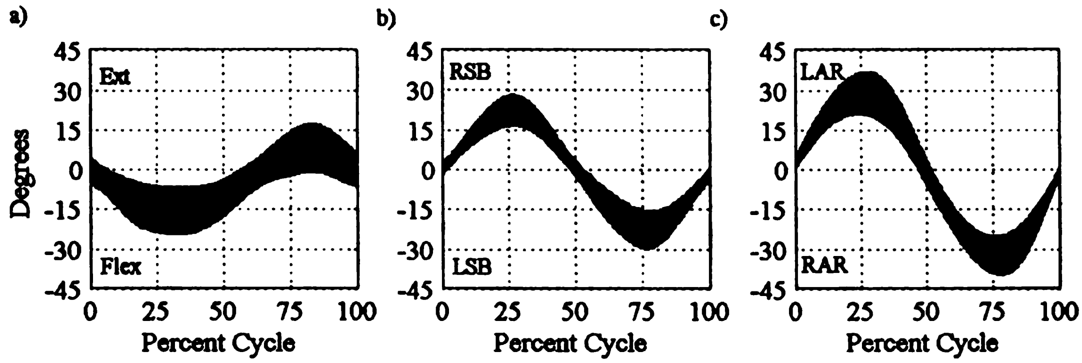

Figure 4.1. Time normalized ensemble average (± SD) for standing a) sagittal, b) frontal and c) transverse plane range of motion.

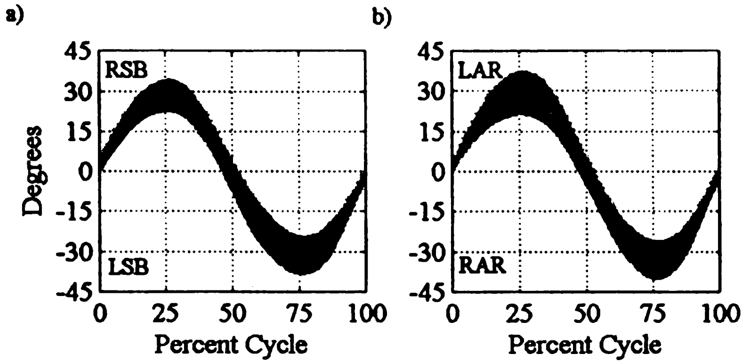

Figure 4.2. Time normalized ensemble average (± SD) for sitting neutral a) sidebending and b) axial rotation range of motion.

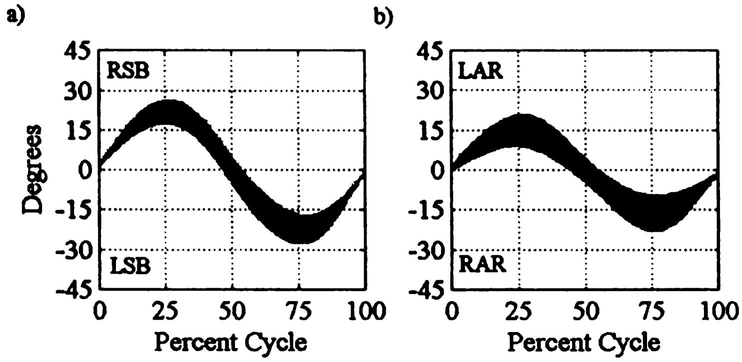

Figure 4.3. Time normalized ensemble average (± SD) for slouched sitting a) sidebending and b) axial rotation range of motion.

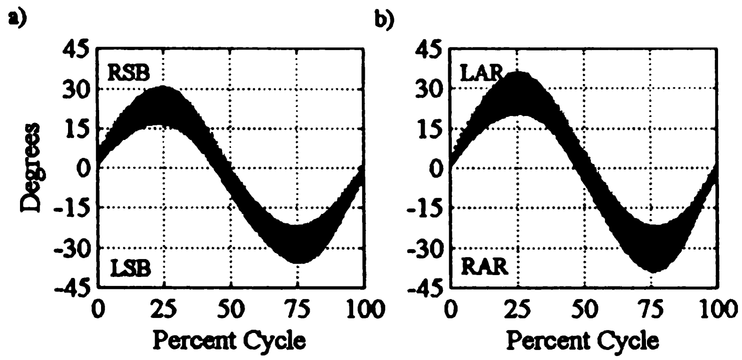

Figure 4.4. Time normalized ensemble average (± SD) for erect sitting a) sidebending and b) axial rotation range of motion.

To examine thoracic range of motion more closely total sagittal plane motion was divided into flexion and extension, total frontal plane motion was divided into right and left sidebending and total transverse plane motion was divided into right and left axial rotation (Table 4.3). For the standing motion tests, mean flexion and extension range of motion approached 17° (± 9.2°) and 8° (± 9.7°), respectively. Mean flexion and extension range of motion for the sitting tests are not presented in Table 4.3 because they represent small tertiary movements and Table 4.2 represent well total sagittal plane motion with the sidebending and axial rotation tests.

Table 4.3. Right/Left SB and AR Range of Motion for Primary Motions

	Right SB	Left SB	Right AR	Left AR
Stand SB	23.2 (7.7)	22.1 (9.7)	-	-
Stand AR	-	-	33.1 (8.1)	28.9 (8.4)
Sit Neutral SB	31.7 (7.8)	28.7 (6.6)	-	-
Sit Neutral AR	-	-	33.4 (7.7)	29.5 (8.7)
Sit Slouch SB	22.6 (6.1)	22.0 (5.1)	-	-
Sit Slouch AR			16.7 (7.7)	15.2 (5.9)
Sit Erect SB	28.9 (7.5)	23.9 (7.4)	-	-
Sit Erect AR	-	-	30.6 (9.2)	28.5 (8.4)

Note. FE = flexion/extension, SB = sidebending, AR = axial rotation. Data are presented as mean (± SD) angle in degrees.

Results demonstrate reasonable right/left symmetry, although, in general, it appears that motion to the right exceeded motion to the left. Right/left differences approximate five degrees, which is considered not to be clinically significant. The moderately high standard deviations suggest large inter-subject variability.

Repeatability of Thoracic Spine Range of Motion

For the purpose of examining the intra-rater, inter-day measurement and waveform consistency ten subjects were selected for re-testing, i.e, tested on different days approximately one to two weeks following the first test (Test 1). The absolute group mean differences for the primary motions ranged from 0° to 9°. The mean (± SD) of the absolute differences between group means for the primary motions of sidebending and axial rotation was 1.6° (± 0.8°) and 5.0° (± 3.8°), respectively, indicating the level of repeatability for the groups. The means of the individual subject differences between Test 1 and Test 2 appear to show greater variability (Table 4.4).

Table 4.4. Mean of Individual Differences Between Test 1 and Test 2 (n = 10)

	Flexion + Extension	Sidebending (R+L)	Axial Rotation (R+L)
Stand FE	7.7 (5.8)[a]	1.1 (0.9)	4.6 (3.2)
Stand SB	2.4 (1.9)[c]	7.6 (5.8)[a]	3.4 (3.2)[b]
Stand AR	3.3 (2.5)[c]	5.3 (3.4)[b]	10.9 (9.4)[a]
Sit Neutral SB	5.4 (6.4)[c]	4.5 (3.0)[a]	9.7 (7.1)[b]
Sit Neutral AR	5.2 (3.4)[c]	7.8 (5.9)[b]	9.2 (7.5)[a]
Sit Slouch SB	2.3 (1.6)[c]	4.5 (3.0)[a]	5.5 (6.8)[b]
Sit Slouch AR	1.9 (1.7)[c]	4.8 (3.9)[b]	5.8 (4.9)[a]
Sit Erect SB	3.9 (4.3)[c]	7.2 (4.4)[a]	6.8 (7.7)[b]
Sit Erect AR	5.1 (4.0)[c]	10.3 (5.1)[b]	11.7 (7.9)[a]

Note. FE = flexion/extension, SB = sidebending, AR = axial rotation; [a] = primary, [b] = secondary, [c] = tertiary motions. Data are presented as mean (± SD) angle in degrees.

An alternative method for evaluating intra-subject, inter-day consistency is to examine waveform repeatability using the coefficient of multiple correlation (CMC). As indicated in Chapter 3, a CMC of 1.0 is be a perfect correlation, values ranging from 0.75-1.0 are considered good to excellent and correlations and values below 0.75 are considered fair. Total motion in the sagittal plane had only fair test/re-test repeatability, with a mean CMC of 0.66 (± 0.29). A CMC range of 0.12 to 0.93 for flexion/extension motion suggests large variability among individuals. For the primary motions in both the frontal and transverse planes the mean CMC was 0.96 (± 0.04), whereas for the coupled motions the mean CMC was 0.78 (± 0.19). There was no apparent difference between CMC's of the primary motions of sidebending (0.98 ± 0.002) and axial rotation (0.95 ± 0.02). On the other hand, sidebending that was coupled to the primary motion axial rotation showed better consistency (0.83 ± 0.04) than axial rotation coupled to the primary motion sidebending (0.73 ± 0.05). Overall, repeatability of the primary motions was excellent with little variability among subjects, whereas repeatability of coupled motions was good with slightly more variability among individuals.

Coupled Motion

From Table 4.2 it is clear that sidebending and axial rotation movements are strongly coupled in the thoracic spine. It is also evident that when either sidebending or axial rotations are the primary motions there is motion in the sagittal plane. One way to analyze the patterns of coupled spinal motion is to examine angle-angle plots.

For thirty subjects a total of two hundred forty three-dimensional (3D) angle-angle plots were constructed and evaluated. Angle-angle plots were not constructed for the standing flexion/extension motion tests since the primary purpose of this study was to examine coupling of sidebending and axial rotation. Of the two hundred forty trials nineteen were discarded. These nineteen trials were not used in the analysis for several reasons; (1) initial observations revealed joint angles that did not seem to resemble patterned movement, (2) evaluation of the angle-angle plots corroborated the initial impression of inability to differentiate clear coupling patterns and (3) cross-correlation data also suggested no significant relationship among the waveforms. The resulting two hundred twenty-one angle-angle plots were evaluated visually for ipsilateral (same) or contralateral (opposite) coupling patterns (Table 4.5).

Table 4.5. Frequency of Coupling Patterns for Standing and Sitting SB and AR Trials

	Stand SB	Stand AR	Neutral Sit SB	Neutral Sit AR	Slouch Sit SB	Slouch Sit AR	Erect Sit SB	Erect Sit SB
Ipsilateral	15	30	25	29	21	15	22	30
Contralateral	8	0	3	0	5	13	5	0
Trials Discarded	7	0	2	1	4	2	3	0

Note. There were a total of 30 trials for each of eight tests. SB = sidebending, AR = axial rotation; Ipsilateral = coupling to same side, Contralateral = coupling to opposite side.

Fryette (1918; 1954) stated that, with the thoracic spine in a neutral posture, sidebending and axial rotation would always be coupled opposite (right sidebending with left axial rotation), regardless of which motion was introduced first. Examination of the data in Table 4.4 shows that with standing motion testing sidebending was coupled with axial rotation in the opposite direction only 35% (8 contralateral/23 total subjects) of the time, whereas when axial rotation was the primary motion in standing motion tests, sidebending was never coupled in the opposite direction. Likewise, when subjects were seated in neutral, sidebending and axial rotation were coupled in the opposite direction only 11% (3 contralateral/28 total subjects) of the time. A typical sidebending/axial rotation ipsilateral coupling pattern for the standing neutral test is illustrated in Figure 4.5. The figure on the left illustrates the strong coupling of sidebending and axial rotation, while the figure on the right illustrates sagittal plane motion coupled with sidebending.

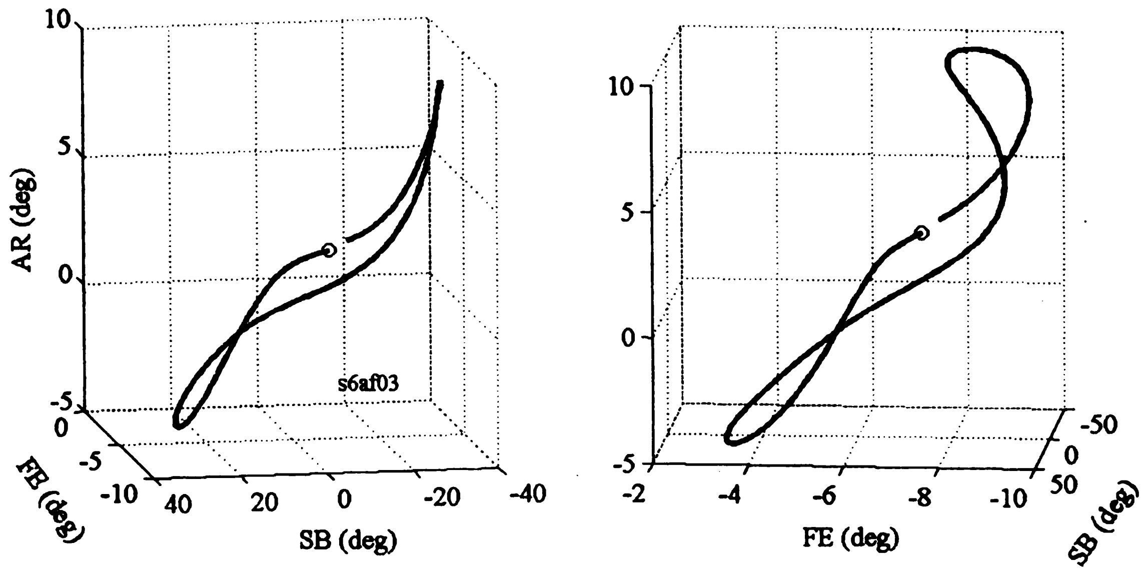

Figure 4.5. Three-dimensional angle-angle plots for the standing sidebending test. The circle denotes the beginning of the motion.

Notice in Figure 4.6 the strong ipsilateral coupling of axial rotation with sidebending and minor coupling with flexion/extension. Similar patterns are seen in Figure 4.7 and Figure 4.8 for the sitting neutral tests.

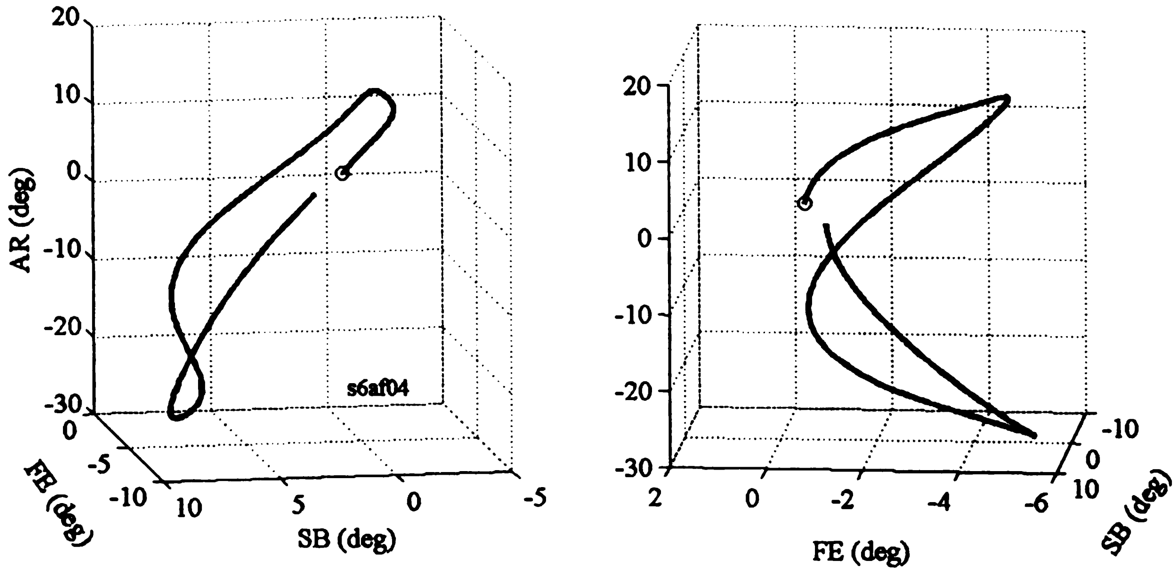

Figure 4.6. Three-dimensional angle-angle plots for the standing axial rotation test. The circle denotes the beginning of the motion.

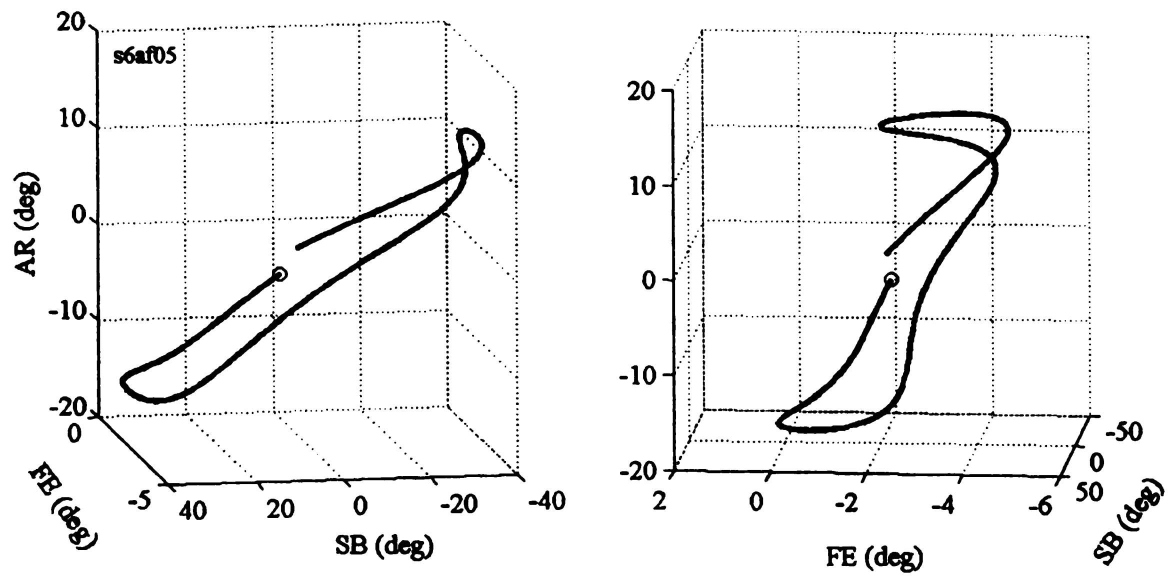

Figure 4.7. Three-dimensional angle-angle plots for the sitting neutral sidebending test. The circle denotes the beginning of the motion.

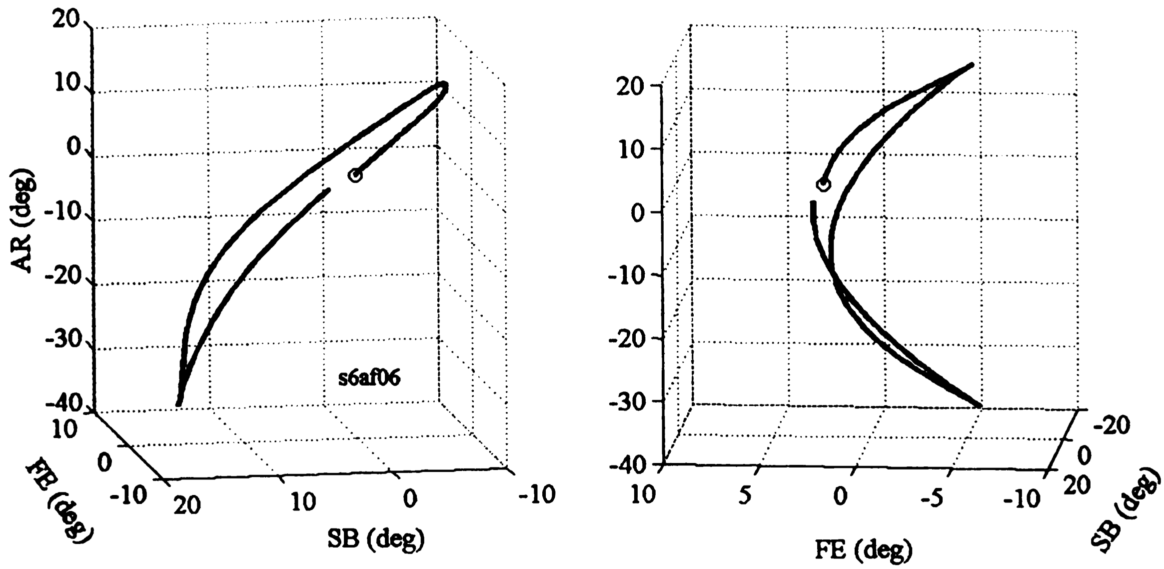

Figure 4.8. Three-dimensional angle-angle plots for the sitting neutral axial rotation test. The circle denotes the beginning of the motion.

For flexed or extended thoracic postures it was expected that sidebending and axial rotation would always be coupled to the same side (Fryette, 1918; 1954). Data in Table 4.4 show that a high percentage of the subjects demonstrated this pattern. For the sidebending and axial rotation tests in the erect (extended) posture, 52 of 57 trials followed the ipsilateral pattern. When sidebending was tested in the slouched sitting posture 81% (22/27) of the tests showed the ipsilateral pattern, but, surprisingly, when axial rotation was the primary motion in slouch only 54% (15/28) of the trials demonstrated the ipsilateral pattern. Representative 3D angle-angle plots showing ipsilateral coupling patterns for the sitting slouch tests are found in Figure 4.9 and Figure 4.10 and the sitting erect tests in Figure 4.11and Figure 4.12.

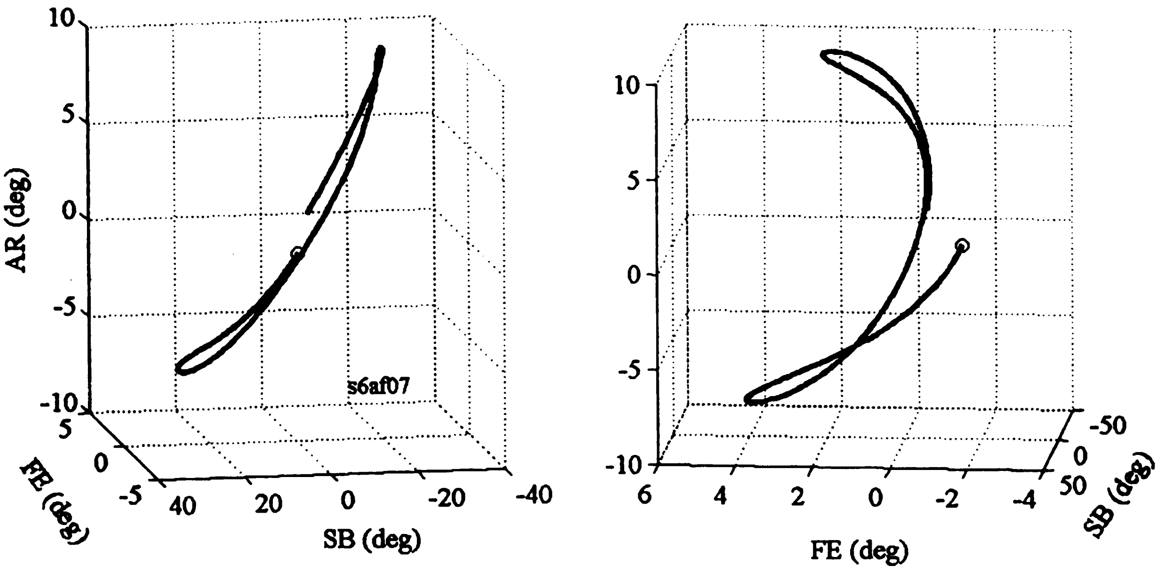

Figure 4.9. Three-dimensional angle-angle plots for the sitting slouch sidebending test. The circle denotes the beginning of the motion.

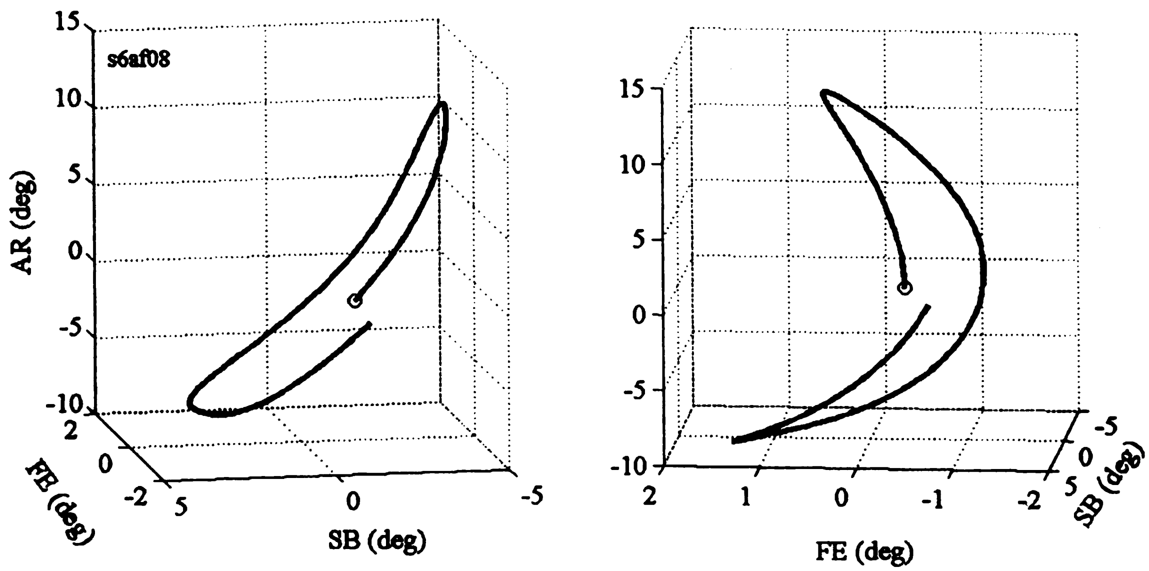

Figure 4.10. Three-dimensional angle-angle plots for the sitting slouch axial rotation test. The circle denotes the beginning of the motion.

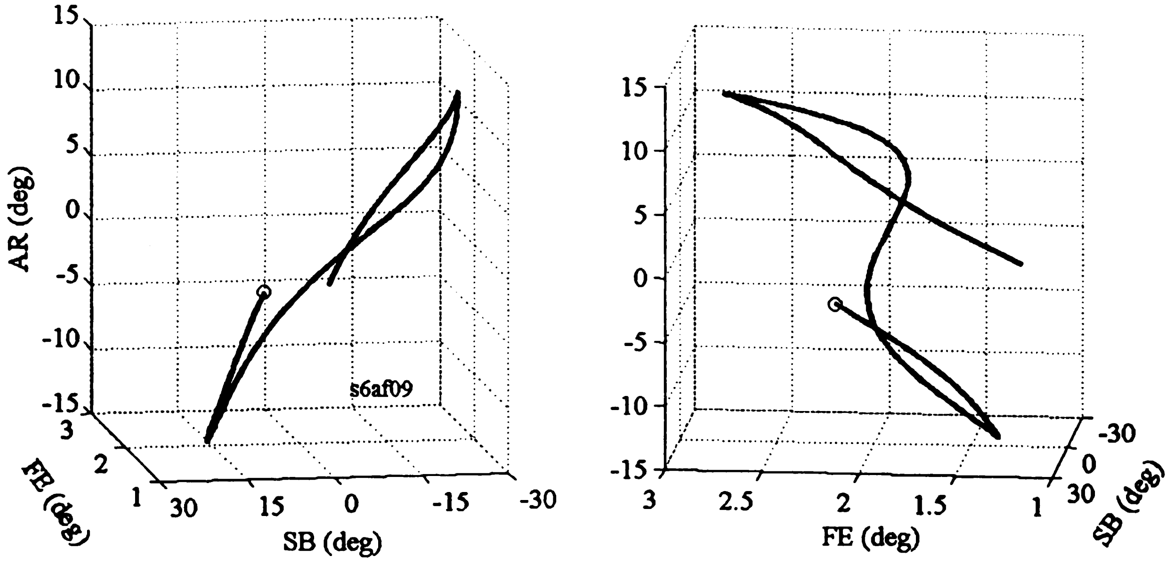

Figure 4.11. Three-dimensional angle-angle plots for the sitting erect sidebending test. The circle denotes the beginning of the motion.

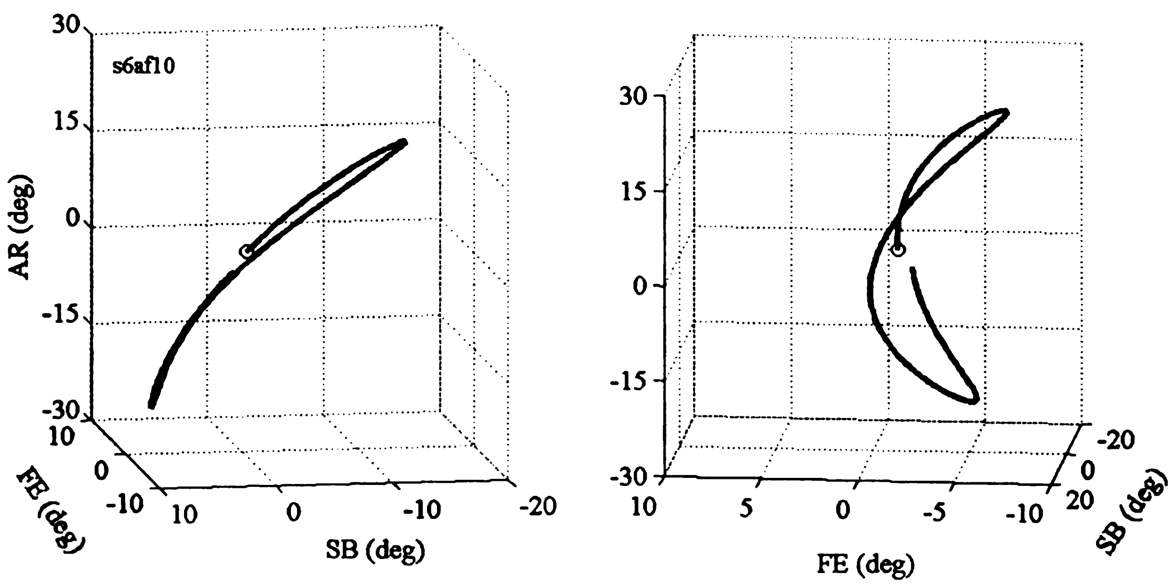

Figure 4.12. Three-dimensional angle-angle plots for the sitting erect axial rotation test. The circle denotes the beginning of the motion.

A typical angle-angle plot showing contralateral coupling of sidebending and axial rotation can be seen in Figure 4.13. Notice again the tertiary sagittal plane motion with this sidebending test.

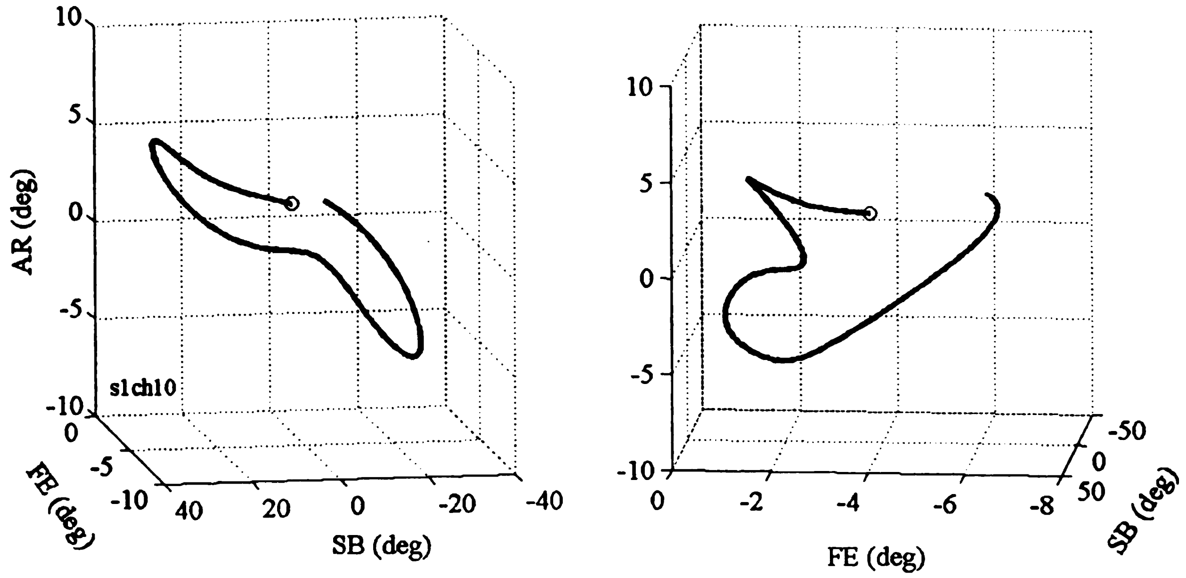

Figure 4.13. Three-dimensional angle-angle plots illustrating contralateral coupling of sidebending and axial rotation during the sitting erect sidebending test. The circle denotes the beginning of the motion.

A cross-correlation analysis of the primary and secondary waveforms was performed to detect the presence of two different, but related, periodic signals. This analysis was performed for eight motion tests; all except the standing flexion/extension test. Peak cross-correlation coefficients would describe the relationship between waveforms, but the square of the coefficient (R^2) is more meaningful since it is indicative of the percentage of the total variance in one variable, e.g., sidebending, that can be explained by another variable, e.g., axial rotation. Mean peak R^2 for all tests was 0.76 (± 0.21), meaning that 76% of the total variance in either sidebending or axial rotation can be explained by its coupled motion. Average peak R^2 at Lag 0 was 0.70 (± 0.23) suggesting there were minor phase shifts between primary and secondary motions. The mean time lag at peak correlation was negligible (0.43 ± 4.82%), suggesting that, in general, there was little phase difference between sidebending and axial rotation, regardless of which motion was introduced first (Table 4.6).

Table 4.6. Cross-Correlation Analysis of Thoracic SB and AR

	R^2	R^2 @ Lag 0	Time Lag (%)
Stand SB (n = 23)	0.63 (0.23)	0.53 (0.25)	-2.28 (6.26)
Stand AR (n = 30)	0.83 (0.18)	0.77 (0.23)	2.34 (5.52)
Sit Neutral SB (n = 28)	0.82 (0.21)	0.76 (0.25)	-0.48 (5.00)
Sit Neutral AR (n = 29)	0.81 (0.21)	0.77 (0.21)	1.78 (2.87)
Sit Slouch SB (n = 26)	0.67 (0.27)	0.63 (0.27)	0.06 (4.12)
Sit Slouch AR (n = 28)	0.79 (0.19)	0.71 (0.22)	1.40 (5.63)
Sit Erect SB (n= 27)	0.80 (0.19)	0.73 (0.22)	-2.28 (5.80)
Sit Erect AR (n = 30)	0.78 (0.22)	0.73 (0.23)	2.92 (3.41)

Note. Data are presented as mean (± SD). SB = sidebending and AR = axial rotation.

Typical cross correlation plots for frontal and transverse plane movements that were coupled in the same and opposite directions are illustrated in Figure 4.14 and Figure 4.15. It can be seen that when movements were coupled in the same direction the peak cross-correlation coefficient was negative, whereas the coefficient was positive when movements were coupled contralaterally. This phenomenon simply is the result of the sign convention used to describe direction of movements, e.g., right sidebending and left axial rotation were assigned positive values.

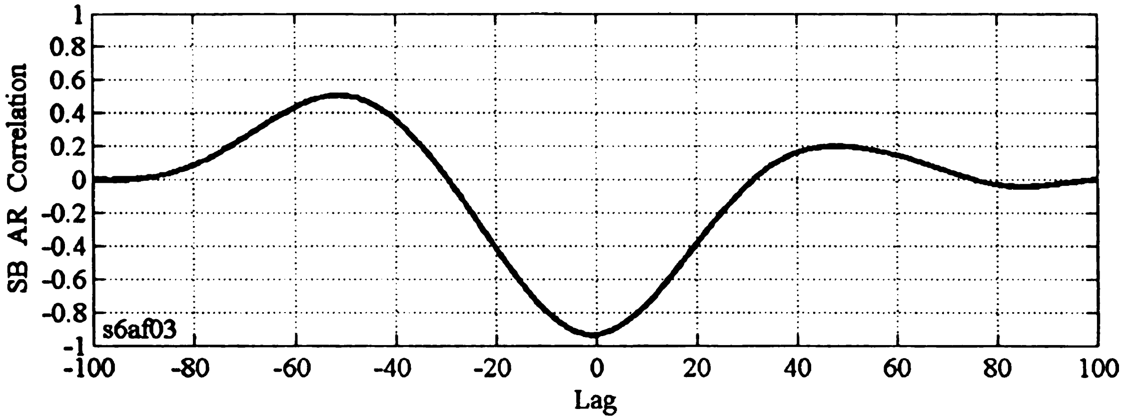

Figure 4.14. Typical cross correlation plot for the standing sidebending test where sidebending and axial rotation are coupled ipsilaterally. The correlation (R) is negative due to the sign convention used to represent sidebending and axial rotation.

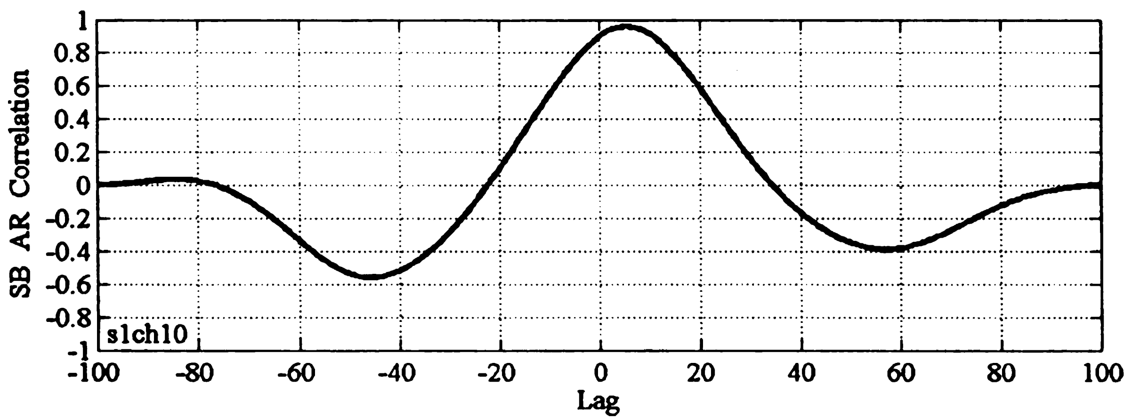

Figure 4.15. Typical cross correlation plot for the sitting erect sidebending test where sidebending and axial rotation were coupled to the opposite side. The correlation (R) is positive due to the sign convention used to describe sidebending and axial rotation.

A somewhat surprising finding was the consistent coupling of sagittal plane with either frontal or transverse plane motion, since this phenomenon has rarely been described in the literature (Buchalter et al., 1989; White, 1969). For example, during the sitting slouched tests an overwhelming majority of individuals did not maintain the slouched position they started in, but actually extended their thoracic spine as they performed either sidebending or axial rotation. Likewise, during the sitting erect tests a large number of subjects were not able to maintain maximal thoracic extension, but flexed as they sidebent or rotated. This phenomenon is suggested by the data in Table 4.2. Figure 4.16 and Figure 4.17 show representative 3D angle-angle and cross-correlation plots, respectively, illustrating the relationship between sagittal and transverse plane motion. Visual inspection of the 3D plot suggests a strong relationship between the

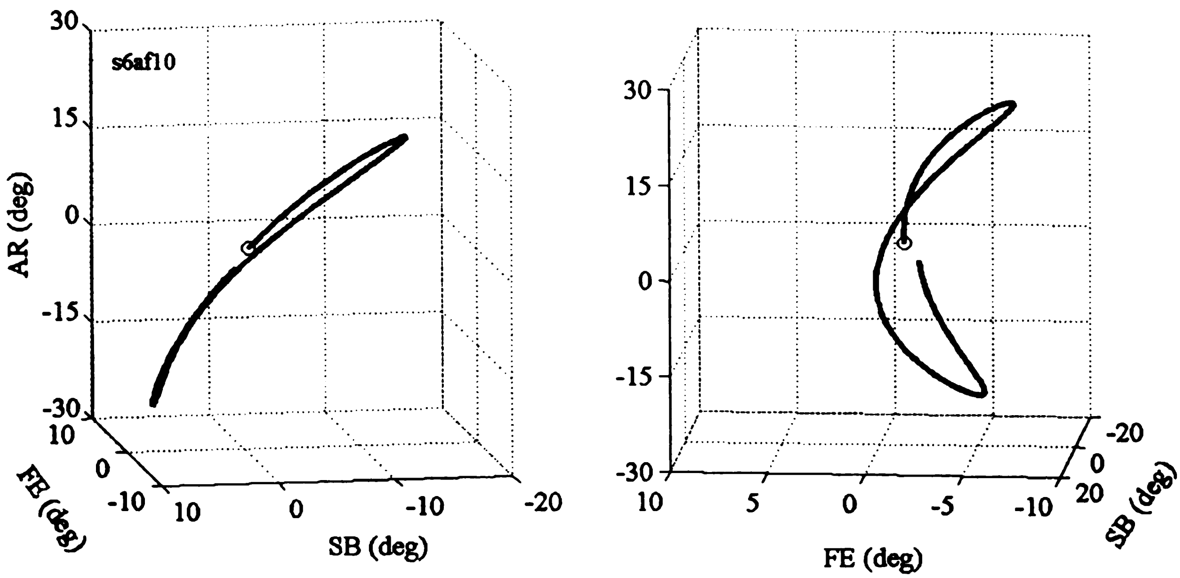

Figure 4.16. Typical three-dimensional angle-angle plot of sitting erect axial rotation test where sidebending and axial rotation are coupled ipsilaterally, also showing the tertiary sagittal plane motion. The circle denotes the beginning of the motion

primary and tertiary motions. However, mean peak R^2 for all subjects and all motion tests was 0.26 (± 0.08), meaning that only 26% of the total variance between either sidebending or axial rotation and sagittal plane motion can be explained. Sidebending and axial rotation had similar correlations with sagittal plane motion.

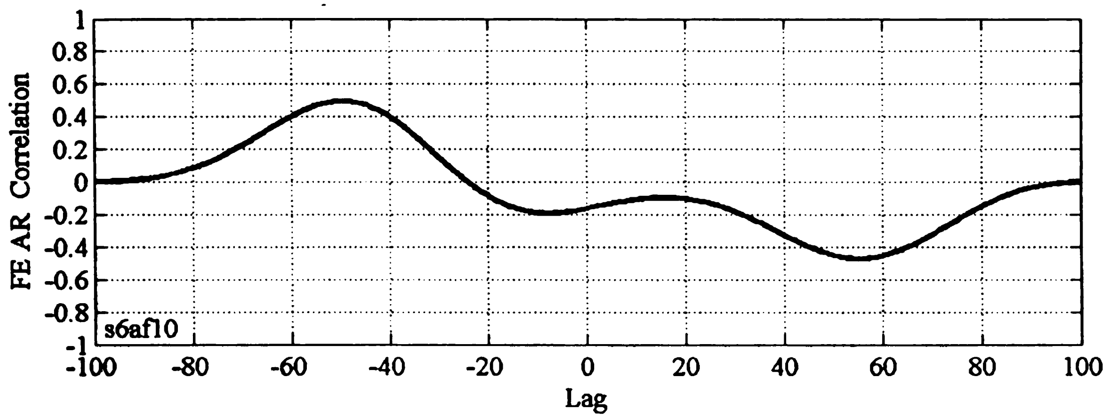

Figure 4.17. A typical cross-correlation plot of the sitting erect axial rotation test illustrating the relationship between axial rotation and flexion. Positive and negative peaks (R) slightly greater than 0.4.

Helical Axis

Finite Helical Axis

The finite helical axis (FHA) parameters were determined for only the primary motions. Since FHAs were computed for one large motion step it was expected that the magnitude of the helical angles would be similar to the Cardan angles. Indeed, comparison of helical and Cardan angles supported the expectation. For example, for the standing flexion and extension tests mean (± SD) Cardan flexion was 16.9° (± 9.2°) and mean helical flexion (i.e., phi during Phase 1) was 18.1° (± 7.5°). Cardan extension averaged 8.4° (± 9.7°), whereas helical extension (i.e., phi during Phase 2) averaged 11.5° (± 6.6°). Frontal and transverse plane motions also showed similarities (Table 4.7).

As with the Cardan angles intersubject range of motion variability is demonstrated by moderately high standard deviations.

Table 4.7. Comparison of Cardan and Finite Helical Angles for Primary Motions

	Cardan (R)	FHA (R)	Cardan (L)	FHA (L)
Stand SB	23.2 (7.7)	23.9 (7.5)	22.1 (6.4)	23.0 (7.8)
Stand AR	33.1 (8.1)	32.2 (7.4)	28.9 (8.4)	29.3 (7.9)
Sit Neutral SB	31.7 (7.8)	29.7 (6.6)	28.7 (6.6)	28.5 (7.4)
Sit Neutral AR	33.4 (7.7)	33.2 (6.8)	29.5 (8.7)	30.2 (7.7)
Sit Slouch SB	22.6 (6.1)	21.7 (4.9)	22.0 (5.1)	21.3 (5.9)
Sit Slouch AR	16.7 (7.7)	18.2 (6.9)	15.2 (5.9)	17.4 (5.7)
Sit Erect SB	28.9 (7.5)	22.4 (6.7)	23.9 (7.4)	26.1 (7.8)
Sit Erect AR	30.6 (9.1)	32.1 (9.3)	28.5 (8.4)	28.9 (6.8)

Note: SB = sidebending; AR = axial rotation; FHA = finite helical angle; R = right; L = left. Data are presented as mean (± SD) angle in degrees.

Complete description of three-dimensional motion using helical theory also includes the parameters: translation (t) along the helical axis, orientation of the helical axes (unit vectors) and piecing points (where the helical axis pieces a plane). In some cases, translation (t, mm) occurred in a negative direction and in other cases in a positive direction along the helical axis. There did not seem to be a relationship between direction of translation and direction or type of thoracic motion, nor was there consistency among subjects. It can be seen (Table 4.8) that t, reported as the mean sum of the two phases, i.e., summed t for flexion and extension and determined the mean for all subjects, suggests that translations along the helical axes are small and quite variable.

Table 4.8. Summed Translation Along Helical Axis

	Stand FE	Stand SB	Stand AR	Sit N SB	Sit N AR	Sit Sl SB	Sit Sl AR	Sit E SB	Sit E AR
t	13.1	4.1	4.1	4.6	3.2	2.8	2.9	3.9	5.5
(mm)	(11.6)	(3.0)	(2.9)	(3.7)	(3.3)	(2.3)	(2.1)	(3.1)	(3.7)

Note: FE = flexion/extension; SB = sidebending; AR = axial rotation; N = neutral; Sl = slouch; E = erect. Values are mean (± SD).

The helical parameters for frontal and transverse plane motions were also determined in two phases. For example, for the standing sidebending test, right sidebending was a Phase 1 movement and left sidebending was a Phase 2 movement; and for standing axial rotation, left axial rotation was a Phase 1 movement and right axial rotation was a Phase 2 movement (this pattern emerged because of the order of testing during data collection). Thus, the helical axis for right sidebending had a unit vector and set of piercing points that was unique and distinct from the helical axis for left sidebending, and so on, resulting in a total of eighteen sets of unit vectors and piercing points.

Examination of the unit vectors corresponding to the standing flexion/extension tests (Table 4.9) suggest that the thoracic flexion and extension movements performed by the subjects in this study were not pure sagittal plane movements. The piercing points show that the flexion/extension axis rests in the y-z plane, although the location shows large individual variability, as suggested by large standard deviations.

Table 4.9. Mean Helical Unit Vectors and Piercing Points for Standing Flexion/Extension

	Ux	Uy	Uz	Px	Py	Pz
Flexion	-0.914	-0.069	-0.168	0.0	391.2	651.4
					(179.6)	(99.8)
Extension	0.829	0.163	-0.038	0.0	370.1	605.8
					(236.6)	(389.1)

Note: Piercing points are presented as mean (± SD) in mm.

Statistical (summary) analysis of the unit vectors and piercing points for movements in the frontal and transverse planes was complicated by the fact that sidebending and axial rotations were not coupled in a similar manner in all tests by all individuals (refer to Table 4.5 and description of coupled motion patterns based on Cardan angles). Analysis of the unit vectors for each subject showed that, in general, when sidebending and axial rotation were coupled in the same direction U_y and U_z had opposite "signs" (Table 4.10) (i.e., if U_y was positive, U_z was negative and vice versa), and when sidebending and axial were coupled contralaterally U_y and U_z had the same sign (Table 4.11). Therefore, helical unit vector and piercing point data for the sidebending and axial rotation tests were organized according to the motion tests that exhibited ipsilateral or contralateral coupling patterns.

Examination of U_x and U_y for right and left motions suggests good symmetry, as noted previously with the Cardan angles. Generally, it does not appear that axial rotation is more strongly coupled with sidebending than sidebending is with axial rotation. However, axial rotation is more strongly coupled with sidebending and sidebending with axial rotation during the sit neutral sidebending and sit erect axial rotation tests, respectively. From Table 4.9 it can be seen that U_x is negative with flexion and positive with extension. Thus, from Table 4.10 it is evident that flexion is consistently coupled with axial rotation during standing and sitting neutral and erect tests. Extension was, in general, coupled with sidebending, but was coupled with both sidebending and axial rotation during the sit slouch test.

Table 4.10. Mean Helical Unit Vectors and Piercing Points for Ipsilateral Coupling of SB and AR

		U_x	U_y	U_z	P_x	P_y	P_z
St SB	R	0031	0.942	-0.250	308.3(65.8)	0.0	730.8(124.2)
	L	0.034	-0.934	0.241	322.4(92.8)	0.0	730.7(159.7)
St AR	R	-0.192	0.230	-0.936	153.4(102.9)	459.8(201.6)	0.0
	L	-0.177	-0.270	0.923	452.7(118.3)	502.9(200.5)	0.0
SN SB	R	0.007	0.904	-0.353	292.0(64.8)	0.0	481.1(132.2)
	L	-0.029	-0.913	0.333	282.0(47.8)	0.0	469.4(106.4)
SN AR	R	-0.208	0.281	-0.924	207.1(47.3)	443.8(221.5)	0.0
	L	-0.233	-0.274	0.912	404.7(57.6)	449.9(224.9)	0.0
Sl SB	R	0.056	0.941	-0.229	294.6(82.8)	0.0	407.3(101.4)
	L	0.096	-0.939	0.250	335.7(65.2)	0.0	414.3(88.8)
Sl AR	R	0.018	0.181	-0.954	303.0(64.5)	317.5(184.6)	0.0
	L	0.027	-0.114	0.914	303.7(42.6)	285.1(177.0)	0.0
E SB	R	-0.055	0.941	-0.205	314.6(60.2)	0.0	401.1(85.4)
	L	-0.063	-0.941	0.214	271.3(67.2)	0.0	409.7(99.5)
E AR	R	-0.171	0.391	-0.856	219.5(52.9)	504.6(271.1)	0.0
	L	-0.158	-0.397	0.858	373.9(64.2)	507.7(246.6)	0.0

Note. R = right; L = left; St SB/AR = standing sidebending/axial rotation; SN SB/AR = sit neutral sidebending and axial rotation; Sl SB/AR = sit slouch sidebending/axial rotation; E SB/AR = sit erect sidebending/axial rotation; piecing points are presented as mean (± SD) in mm.

Contralateral coupling of sidebending and axial rotation was not demonstrated in all tests. In fact, contralateral coupling only occurred during standing sidebending, sit neutral sidebending, slouch sidebending and axial rotation and erect sidebending tests. Note that for the sit neutral sidebending test only three subjects demonstrated contralateral coupling; therefore, the abnormal "sign" pattern is likely related to a small sample. Several noteworthy findings: contralateral coupling appears to occur more often when sidebending is the primary motion, when contralateral coupling occurs during the sit slouch axial rotation test it appears that sidebending is nearly as dominant as axial rotation and contralateral coupling may be linked more strongly to thoracic extension than flexion.

Table 4.11. Mean Helical Unit Vectors and Piercing Points for Tests that Demonstrated Contralateral Coupling

		U_x	U_y	U_z	P_x	P_y	P_z
St SB (n = 8)	R	0.071	0.981	0.071	263.2(38.4)	0.0	611.6(76.0)
	L	0.059	-0.963	-0.113	328.0(65.2)	0.0	599.4(89.9)
SN SB (n = 3)	R	0.117	0.985	-0.056	235.6(36.8)	0.0	390.0(82.1)
	L	0.007	-0.992	-0.006	295.7(55.7)	0.0	351.0(43.6)
Sl SB (n = 5)	R	0.211	0.970	0.016	200.5(53.2)	0.0	353.8(46.6)
	L	0.278	-0.944	-0.079	421.3(57.2)	0.0	327.6(53.3)
Sl AR (n = 13)	R	0.072	-0.644	-0.609	347.1(78.9)	-104.7(564.8)	0.0
	L	0.048	0.606	0.657	286.6(98.6)	-100.0(541.5)	0.0
E SB (n = 5)	R	0.107	0.930	0.175	222.0(114.6)	0.0	197.5(227.5)
	L	-0.092	-0.948	-0.262	234.8(81.6)	0.0	163.9(117.5)

Note. R = right; L = left; St SB/AR = standing sidebending/axial rotation; SN SB/AR = sit neutral sidebending and axial rotation; Sl SB/AR = sit slouch sidebending/axial rotation; E SB/AR = sit erect sidebending/axial rotation; piecing points are presented as mean (± SD) in mm

Instantaneous Helical Axis

Calculating the FHA for every frame of data approximated the instantaneous helical axis (IHA), however, for graphing purposes illustrating the IHAs of cycle 3 for every second frame seemed to be adequate. Recall, that in order to minimize error the motion tests were divided into four phases. For example, for flexion/extension, Phase I ran from neutral to end-range flexion, Phase II ran from end-range flexion to neutral, Phase III from neutral to end-range extension and Phase IV from end-range extension back to neutral. For sidebending (SB) tests, Phase I ran from neural to maximum right SB, Phase II from maximum right SB back to neutral, Phase III from neutral to maximum left SB and Phase IV from maximum left SB back to neutral, and likewise for axial rotation tests. Recall that the IHAs represent the axis that the thoracic segment is moving about, and along, relative to the lumbar segment. The IHAs are visualized graphically with thoracic, lumbar and pelvic markers joined to make a geometric shape. For each set of graphs the reader will see the beginning and ending (color coded) position of the IHA for each phase. Figure 4.18, Figure 4.19 and Figure 4.20 are representative graphs of subject S56JD that illustrate several features of thoracic spine motion.

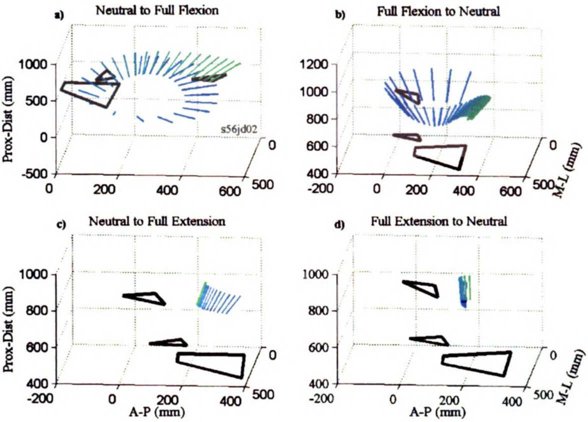

Figure 4.18. Sagittal view of IHAs for the third cycle of the standing flexion/extension motion test. The proximal triangle represents the thoracic segment, the middle triangle the lumbar segment and the distal quadrangle the pelvis. Blue denotes the beginning of the motion and green the end of the motion.

Figure 4.18 shows the IHAs during standing flexion/extension, and, from the view represented (as if you were looking at the individual slightly above and right lateral), it is clear that the predominant motion is in the sagittal plane, with mild out-of-plane motion. For this subject it appears as if the IHAs translate posterior, then anterior during flexion. On returning to neutral the axes also appear to move from posterior to anterior. During extension it appears that there is a posterior movement of the IHAs. In general, axis location followed the pattern described above, however, there was significant variability among subjects. Additional views of sagittal plane IHAs can be seen in Figure 4.19 and Figure 4.20.

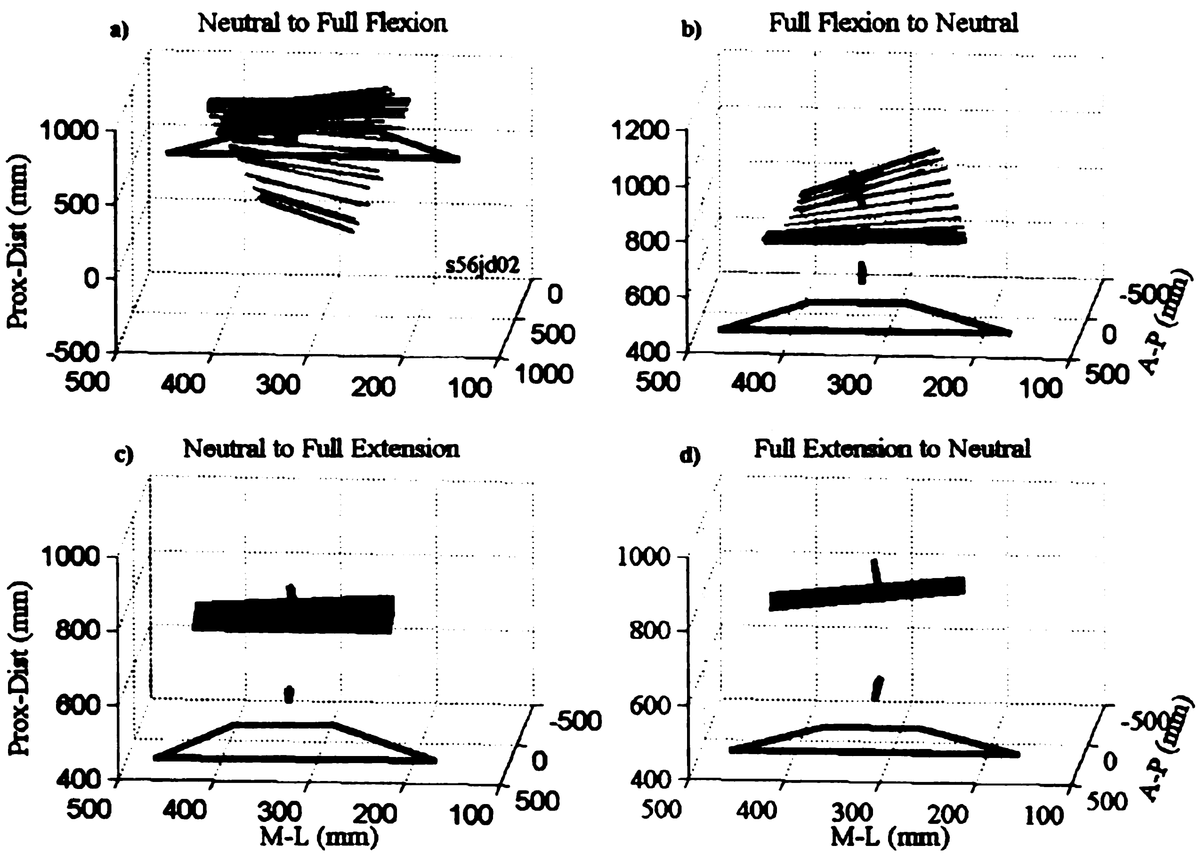

Figure 4.19. Frontal view of IHAs for standing flexion/extension. Blue denotes the beginning of the motion and green the end of the motion.

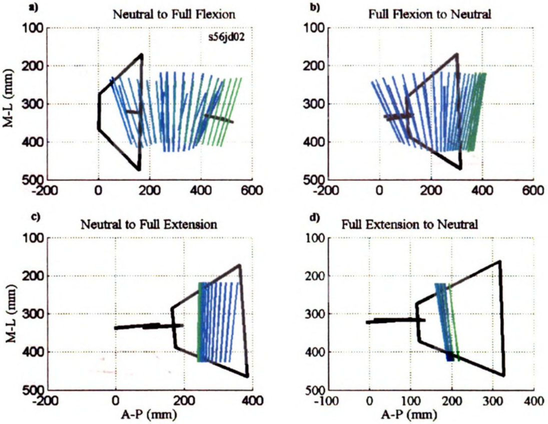

Figure 4.20. Transverse (top) view of IHAs for standing flexion/extension. Blue denotes the beginning of the motion and green the end of the motion.

Standing sidebending, as seen in a frontal view (Figure 4.21), shows IHAs that represent a complex motion since if sidebending were pure the axis would appear as a dot. During right sidebending the IHAs translated right, then left and then ended up to the right of midline at the extreme of right sidebending (Phase I). Upon returning to neutral (Phase 2) the axis translated left and returned to more of a midline position.

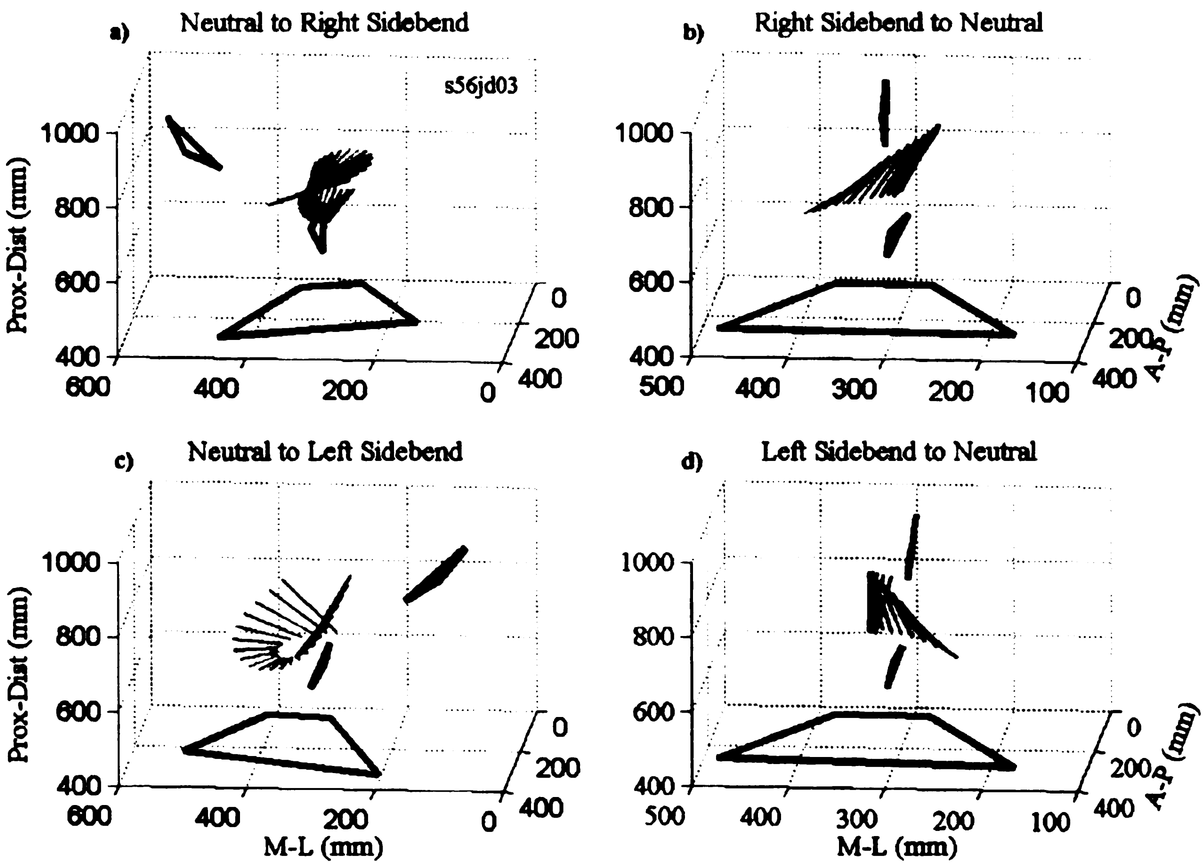

Figure 4.21. Frontal view IHAs for standing sidebending. Blue denotes the beginning of the motion and green the end of the motion.

During left sidebending the IHAs move right, then back toward midline at end range left sidebending. IHAs return to midline during Phase 4. For the cohort, IHAs migrated to the same side as the motion 60% of the time (IHAs moved right during right sidebending and left during left sidebending). Additional views of frontal plane motion can be seen in Figure 4.22and Figure 4.23.

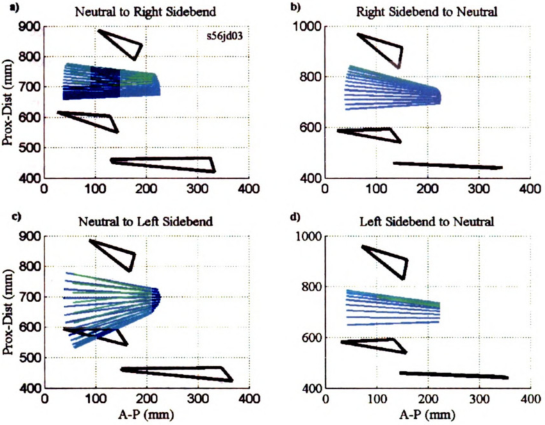

Figure 4.22. Sagittal view of IHAs for standing sidebending. Blue denotes the beginning of the motion and green the end of the motion.

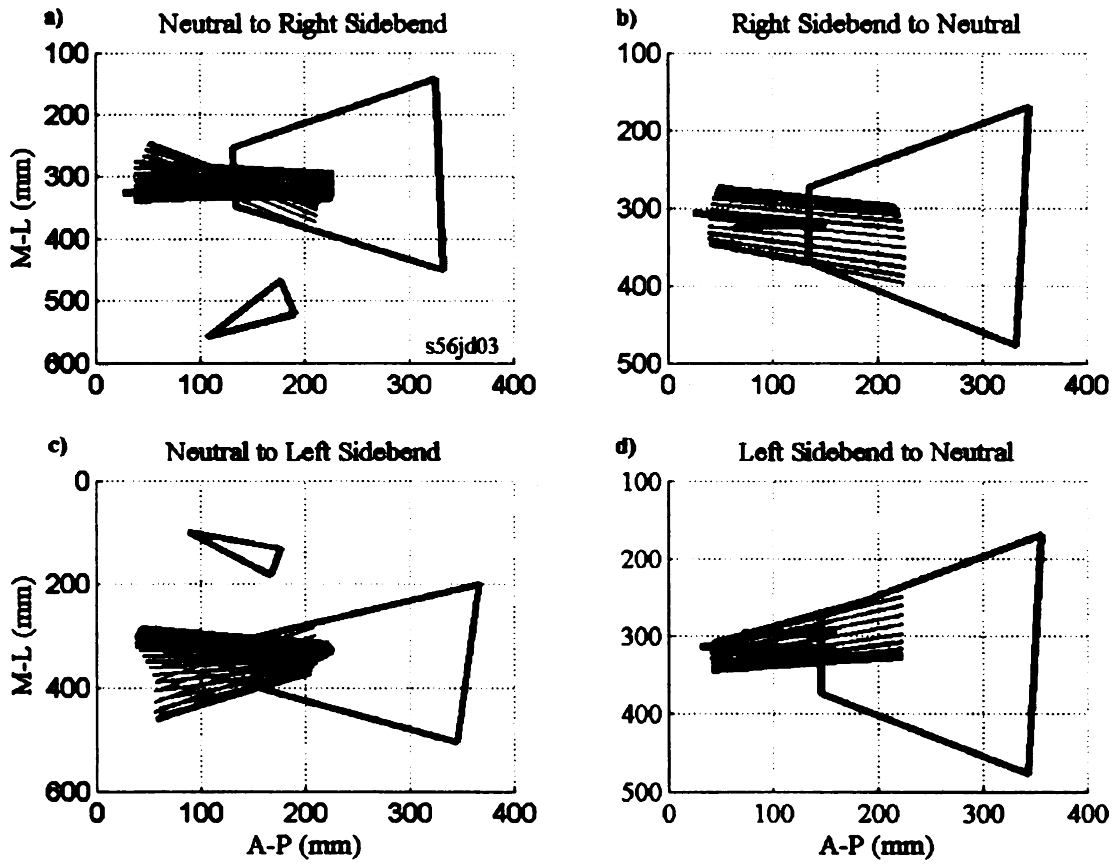

Figure 4.23. Transverse (top) view of IHAs for standing sidebending. Blue denotes the beginning of the motion and green the end of the motion.

Figure 4.24 shows IHAs during standing axial rotation. Clearly there is strong coupled motion during axial rotation, as illustrated by the scatter of the IHAs. This superior planar view shows that during left axial rotation (Phase I) the IHAs followed a right to left path and moved more centrally as the individual returned to near neutral (Phase II). During right axial rotation (Phase III) the IHAs translated left and then centralized again upon returning to the starting position (Phase IV).

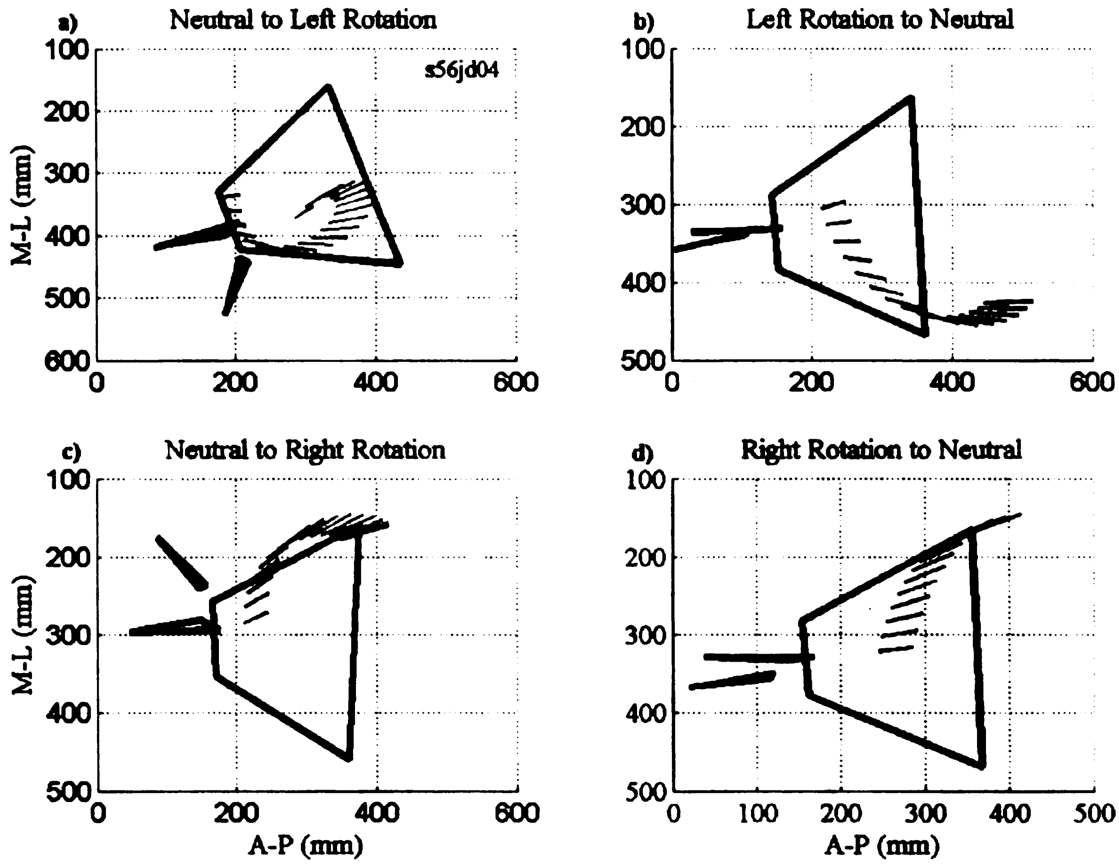

Figure 4.24. Transverse (top) view of IHAs for standing axial rotation. Blue denotes the beginning of the motion and green the end of the motion.

The pattern of IHA movement during Phase 3 is quite typical of that seen in the cohort; that is, IHAs tended to move the opposite direction the individual turned (this was found approximately 76% of the time). Additional views of standing axial rotation can be seen in Figure 4.25 and Figure 4.26.

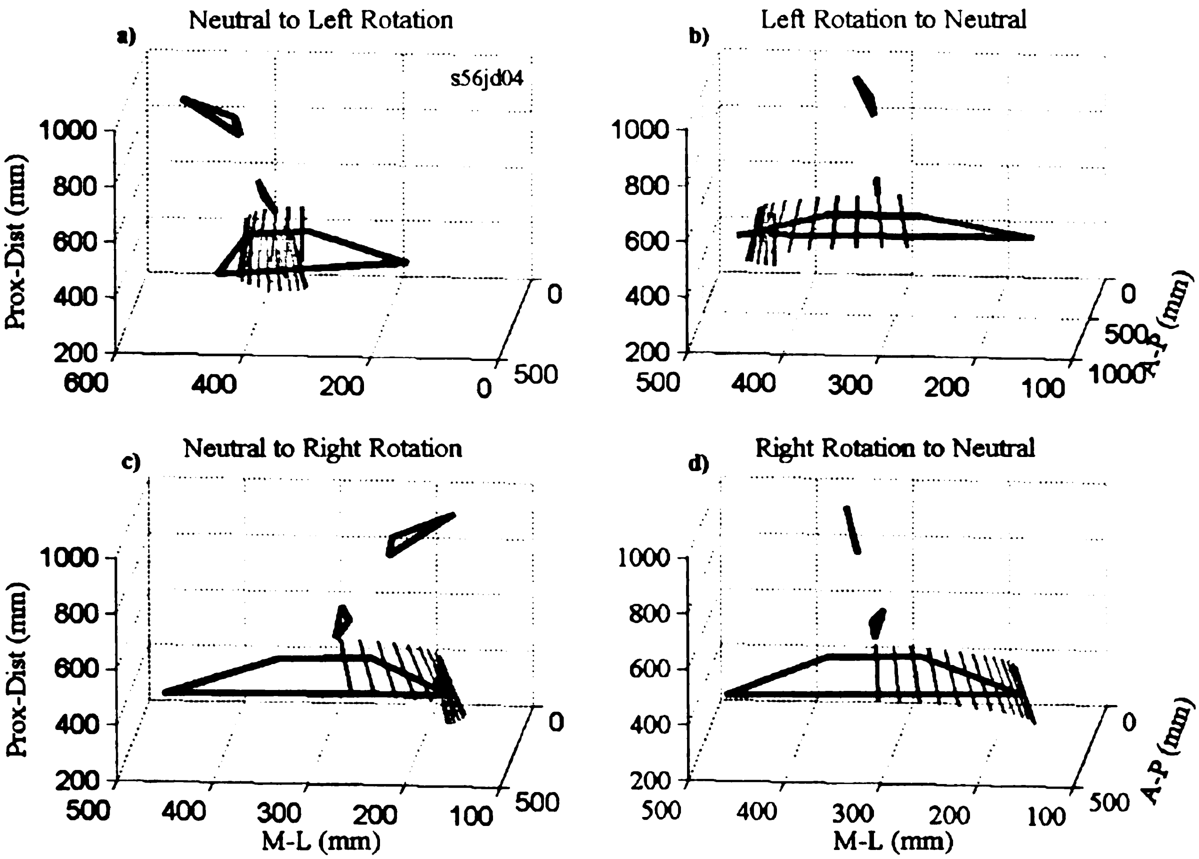

Figure 4.25. Frontal view of IHAs for standing axial rotation. Blue denotes the beginning of the motion and green the end of the motion.

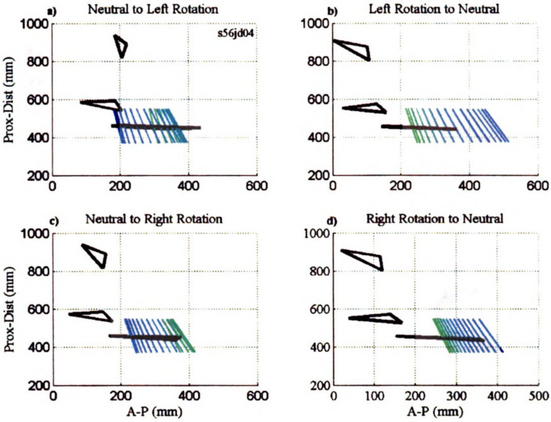

Figure 4.26. Sagittal view of IHAs during standing axial rotation. Blue denotes the beginning of the motion and green the end of the motion.

Examination of the IHAs during the sitting neutral sidebending (Figure 4.27) and axial rotation (Figure 4.28) motion tests reveal patterns that are slightly different to those seen in standing. Figure 4.27 shows that the IHA translated to the right during

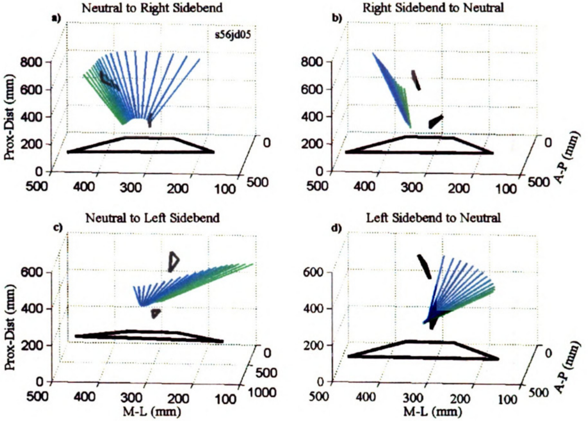

Figure 4.27. Frontal view of IHAs for sitting neutral sidebending. Blue denotes the beginning of the motion and green the end of the motion.

right sidebending and to the left during left sidebending. "Splaying" of the IHAs is indicative of significant out-of-plane motion. Figure 4.28 shows that during the sit neutral axial rotation test the IHAs translated to the right during Phase 1 (left axial rotation and to the left during right axial rotation (Phase III).

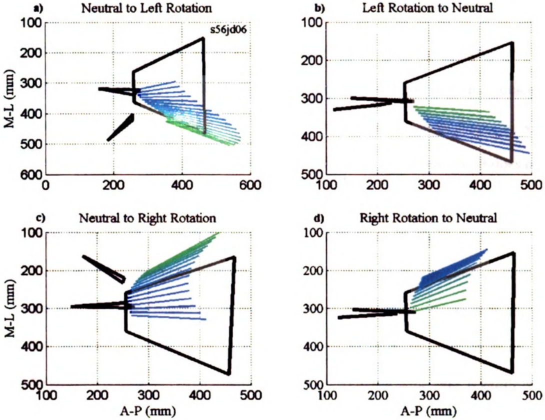

Figure 4.28. Transverse (top) view of IHAs for sitting neutral axial rotation. Blue denotes the beginning of the motion and green the end of the motion.

As mentioned above, there appeared to several trends with regard to IHA locations during the various motion tests, but variability among subjects precludes this author from making any broad generalizations. Because it is difficult to appreciate the complexity of IHA location with thoracic spine movements with one view, three views for each motion test were constructed. Multiple views of the IHAs for all motion tests for S56JD can be reviewed in Appendix K.

Summary

Examination of total range of motion data suggests that frontal and transverse plane motion, sidebending and axial rotation, respectively, predominate in the thoracic spine. For this cohort of normal, healthy men and women, the data show that there is reasonable right/left symmetry with thoracic sidebending and axial rotation. It does not appear the sidebending and axial rotations are largely reduced when the thoracic spine is either flexed or extended. Despite coaching, individuals were not able to maintain slouched or erect postures during sidebending and axial rotation motion tests. When persons perform thoracic flexion and extension a pure sagittal plane motion does not occur. Sidebending and axial rotation are strongly coupled. In a high percentage of motion tests, sidebending and axial rotation were coupled to the same side, regardless of which motion was introduced first. Evidence of sagittal plane coupling during sidebending and axial rotation also suggests a more complex motion system than that described by Fryette.

Chapter 5

DISCUSSION

Introduction

The design of this project was descriptive/exploratory in nature. Recall, that one of the purposes for this research was to develop an accurate and reliable video-based methodology for measuring kinematics of the thoracic spine. The motivation for the development and testing of this methodology was to examine the spinal motion hypotheses of Fryette (1918, 1954) and answer the following questions: (1) When sidebending (or axial rotation) is introduced when the thoracic spine is in a neutral posture will axial rotation (or sidebending) be coupled to the opposite side? (2) When sidebending (or axial rotation) is introduced when the thoracic spine is fully flexed or extended (hyperextended) will axial rotation (or sidebending) be coupled to the same side? (3) When spinal motion is introduced in one plane (e.g., frontal), will mobility be reduced in the other planes (sagittal and transverse)? Therefore, the goal of this project was to investigate whether stereotypical movement patterns of the thoracic spine/cage existed in normal, healthy subjects. Stereotypical patterns of motion were examined and described using both Cardan angles, as well as the helical axis parameterizations.

Measurement Error

Measurement error comes in two forms, systematic and random, and cannot be avoided. Especially in biomechanics research involving living subjects, whether human or animal, random errors and biologic variability affect measurement outcomes. Although measurement error issues were addressed in Chapter 3, this topic is being re-visited, because without some assurance of measurement fidelity, generalization of the results of this study cannot be made.

Generally, systematic and random errors associated with the measurement system are small and can be controlled. For this research, linear and angular errors associated with the measurement system were documented in several ways. Calibration residuals are the root mean square of the distance between two rays (from two cameras) that are intersecting to locate a marker in spatial coordinates. Sets of ten consecutive calibrations were performed to assess accuracy and reliability of the motion capture system. Mean residuals for all six cameras were 0.74 (± 0.05) mm. Additionally, prior to subject testing system calibrations were also performed yielding, on average, residuals ranging from 0.65 to 0.92 mm. These data are below manufacturer's recommendations of 1 to 4 mm suggesting high system accuracy and repeatability.

Collecting marker data with a wand that had two markers attached to the ends separated by 250 mm and calculating the mean distance (± SD) separating markers was another test of linear accuracy. Wand data following ten consecutive calibrations resulted in a mean RMS error (RMSE) of 0.72 mm, that is with a mean camera distance to volume center of 3.7 m. The triangle linear accuracy test yielded linear errors ranging from 0.75 to 1.86 mm, with RMSEs averaging 0.47 mm. For the wand trials associated with calibrations on testing days the mean RMSE was 0.62 mm. The linear errors found in this research are similar to those found (0.60 to 1.29 mm) in a previous study that used an earlier generation of the Vicon system (Richards, 1999).

Angular errors were determined by measuring the location of markers located on the vertices of 30°-60°-90° right triangle. The triangle was moved to different regions of the calibrated capture volume and held while data were collected, so it was primarily a static test. The mean difference between measured and true angles was 0.75° with a RMSE of 0.12°. In other investigations testing the precision of the Vicon motion capture system static and dynamic RMSE errors approximated 0.2° and 1.4°, respectively (Richards, 1999; Schache, et al., 2001). The linear and angular data error measures found in this research are similar to what has been reported elsewhere and suggest that the overall accuracy and repeatability of the motion capture system is good.

A more problematic measurement concern arises when measuring spatial location of skin-mounted markers on human subjects. Ideally, markers are placed on bones that are superficial so that random and unpredictable skin movement over the bones can be minimized. However, motion of skin-mounted markers relative to underlying bone causes errors in determining segment coordinate system axes. Thus, dynamic error and misalignment in the segment fixed axes used for Cardan rotation conventions may result in variability of joint angle data. For example, skin marker artifacts ranging from 10 to 30 mm on the thigh and shank during walking (Cappozzo et al., 1996; Cappello et al., 1997) have been shown to result in large differences in knee joint angle calculations (Fuller et al., 1997).

No such quantification of errors has been reported for tests involving the spine, although Lundberg (1996) stated that skin movement followed bone (spinous process) movement closely because fascia over the spinous processes was reasonably rigidly fixed to the bone. Observation of test movements (prior to data collection) to evaluate marker adherence to the skin verified Lundberg's assertion. Furthermore, Gracovetsky (1988) concluded that spine marker motion in normal subjects was not random but contained relevant physiologic information.

Since skin motion artifact influence on spine angle calculations had not been reported previously in the literature, this research attempted to determine an estimate. Using a range of potential skin marker artifact (10 to 30 mm) and projection angles for determination of thoracic sidebending and axial rotation, it was estimated that frontal plane errors could range from 2° to 6° and transverse plane errors could range from 4° to 13°. Given these potentially large errors, the results of this research need to be evaluated with some caution; however, it should be noted that these two-dimensional estimates may not accurately represent the true three-dimensional nature of motion artifact.

Performing repeated measures was another attempt to evaluate measurement error in this research. Waveform repeatability was evaluated using the coefficient of multiple correlation (CMC). The CMC formulation used for this research evaluated intra-subject, inter-day consistency. Intra-subject repeatability of "joint" angle motion is influenced by the inherent physiologic variability, as well as variability introduced by the measurement system. As discussed above, the latter includes the effects of finite accuracy and resolution of the motion analysis system and the marker system used in the computation of joint angle patterns, including the uncertainties related to reapplication of markers on successive days (Kadaba et al., 1989). Inherent physiologic variability has been related to motor control adjustments and other adaptive strategies (Winter, 1984; Winter, 1991).

For standing flexion/extension tests the mean CMC was 0.66 suggesting only fair intra-subject, inter-day consistency. As discussed in Chapter 3, it is not likely that skin-motion artifact greatly influences flexion/extension angles since cephalo-caudal movement of markers represents well the movements of the vertebral segments. It could be that the lower CMC for thoracic flexion/extension is related to the fact that sagittal plane motion is not inherently "preferred" in this region (especially extension) or due to human subject variability. In a different study, Troke et al. (1998) reported good inter-operator, inter-day consistency (Intraclass Correlation Coefficient or ICC of 0.77) when using the OSI CA 6000 Spine Motion Analyzer on the thoracic spine. Delineating reasons for low CMCs for thoracic flexion/extension may become more apparent with additional research.

The primary motions in the frontal and transverse plane demonstrated excellent intra-subject, inter-day repeatability (0.96), which might be expected since these motions are well suited to the thoracic spine (as presented in the anatomy section of the literature review). Large potential errors in determination of frontal and transverse plane angles were presented in Chapter 3, but results of the CMC analysis suggest that these errors were, in fact, minimal. If large errors existed, they would likely be systematic errors; errors that could be elucidated with further analysis. Willems et al. (1996), using repeated measures ANOVA, reported intra-day consistency errors ranging from 1° to 3° for the primary motions tested and considered these errors acceptable. Inter-tester, inter-day ICCs for sidebending and axial rotation measures from Troke et al. (1998) were 0.88

and 0.84, respectively, also suggesting better repeatability of frontal and transverse plane motions.

Chao (1980) discussed the effects of "downstream" errors on the out-of-primary plane angles associated with Cardan angle calculations. He suggested that small misalignments of the first axis of rotation with the true axis of rotation (due to fixed axis assumptions and skin-mounted marker motion) would cause small errors in the measured rotation about the first axis. These initial misalignments would accumulate into larger errors in "downstream" angles. Assuming that these misalignments of the first axis were random in nature, these smaller "upstream" and larger "downstream" errors would manifest themselves as variability in joint angle data. As such, out-of-plane angles would appear more variable and less reproducible than the primary angles. Additionally, the smaller ranges of motion of out-of-plane measures compromise the signal-to-noise ratio of small angles and thus compromise their reproducibility (Growney et al., 1997).

In this research, sensitivity tests using dummy data were one way to test for errors related to skin motion artifact and "downstream" errors. Angular errors associated with these tests ranged from 1° to 10° (see Chapter 3). On the other hand, the CMCs for secondary motions was good (0.78), with better reproducibility of sidebending as the secondary motion (0.83) than axial rotation as the secondary motion (0.73).

Cross-talk is a phenomenon (likely related to Chao's "downstream" errors) where rotations about one axis are also visible in the angles of other axes (Chao, 1980; Woltring, 1994). These 'false angles' or errors are thought to result because the instantaneous axis of rotation does not, in general, coincide with one of the local coordinate axes (Hof et al., 2001; Woltring, 1994). Hof et al. (2001) suggested that as long as no solution seemed to be available that could exclude cross-talk effects any reported coupling effect in spinal motion needed to be interpreted with caution. Since the primary purpose of this research was to specifically examine coupled motion the existence and quantification of cross-talk was critical.

First, it was necessary to determine the Cardan sequence that would best parameterize spinal motions. Based on the work of many (Crawford et al., 1996; Crawford, 2002; McGill et al., 1997), and verified by collection of 'dummy' data, it became apparent that the Cardan *xyz* rotation sequence minimized cross-talk for spinal motions. Following a series of 24 motion tests that involved one-plane, two-plane and three-plane motion tests it was determined that cross-talk existed as follows: a range of 2° to 4° of transverse and frontal plane cross-talk, respectively, during simulated spine flexion/extension; ~ 3° of sagittal plane cross-talk during simulated spine sidebending; and ~ 1° of sagittal plane cross-talk with axial rotation of the spine. Given these relatively small cross-talk errors interpretation of coupled spinal motion proceeded with confidence.

The accuracy of helical axis calculations was also estimated. First, determination of accuracy of the instantaneous helical axis calculations was made qualitatively. This was accomplished by comparing the known vector location of two markers placed along the flexion/extension axis of the 'dummy' spine to the calculated IHA during 'dummy' spine flexion/extension. The known and calculated IHA matched well. Secondly, finite helical axis angles for large motion steps were compared to the known angles of the 'dummy' spine for a flexion/extension motion test. Evaluation of these results demonstrated that the calculated finite helical angles matched both the Cardan and known angles well. These data suggested that interpretation of helical parameters could proceed with confidence.

Thoracic Spine Range of Motion

Primarily, orientation of the zygapophyseal joints, thickness of the intervertebral disc and attachments of the ribs to the vertebra and sternum dictate spatial motion of thoracic vertebral elements. Orientations of zygapophyseal joints greatly influences motion patterns and theoretically, in the thoracic spine, favor axial rotation more than sidebending, and flexion/extension the least (Lovett, 1905). In this study flexion/extension was measured approximately between the T3 and T12 segments and totaled approximately 25° (17° flexion, and 8° extension). The magnitude of sagittal plane motion measured in this study was far less than what has previously been reported (Bakke, 1931; Buchalter et al., 1989; Gregerson & Lucus, 1967; Troke et al., 1998; White, 1969; Willems et al., 1996); however, these other studies examined motion of the entire thoracic spine (Table 5.1). Since White examined spinal functional units it was possible to extrapolate the T5 to T12 motion as follows: 27° of flexion/extension, 33° of sidebending and 29° of axial rotation. Also, since Willems et al. divided the thoracic spine into three regions, they had motion measures for the T4 to T12 segments and reported flexion/extension of 41°, 40° of sidebending and 65° of axial rotation. Thus, the thoracic range of motion reported here appears to be comparable to previous work.

One can also see that of the five data sets in Table 5.1, three show more sagittal plane motion than frontal or transverse plane motion. This suggests that the upper thoracic segments may function more like typical cervical segments (i.e., sagittal plane motion more favored) than typical thoracic segments.

Table 5.1. Thoracic Spine Range of Motion Comparisons with Previous Studies

Source Movement	A	B	C	D	E	F	G
Flexion/extension	68	40	70	50	58	-	25
Sidebending	-	50	75	47	52	-	45
Axial Rotation	-	82	64	54	92	74	62

Note. A: Bakke; B: Buchalter et al.; C: Troke et al.; D: White; E: Willems et al.; F: Gregerson & Lucus; G: this present study. Data are mean angles in degrees.

The data in Table 5.1 show large discrepancies among studies with regard to range of motion in the frontal and transverse planes. These differences are likely due to differences in methodology: radiographs (Bakke, 1931), functional spinal units (White, 1969), three-dimensional electrogoniometer (Troke et al., 1998), 3SPACE electromagnetic systems (Buchalter et al., 1989; Willems et al., 1996), and invasive in vivo techniques (Gregerson & Lucus, 1967), but also may reflect differences in age, gender and how subjects were tested (standing versus sitting). Furthermore, it is possible that differences in Cardan angle computation could explain some of the range of motion differences seen among the studies reviewed (see discussion on importance of Cardan sequence choice in Chapter 3).

Fryette's Laws: Physiologic Motion of the Thoracic Spine

Law I. Neutral Mechanics

From Fryette (1918, 1954), "when any area of the spine is in easy flexion, i.e., neutral, the articulating facets are not locked, and the load is thrown more upon the bodies of the vertebrae.. The super-imposed load becomes an important factor, and when the spine is sidebent the bodies naturally have a tendency to crawl out from under the load, or, in other words to rotate toward the convexity". He believed that coupled frontal and transverse plane motion would be contralateral regardless of which motion was primary, sidebending or axial rotation. Furthermore, Fryette reported that coupling patterns changed when the thoracic spine was in different postures. These assertions were based on manual manipulation of a Halladay spine (cadaver specimen treated to preserve flexibility of ligaments) and articulated spine, confirmed by palpating living subjects.

Lovett was motivated to study the mechanical behavior of the spine because of his interest in the deformities associated with scoliosis (1902, 1905). Lovett claimed that sidebending and axial rotation were coupled in the opposite direction when the dorsal spine was flexed and coupled in the same direction when the spine was neutral or hyperextended; however, when axial rotation was introduced first sidebending was coupled in the same direction. His work was based on experiments using rods of various stiffness, fish and cat spines, human cadavers and living models. Since Lovett and Fryette, many others have investigated spatial motion of the thoracic spine and presented results that are discrepant. Neither Lovett, nor those who followed, defined what they meant by a neutral spine, but is assumed by this author that neutral is that position of the spine where the natural curves (i.e., lordotic for the cervical and lumbar regions, and kyphotic for thoracic spine) exhibit near ideal alignment. Prior to this research no one has systematically examined Fryette's spinal motion concepts, as he expressed them in 1918.

For this research neutral mechanics of thoracic vertebral coupling were tested in two positions: standing and sitting. To reiterate, "neutral" in this research was that postural position where the natural cervical, thoracic and lumbar curves were in a near ideal position, as observed sagittally and frontally. For the standing tests, sidebending and axial rotation were coupled opposite only 35% of the time (Table 4.5). With axial rotation as the primary motion, sidebending never coupled contralaterally. For the sitting tests, neutral spinal posture was assumed if the lumbo-pelvic complex could be maintained in the same position as in standing. Lumbo-pelvic position was monitored with the use of a gravity inclinometer. For the sitting tests, contralateral coupling of sidebending and axial rotation occurred in only three instances (5%), or, conversely, ipsilateral coupling occurred 95% of the time.

How can the discrepancy between Fryette's motion concepts and the results of this research be explained? Fryette's contention was that contralateral coupling occurred when the spine was in a neutral posture because the facet joints were not "loaded", as they are when the dorsal spine is flexed or hyperextended. If Fryette's proposed mechanism for neutral vertebral coupling is true then the results in the present research suggest that subjects were performing sidebending and axial rotation out of a neutral position. In other words, subjects must have been bending and twisting with the facets in a more "loaded" position. Re-examination of Table 4.2 shows that there was a small amount of flexion/extension during standing, with slightly more during the sitting neutral, motion tests. Although the "dummy" motion test results suggested that there might be 1° to 3° of flexion/extension cross-talk during frontal and transverse plane motion testing, other investigators have also demonstrated small, but variable, amounts of sagittal plane motion with thoracic sidebending and axial rotation (Buchalter et al., 1989; Schultz et al., 1973; White, 1969). Re-examination of the helical axis unit vectors (Table 4.10 and Table 4.11) provides additional evidence that sagittal plane motion accompanies both sidebending and axial rotation. Additionally, it seems more likely that the thoracic vertebral segments were more loaded in the sitting neutral, than standing, tests because flexion/extension motion was greater and previous research suggests that compressive loading (which is greater in sitting postures according to Nachemson & Morris, 1964) tends to increase torsional stiffness (Edwards et al., 1987; Janevic et al., 1991; Oda et al., 1996).

What have other researchers reported with regard to the coupling of sidebending and axial rotation in a neutral posture? Several reported that sidebending and axial rotation were coupled contralaterally (Arkin, 1950; Buchalter et al., 1989; Cheng, 1993; Farahpour et al., 1995; Panjabi et al., 1976a; 1976b; Steindler, 1955). About an equal number of researchers reported ipsilateral coupling (Fick as referenced by White, 1969; Gregersen & Lucus, 1967; Keller, 1924; Novogrodsky as referenced by White, 1969; Oxland et al., 1992; White, 1969; Willems et al., 1996). White and Oxland et al., however, found this pattern primarily in the upper thoracic region, with more variability in the coupling patterns in the middle and lower regions (Scholten, 1986; White, 1969). With the Willems et al. study ipsilateral coupling occurred 50% of the time in the T1 to T4 segments, 80% of the time in the T5 to T8 segments and 70% of the time in the T9-T12 segments. Willems et al. results are similar to results in this study because they also tested subjects in sitting with the pelvis supported in a neutral position. Panjabi et al. and Willems et al. looked also at how sidebending was coupled with axial rotation as primary, and reported that these motions were coupled ipsilaterally always and 90% of the time in the middle and lower thoracic regions, respectively. Only Buchalter et al. found that axial rotation and sidebending were always coupled contralaterally when axial rotation was the primary motion.

It appears that several reports support Fryette's hypotheses, however, most of these studies had small sample sizes (Arkin, 1950; Chen, 1993; Farahpour et al., 1995) or present no data to support their claims (Steindler, 1955). Only, Buchalter et al. (1989) had a larger sample (60 subjects), but even their data must be accepted with some caution since they did not clearly describe how Cardan angles were determined. Recall (Chapter 3), that the rotation sequence one chooses to determine Cardan angles can influence outcomes. Additionally, although all of these authors examined healthy subjects with no back pain, it is not clear how they determined whether, in fact, subjects were cleared of thoracic spine dysfunction. As noted in Chapter 4, sixty-three healthy subjects without back pain were screened in this present study, but only thirty were free of spine dysfunction based on a total body physical examination. Thus, it is possible that subjects in previous studies had spinal dysfunctions that were not detected and their motion patterns reflected abnormal, rather than normal coupling patterns. Data from studies using spinal functional units (Panjabi et al., 1976a; 1976b) also have to be interpreted with caution since the induced motions may not be physiologic and typically the motion segments are devoid of ribs and muscle.

In summary, within the limitations of the present study, Fryette's first law of physiological motion is called into question. Furthermore, there appears to be corroborating evidence from the literature that would support this skepticism. This author suggests that, although Fryette's neutral spine motion concept may be feasible theoretically, practically or functionally the thoracic spine does not move this way because individuals are unable to maintain their spine in a neutral or "easy flexion" posture.

Law II. Non-Neutral Mechanics

The second law states that if any area of the spine is in hyperextension or, to a less degree, in hyperflexion and sidebent, the bodies rotate toward the concavity, or, in other words, sidebending and axial rotation go to the same side (regardless of which motion is introduced first). For this study, the second law was tested by having subjects perform frontal and transverse plane movements in either a sit slouch (hyperflexed) or erect (hyperextended) position.

Besides Fryette (1918), only Lovett (1905) examined coupling of sidebending and axial rotation with the thoracic spine in other postures, thus the results of the present study are an important contribution to the literature. Lovett stated that sidebending and axial rotation had a tendency to be coupled in the same direction if the spine was hyperextended, but opposite if the spine was flexed. However, Lovett also suggested that hyperextension locked the dorsal spine, thereby preventing appreciable sidebending and axial rotation movements. Scholten (1986), using a mathematical model of thoracic biomechanics, reported that with the spine flexed sidebending and axial rotation were coupled ipsilaterally. However, Scholten's extended spine model demonstrated sidebending and axial rotation that were coupled contralaterally. It is not clear if Scholten's spine was hyper-extended, which was a Fryette prerequisite for non-neutral spine mechanics.

In the present research, sidebending and axial rotation were coupled ipsilaterally 79% of the time during sit slouch and sit erect tests (Table 4.5). When axial rotation was the primary movement sidebending was coupled ipsilaterally 100% of the time during the sit erect test. When axial rotation was the primary motion during the sit slouch test only 54% of the trials showed ipsilateral coupling, a finding that is inconsistent with Lovett's (1905) findings. Coupling results of the axial rotation sit slouch test was surprising because all subjects appeared to maintain a slouched position while twisting, even though subsequent examination of the Cardan angle data showed that most subjects were not able to maintain the fully slouched or flexed position (they extended their spine during axial rotation). Perhaps these results reflect what Fryette meant when he said "...to a less degree hyperflexion..." Another possibility for a lower percentage of ipsilateral coupling with the sit slouch test might in some way be related to the finding that subjects were not able to maintain a slouch position, and as they extended placed different loads on the facet joints that altered the coupling pattern. Further study of this phenomenon is warranted. Overall, the findings of this research, however, support Fryette's second law of spinal motion.

Law III. Reduction of Mobility in Secondary Planes

Fryette (1918; 1954) showed that when motion was introduced to a vertebral joint in one plane mobility in the other two planes was automatically reduced. For example, if an individual hyperflexed or hyperextended their thoracic spine, both sidebending and axial rotation would be reduced compared to their range of motion if the spine was in more of neutral posture. Lovett (1905) also noted that sidebending and axial rotation were limited in range when the spine was flexed, and much more so if the spine was hyperextended. Intuition suggests that Fryette's third law is reasonable since if motion is introduced in one direction to the end of the range of motion, the periarticular soft tissues, i.e., capsule, restraining ligaments, etc, would be placed on tension, thus restricting motion in other planes. Others have described this "locked" type of position as a close-packed position, but for the thoracic spine this "locking" only occurs when the spine is hyperextended (Magee, 2003). The present study did not examine spinal functional units, i.e., single vertebral movements. However, it was assumed, given that no thoracic dysfunctions were present, that the mechanics of a group of vertebral segments would demonstrate behavior that was similar to that of a single vertebra.

What is the relevance of Fryette's third law? Manual medicine practitioners use this law during both examination and treatment. If, for example, the T3 segment demonstrates isolated dysfunction with regard to its ability to rotate to the left during forward bending, the practitioner will attempt to restore this movement. In order to isolate and treat only T3 the practitioner will position the patient so the proximal (and sometimes distal) segments (T1 and T2) will not move while T3 is being treated. To "lock" T1 and T2, motion in one plane (usually flexion or extension) is introduced until the end of the range of motion of T1 and T2 is realized. Thus, when attempting to rotate T3, T1 and T2 would not be able to rotate since motion was introduced to those segments in the sagittal plane. It should be stressed that most of the time these "locking" maneuvers are performed passively by the manual medicine practitioner, without the active assistance of the patient. However, on occasion, active assistance of the patient is requested.

Besides Lovett's (1905) work with cadavers, there is little other evidence to support Fryette's third law. By having subjects side bend or rotate in either a sit slouched or erect position an attempt was made in the present study to examine Fryette's third law. Examination of data in Table 4.2 shows that during the sit slouch and erect tests there was approximately 45° and 53° of sidebending, respectively. These values compare to 45° and 60° of sidebending during the standing and sit neutral sidebending tests, respectively. From these results it appears that slouch sidebending was reduced compared to sidebending in the sit neutral, but not the standing, test. It is unclear as to why there was more sidebending in sitting than standing. Certainly, more research is needed to examine the effect of flexed postures on sidebending range of motion. There was an equal amount of axial rotation range of motion with the both the standing and sit neutral tests. Axial rotation was reduced about 50% during the sit slouch test, but was not different during the sit erect test. Recall, that during the sit erect test most subjects were unable to maintain the hyperextended posture so the axial rotation results with this test need to be examined with caution. Overall, there is some evidence to support Fryette's third law, but more research is needed.

Helical Axis Analysis

Finite Helical Axis

Woltring (1991; 1994) argued, from a biomechanical perspective, that screw axis analysis was the most appropriate representation of joint motion, since all spatial information was inherent in the helical parameters. Further arguments for a more extensive use of helical analysis for both the biomechanics and clinical community were based on several principles: (1) there does not seem to exist an accepted standard on how to represent three-dimensional angulation, (2) sequence dependency of Cardan/Bryant angles, (3) asymmetrical properties of Cardan/Bryant angles, (4) the occurrence of gimbal-lock and (5) Cardanic conventions allow decomposition along only two arbitrarily chosen, anatomical segment axes, one for each segment, plus one along a third, "floating" axis, which generally has no direct anatomical meaning. It has been demonstrated that: (1) in movement about a coordinate axis, the helical angles are identical to those under any Cardan/Bryant convention (Woltring, 1991; 1994), (2) the helical angles' axes are always mutually orthogonal (Woltring, 1991; 1994) and are well-determined from noisy data (Woltring et al., 1985), and (3) the helical angles are equivalent to the mean value of Cardan/Bryant angles (1994; Durá, 2003), i.e., compute Cardan/Bryant angles using six different rotation sequences and determine the mean of these results.

Acknowledging the limitations of Cardan/Brant angle analysis, Grood (in Woltring, 1994), nonetheless, argued against Woltring's proposal primarily because of the absence of a physical (geometrical) interpretation of the three attitude vector components in terms of rigid-body rotations. In turn, the biomechanical community has sided with Grood since the helical parameters seem to lack clinical relevance and meaning. Recently, an alternative to the Cardan/Bryant, projection vector and helical angles methods has been proposed (Crawford, Yamaguchi & Dickman, 1999) that eliminates the problems identified by both Woltring and Grood. The new method, called tilt/twist, has yet to be tested and used by the larger biomechanics community; however, Crawford has recently posted conversion algorithms on the ISB website (http://www.isbweb.org) for users to test.

Two methods could be used to determine angular motion from helical axis analysis. In the first, one could sum the small angles that correspond to successive instantaneous helical axes (IHA). When this was attempted in this research the "helical" angle was much larger than expected (compared to the Cardan angle for that motion), due to the accumulation, i.e., sum, of errors associated with IHA calculations with small step sizes. These errors occur because the direction of the rotation has error associated with it, and this error goes to infinity as the amount of rotation goes to zero (van den Bogert, personal communication).

The alternative method employed in the present study was to calculate the helical angle using a larger step size, thus changing the helical analysis from an instantaneous to a finite one. In this study, then, a finite helical analysis was performed for one large step size for each motion tested, e.g., flexion, extension, right sidebending, left sidebending, right axial rotation and left axial rotation. With this approach it was expected (van den Bogert, personal communication) that the magnitudes of the finite helical (FHA) and Cardan angles would be similar. It should be noted that the finite helical angles computed in this report are not the same as the helical angles (attitude vector) advocated by Woltring (1991; 1994), but the arguments for their use are similar.

The Cardan and helical angles compared very well (Table 4.7). These findings are significant because they suggest that finite helical angles may have clinical relevance. Of course, more work is needed to substantiate this conclusion, not only for the thoracic spine, but also for other regions of the spine.

If all that was derived from the helical analysis were the helical angles there would be no reason to go through the trouble since Cardan angles provide all the relevant information that is needed. However, three additional helical parameters are derived that include translation, t, along the helical axis, piercing points and the orientation vector (unit vector) of the helical axis. Mean translations were generally small (4 to 13 mm) with large standard deviations (Table 4.8) making these data difficult to interpret. Perhaps these data suggest that normal individuals have only small translation movements along some spatial axis of movement because the vertebral elements are stable, or perhaps because normal subjects move within well-defined limits. The test-retest data suggest that the cohort in this research had reasonably stable, invariable movement patterns (CMC of 0.96, see repeatability section in Chapter 4).

The piecing points (Table 4.9, Table 4.10 and Table 4.11), expressed in mm relative to the fixed segment (lumbar region in this case), describe where the FHA pierces its movement plane. For example, the *y-z* plane is where the FHA lies during sagittal plane movement, i.e., flexion/extension. Likewise, axes of motion for frontal and transverse planes movements occur primarily in the *x-z* and *x-y* planes, respectively. Examination of Table 4.9 show that the axis for flexion/extension maintains a relatively stable position, although the standard deviations are quite large. For sidebending tests (Table 4.10 and Table 4.11) a similar stable planar position is evident for all tests, whereas for rotation stability is apparent only for the sit slouch test. For all frontal and transverse plane movement tests the standard deviations of the mean piercing points are high suggesting large individual variability. A few studies have used helical axis parameters (in particular the piercing points) to compare normal and pathological cervical spine motion (Osterbauer et al., 1992; 1996; Ribaudo, 1993; Woltring et al., 1994), but this present research is the first to analyze helical parameters for the thoracic spine in normal, healthy living subjects. More research will be needed to be able to make generalizations regarding the clinical relevance of helical axis piercing points.

The final helical parameter that appears to provide most insight into the spatial movement of the thoracic relative to the lumbar spine are the helical unit vectors (Table 4.10 and Table 4.11.). Inspection of the unit vectors in Table 4.10 show that when sidebending and axial rotation were coupled to the same side the "signs" of U_y and U_z were opposite. For example, in the standing sidebending test for right sidebending U_y was positive and U_z was negative; and for left sidebending U_y was negative and U_z was positive. Likewise, inspection of the unit vectors associated with the tests that demonstrated contralateral coupling of sidebending and axial rotation (Table 4.11) show, for the most part, that U_y and U_z have the same "sign." For example, for subjects (n = 8) with contralateral coupling for the standing sidebending test U_y and U_z were positive for right sidebending and negative for left sidebending. Only for the sit neutral sidebending test did this pattern fail to emerge; however, there were only three subjects that demonstrated contralateral coupling for this test so perhaps these data reflect small group artifact.

Two additional findings related to the helical unit vectors can be highlighted. The first has already been alluded to, that is, the unit vectors show that pure cardinal plane spinal motions likely do not exist. For example, during the standing flexion/extension motion tests there were minor movements in the frontal and transverse planes, as indicated by the U_y and U_z values. Likewise, during the sidebending and axial rotation tests small movements occurred in the sagittal plane, as indicated by the U_x values. The second, and perhaps more interesting finding, is that the sign of U_x indicates whether the spine is flexing or extending. Note, that during the standing flexion/extension test U_x had a negative sign during the flexion phase and a positive sign during the extension phase. Examination of data in Table 4.10 shows, for example, that during the sit slouch sidebending and axial rotation tests U_x is positive, indicative of thoracic extension (which is what was also noted observationally). White (1969) described the helical axis of motion for thoracic spinal functional units. However, White's sample size was very small and he did not attempt to correlate his conventional and helical angle data. In summary, it appears that the helical axis unit vectors not only indicate the direction of movements, but also the direction of spinal coupling. These findings are exciting because for the first time, to this author's knowledge, helical axis unit vectors are shown to correlate with meaningful clinical data.

Instantaneous Helical Axis

The illustrations, in Chapter 4, of the instantaneous helical axes (IHAs) for all motion tests for a representative subject (S56JD) are not, by any means, representative of all subjects. However, S56JD shows patterns that can illustrate some virtues of an IHA analysis. For the standing flexion/extension test the IHA pattern certainly showed that the major motion occurred in the sagittal plane (Figure 4.19), with smaller movements in the frontal and transverse planes (Figure 4.18 and Figure 4.20). Figure 4.18 and Figure 4.19 also show that the IHAs translate in a cephalo-caudal direction during flexion/extension, while Figure 4.20 illustrates that an anterior/posterior migration of the IHAs occurs. As noted previously, orientation of the thoracic zygapophyseal joints do not favor sagittal plane movement. If any generalization can be made with regard to IHA patterns for flexion/extension it would be that there did not appear to be a consistent pattern, which may be a reflection of the inherent difficulty to move the thoracic spine into flexion and extension.

The IHAs in Figure 4.21 well illustrate the now well-established fact, that sidebending is coupled with axial rotation. For if the thoracic spine moved in the pure frontal cardinal plane the axis would appear as a dot. One can see both vertical (indicating axial rotation), as well as, a medial/lateral (indicating some flexion/extension) orientations of the IHAs in Figure 4.21, Figure 4.22 and Figure 4.23. A similar display of multiple orientations for the IHAs of the standing axial rotation test can be seen in Figure 4.24, Figure 4.25 and Figure 4.26. Anterior/posterior translation of the axial rotation IHAs suggest the sagittal plane motion that is also occurring. Medial/lateral translations of the axial rotation IHAs imply coupled sidebending. In general, for the cohort, these patterns existed to greater and lesser extents. For example, during sidebending tests IHAs migrated in the same direction of the motion 60% of the time and for axial rotation tests the IHAs translated in the same direction only about 24% of the time. Thus, there appears to be significant inter-subject variability. These results suggest that significantly more research needs to done to understand how the IHAs can be used clinically. No previous research has the examined use of IHAs for evaluating thoracic spine function; however, several researchers have investigated the use of FHA/IHAs to compare spatial movement of the cervical spine in healthy persons and individuals that had a whiplash injury (Osterbauer et al., 1992; 1996; Ribaudo, 1993; Winters et al., 1988; 1993; Winters & Peles, 1990; Woltring et al., 1994). In the cervical spine there seemed to be consistent IHA patterns that distinguished normal from pathological (Osterbauer et al., 1992; 1996; Ribaudo, 1993; Woltring et al., 1994).

Engineering and Biomechanical Significance

The findings of this research were derived based on several important bioengineering ideas. First, prior to data collection significant effort was made to insure the fidelity of the body marker system. It was important to find the best means by which to secure markers to the skin over the spine since it was assumed that minimizing skin motion artifact would be absolutely critical to obtaining good data. The marker system that was eventually used survived several revisions that came about as a result of pilot testing that revealed good tracking of spinal movement with a minimum of skin motion.

Several tests were performed to examine the ability of the motion capture system to accurately measure the three-dimensional position of markers, the linear distance between markers during static and dynamic tests and the angles between fixed markers in a static test. Additionally, the consistency of accurate measures was demonstrated through repeated calibration tests.

A dummy spine model of the marker set configuration was designed to test several things. First, the dummy spine was put through several motion tests, tests that simulated the testing protocol. Data collected from these trials were used to calculate Cardan and helical angles, as well as IHAs that were compared to known angles and axis locations. The dummy data were also used to verify that the Cardan sequence used for this research was correct and to quantify cross talk. Results suggest that the rotation sequence chosen, indeed, can influence results. These data will be reported to the biomechanics community to remind them of the importance of describing the rotation sequences used in research involving three-dimensional angle calculations.

The marker rig/protocol used in this research was verified, as evidenced by the high CMC values for both the primary and secondary motions. Although biologic variability is known to influence test-retest data, the high CMC values in this research demonstrate that the data collection method used in this research is consistent. The data collection and analysis method was sufficiently accurate and reliable to detect not only small secondary, but also tertiary movements of the thoracic spine.

Finally, application of helical axis theory was applied for the first time to analyze thoracic spine motion in living, healthy subjects. Preliminary establishment of the relationship of the helical parameters to the more clinically accepted Cardan parameters is a unique contribution to the literature and appears to have clinical relevance.

Clinical Significance

Results of this research reaffirm the existence of spine coupling of sidebending and axial rotation. Additionally, the existence of a small amount of sagittal plane motion during thoracic sidebending and axial rotation is quantified suggesting that spinal motion is more complex than traditionally thought.

Evidence here, that corroborates previous research results, refutes Fryette's first law of neutral spine mechanics. Thus, it does not appear that when the thoracic spine is in a neutral posture sidebending and axial rotation are coupled opposite. In fact, both Cardan and helical parameter analysis suggests that because of the sagittal plane motion that occurs during trunk sidebending and axial rotation a theoretical "neutral", as described by Fryette, may not exist functionally. That is, as soon as an individual begins to sidebend or rotate that individual will "load" their facets in compression so that sidebending and axial rotation will occur to the same side. This notion assumes that

Fryette's hypothesis about the mechanics of spine coupling is true (testing this hypothesis is left for future projects). An implication of this finding is that manual medicine practitioners who use Fryette's concept of neutral mechanics may need to develop new hypotheses with regard to examination and intervention strategies. There is sufficient evidence from this research to support Fyrette's law of non-neutral spine mechanics; that is, when the spine is flexed or extended sidebending and axial rotation are coupled to the same side. Additional testing of the sit slouch axial rotation test is warranted since these results were somewhat equivocal.

There was borderline evidence to support the third law of Fryette. However, the data on this matter were mixed suggesting that more research is needed to completely verify or refute. In the meantime, manual medicine practitioners who use Fryette's third concept as part of their examination and treatment, again, may need to begin to revise their ideas about how they are "locking" segments of the spine in order to treat isolated spinal segments. It should be pointed out that subjects in this research actively controlled their movements, whereas typically during treatment patients are moved passively. Measuring the quality of differences between passive and active movements of the thoracic spine is suggested.

Finally, preliminary evidence has been established to support the clinical relevance and usefulness of helical axis analysis for the thoracic spine. Theoretically, helical parameters can best parameterize full six degree-of-freedom description of rigid body motions in space.

Limitations

There are several limitations related to this research. First, the sample tested was one of convenience and was small. Additionally, although there was equal representation of males and females, the cohort was too homogeneous with regard to age and body type.

Despite error estimates, the uncertainty of the contribution of skin motion artifact raises some questions with regard to accuracy of the magnitude of the motion data, although motion pattern data are not likely affected as much. Numerical error analysis of helical parameters was insufficient; a concern since it is known that helical axis analysis is sensitive to error. Finally, the marker arrangement for the lumbar spine was inadequate. Observation during testing suggested that the lumbar markers did not consistently follow the spine, which was why lumbar motion relative to the pelvis and thoracic motion relative to the pelvis were not determined.

Future Directions

As is typical with most research endeavors, partial answers to original research questions raise many more questions. Thus, there are several things that need to be pursued. First, more normal individuals need to be tested and added to this database; individuals who represent different ages and body types are also needed. The marker protocol needs to be altered and can be improved by adding more markers to the thoracic segment and by creating a different marker system for the lumbar spine. These changes can improve accuracy of the transformation matrices but need to be tested and validated.

Continued research needs to be done to better quantify skin motion artifact in the thoracic, cervical and lumbar regions, and to more precisely define error related to helical axis analysis. Future research will add to the understanding of the relationship between clinical descriptors of spine motion and the helical parameters, not only to assess thoracic motion, but also to examine cervical and lumbar spine motion. Finally, although there is insufficient evidence to support the use of biomechanical/kinematic data in the management of spine patients (Barker & McCombe, 1999; Cox et al., 2000; Dall'Alba, Sterling, Treleaven, Edwards, & Jull, 2001; Parks, Crichton, Goldford, & McGill, 2003; Zuberbier et al., 2001) this research needs to be expanded to begin to examine the kinematics of pathological spine motion.

Summary and Conclusion

For the coordinate system orientation used in this research (positive x right lateral, positive y anterior, and positive z superior) the Cardan sequence xyz (flexion followed by lateral bending, then axial rotaion), each taken about local, body-fixed axes, produced the best results for the study of three-dimensional kinematics of the thoracic spine. Use of a dummy spine model verified this choice.

The Vicon 512 Motion Capture System was used to collect three-dimensional position data. Error analysis revealed excellent repeatability of calibration residuals. Additionally, linear measures had a root mean square error (RMSE) of approximately 0.77 mm. Angular measures reported a RMSE of approximately 0.1°.

A dummy spine model was used to evaluate the accuracy of Cardan and helical angle calculations, as well as the amount of cross-talk. Calculated Cardan and finite helical angles were similar to known angles used during simulated movements. With a simulated flexion/extension test as the primary motion, approximately 4° cross-talk was found in the frontal and transverse planes. When sidebending was the primary motion approximately 3° cross-talk was found in the sagittal and transverse planes. Approximately 2° cross-talk occurred in the other planes when axial rotation was introduced. Similar findings were found when simulated skin motion artifact of 10 mm was introduced to the dummy spine marker set.

The coefficient of variation (CV) was used to evaluate motion cycle repeatability. The mean CV for three cycles of the primary motions for all motion tests was approximately 15%, suggesting excellent cycle-to-cycle consistency. The secondary motions, e.g., sidebending when axial rotation was primary, had a mean CV of 36%.

The coefficient of multiple correlation (CMC) was used to examine test-retest reliability. The mean CMC for the primary motions of sidebending and axial rotation was approximately 0.97, suggesting excellent intra-subject, inter-day repeatability. Mean CMCs for the secondary motions, e.g., sidebending when axial rotation was primary, averaged 0.78, which exceeded the CMC for sagittal plane motion (0.66).

Total range of motion for the thoracic segments (T3-T12) examined in this research for standing flexion/extension (25°), right and left sidebending (45°), and right and left axial rotation (62°) was similar to what has been previously reported in the literature. As expected, frontal and transverse plane motion exceeded sagittal plane motion, likely due to zygapophyseal joint orientation and vertebra morphology.

Examination of Fryette's laws of motion for the thoracic spine was the primary purpose of this research. Recall, that subjects performed all motion tests actively. Analysis of three-dimensional angle-angle plots and cross-correlation analysis provided corroborative and convincing evidence for coupling of sidebending and axial rotation in the thoracic spine. With the thoracic spine in neutral, for both the standing and sitting tests, sidebending and axial rotation coupled in the same direction 90% of the time, which is counter to Fryette. With the thoracic spine flexed or hyperextended sidebending and axial rotation coupled in the same direction 79% of the time; this total was influenced by the axial rotation test in slumped sitting position where only 54% exhibited same side coupling. Reduction of mobility in secondary planes did not occur consistently. Some evidence exists for the coupling of sagittal plane motion with movements in the frontal and transverse plane, a fact identified by previous researchers but not described by Fryette.

The present research was the first to identify the possible clinical utility of helical axis analysis for the spine. Finite helical and Cardan angles for the primary motions were comparable. Finite helical unit vectors appear to precisely define the three-dimensional motion of the thoracic spine, where the sign of u_x indicates whether the thorax if flexing or extending, and the signs of u_y and u_z indicate the direction of spinal coupling. Identification of instantaneous helical axes qualitatively describe the three-dimensional nature of thoracic spine motion.

In conclusion, results from this research do not support Fryette's law of neutral spine mechanics for the thoracic spine in young, healthy individuals. There is some evidence to support Fryette's contention that mobility reduction occurs in secondary planes. More convincing evidence was presented that supports Fryette's law on non-neutral spine mechanics. Manual medicine practitioners may need to re-examine the assumptions upon which they base their examination and intervention strategies. It appears that useful information about spatial movement of the thoracic spine can be derived from helical axis analysis, as long as this information can be made clinically relevant. Given the small sample size of this research more data must be gathered on normal, healthy individuals to be able to broaden the application of these results. Application of the methods used in this research also needs to be extended to examination of individuals with thoracic spine pathology.

APPENDIX A

Table A1. Repeated Calibration Wand Tests

Tests	Camera Residuals (mm)						Mean** (SD)	SR (%)	Wand (mm)
Cal 1	0.86	1.01	0.73	0.69	0.78	0.85	0.82 (0.11)	0.90	1.66
Cal 2	0.75	0.89	0.70	0.62	0.66	0.69	0.72 (0.09)	0.81	0.91
Cal 3	0.83	1.02	0.69	0.66	0.63	0.64	0.75 (0.15)	0.92	0.65
Cal 4	0.95	0.91	0.66	0.69	0.74	0.69	0.74 (0.12)	0.90	0.64
Cal 5	0.59	0.88	0.74	0.61	0.70	0.75	0.71 (0.11)	0.81	0.79
Cal 6	0.64	0.79	0.71	0.60	0.62	0.55	0.65 (0.09)	1.04	0.43
Cal 7	0.76	0.91	0.68	0.69	0.71	0.72	0.75 (0.09)	0.76	0.57
Cal 8	0.85	0.79	0.73	0.67	0.58	0.65	0.71 (0.09)	0.85	0.42
Cal 9	0.77	0.81	0.71	0.63	0.62	0.62	0.69 (0.08)	0.79	0.56
Cal 10	0.74	0.81	1.04	0.82	0.69	0.87	0.83 (0.12)	0.96	0.54
Mean*	0.79	0.88	0.74	0.67	0.67	0.70	0.74	0.88	0.72
SD	0.11	0.08	0.11	0.06	0.06	0.09	0.05	0.09	0.36

Note. * = Mean (± SD) in mm by camera; ** = Mean (± SD) in mm for all six cameras. SR = static reproducibility. Wand = SD of mean distance between markers.

APPENDIX B

Table B1. Angle Accuracy Test Results

Trial	Mean Angle (SD)°	Difference (°)*
B1X	60.9 (0.80)	0.9
B1Y	60.8 (0.05)	0.8
B1Z	60.7 (0.03)	0.7
B3X	60.7 (0.04)	0.7
B3Y	60.8 (0.03)	0.8
B3Z	60.6 (0.05)	0.6
B4X	60.7 (0.05)	0.7
B4Y	60.9 (0.09)	0.9
B4Z	61.0 (0.12)	1.0
B6X	60.7 (0.06)	0.7
B6Y	60.8 (0.03)	0.8
B6Z	60.9 (0.04)	0.9
T1X	60.8 (0.04)	0.8
T1Y	60.7 (0.12)	0.7
T1Z	60.4 (0.10)	0.4
T3X	60.8 (0.04)	0.8
T3Y	60.8 (0.05)	0.8
T3Z	60.6 (0.15)	0.6
T4X	60.8 (0.11)	0.8
T4Y	60.8 (0.05)	0.8
T4Z	60.7 (0.05)	0.7
T6X	60.8 (0.06)	0.8
T6Y	60.8 (0.03)	0.8
T6Z	60.5 (0.13)	0.5
CX	60.7 (0.16)	0.7
CY	60.8 (0.05)	0.8
CZ	60.7 (0.16)	0.7
Grand Mean (SD)	60.75 (0.12)	0.75 (0.12)**

Note: * = Actual – measured angle; ** SD (number in parentheses) = Root Mean Square Error (RMSE).

APPENDIX C

Table C1. Linear Accuracy Test Results

Trial	Distance 1 Mean (SD)	Diff	Distance 2 Mean (SD)	Diff	Distance 3 Mean (SD)	Diff
B1X	242.9 (0.29)	0.9	371.5 (0.21)	0.5	423.1(0.47)	1.1
B1Y	242.6 (0.24)	0.6	371.7 (0.19)	0.7	423.8 (0.20)	1.8
B1Z	242.7 (0.18)	0.7	371.6 (0.18)	0.6	424.0 (0.17)	2.0
B3X	242.8 (0.14)	0.8	371.6 (0.21)	0.6	424.0 (0.27)	2.0
B3Y	242.9 (0.14)	0.9	371.6 (0.14)	0.6	423.4 (0.16)	1.4
B3Z	244.2 (0.32)	2.2	370.4 (0.23)	0.6	422.8 (0.23)	0.8
B4X	242.8 (0.18)	0.8	371.7 (0.24)	0.7	424.2 (0.24)	2.2
B4Y	242.5 (0.46)	0.5	371.8 (0.14)	0.8	423.6 (0.42)	1.6
B4Z	243.5 (0.69)	1.5	371.8 (0.14)	0.8	422.7 (0.75)	0.7
B6X	243.4 (0.58)	1.4	372.0 (0.23)	1.0	424.7 (0.21)	2.7
B6Y	242.6 (0.18)	0.6	371.9 (0.14)	0.9	423.9 (0.17)	1.9
B6Z	242.8 (0.15)	0.8	372.0 (0.16)	1.0	423.8 (0.17)	1.8
T1X	242.8 (0.19)	0.8	372.1 (0.29)	1.1	424.2 (0.32)	2.2
T1Y	242.5 (0.30)	0.5	371.7 (0.17)	0.7	424.2 (0.72)	2.2
T1Z	241.6 (0.29)	0.4	371.9 (0.19)	0.9	426.3 (0.63)	4.3
T3X	242.6 (0.17)	0.6	372.0 (0.23)	1.0	424.0 (0.28)	2.0
T3Y	242.5 (0.21)	0.5	371.3 (0.29)	0.3	423.3 (0.18)	1.3
T3Z	243.0 (0.45)	1.0	370.9 (0.28)	0.1	424.1 (0.70)	2.1
T4X	242.2 (0.63)	0.2	371.8 (0.27)	0.8	423.9 (0.55)	1.9
T4Y	242.5 (0.22)	0.5	371.6 (0.23)	0.6	423.7 (0.25)	1.7
T4Z	243.3 (0.31)	1.3	371.0 (0.23)	0.0	423.6 (0.23)	1.6
T6X	242.4 (0.19)	0.4	371.5 (0.55)	0.5	423.5 (0.32)	1.5
T6Y	242.7 (0.27)	0.7	371.6 (0.15)	0.6	423.7 (0.12)	1.7
T6Z	242.1 (0.77)	0.1	371.3 (0.35)	0.3	424.8 (0.57)	2.8
CX	242.4 (0.47)	0.4	371.3 (0.73)	0.3	42 4.0 (0.30)	2.0
CY	242.4 (0.16)	0.4	371.6 (0.24)	0.6	423.6 (0.19)	1.6
CZ	242.9 (0.55)	0.9	371.2 (0.19)	0.2	423.4 (0.83)	1.4
Mean	242.7	0.75	371.6	0.62	423.9	1.86
SD	0.49	0.44*	0.38	0.28*	0.68	0.68*

Note: All measures in mm; Distance 1 = 242 mm; Distance 2 = 371 mm; Distance 3 = 422 mm; Diff = actual – measured; * = Root Mean Square Error (SD) between actual and measured linear distances.

APPENDIX D

CARDAN ANGLES CROSS-TALK FROM DUMMY TEST DATA

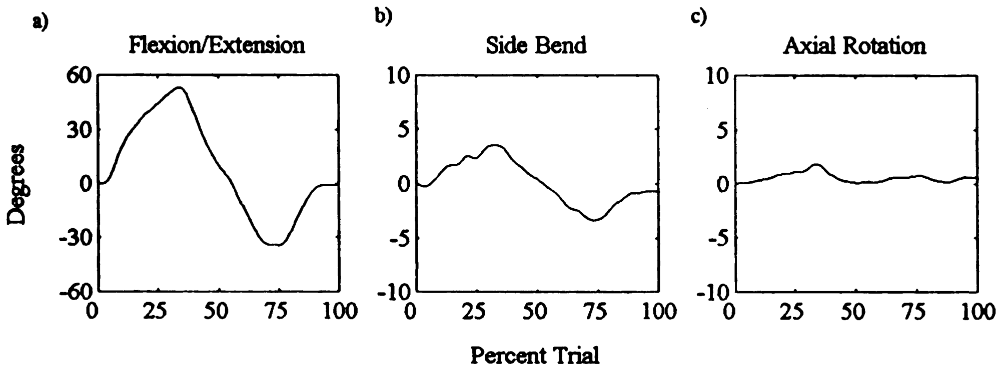

Figure D1. Dummy trial 04 where ~60° flexion and 30° extension was introduced. Note ~3.5° sidebending and <2° axial rotation cross-talk.

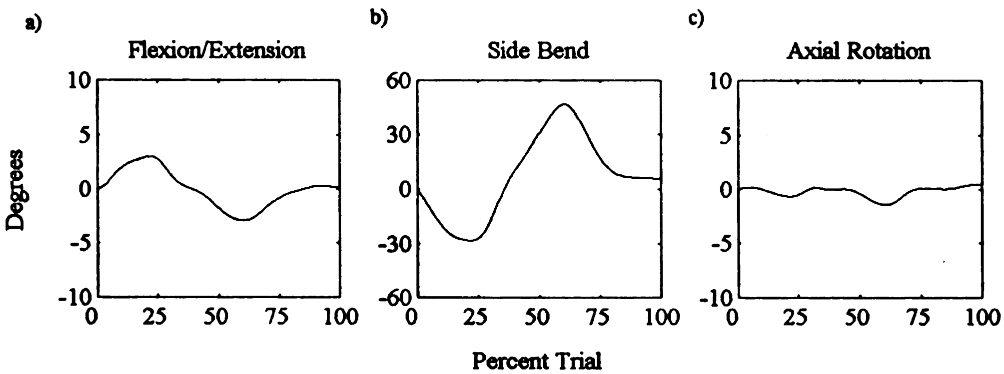

Figure D2. Dummy trial 07 where ~30° of right and left sidebending was introduced. Note ~3° flexion/extension and <2° axial rotation cross-talk.

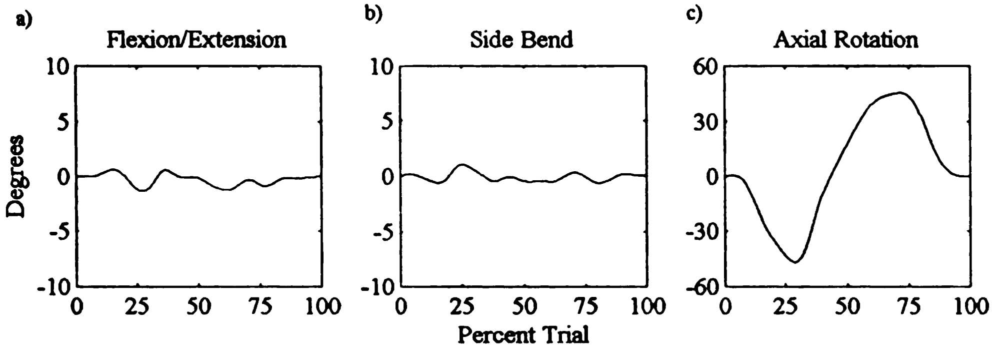

Figure D3. Dummy trial 11 where ~45° of left and right axial rotation were introduced. Note ~1.5° flexion/extension and <1° sidebending cross-talk.

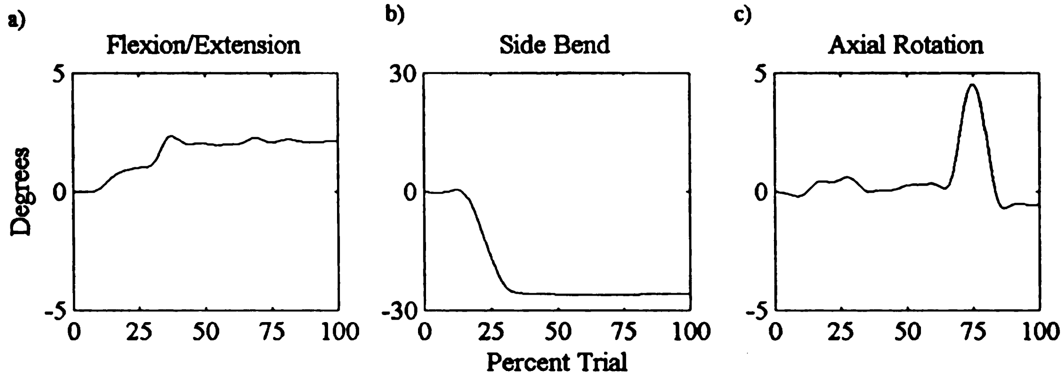

Figure D4. Dummy trial 12 where ~20° right sidebending then ~5° right axial rotation was introduced. Note <2° flexion cross-talk.

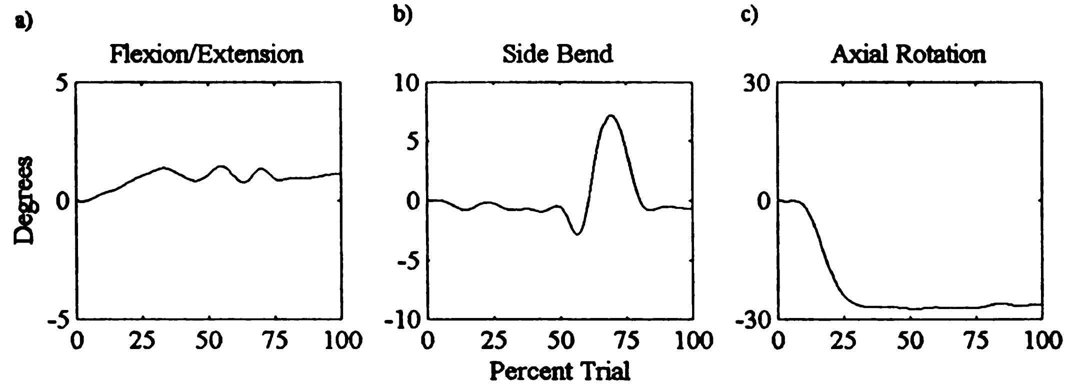

Figure D5. Dummy trial 14 where ~30° left axial rotation then ~5° left sidebending was introduced. Note <2° flexion cross-talk.

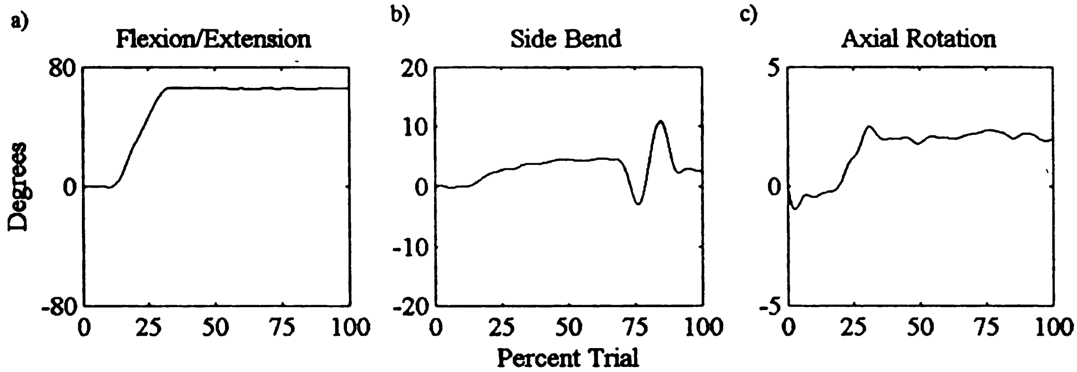

Figure D6. Dummy trial 18 where ~60° flexion, then 5° right and 5° left sidebending was introduced. Note ~4° left sidebending and ~2.5° axial rotation cross-talk.

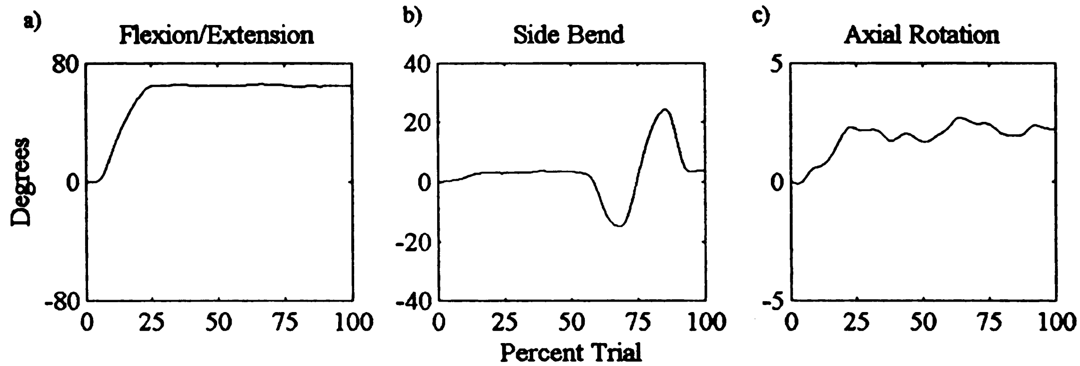

Figure D7. Dummy trial 19 where ~60° flexion, then ~15° right and left sidebending was introduced. Note ~3° sidebending and ~2° axial rotation cross-talk.

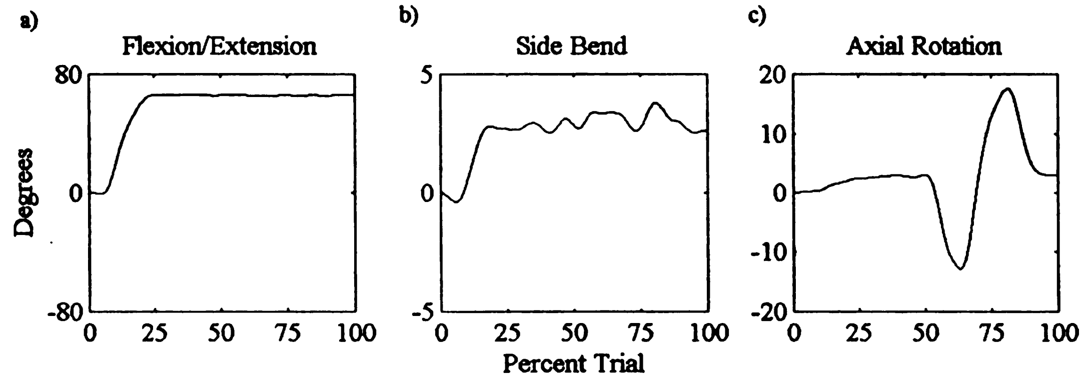

Figure D8. Dummy trial 111 where ~60° flexion, then ~15° left and right axial rotation was introduced. Note ~3.5° sidebending and ~2° axial rotation cross-talk.

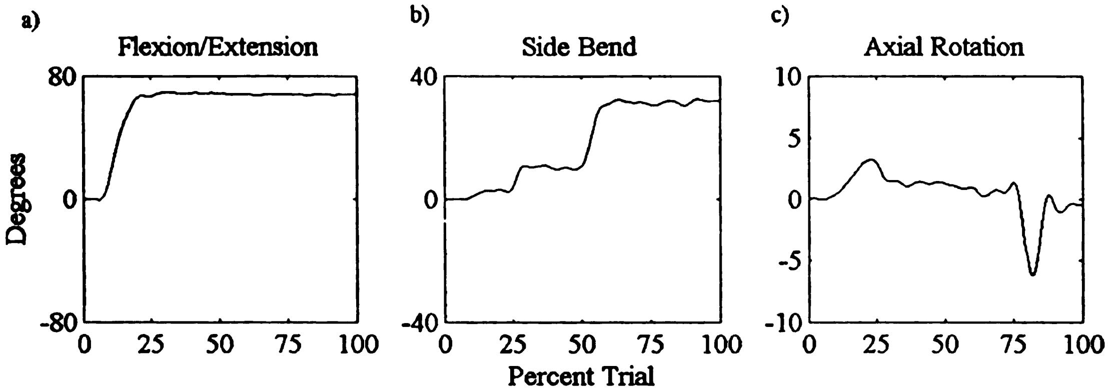

Figure D9. Dummy trial 112 where ~60° flexion, then ~15° left sidebending and ~5° left axial rotation was introduced. Note ~10° sidebending and ~3° axial rotation cross-talk.

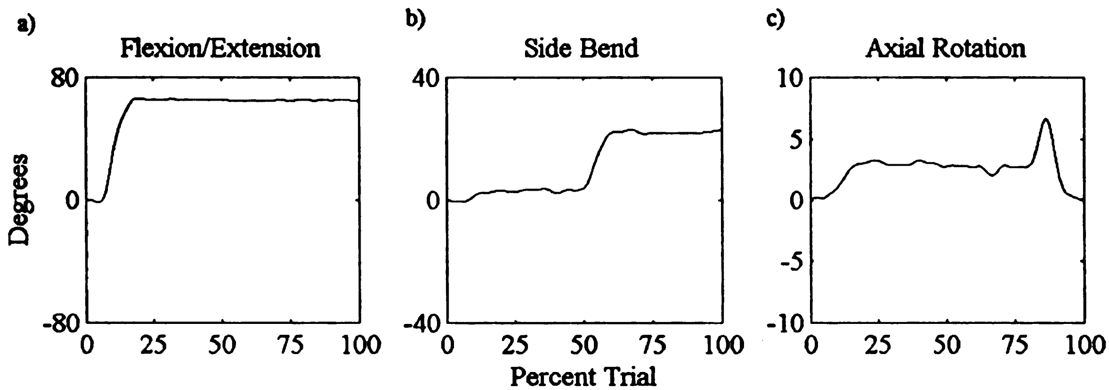

Figure D10. Dummy trial 114 where ~60° flexion, then ~15° left sidebending and ~5° right axial rotation was introduced. Note ~3° sidebending and ~3° axial rotation cross-talk.

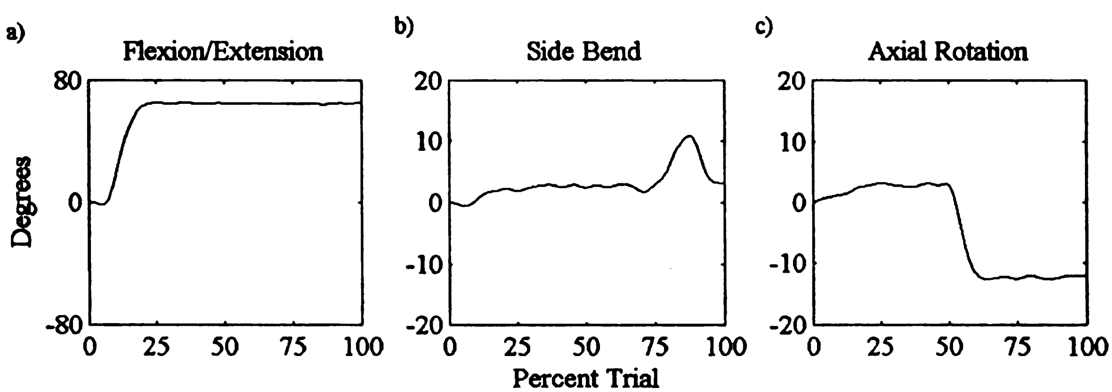

Figure D11. Dummy trial 116 where ~60 flexion, then ~15° left axial rotation and ~5° left sidebending was introduced. Note ~3° sidebending and axial rotation cross-talk.

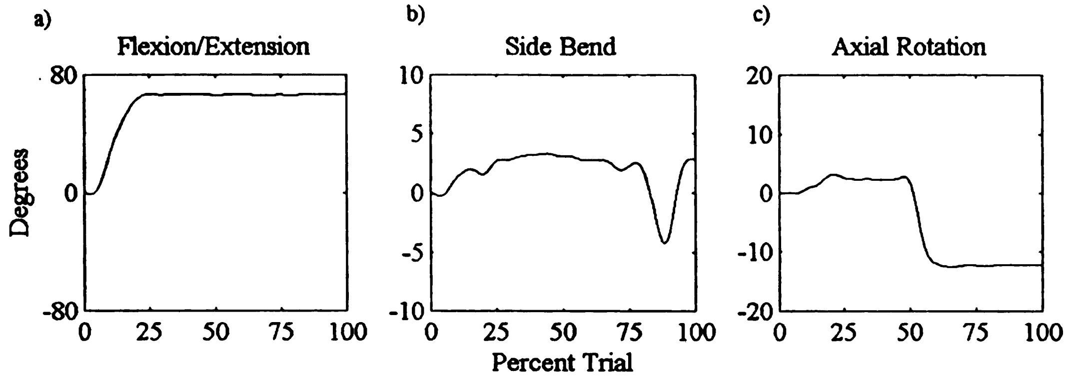

Figure D12. Dummy trial 118 where ~60° flexion, then ~15° left axial rotation and ~5° right sidebending was introduced. Note ~3° sidebending and axial rotation cross-talk.

APPENDIX E

INSTANTANEOUS HELICAL AXIS FOR DUMMY TRIAL 04

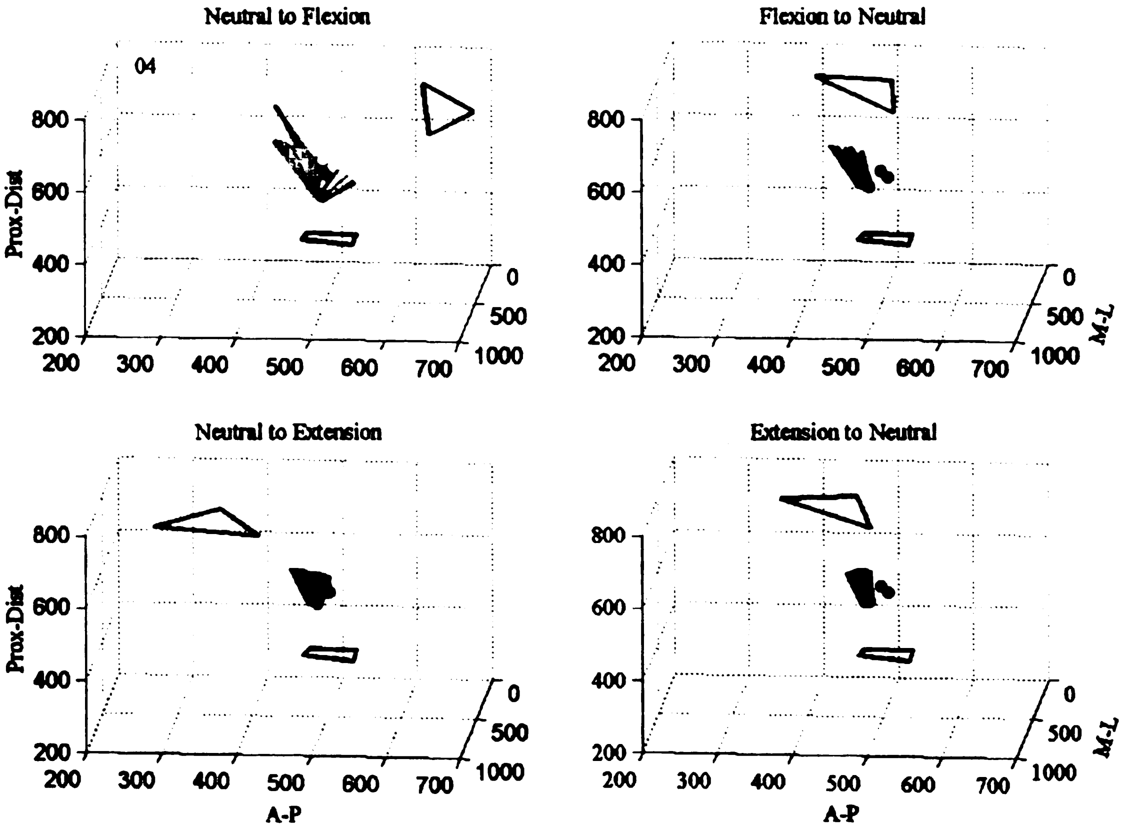

Figure E1. Sagittal view of IHA relative to fixed flexion/extension axis. Upper triangle represents 'thoracic' segment and lower rectangle represents 'lumbar' segment. Blue denotes the beginning of the motion and green the end of the motion.

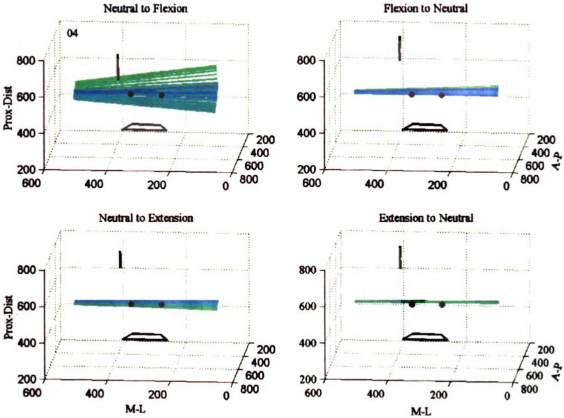

Figure E2. Frontal view of IHA relative to fixed flexion/extension axis. Blue denotes the beginning of the motion and green the end of the motion.

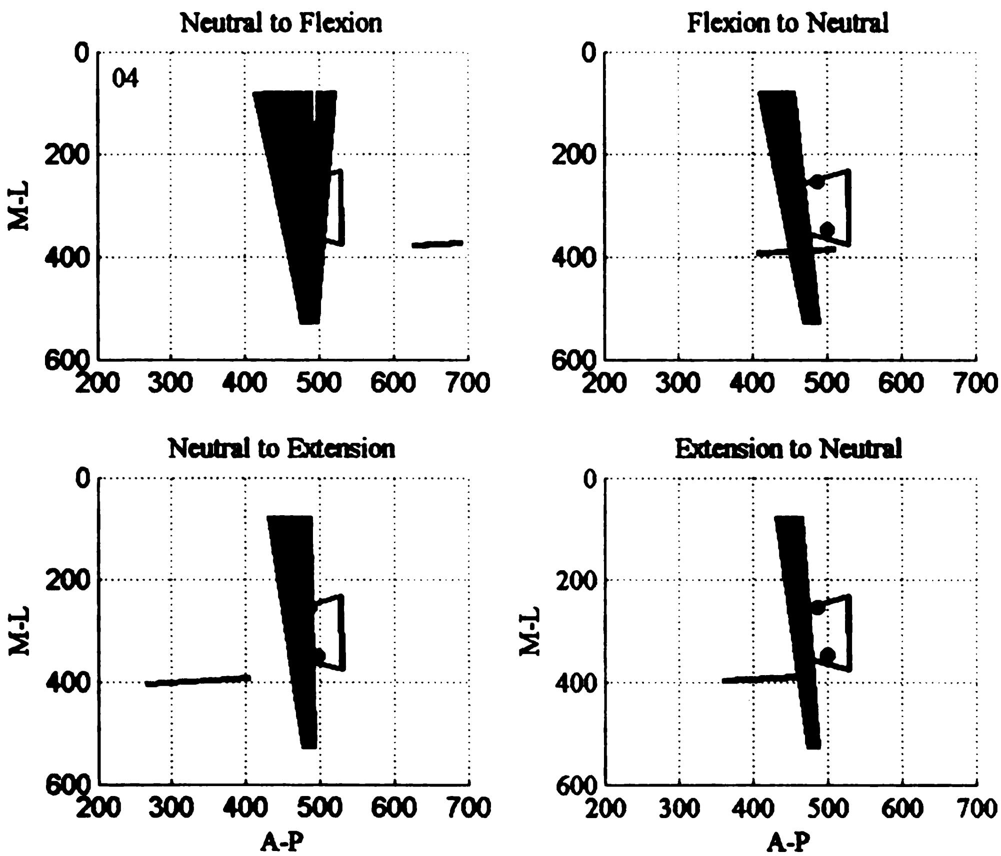

Figure E3. Transverse (top) view of IHA relative to fixed flexion/extension axis. Blue denotes the beginning of the motion and green the end of the motion.

APPENDIX F

INFORMED CONSENT

MARY FREE BED HOSPITAL & REHABILITATION CENTER
GRAND VALLEY STATE UNIVERSITY
MOTION ANALYSIS CENTER

THREE-DIMENSIONAL KINEMATIC ANALYSIS OF THE THORAX IN STANDING AND SITTING

You are being asked to participate in a research study designed to examine movement patterns of the spine while standing and sitting in various postures. You will be asked about your past medical history and will undergo a physical examination to determine if you meet the study's inclusion criteria. The physical examination will screen for leg length equality, walking ability, posture, and motion of the spine and thorax, and upper and lower extremities. If you meet inclusion criteria you will be one of 30 subjects participating in this study. If your history and physical examination are not consistent with normal standards, you may not be able to participate in this study.

You will allow the researcher to tape reflective markers on your skin at various sites on the back and pelvis. During the test you will be wearing only shorts, or shorts and a top (women), in order to allow exposure of the reflective markers during the test procedures. You will be photographed and/or videotaped as part of the testing. The Motion Analysis Center/researcher will have custody of these data, but will use the data only for the purpose of analysis, education, and/or reporting scientific results. You will remain anonymous in any report of research findings and your privacy will be protected to the maximum extent allowable by law. Upon request, results of the study may be made available to you.

All of the procedures involved in this study will take approximately two (2) hours and are non-invasive (nothing will penetrate the skin). You may be asked to return for an additional two (2) hours for repeat testing of your trunk movements. The risks associated with the postures and trunk movements tested are minimal, but may include minor muscle stiffness the following day. In the unlikely event of minor injury first aid will be provided. If the injury is not caused by the negligence of the primary investigator of this study further medical care will continue under the direction of your physician in accordance with your own particular financial arrangement. In the case of a research-related injury you should notify the primary investigator (Gordon Alderink) of this project.

The benefits of these tests will be explained to you. They include assisting the researcher, other health care practitioners, and the Motion Analysis Center in establishing trunk motion data on non-impaired individuals. This information can be used to aid in diagnosis, treatment, and assessment of treatment outcomes for individuals with spinal disorders. Information from this study may also provide you with scientifically collected and interpreted data on your trunk movement patterns.

Your participation in this study is strictly on a volunteer basis. You may choose not to participate at all, may refuse to participate in certain procedures or answer certain questions, or may withdraw at any time. In no way would non-participation or withdrawal from this study affect treatment while at Mary Free Bed Hospital & Rehabilitation Center or educational status at Grand Valley State University. There will be no payment for your participation. Mr. Alderink or his major advisor, Robert Hubbard, PhD, will answer your questions. Questions regarding your rights as a human subject of research may also be directed to David E. Wright (Phone: 517/355-2180), Chair of the Michigan State University, University Committee on Research Involving Human Subjects.

PARTICIPANT STATEMENT:
This test has been explained to you and you freely consent to participate. You have also been given the opportunity to ask questions.

____
Signature of Participant Date

INVESTIGATOR STATEMENT:
I have offered an opportunity for further explanation of this test.

____
Signature of Investigator Date

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APPENDIX G

MEDICAL HISTORY FORM

SUBJECT NUMBER: _________ **DATE:_________**
AGE:_________ GENDER: M F

PAST MEDICAL HISTORY: (Describe childhood illnesses, injuries such as sprains/strains, etc., and other congenital or acquired diseases such as congenital heart condition, diabetes, hypertension, etc.)

PAST SURGICAL HISTORY: (List any and all significant surgeries, such as appendectomy, fracture internal fixations, etc.)

CHECK BELOW IF YOU HAVE ANY OF THE FOLLOWING SPINAL CONDITIONS:
_____ Scoliosis _____ Spondylolysis(thesis) _____ Spinal Surgery

_____ Vertebral Fracture _____ Disc Injury _____ Ankylosing Spondylitis

_____ Neurological injury to the spinal cord and/or spinal nerves _____ Other spinal

condition(s)

Have you had any muscle or skeletal injuries within the past six months that required medical attention? _____ Yes _____ No.

If yes, describe:

APPENDIX H

SCREENING EXAMINATION

Subject Number __________ **Date __________**
Height _____ (cm) **Weight _____ (kg)** **Age _____ (yrs.)**

1. Gait Normal ☐ Abnormal ☐
2. Posture
   a. Posterior View
      Shoulder level low on: L ☐ R ☐ Equal ☐
      Iliac crest low on: L ☐ R ☐ Equal ☐
      Head sidebent to: L ☐ R ☐ Equal ☐
      T spine paravertebral fullness :L ☐ R ☐ Equal ☐
      L spine paravertebral fullness: L ☐ R ☐ Equal ☐
   b. Lateral views
      Cervical lordosis Increased ☐ Decreased ☐ Normal ☐
      Thoracic kyphosis Increased ☐ Decreased ☐ Normal ☐
      Lumbar lordosis Increased ☐ Decreased ☐ Normal ☐
3. Standing Trunk Sidebending
   a. Restricted sidebending L ☐ R ☐ Normal ☐
   b. Restricted axial rotation L ☐ R ☐ Normal ☐
4. Standing Flexion Test
   a. Negative ☐ Positive ☐ L ☐ R ☐
   b. Thoracic spine paravertebral fullness L ☐ R ☐
   c. Lumbar spine paravertebral fullness L ☐ R ☐
5. Stork Test
   a. Left Negative ☐ Positive ☐
   b. Right Negative ☐ Positive ☐
6. Seated Flexion Test
   a. Negative ☐ Positive ☐ L ☐ R ☐
   b. Thoracic spine paravertebral fullness L ☐ R ☐
   c. Lumbar spine paravertebral fullness L ☐ R ☐
7. Seated Upper Extremity Motion
   a. Restricted? Yes ☐ No ☐ L ☐ R ☐ Equal ☐
8. Seated Trunk Axial Rotation
   a. Restricted? Yes ☐ No ☐ L ☐ R ☐ Equal ☐
9. Seated Trunk Sidebending
   a. Restricted? Yes ☐ No ☐ L ☐ R ☐ Equal ☐

10. Seated Head and Neck Motion

a. Extension restricted? Yes ☐ No ☐
b. Flexion restricted? Yes ☐ No ☐
c. Axial rotation restricted? L ☐ R ☐ Equal ☐
d. Sidebending restricted? L ☐ R ☐ Equal ☐

11. Supine Thoracic Cage Motion

a. Upper ribs:
   Inhalation restricted L ☐ R ☐ Equal ☐
   Exhalation restricted L ☐ R ☐ Equal ☐
b. Middle ribs:
   Inhalation restricted L ☐ R ☐ Equal ☐
   Exhalation restricted L ☐ R ☐ Equal ☐
c. Lower ribs:
   Inhalation restricted L ☐ R ☐ Equal ☐
   Exhalation restricted L ☐ R ☐ Equal ☐

12. Lower Extremity Motion

a. SLR restricted? L ☐ R ☐ Equal ☐
b. Leg length (ASIS-MM) L _____R _____ Equal ☐ (cm)
c. Squatting restricted? Yes ☐ No ☐

Examiner_______________________________________

APPENDIX I

Table I1. Test Date Calibration Residuals

Test Dates	Camera Residuals (mm)						Mean**	SR(%)
2.12.02	0.86	0.55	0.99	0.75	0.58	0.84	0.76(0.17)	0.79
2.21.02	0.79	0.65	0.78	0.75	0.65	0.95	0.76(0.11)	0.73
4.11.02	0.72	0.57	0.92	0.81	0.57	0.75	0.72(0.14)	0.49
4.12.02	0.59	0.96	0.76	0.62	0.66	0.76	0.72(0.13)	0.76
5.31.02	1.01	0.57	0.79	1.08	0.66	0.94	0.84(0.20)	0.74
6.04.02	0.73	0.77	1.03	0.75	1.07	1.19	0.93(0.19)	0.56
6.14.02	0.56	0.67	0.80	0.59	0.70	0.96	0.71(0.15)	0.59
6.25.02	0.62	0.88	1.21	0.67	0.67	1.03	0.85(0.24)	0.75
6.28.02	0.60	0.72	0.76	0.66	0.66	0.97	0.73(0.13)	0.57
7.05.02	0.63	0.63	0.99	0.65	0.75	0.70	0.73(0.14)	0.83
7.09.02	0.67	0.58	0.72	0.65	0.64	0.67	0.65(0.04)	0.61
7.18.02	0.60	0.76	0.96	0.65	0.65	0.72	0.72(0.13)	0.78
7.29.02	0.70	0.65	0.84	0.71	0.82	1.05	0.79(0.14)	0.51
7.31.02	0.83	0.67	0.72	1.14	0.58	0.62	0.76(0.21)	0.96
8.14.02	0.86	0.77	0.75	0.79	0.68	0.76	0.77(0.06)	0.76
8.29.02	0.74	0.82	1.02	0.67	0.61	1.29	0.86(0.25)	0.92
8.30.02	0.69	0.80	1.02	0.65	0.59	1.07	0.81(0.19)	0.62
9.04.02	0.65	0.81	0.89	0.61	0.73	1.17	0.81(0.20)	1.05
Mean*	0.72	0.71	0.89	0.73	0.68	0.91		0.72
SD	0.12	0.12	0.14	0.15	0.12	0.19		0.16

Note: * = Mean (± SD) in mm by camera; ** = Mean (± SD) in mm for all six cameras.
SR = static reproducibility

APPENDIX J

DATA COLLECTION SHEET

Subject Number: ______________________ **Test Date:** ________

Kinematic Collection Rate (Hz)	**30 Hz**	**Marker Set:**

File	Description	Reconstr uct	Cut File	Label	Defrag Traj	Fill Gaps	Woltring	BB MODEL	Notes
	Standing file								
	Stand flexion/extension								
	Stand sidebend R/L								
	Stand axial rotation L/R								
	Sit neutral sidebend R/L								
	Sit neutral axial rotation L/R								
	Sit slouch sidebend R/L								
	Sit slouch axial rotation L/R								
	Sit erect sidebend R/L								
	Sit erect axial rotation L/R								

Standing lumbo-sacral angle =

Sitting neutral lumbo-sacral angle =

APPENDIX K

THREE-DIMENSIONAL AND PLANAR REPRESENTATION OF IHAS FOR S56JD

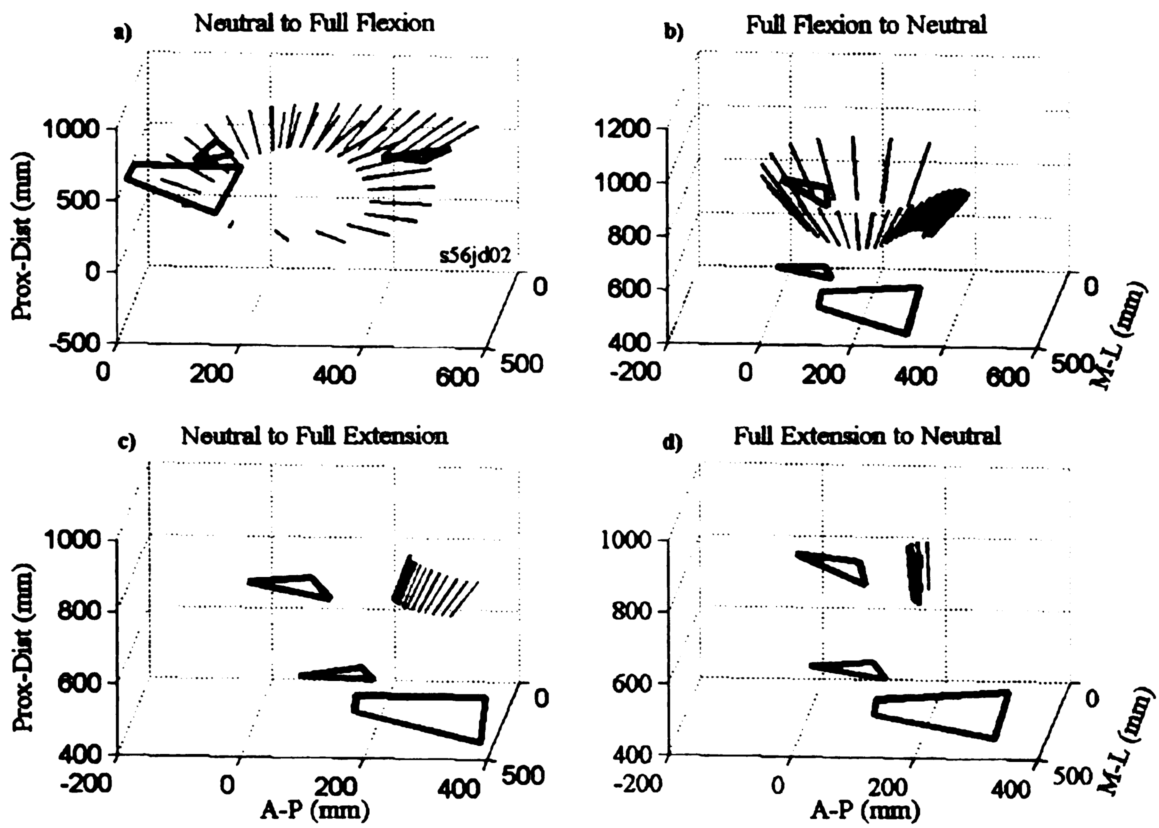

Figure K1. Sagittal view of IHAs for standing flexion/extension. Blue denotes the beginning of the motion and green the end of the motion.

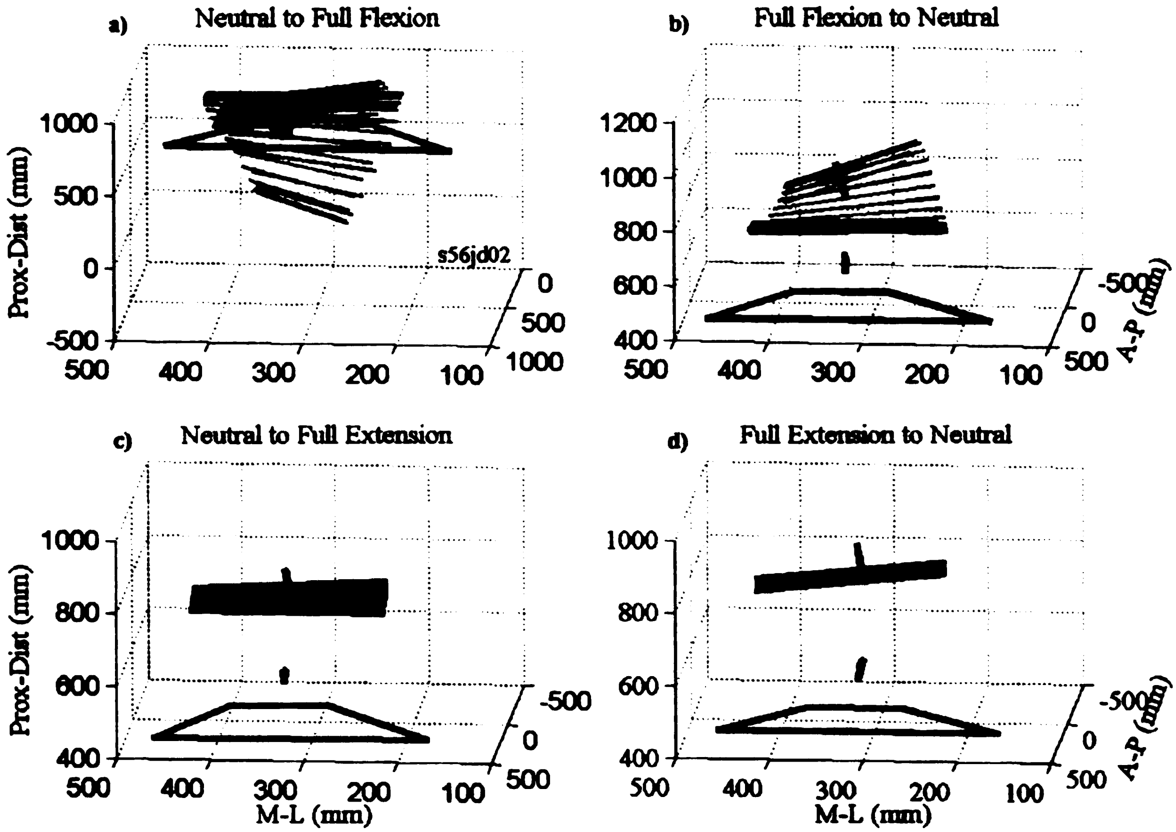

Figure K2. Frontal view of IHAs for standing flexion/extension. Blue denotes the beginning of the motion and green the end of the motion.

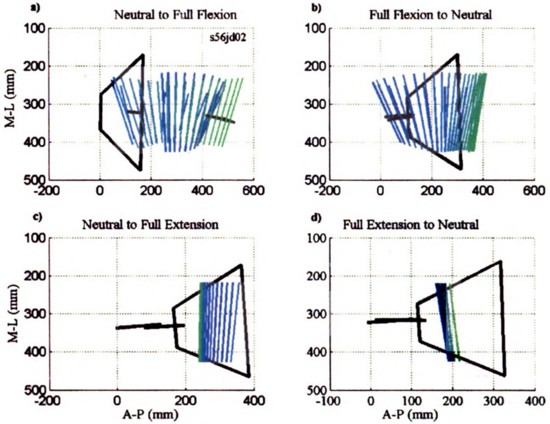

Figure K3. Transverse (top) view of IHAs for standing flexion/extension. Blue denotes the beginning of the motion and green the end of the motion.

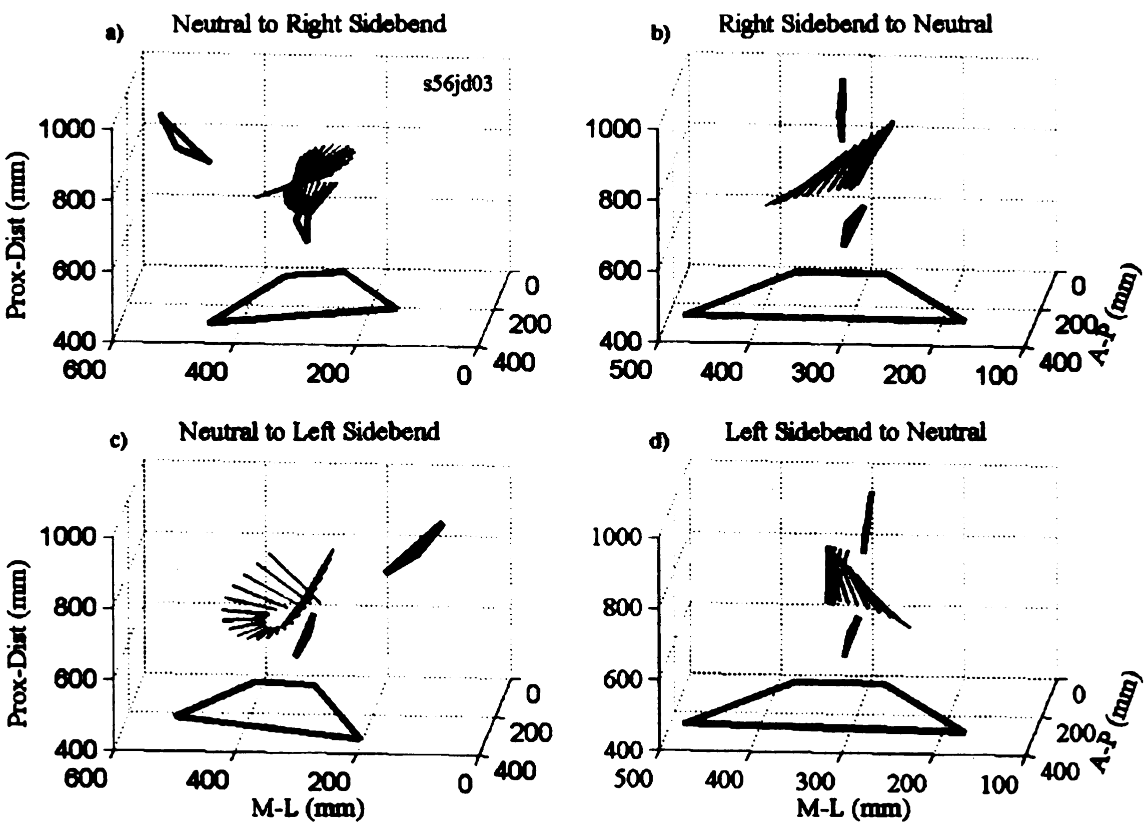

Figure K4. Frontal view of IHAs for standing sidebending. Blue denotes the beginning of the motion and green the end of the motion.

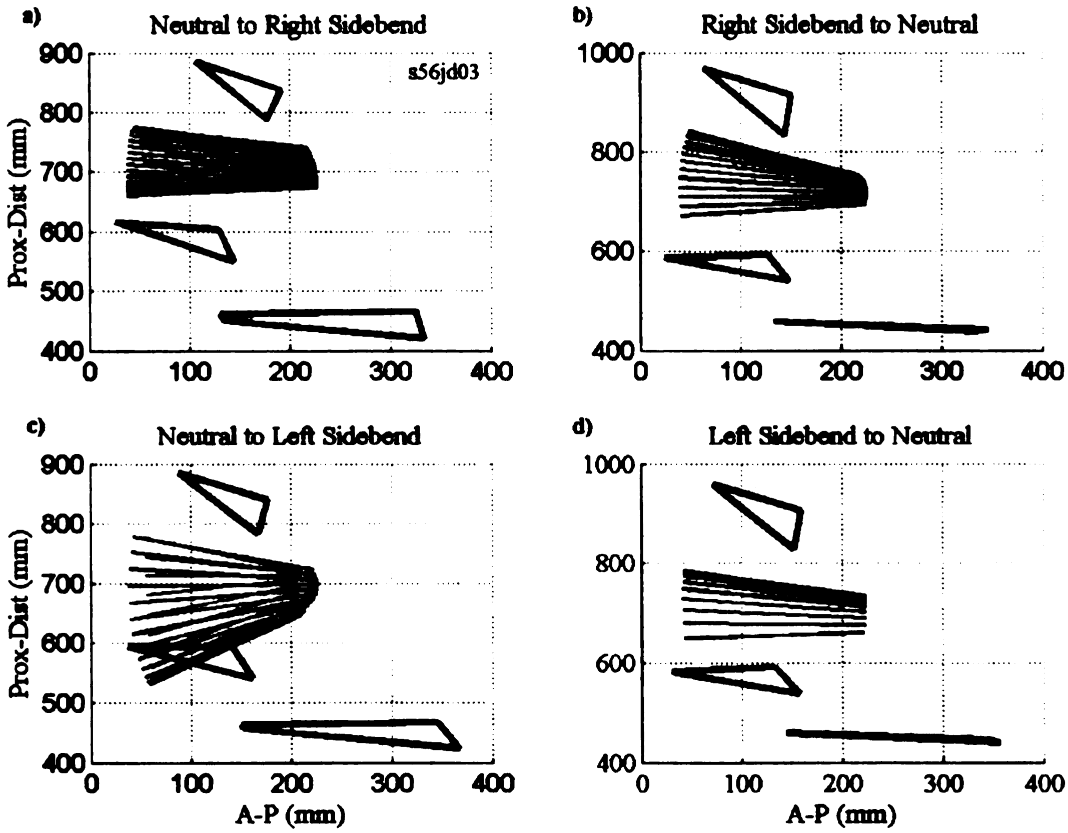

Figure K5. Sagittal view of IHAs for standing sidebending. Blue denotes the beginning of the motion and green the end of the motion.

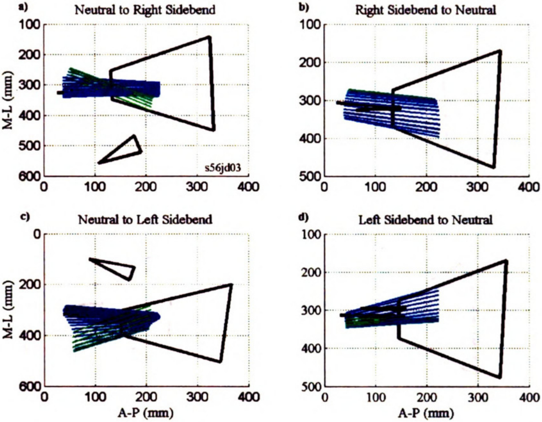

Figure K6. Transverse (top) view of IHAs for standing sidebending. Blue denotes the beginning of the motion and green the end of the motion.

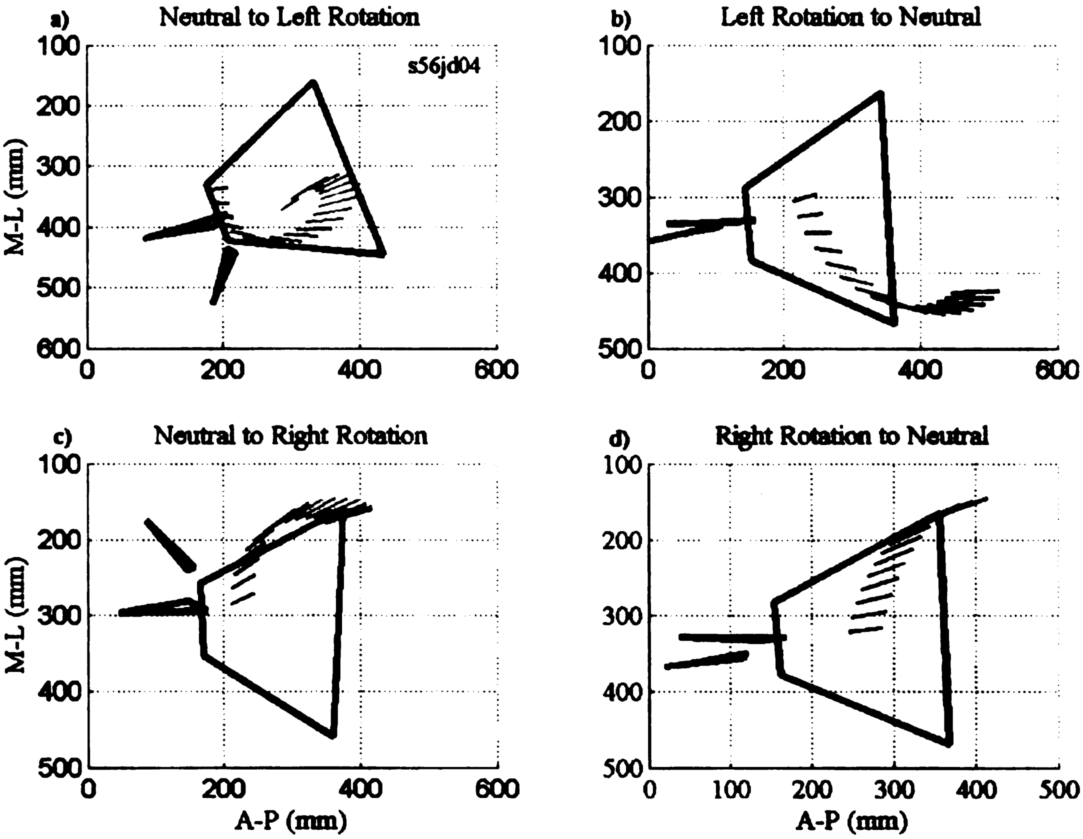

Figure K7. Transverse (top) view of IHAs for standing axial rotation. Blue denotes the beginning of the motion and green the end of the motion.

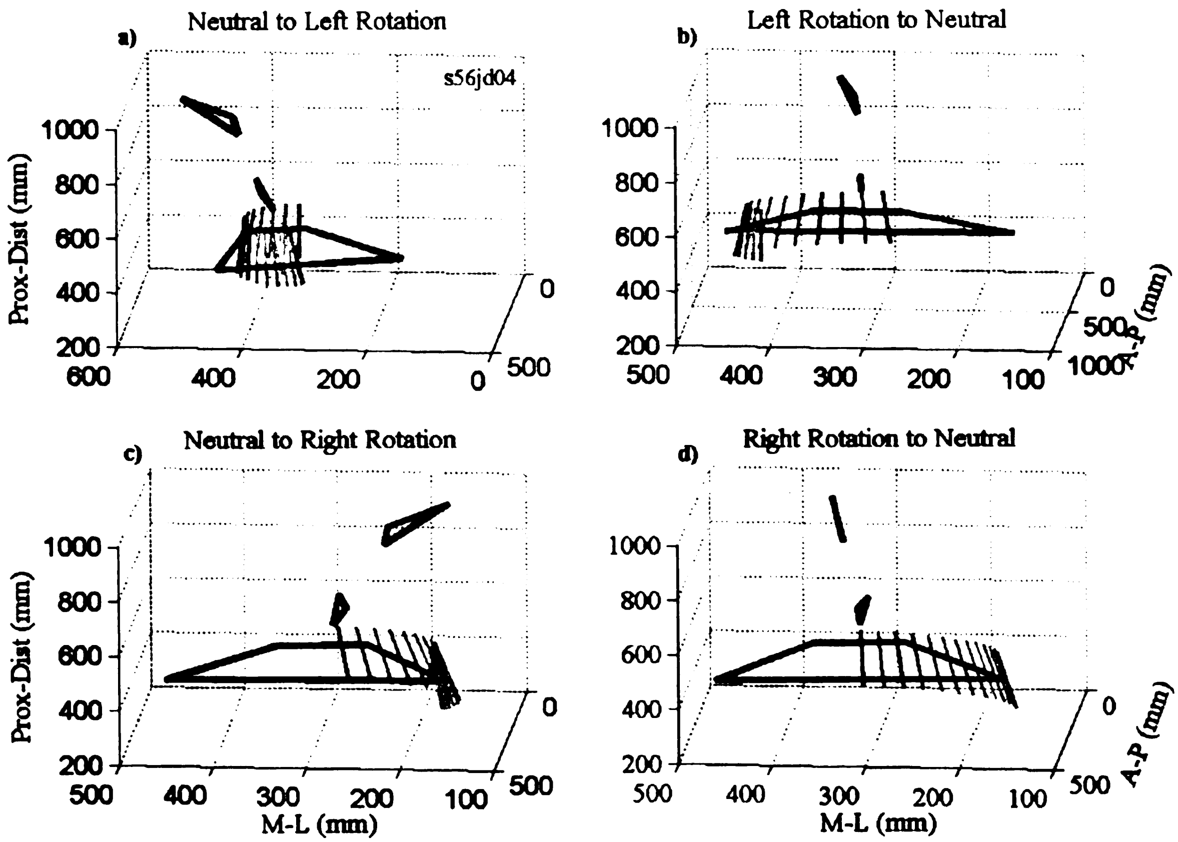

Figure K8. Frontal view of IHAs for standing axial rotation. Blue denotes the beginning of the motion and green the end of the motion.

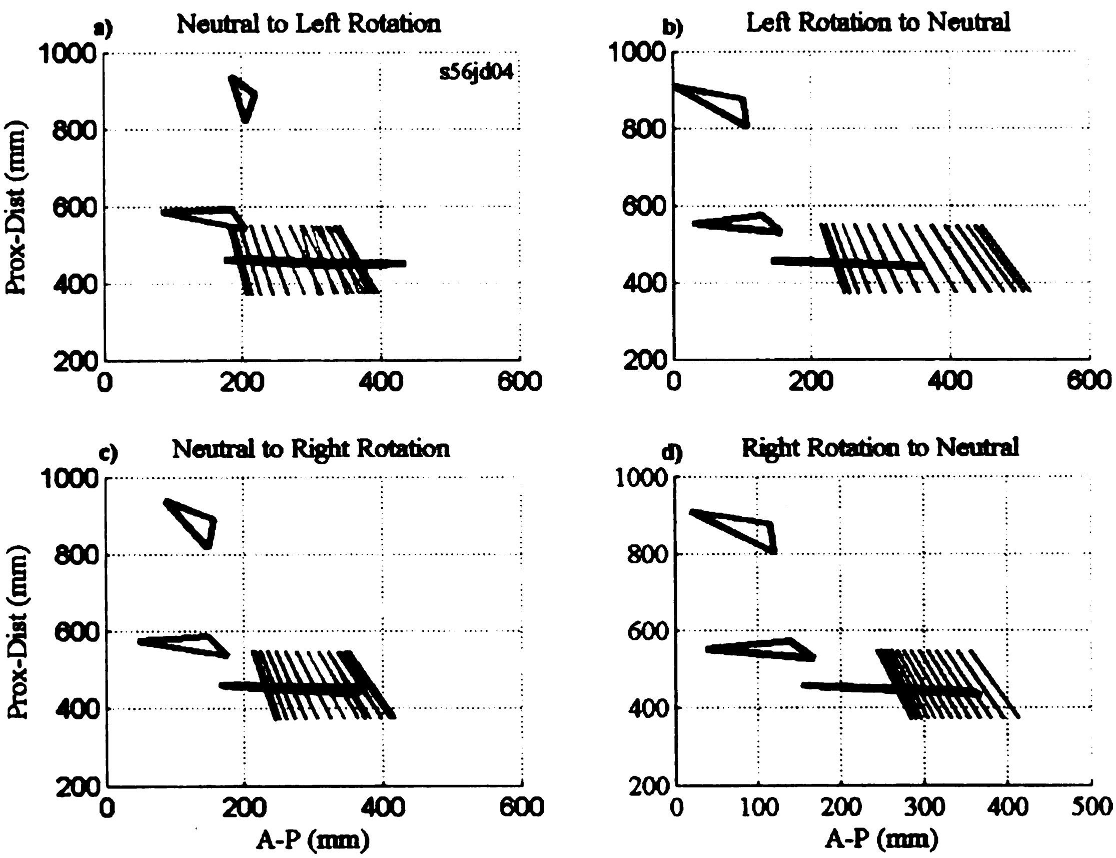

Figure K9. Sagittal view of IHAs for standing axial rotation. Blue denotes the beginning of the motion and green the end of the motion.

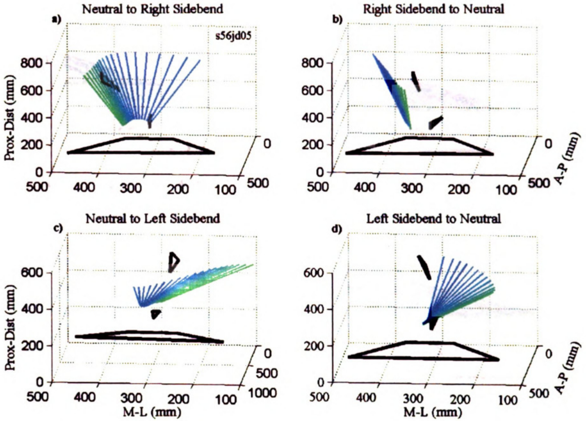

Figure K10. Frontal view of IHAs for sitting neutral sidebending. Blue denotes the beginning of the motion and green the end of the motion.

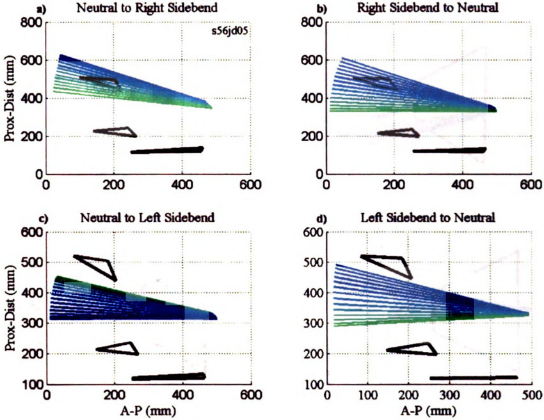

Figure K11. Sagittal view of IHAs for sitting neutral sidebending. Blue denotes the beginning of the motion and green the end of the motion.

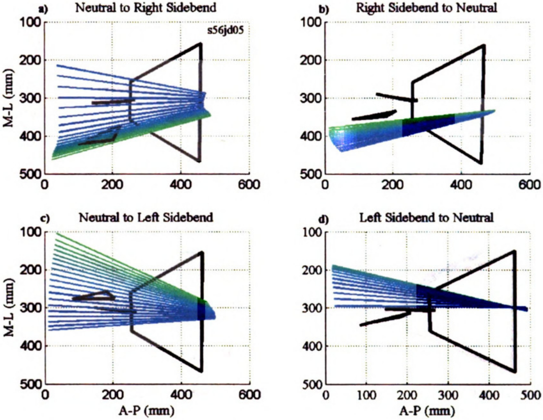

Figure K12. Transverse (top) view of IHAs for sitting neutral sidebending. Blue denotes the beginning of the motion and green the end of the motion.

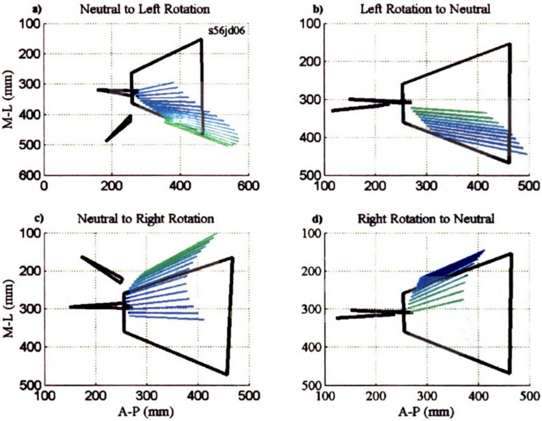

Figure K13. Transverse (top) view of IHAs for sitting neutral axial rotation. Blue denotes the beginning of the motion and green the end of the motion.

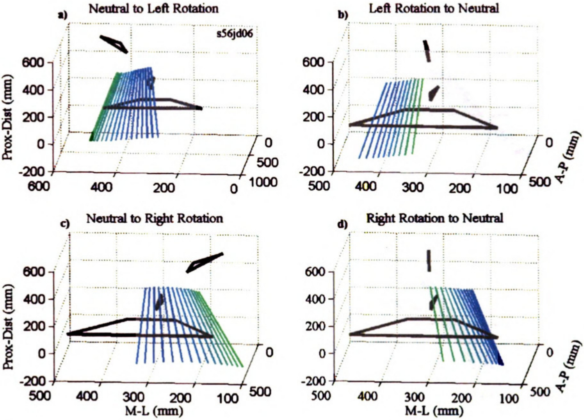

Figure K14. Frontal view of IHAs for sitting neutral axial rotation. Blue denotes the beginning of the motion and green the end of the motion.

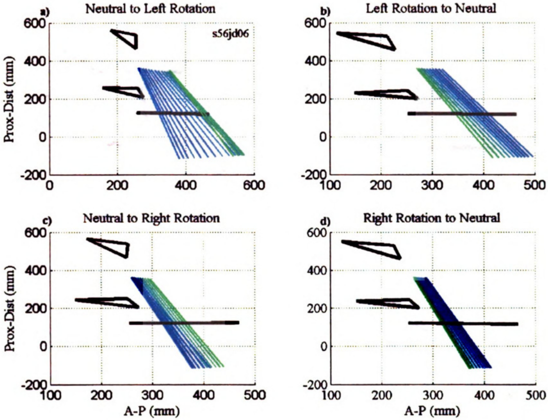

Figure K15. Sagittal view of IHAs for sitting neutral axial rotation. Blue denotes the beginning of the motion and green the end of the motion.

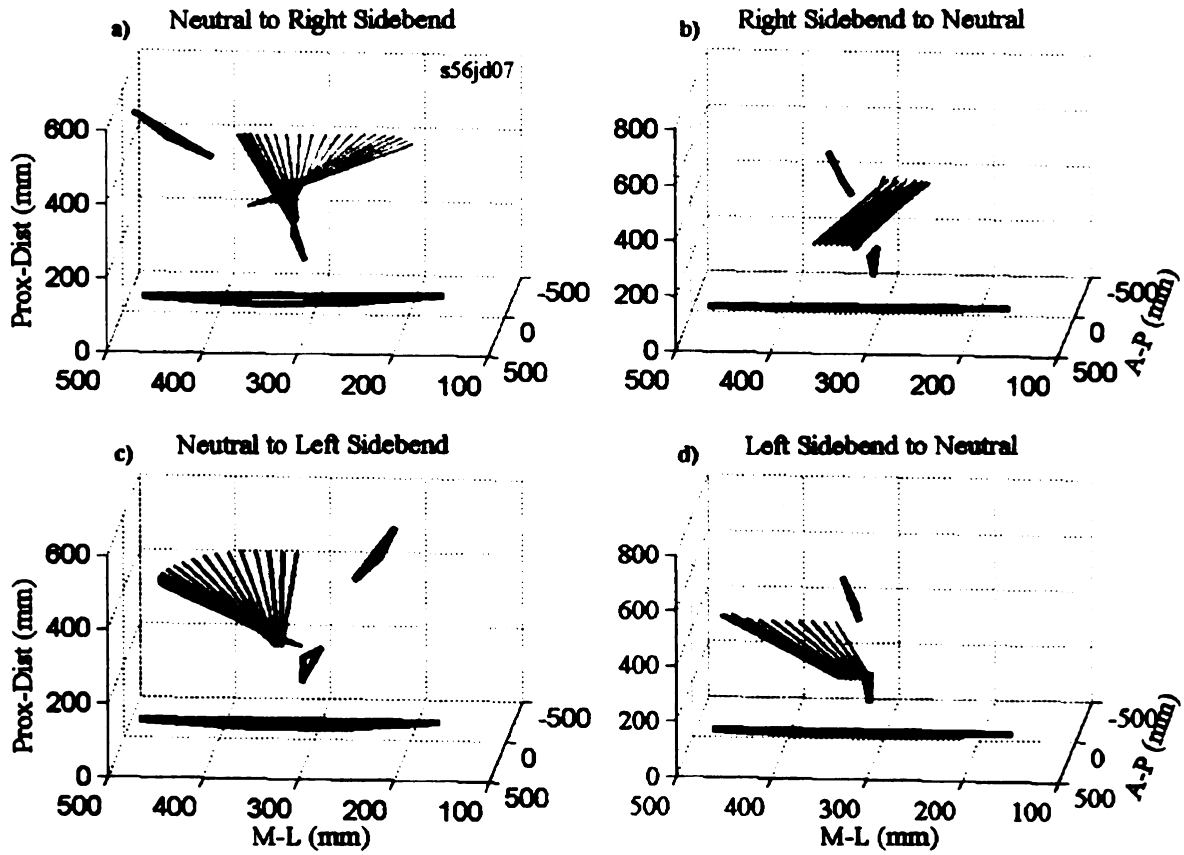

Figure K16. Frontal view of IHAs for sitting slouch sidebending. Blue denotes the beginning of the motion and green the end of the motion.

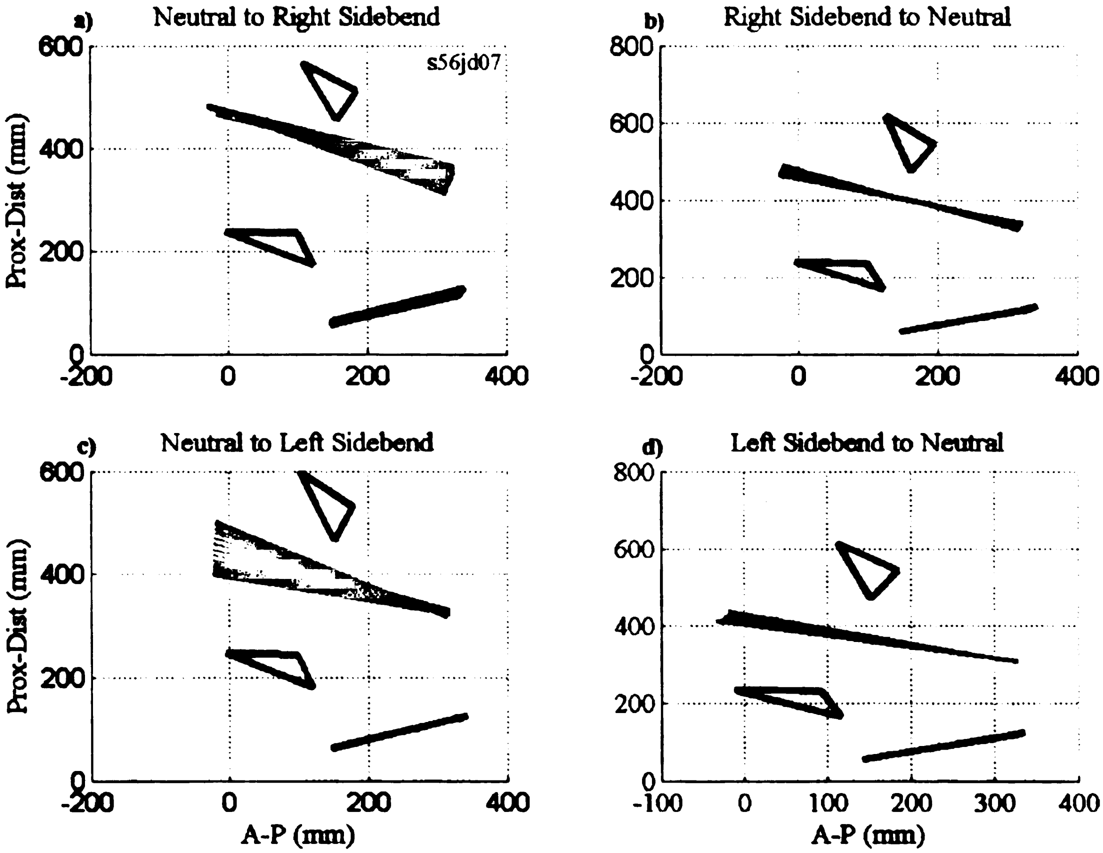

Figure K17. Sagittal view of IHAs for sitting slouch sidebending. Blue denotes the beginning of the motion and green the end of the motion.

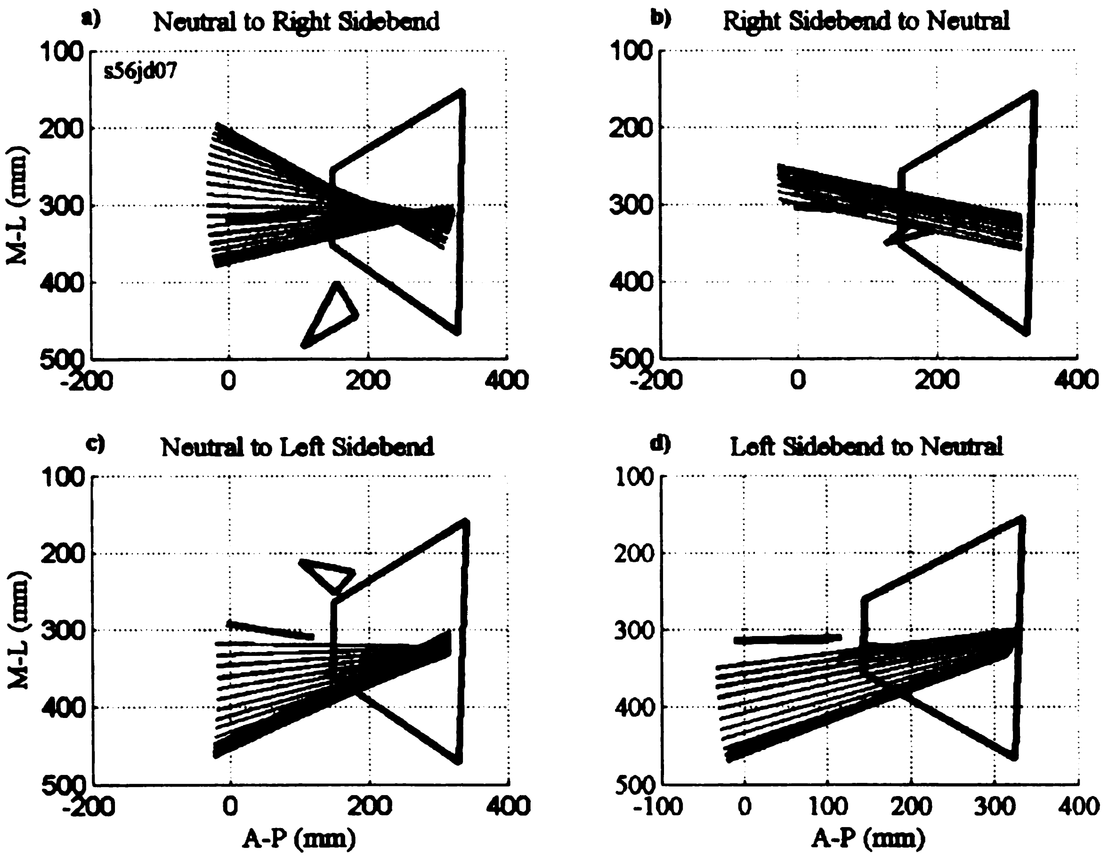

Figure K18. Trasnverse (top) view of IHAs for sitting slouch sidebending. Blue denotes the beginning of the motion and green the end of the motion.

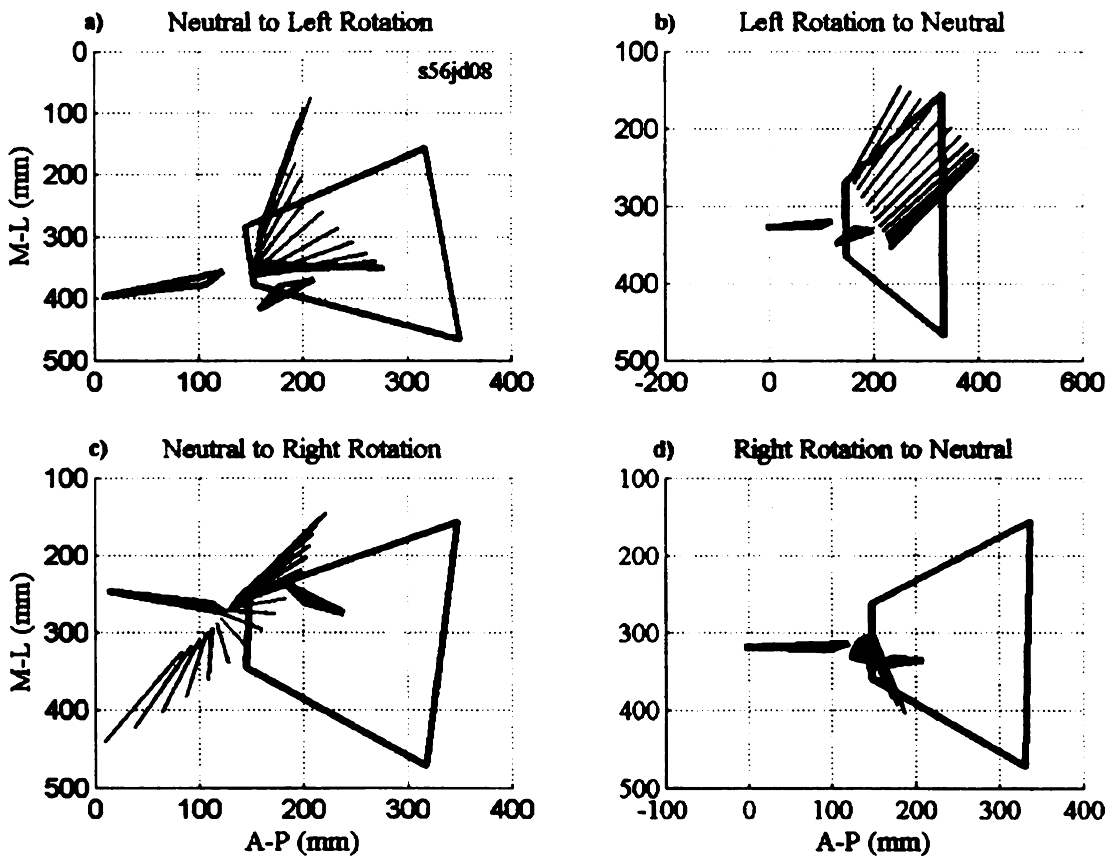

Figure K19. Transverse (top) view of IHAs for sitting slouch axial rotation. Blue denotes the beginning of the motion and green the end of the motion.

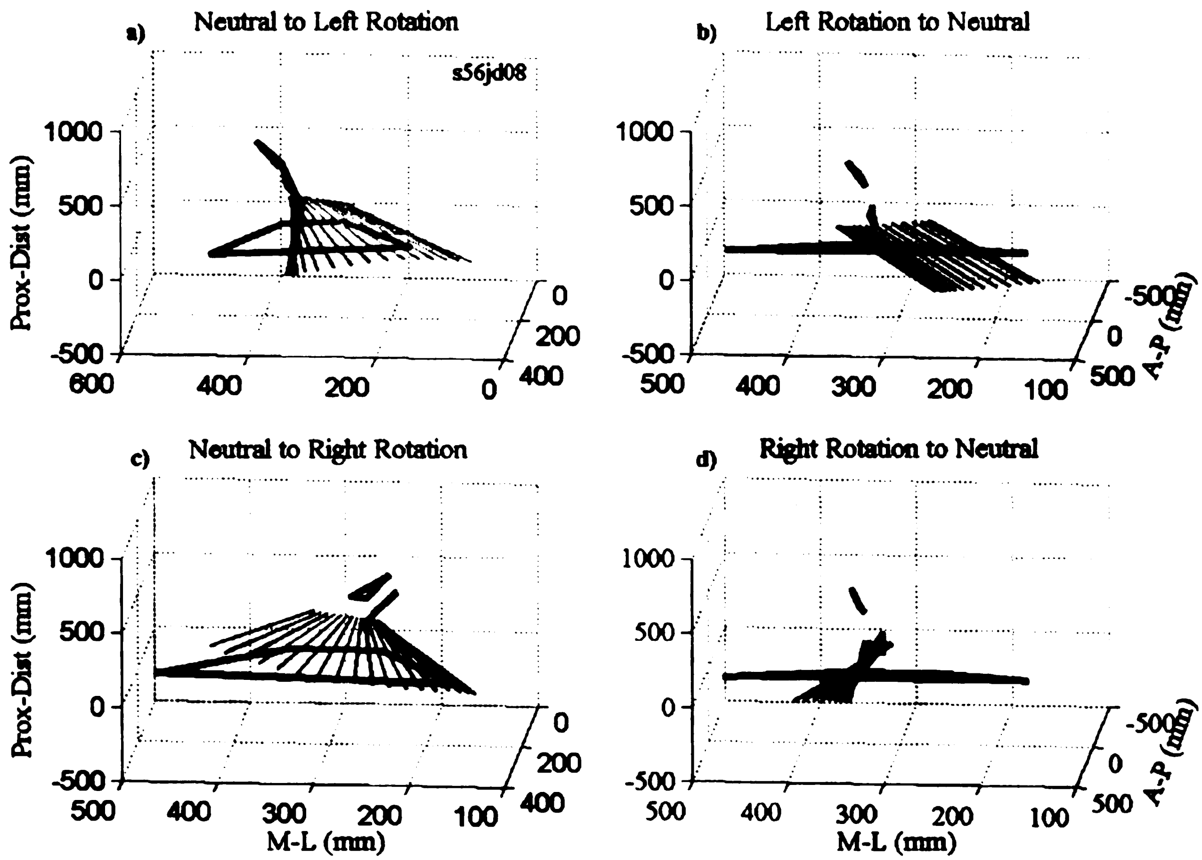

Figure K20. Frontal view of IHAs for sitting slouch axial rotation. Blue denotes the beginning of the motion and green the end of the motion.

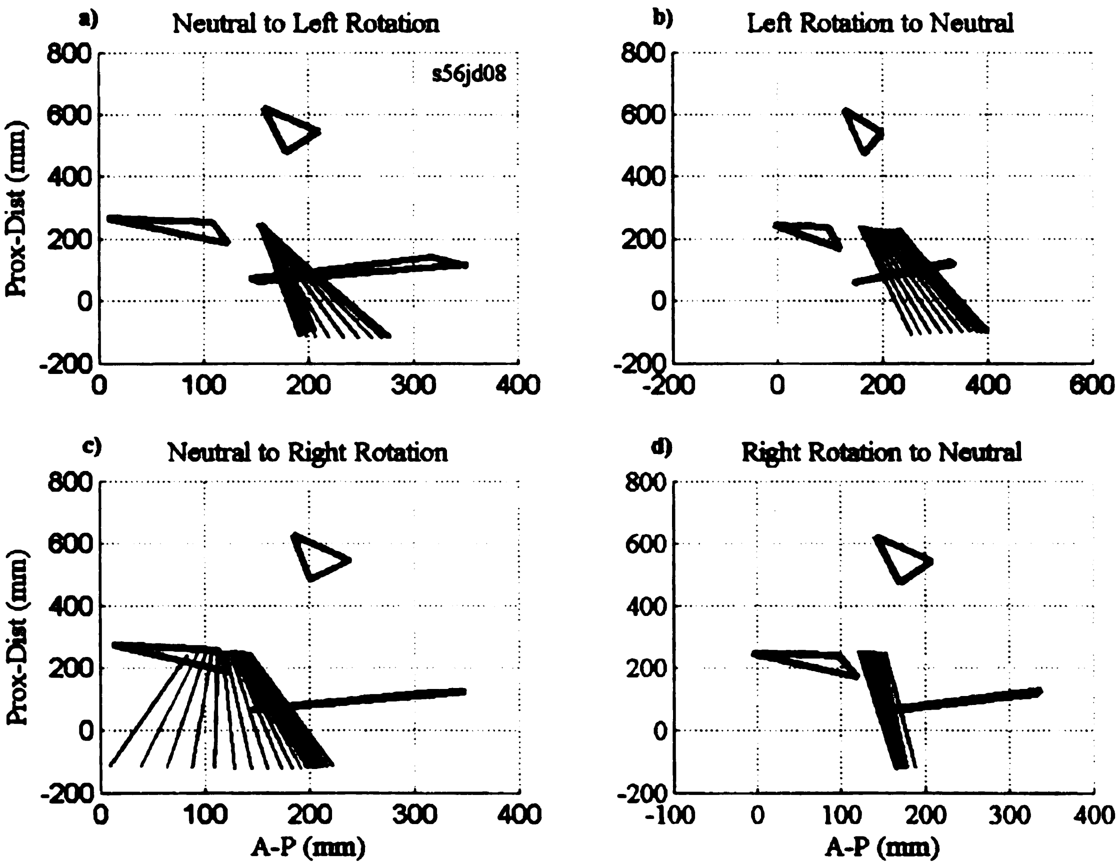

Figure K21. Sagittal view of IHAs for sitting slouch axial rotation. Blue denotes the beginning of the motion and green the end of the motion.

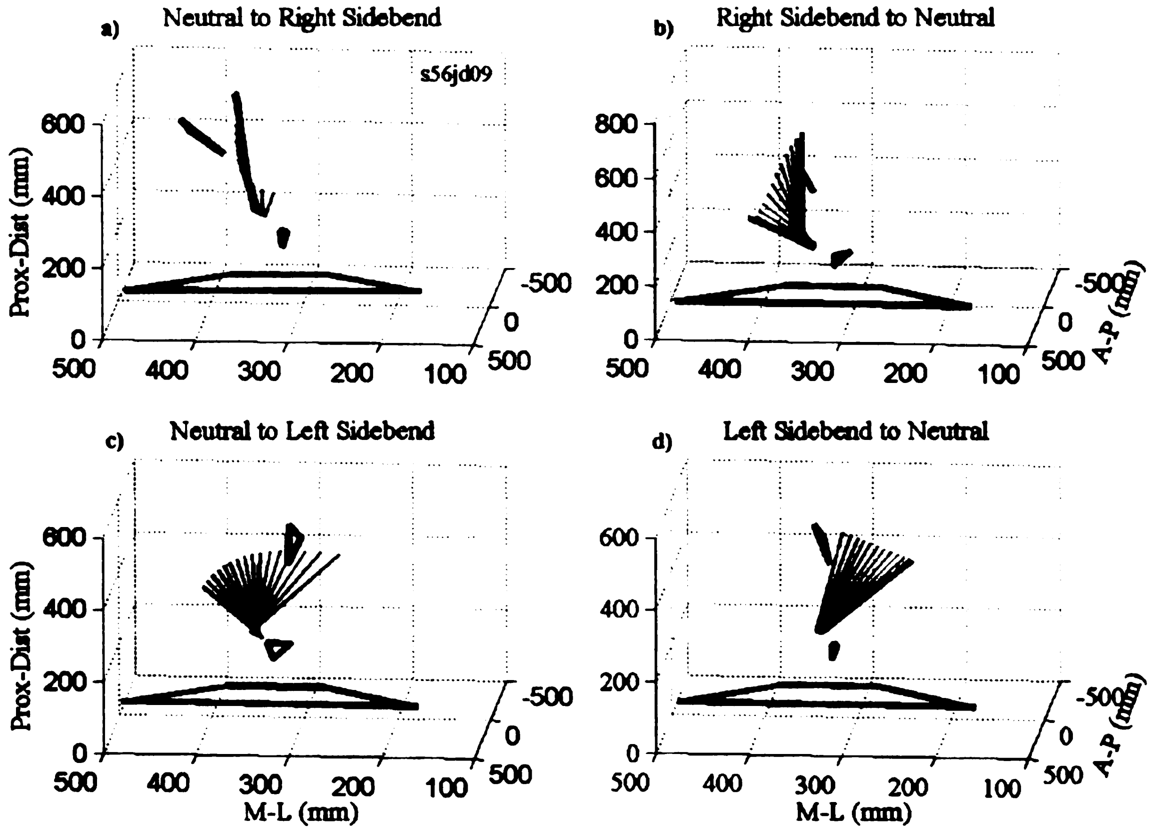

Figure K22. Frontal view of IHAs for sitting erect sidebending. Blue denotes the beginning of the motion and green the end of the motion.

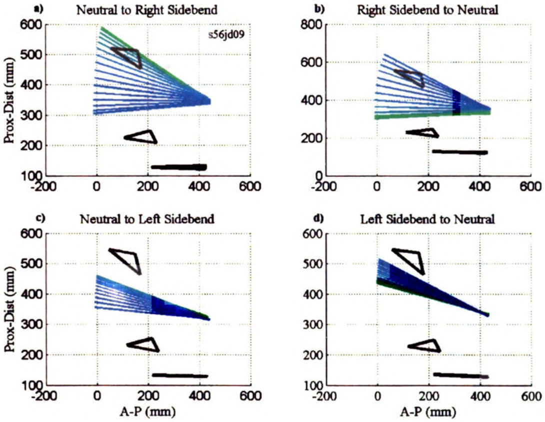

Figure K23. Sagittal view of IHAs for sitting erect sidebending. Blue denotes the beginning of the motion and green the end of the motion.

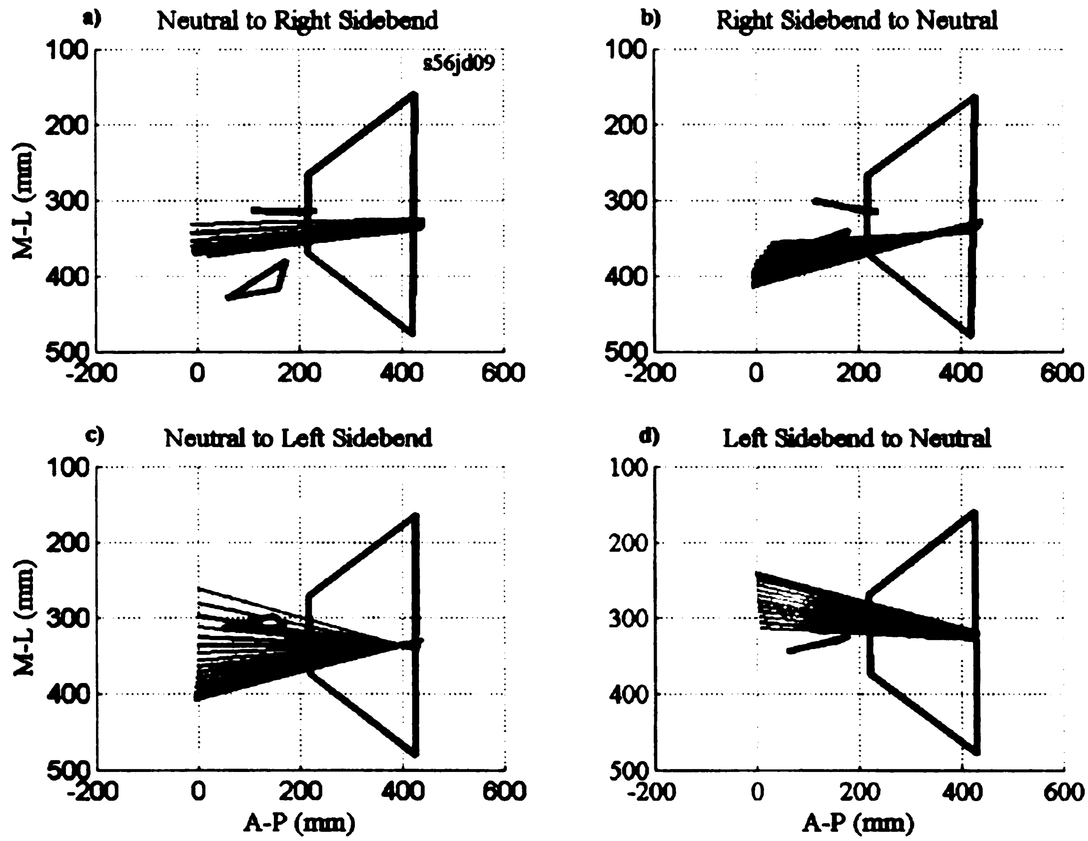

Figure K24. Transverse (top) view of IHAs for sitting erect sidebending. Blue denotes the beginning of the motion and green the end of the motion.

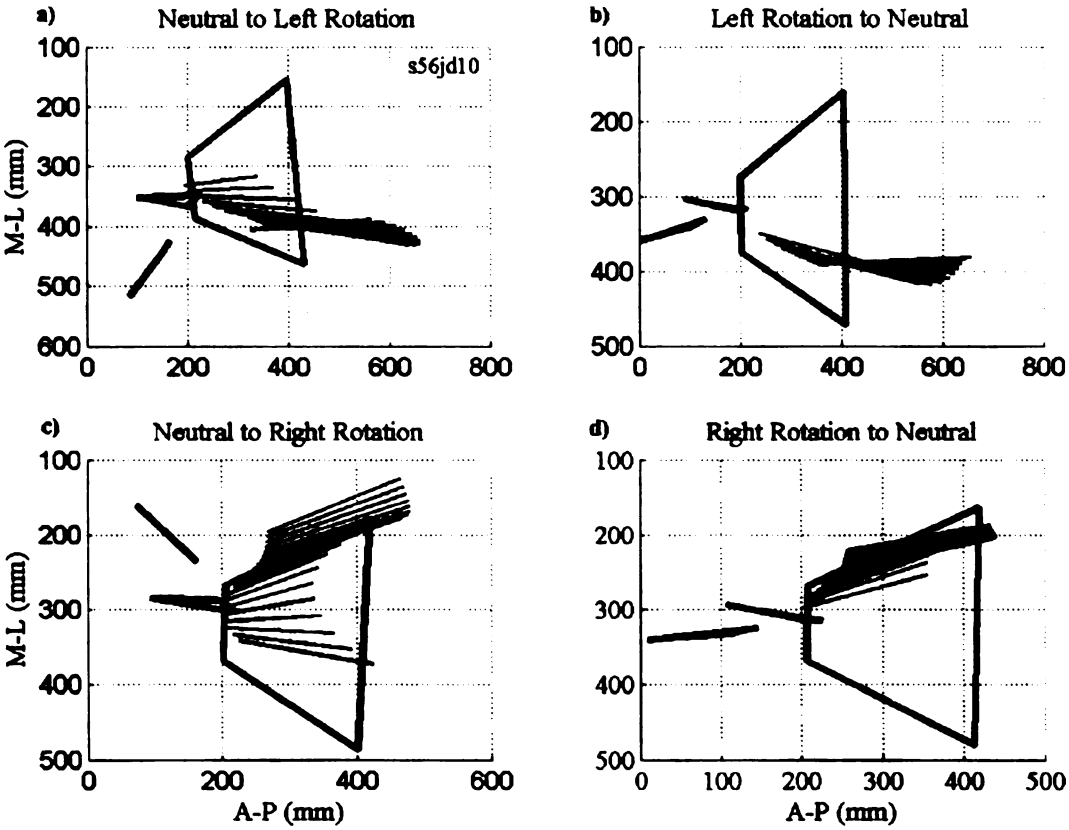

Figure K25. Transverse (top) view of IHAs for sitting erect axial rotation. Blue denotes the beginning of the motion and green the end of the motion.

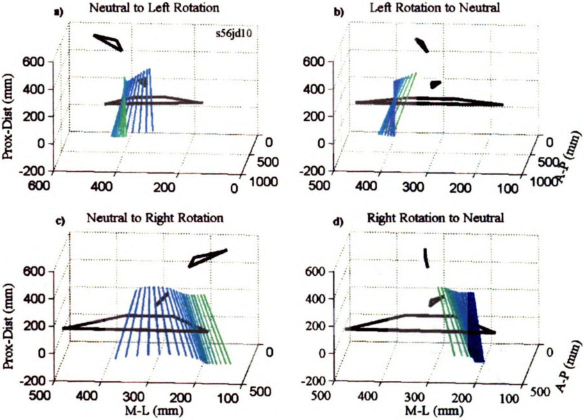

Figure K26. Frontal view of IHAs for sitting erect axial rotation. Blue denotes the beginning of the motion and green the end of the motion.

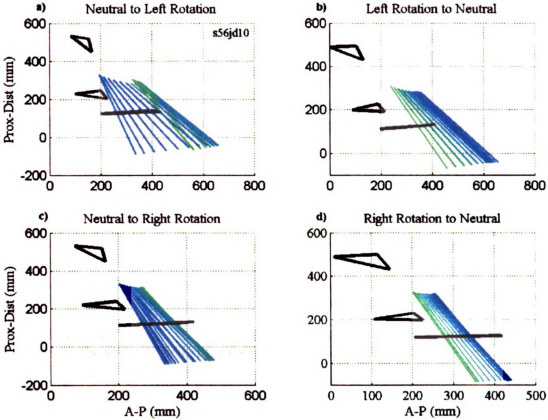

Figure K27. Sagittal view of IHAs for sitting erect axial rotation. Blue denotes the beginning of the motion and green the end of the motion

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