Biomechanical Assessment of Adolescent Idiopathic Scoliosis Deformity and Treatment

By

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Submitted to the graduate degree program in Bioengineering and the Graduate Faculty of the University of Kansas in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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Date approved: February 18th, 2016

Abstract

Each of the four studies presented focus on the biomechanics of scoliosis deformity or treatment and products and devices which model or treat this condition. The main purpose of the four studies was to: characterize the trunk motion for the non-pathologic adolescent population, evaluate the trunk motion for the adolescent idiopathic scoliosis population, define the contribution of the scoliotic deformity to spinal motion changes, and biomechanically assess a scoliosis correction construct in a cadaver model. The first study determined there were no significant age related effects in spinal mobility and the only gender differences were located in the upper lumbar and torso region. The second study identified conflicting relationships between chronologic age and skeletal maturity and spinal mobility. Correlations of curve severity and spinal mobility varied depending on the spinal region and motion task. The third study determined scoliosis subjects have greater mobility in many spinal segments compared to their non-pathologic counterparts, especially in periapical regions. The fourth study identified very few significant biomechanical differences between an intact thoracic spine and rib cage and the same specimen with scoliosis correction instrumentation implanted. The results of these studies provide additional information regarding spine biomechanics in three models: *in vivo* non-pathologic adolescent thoracic and upper lumbar spine, *in vivo* scoliotic adolescent thoracic and upper lumbar spine, and adult cadaveric thoracic spine with and without an implanted rod construct.

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Chapter 1 Introduction

The motivation of this work comes from the current status of adolescent idiopathic scoliosis (AIS) treatment. Treatments for the AIS spinal deformity were developed without complete characterization of the adolescent spine and assumed adolescent and adult spines were biomechanically equivalent. While the spine biomechanics of the adult spine are well characterized, little research has explored the characterization of adolescent spine biomechanics.

The long term objective of this research was to construct and validate a physical analogue spine model that could represent and replicate the spinal form and function of a patient with AIS. This model could be used for medical education and medical device development and testing. Developing and validating a biomechanically and anatomically accurate spine model is a challenging undertaking, which must be completed in stages. First, biomechanical targets must be developed. These targets can come from previous *in vitro* or *in vivo* research or from new research conducted for this specific project and pertain to the mobility and stiffness of motion units, segments, or regions of the spine. Second, materials and manufacturing methods must be developed to create the analogue model. Third, the model must be validated with through mechanical testing to ensure a match to the biomechanical targets established previously.

For models that replicate a disease state, additional steps are required to understand the differences between the normal and abnormal state, both anatomically and biomechanically. Instead of collecting or referencing data to establish one set of biomechanical targets, two set of biomechanical targets are needed: one for the normal adolescent spine and one for the scoliotic adolescent spine. The majority of the biomechanical and kinematics information of the spine comes from cadaveric investigation. Due to practical and ethical concerns, adolescent cadavers

are very rare. Therefore, little information regarding adolescent spine biomechanics and kinematics exists. Studies of *in vivo* adolescent spinal kinematics are also lacking. This made it necessary to collect *in vivo* data specifically for the purpose of determining mobility targets for adolescents both with and without scoliosis.

This dissertation is presented in partial fulfillment of the requirements for the degree of Doctor of Philosophy completed in the Biomedical Product Design and Development track of the Bioengineering Program. As such, diverse experiences in biomechanical testing and medical device development and evaluation are preferred. Each of the four studies presented below focus on the biomechanics of scoliosis deformity or treatment and products and devices which model or treat this condition.

The first study characterized the trunk motion for the non-pathologic adolescent population. Thoracic and thoracolumbar mobility was determined using range of motion measures in seven anatomic regions during sagittal and coronal plane tasks. It was hypothesized that there would be gender based differences in mobility, relationship between mobility and age, and motion symmetry. Chapter 4 addresses the first study.

The second study characterized the trunk motion for the AIS population. Normalized thoracic and thoracolumbar mobility was determined for six anatomic regions during sagittal and coronal plane bending tasks. Mobility measures were correlated with predictors of mobility changes including curve severity, chronological age, and skeletal maturity. It was hypothesized that there would be no correlation with mobility age or maturity and a negative correlation between curve severity and mobility. Chapter 5 addresses the second study.

The third study defined the contribution of the deformity to motion changes. For both the non-pathologic group and AIS group, normalized thoracic and thoracolumbar mobility was determined for six anatomic regions during sagittal and coronal plane bending tasks. Using age and gender matched groups, mobility comparisons were made in the six anatomic regions. It was expected that the AIS group would present with limited mobility compared to the non-pathologic group for all regions and modes of bending. Chapter 6 addresses the third study.

The fourth study biomechanically assessed a scoliosis correction construct in a cadaver model. Using a mechanical test system designed to accommodate the thoracic spine and rib cage, motion, stiffness, and intradiscal pressure were measured for the intact thoracic spine and the spine post-implantation of the scoliosis correction system. Kinematic differences between the intact and construct cases were assessed above and within the construct region to better understand the biomechanics of surgical treatment. It was expected that the construct would reduce motion and increase stiffness of the spine. Chapter 7 addresses the fourth study.

In summary, a paucity of biomechanical and kinematic data is available related to the spinal biomechanics of scoliosis. This research sought to (1) develop a set of kinematic targets through *in vivo* characterization of a non-pathologic adolescent population for use as spine model inputs, (2) develop a set of kinematic targets through *in vivo* characterization of an AIS population presenting with right thoracic curves for use as spine model inputs, (3) determine mobility differences caused by the scoliotic deformity as evident from the non-pathologic and AIS *in vivo* populations, and (4) assess the biomechanics of treatment through *in vitro* analysis of a growth-friendly scoliosis correction construct. The results of these studies provide additional information regarding spine biomechanics in three models: *in vivo* non-pathologic adolescent

thoracic and upper lumbar spine, *in vivo* scoliotic adolescent thoracic and upper lumbar spine, and adult cadaveric thoracic spine with and without an implanted rod construct.

Chapter 2 Background and Significance

This work will discuss the biomechanics of the spine and trunk; therefore, it is imperative to begin by describing the nomenclature and anatomy that will be used throughout. The body is divided into three anatomic planes: sagittal, coronal, and axial, as shown in Figure 1. In terms of the spine and trunk motion, flexion and extension occur in the sagittal plane. Left and right lateral bending takes place in the coronal plane. Bilateral axial rotation takes place in the axial plane. These movements are shown in Figure 2. Superior or cephalad will be used to describe areas above or closer to the head whereas inferior or caudal will describe areas below or towards the tail. Posterior or dorsal describes areas towards the back and anterior or ventral describes areas towards the front. These are also shown in Figure 3.
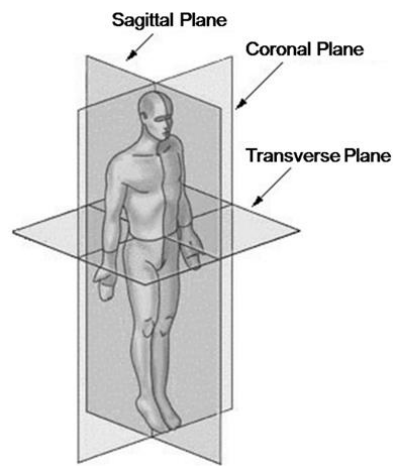
Figure   1: Anatomic Planes

FLEXION	EXTENSION	RIGHT TORSION	LEFT TORSION	RIGHT BENDING	LEFT BENDING
SAGITTAL PLANE		AXIAL PLANE		CORONAL PLANE	
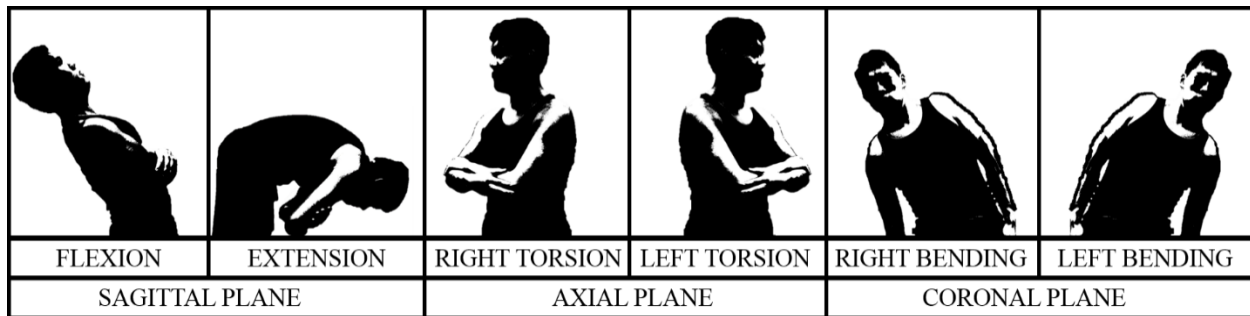
Figure   2: Primary Movements of the Spine
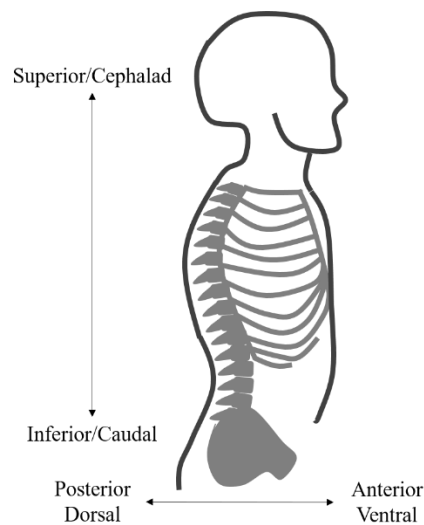
Figure   3: Anatomic Directions as Related to the Spine

Typical Spinal Anatomy

The spine is divided into three grand regions: cervical, thoracic and lumbar. The bones of the spine are called vertebrae. There are seven vertebrae in the cervical spine; twelve vertebrae in the thoracic spine; and five vertebrae in the lumbar spine. The combination of body weight and muscle forces the

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spine supports increases moving inferiorly. The vertebral size increases in inferior regions to help support

the increasing load. The full spine is shown in Figure 4.
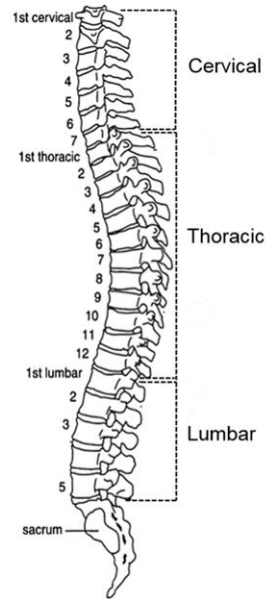
Figure   4: Full Spine with Three Regions

Cervical spine

The cervical spine provides the main structural support of the neck and bears the weight of the

head. The atlas and axis are special vertebrae that cradle the skull and are primarily responsible for axial

rotation. The rest of the cervical vertebrae, C3-C7, are similar to one another in both anatomy and

biomechanics, though they do increase in size moving inferiorly. The cervical region has a natural

lordotic curvature in the sagittal plane, which develops during infancy once a child can hold up their head.

The seventh vertebra is also known as the vertebra prominens, as it is the most posteriorly prominent

vertebra, and marks the end of the cervical region.

Thoracic Spine

The thoracic spine and accompanying rib cage provides thoracic stability and protection for vital

organs. This region has a naturally kyphotic curve present at birth. Though similar to cervical vertebrae,

thoracic vertebrae are larger and have a costovertebral joint where the rib head attaches to the spine. The thoracic spine moves fairly equally in all modes of bending; however, in lower levels (T10-L1) there is a marked increase in sagittal and coronal plane motion and a decrease in axial plane motion.[1] The thoracic region is thought to be more stiff than the cervical or lumbar spine due to the presence of the rib cage. While each thoracic vertebra has a rib attachment, the T11 and T12 ribs do not have any connection to the sternum, denoting them as floating ribs. These joints are sometimes considered to function similar to the lumbar spine because of their lack of sternal connection.

Lumbar Spine

The lumbar spine is the support structure for the lower back and carries load approximately equal to three times body weight. The lumbar region has a natural lordotic curvature which develops once an infant begins to walk. This allows for sagittal balance of the spine. Compared to the thoracic spine, the lumbar vertebrae are larger with a more lateral orientation of the transverse processes. The lumbar spine is primarily responsible for flexion and extension in the spine.[1] Inferior to the lumbar spine are the sacrum and coccyx, known as the tail bone. These begin as separate bones but fuse to create one rigid structure. When sacral vertebrae fail to fuse, it is known as lumbarization of the sacrum.

Functional Spinal Units

The main motion segment of the spine is known as the functional spinal unit or FSU. An FSU is composed of two adjacent vertebrae, the intervertebral disc, and the multiple adjoining ligaments. The two main areas of motion are at the intervertebral disc and at the facet joints, or diarthrodial joints. The orientation of the facet joints can vary based upon the region of the spine, which contributes to mobility differences between spinal regions. A schematic of an FSU is shown in Figure 5.
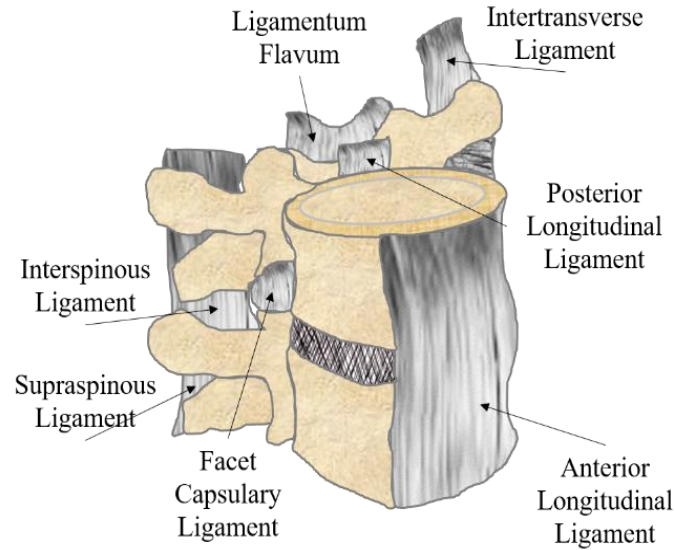
Figure 5: Functional Spine Unit (FSU)

Typical Spinal Mobility

Flexibility measures and the factors that affect them are a common concern in literature.[1,2] Some studies seek to establish normative mobility values *in vivo*. Some of these studies examine the overall trunk or spine range of motion of a given population while some examine at the movement of specific spine segments, such as the lumbar spine.[2–6] Other studies seek to understand the range of motion at each FSU.[1,3,7] Regardless of the method of reporting normative values, most asymptomatic populations are merely studied as a control group for a comparative pathologic group, predominantly low back pain sufferers, to determine the pathology's effect on spinal flexibility.[5,6,8,9] Many studies segment their data by age or gender to determine the effect age and gender play in spinal flexibility measures.[2,4,8] These studies provide a fairly complete picture of spinal flexibility in the normal adult spine. While the cervical spine is an important and well researched region of the spine, the following subsections will only highlight the current findings of spinal flexibility and range of motion research for the lumbar and thoracic spine.

Thoracic Mechanics

Considering the three regions that comprise the spine, the thoracic spine has been the least studied. It has long since been assumed that the thoracic spine, due to the attachment of the rib cage, acted as a rigid unit, with no nuanced flexibility throughout. This notion discouraged investigation into the characterization of thoracic flexibility in smaller regions or units rather than as a whole.

There are very few *in vivo* studies that attempt to characterize thoracic mobility in part or all together. There are more extensive *in vitro* studies in thoracic region; however, the standard test methods in the field preclude the possibility of biomechanically assessing the thoracic spine with an intact rib cage. As a major stabilizing structure of the thorax, the rib cage must be included in biomechanical analysis for accurate characterization to take place. A few studies have since adapted standard testing methods to allow for the inclusion of the intact rib cage and have found the presence of the rib cage had a significant effect on the mobility and stiffness of the thoracic spine.[10,11] Prior to these advances, Panjabi and White laid the ground work for thoracic spine biomechanics and have written extensively on the subject.[1]

The flexibility of the thoracic spine changes depending on the level's location within the spine with mobility increasing cephalocaudally. In the upper thoracic spine, each level provides about 4° in flexion/extension, 6° in lateral bending, and 8°-9° in axial rotation. In the middle thoracic region, each level provides about 6° in flexion/extension, 8°-9° in lateral bending, and 8°-9° in axial rotation. In the lower thoracic spine, including the levels of the floating ribs, each level contributes about 12° in flexion/extension, 8°-9° in lateral bending, and 2° in axial rotation.

Few studies have sought to define typical thoracic flexibilities. One study investigated normal thoracic extension in young adults. In males, they found typical thoracic motion (T1-T12) to be 11.3°, typical upper (T1-T8) thoracic motion to be 9.9°, and typical lower (T8-T12) thoracic motion to be 6.6°. Similarly, in females they found typical thoracic motion to be 7.7°, typical upper thoracic motion to be 6.2°, and typical lower thoracic motion to be 3.9°.[12] Axial rotation was the focus of another *in vivo* study where an average of 6° of motion per thoracic level was found.[13] A third study looked at both flexion and lateral bending across normal and obese groups of young females. The normal group had overall thoracic (T1-L1) motion of 45.0° in flexion and 59.9° in lateral bending; whereas the obese group had an overall thoracic motion of 36.4° in flexion and 48.6° in lateral bending.[14] The most comprehensive research on thoracic flexibility was done by Willems. In it, average range of motion for upper (T1-T4), mid (T4-T8), and lower (T8-T12) thoracic regions are presented for males and females in flexion/extension, bilateral bending, and bilateral axial rotation. These findings are summarized in Table #. [15]

As thoracic spine flexibility is not often investigated, thoracic motion symmetry is research is rare. However, by looking at values presented for each direction of bending, symmetries can be extrapolated. In lateral bending, range of motion values were highly symmetric, often within 0.5° of each other. Axial rotation was less symmetric, with left and right ranges staying within approximately 3° of each other. However, the range of thoracic rotation is much larger than lateral bending and the differences in symmetries are proportionally higher in lateral bending than in axial rotation.[15]

Table 1: Adult Thoracic Mobility

The asterisk denotes a significant difference between genders (p < 0.005)

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)
Right Bending	6.2 (2.7)	6.2 (2.1)	7.7 (2.3)	8.5 (2.3)	12.4(2.9)	11.9(2.3)
Left Bending	5.6 (2.5)	6.1 (2.9)	8.1 (2.5)	7.9 (2.1)	13.2(2.4)	12.0(2.3)
Right Torsion	15.9 (4.9)	14.4 (4.6)	25.3 (6.7)	24.3 (6.1)	8.3(6.1)	7.9(5.5)
Left Torsion	12.1 (5.1)	11.8 (4.4)	22.1 (6.3)	21.5 (4.6)	11.8(4.9)	8.3(4.2)*

Lumbar Mechanics

The literature focuses primarily on the lumbar section of the spine, as it is more prone to injury and pathologies. Lumbar range of motion has been measured both *in vivo* and *in vitro* studies successfully in the normal adult spine. The standard in this field comes from the *in vitro* work of Panjabi and White; however, technology advances have made *in vivo* research more practical and reliable in recent years. Research investigating single level motion is primarily *in vitro* biomechanical or *in vivo* radiographic, as typical *in vivo* biomechanical studies lack sufficient detail to characterize motion at a single level, though there is crossover in research methodology.

Looking at single level flexibility both *in vivo* and *in vitro*, typical spinal flexibilities have been defined. On average, each motion segment in the adult lumbar spine produces about 15° of flexion, between 5° and 10° of lateral bending, and less than five degrees of rotation.[1,16] A radiographic *in vivo* study looking to the flexibility of individual lumbar units found slightly different results, with 10-20° of flexion and a trend of increased per unit motion moving cepholocaudlly.[17] Due to the variability of motion outcomes between subjects, it is difficult to establish characteristic behavior at each level for each motion. Furthermore, none of these studies break down the results by age and gender, further hindering motion characterization by functional spine unit.

Other studies have determined range of motion values for the full lumbar spine rather than looking at the flexibility of a single lumbar motion unit.[4–6,18] Those values are shown in Table 2. Only two of these studies looked at lumbar motion in all three planes and provide sufficient detail for complete trunk motion characterization.[2,18] These *in vivo* studies agree fairly well on flexion and extension range of lumbar motion; however, they lack agreement on range of motion for lateral bending and torsion.[2,4–6,18] Several of these studies cover a wide range of ages or group genders despite evidence that both age and gender influence lumbar mobility.[2,4,8,19]

Table 2. Lumbar Mobility Values in Adults

All mobility values are presented as averages or ranges, measured in degrees except where noted. Standard deviations are given in parenthesis where available. The asterisk indicates the values were a measure of trunk mobility, not lumbar mobility, and they were measured in mm, not degrees. These studies either included both genders (B) or focused on male participants (M). The dash indicates where the values was not calculated by the given study.

Author	N	Sex	Age	FLEXION/EXTENSION			LATERAL BENDING			AXIAL ROTATION		
				Flex	Ext	Both	Left	Right	Both	Left	Right	Both
Ng	35	M	30 (7)	52 (9)	19 (9)	71 (12)	30 (6)	31 (6)	60 (11)	33 (9)	32 (9)	65 (17)
Alaranta	34	B	35-54	44	18	-	-	-	113*	-	-	103*
Mayer	13	B	31	55 (9)	27 (13)	82 (18)	-	-	-	-	-	-
Esola	21	B	28 (5)	40 (14)	-	-	-	-	-	-	-	-
Troke	405	B	16-90	40-72	6-29	-	16-29	15-28	-	7	7	-
Van Herp	100	B	20-60+	51-59	15-37	-	15-26	15-26	-	11-19	13-19	-
Pearcy and Tibrewal	31	M	21-37	-	-	-	18	17	35	5	4	8
Burton	294	B	16-84	24 (9)	39 (10)	63 (14)	-	-	-	-	-	-

No significant difference was found in lateral bending and axial rotation for each side, meaning no significant asymmetry in the lumbar spine for lateral bending or axial rotation.[3] Referring to the table of normative lumbar range of motion values above (Table 2), there is fairly consistent symmetry in both lateral bending and rotation.[3,4,18]

Factors Affecting Spinal Flexibility

Several researchers have tried to quantify the gender and age related effects on spinal mobility so that lumbar motion could be more fully characterized. One study found that thoracolumbar range of motion was decreased for females compared to males for flexion and extension but not for lateral bending.[19] Other studies have shown that differences between men and women for lumbar range of motion are age dependent.[2,8] Regardless of gender, range of motion is also found to be age dependent with the maximum range of motion occurring between the ages of 15 and 34 and decreasing after.[19] The percent reduction in spinal mobility due to age is varied across motion type but is most evident in extension.[2,19]

The Typical Adolescent Spine

The spine is an important structure to the musculoskeletal system. It changes throughout the course of development and aging processes. To fully characterize spine biomechanics, the spine must be assessed in multiples stages of life. While there are very few changes during adulthood, aging brings about degeneration of tissues and structures of the spine. However, the most drastic changes to the spine occur during development. These changes occur over the course of many years, from infancy to adolescence. The focus of this work is adolescent spinal biomechanics therefore it is important to understanding the underlying characteristics of the typical adolescent spine. While pubertal timing can vary up to four years, females normally

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begin puberty at 9-10 years while males begin at 10-11 years.[20,21] For this work, adolescent will

be defined as ages 9-18 though other works cited here may not adhere to this chronological

range. The following sections will detail research focused on physical changes of the spine, rib

cage, and surrounding tissues and the effect on spinal biomechanics.

Curvatures

Although lordotic and kyphotic curves are established in earlier years, both lordotic and

kyphotic curves evolve throughout development (Figure 6). Average kyphotic curves for

adolescents are about 35° with a range of 11-72[22–25] Many characteristics can effect these

kyphotic curvature values including age[23,24,26], gender[22,23,25], and handedness.[27] After skeletal

maturity is reached, thoracic curvature continues to increase linearly for both males and females,

but begins to significantly differ across genders after age forty.[26] Average lordotic curves for

adolescents are about 30° with a range of 26° -77° found in literature.[22–25] In the adolescent

populations reviewed (ages 8-17), significant age effects were not found but significant gender

differences were evident in some studies.[23,25] Willner and Johnson found that kyphosis and

lordosis significantly correlate in the adolescent population and hypothesized a similar positive

correlation exists between kyphosis and growth velocity.[23]
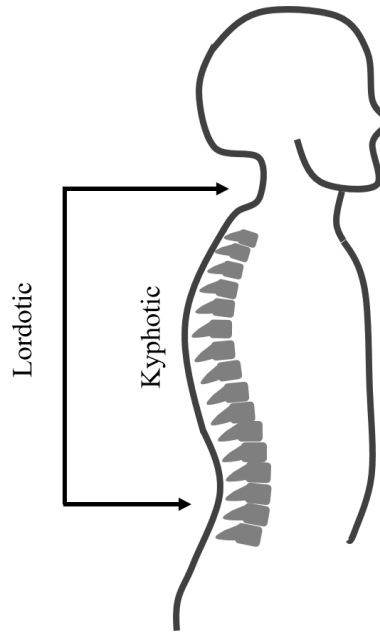
Figure 6: Typical Sagittal Curves of the Spine

Growth of the Spine and Rib Cage

The spine continues to grow throughout development, with rapid changes occurring during infancy and puberty.[28] The largest spinal growth is longitudinal growth but growth occurs in all planes and directions.[29] Average pubertal growth velocity ranges from less than 1cm/year to approximately 10 cm year in girls, peaking around age 12.[21] Average growth velocity in boys ranges from less than 1cm/year to 11cm/year, peaking at approximately 14 years of age.[21] Individual vertebral height increases at approximately 0.8mm/year for thoracic vertebrae and 1.0mm/year for lumbar vertebrae.[30] During the adolescent growth spurt, the spine and trunk grows about 10cm in height.[20] As vertebrae grow, they increase in stiffness by about 33% for lateral bending and extension tasks and about 44% during flexion. Most of this change occurs between the ages of 10-14.[31] Longitudinal growth of the posterior elements stops around 5-8 years while anterior column growth continues, ending around 16-18 years.[32] Many spinal

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deformities are linked with abnormal growth therefore it is important to characterize typical vertebral growth patterns.

The rib cage grows most rapidly before two years of age and the rib angle rotates inferiorly from infancy through adolescence.[33,34] Although rib cage growth ends between 20-30 years, the angle of the ribs continues to evolve throughout adulthood.[34,35] In addition the cage itself growing through adolescence, the cortical area of the rib increases positively with age.[36] As the size and histological makeup of the ribs change during adolescence, the elasticity, specifically Young's modulus significantly increases with age.[37] As the bones of the spine and rib cage continue to grow and remodel, the surrounding soft tissues evolve as well.

Soft Tissues

Although it is well established that children are more flexible than adults, it is important to explore the soft tissue changes that occur throughout development. These soft tissues include tendons, ligaments, muscles, and the intervertebral discs. All of these tissues are composed of elastin and collagen. There is greater ligamentous laxity in children than with adults.[38] This could be because the number of cross links and the cross-sectional area of the collagen fibers is greater at maturity. Ligament properties change with age. For example, the ultimate tensile strength decreases with increasing age. The elastin fibers begin to shrink around Risser grade 1, which initiates a decline in elasticity of tendons and ligaments. This results in decreased flexibility throughout the body but most importantly, throughout the spine. Intervertebral discs increase in height by 0.2-0.6mm/year for thoracic discs and 0.3-0.8mm/year for lumbar discs.[28]

Maturity

The determination of skeletal maturity is made with a combination of factors.[39] Chronologic age is not a good indicator of skeletal maturity, as the skeleton matures in a non-linear fashion and normal puberty timing can vary up to four years.[20] Maturity is actually tied strongly to growth velocity. This adolescent growth spurt lasts about two years before the peak height velocity (PHV) and then continues another 1-2 years after the peak. Measuring the growth or height velocity can indicate the stage of skeletal maturity. Peak height velocity is about 8-10cm/year in females and 9-11 cm/year in males.[20,21] Primarily, Risser sign, a measurement of the iliac growth plate, is used (Figure 7).[20,39] However the Risser grade has its drawbacks. Patients can maintain a Risser grade of zero for a months or years, providing an unclear picture of skeletal maturity development during this time.[20] During this phase, tri-radiate cartilage (TRC) closure monitoring is helpful. The TRC is another area of cartilage that ossifies with skeletal maturity but closes before the iliac ossification begins, marking the beginning of Risser stage 1.[20] Clinicians also use menarche as an important milestone on the skeletal maturity timeline though it alone is not a measure of skeletal development. Menarche nearly always occurs after peak height velocity and can be too variable for accurate skeletal maturity assessment.[20] Each of these maturity markers provides additional information about skeletal maturity and together these factors help physicians to establish the stage of skeletal maturity in their patients.
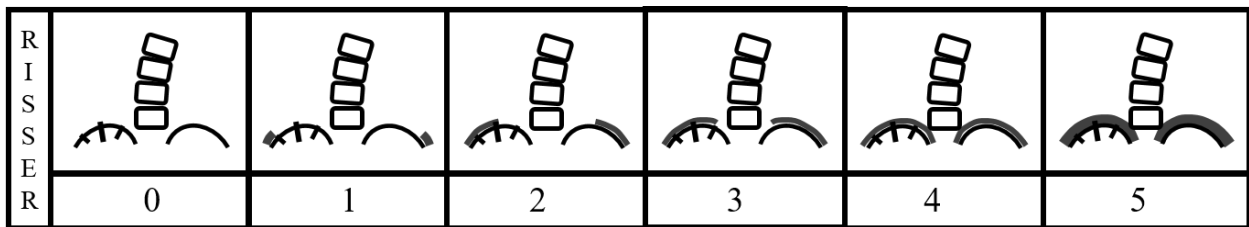
Figure   7: Risser Stages as shown on the Iliac Crest

Mobility

Although most studies focus on the mechanics of the adult spine, some studies do focus on adolescent and pediatric spine mechanics. Age-related and gender-related lumbar mobility changes were the major focus of these studies. One research group, encompassing multiple studies, does measure thoracic mobility. Evaluating both lumbar and thoracic mechanics provide a complete picture of adolescent spinal mobility. Some of the following studies investigated the lumbar or thoracolumbar mobility [40,41], others investigated thoracic and lumbar mobility[22,42–44], and others investigated different measures of flexibility in the lumbar, thoracolumbar, and full spine[19,45–49].

Lumbar and Thoracolumbar Mobility

Kondratek: This study investigated the lumbar mobility of five to eleven-year-old children in flexion, extension, bilateral bending, and bilateral torsion. This covers both pediatric and adolescent spine mobility. Significant age related differences for every motion type exist.[40] Often there were significant range of motion changes between the five and eleven and five and nine year old groups.[40] Females tended to show more age related changes than males.[40] Mobility data is presented in Table 3.

Smidt: This study investigates the change in thoracolumbar postures and range of motion during standing and seated positions in adolescents with idiopathic scoliosis (13-17) and typical young adults (22-33). In this study thoracolumbar postures were found to change depending on the type of positioning.[41] All postures were found to be well within the thoracolumbar range of motion of the participants.[41] Mobility values, presented in degrees, can be found in Table 3.

Thoracic and Lumbar Mobility

Mellin and Poussa: These encompass three studies conducted on the mobility of the adolescent spine. The first study investigated the thoracic and lumbar mobility during flexion, extension, bilateral bending, and bilateral torsion in 13 and 14 year olds. Sagittal curvature and mobility as well as lateral bending mobility was reduced in females compared to males.[42] Females had a negative correlation between flexion left axial rotation and growth velocity.[42]

The second study investigated thoracic and lumbar flexibility during flexion, extension, bilateral bending, and bilateral torsion in an adolescent population compared to a population with adolescent idiopathic scoliosis. Both groups averaged about 14 years, with all participants well within the adolescent range. In this study, left and right axial rotation were found to be asymmetric.[43]

The third study investigated thoracic and lumbar flexibility during flexion, extension, bilateral bending, and bilateral torsion in an adolescent population spanning eight to sixteen years. This study primarily covers adolescent spinal mobility. A trend was found of reduced flexion and torsion mobility around age twelve that returned to previous levels by age sixteen.[22] This decrease in mobility is thought to coincide with the thoracic growth spurt.[22] The mobility values from these three studies can be found in Table 3.

Viola and Andrassy: This study investigates the longitudinal effect of thoracic and lumbar mobility during flexion, extension, lateral bending, and axial rotation with measures taken at five, ten, and fourteen years of age. No gender or symmetry differences were found but mobility was found to increase with age in this population.[44] Average mobility values can be found in Table 3.

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Table 3. Mobility of the Thoracic, Thoracolumbar, and Lumbar Spine in the Adolescent
All mobility values are presented as averages or ranges in degrees. Standard deviations are included in parentheses where available. Where sided bending or rotation was not available, combined bending or rotation is presented.

Author	Gender	Region	Flexion	Extension	Left Bending	Right Bending	Left Rotation	Right Rotation
Smidt	Female	Thoracolumbar	22 (6.2)	42 (6.0)	21.0 (6.3)	18.0 (4.1)	-	-
Viola and Andrassy	Both	Full Spine						
Kondratek	Males	Lumbar	22.8 (1.5)	15.1 (1.6)	20.2 (2.1)	20.6 (2.4)	18.5 (3.1)	18.1 (2.9)
	Females	Lumbar	22.7 (2.4)	15.7 (1.1)	19.3 (5.0)	19.6 (4.2)	18.0 (4.2)	18.3 (4.9)
Mellin and Poussa	Males	Thoracic	66.7 – 70.3	-4.0 – 9.5	74.6 – 82.6		34.5 – 45.6	
	Females	Thoracic	62.2 – 67.7	0.5 – 13.0	65.8 – 81.8		31.8 – 47.1	
	Males	Lumbar	27.2 – 29.6	42.4 – 46.8	34.8 – 45.4		63.4 – 74.0	
	Females	Lumbar	26.3 – 28.8	43.9 – 50.5	40.8 – 48.6		67.3 – 76.9	
Mellin	Males	Thoracic	69.2 (8.2)	-2.6 (14.2)	37.2 (5.7)	35.5 (5.7)	15.3 (8.3)	17.5 (6.6)
	Females	Thoracic	62.0 (9.1)	-3.3 (14.1)	34.1 (7.3)	32.2 (7.0)	13.7 (7.0)	17.5 (6.4)
	Males	Lumbar	27.0 (7.2)	43..2 (8.7)	18.7 (4.6)	19.8 (5.7)	37.4 (6.7)	36.5 (6.7)
	Females	Lumbar	25.7 (5.0)	45.6 (8.9)	20.6 (6.4)	21.8 (5.5)	37.2 (5.3)	36.9 (5.6)

Spinal Flexibility

Haley: This study investigated lumbar mobility in flexion and bilateral bending of five to nine year olds. This primarily evaluates pediatric spinal mobility. Females tended to have significantly higher mobility in both flexion and lateral bending compared to their male counterparts.[45] No linear trend with regard to age-related mobility changes were found.[45] Mobility values, measured in centimeters, are found in Table 4.

Moran: This study investigated lumbar mobility in flexion and bilateral bending in ten to fifteen year olds. Flexion mobility was found to decrease with increasing age while lateral bending mobility was found to increase with increasing age.[46] Gender differences were also found in this study, citing increased flexion mobility and decreased lateral bending mobility for males compared to females.[46] Flexibility values are presented in Table 4.

Mattson: This study investigated the joint flexibilities of adolescents age 10-16 years with and without scoliosis. Spine flexibilities were measured as ratios between the upright C7-S1 distance to the fully flexed or bent C7-S1 distance.[47] The scoliosis group was found to be equally flexible or less flexible than the typical adolescent group.[47] These values are presented in Table 4.

Moll and Wright: This study investigated the thoracolumbar flexibility during flexion, extension, and bilateral bending in men and women from age 20-75+. Mobility values of the young adult group, age 15-24 are presented in Table #. While effect of age within the young adult group was not investigated, age and mobility had a negative correlation for the group as a whole.[19] Gender differences were also found with females having greater lateral bending mobility and males having greater sagittal mobility.[19] Values are in Table 4.

Netzer and Payne: This study investigated mobility of the cervical spine and back during axial rotation and lateral bending in children through older adults. While age differences were found, there were no gender differences. Specifically, the adolescent group (12-15 years) had a decreased mobility in all modes of bending compared to the two age adjacent groups: children (6-8 years) and young adults (20-30 years).[48] Normalized mobility values are shown in Table 4.

Veldhuizen and Scholten: This study investigated the idea that the spine can be modeled as a column and, based on this model, bending stiffness can be calculated for 10-16-year-old participants both with and without scoliosis. Joint flexibilities of seven anatomic locations including the spine during flexion and lateral bending were also measured.[49] Joint flexibilities did not correlate among anatomic areas.[49] Bending stiffness values for the spine were calculated.[49] Spine flexibility, measured in percent flexibility, are located in Table 4.

While these studies provide information regarding adolescent and pediatric spine mobility, they do not agree on age and gender related effects on spinal mobility. Of these six mobility studies, only three mention thoracic measures. In these three studies, the thoracic spine is assumed to act as a rigid unit, with no sublevel detail provided. This is often the case for the lumbar mobility presented as well. To truly characterize adolescent spinal mobility, sufficient scope and detail are required which are lacking in the current literature.

Table 4. Flexibility of the Thoracolumbar and Lumbar Spine in the Adolescent

The values for spinal flexibility, as measured in percent or in centimeters, are presented here for healthy adolescents. Standard deviations are listed in parentheses. Dashes indicate where the study did not calculate a particular parameter.

Authors	Gender	Region	Flexion	Extension	Left Bending	Right Bending	Left Rotation	Right Rotation
Mattson	Female	Full Spine	20.6 (4.0) %	-	27.6 (6.4) %	27.6 (6.2) %	-	-
Moll and Wright	Male	Thoracolumbar	7.23 (0.92) cm	4.21 (1.64) cm	5.06 (1.40) cm	5.43 (1.30) cm	-	-
	Female	Thoracolumbar	6.66 (1.03) cm	4.34 (1.52) cm	7.02 (1.66) cm	6.86 (1.46) cm	-	-
Netzer and Payne	Both	Full spine	-	-	12.7			9.7
Veldhuizen and Scholten	Female	Full Spine	24.4 (3.9) %	-	31.4 (6.3) %	31.4 (6.4) %	-	-
Haley	Male	Thoracolumbar	6.6 (0.3) cm	-	4.2 (0.4) cm	4.2 (0.4) cm	-	-
	Female	Thoracolumbar	6.8 (0.3) cm	-	4.7 (0.5) cm	4.7 (0.5) cm	-	-
Moran	Male	Thoracolumbar	6.9 (0.4) cm	-	6.5 (0.6) cm		-	-
	Female	Thoracolumbar	6.4 (0.5) cm	-	6.8 (0.9) cm		-	-

Adolescent Idiopathic Scoliosis

While the characteristics described here are typical for adolescents they can vary widely, especially if an adolescent has a complicating disease or deformity. One of the most common adolescent spine disorders is adolescent idiopathic scoliosis (AIS). This can cause minor or sometimes drastic deviations in anatomy and biomechanics of the spine compared to typical adolescent populations. The objective of this work in part is to characterize the biomechanical differences caused by the scoliotic deformity in AIS patients. To fully characterize the biomechanical changes caused by AIS, first the known differences must be explored.

Scoliosis is a three-dimensional spinal deformity including lateral curvature and axial rotation.[50,51] Patients often present with uneven shoulder, waist or hip height and a prominent rib hump, especially during forward bending.[39,52] Scoliosis is confirmed with a standing coronal x-ray, yielding a Cobb angle of at least 10º (Figure 8).[50,51] Only approximately 1-3% of the population has scoliosis as it is clinically defined.[50–54] Large curves are rarer, with less than 1% having curves 20º or more, 0.1% of the population having curves greater than 40º.[51,54,55] Approximately 0.23% of the population will require treatment and 0.1% will require surgery.[51,55]
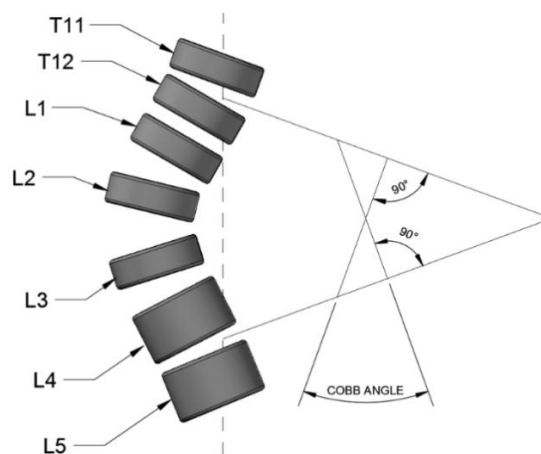
Figure   8: Cobb Angle Measurement

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Adolescent idiopathic scoliosis is specific type of scoliosis with an unknown cause that develops during adolescence. Age of onset for AIS is usually defined as between 10 and 18 years of age, though the end points are somewhat debated. A diagnosis of idiopathic scoliosis is one of exclusion; this diagnosis can only be made after all of the other causes, neuromuscular or congenital, have been eliminated.[39,50,52] Of the numerous scoliosis patients, 80% of them are classified to have adolescent idiopathic scoliosis (AIS).[51] Adolescent idiopathic scoliosis is the most prevalent presentation of scoliosis, with approximately 600,000 cases requiring treatment annually. Many clinicians and researchers believe the high prevalence of AIS is due to the increased growth velocity during pubescence exaggerating or causing abnormal growth. Higher prevalence also occurs in females, with the disparity more apparent in larger curves, on average females present with scoliosis seven times more often than males.[39,51]

Etiology

A large portion of AIS research is dedicated to determining the etiology of this condition, as many researchers believe that finding the cause of AIS will unlock the cure for AIS.[50] Although there is a fairly large consensus that the etiology of idiopathic scoliosis is multifactorial in nature, a broad range of topics are currently investigated as possible causes. Many researchers are looking into any possible genetic, biochemical, or biomechanical cause of AIS.[39,50,51,53,56]

Genetic research has found evidence showing an increased incidence rate among families.[50,56] However, no single gene has been linked to scoliosis.[57] Additionally the mode of inheritance remains inconclusive.[58] Despite the lack of specific genetic source or mode of inheritance, heredity remains the most widely accepted etiological theory regarding AIS.[59]

Biochemical research has hypothesized a correlation between AIS and calcium, alkaline phosphatase, and other bone-associated biochemicals, growth hormones including growth factors and estrogen, trace elements like copper and Selenium, and even melatonin deficiency.[53,56,58]

Other researchers look to a biomechanical cause. Proposed growth and biomechanical related theories include relative anterior spinal over-growth, biomechanical growth modulation, uncoupled neuro-osseous growth, dorsal shear forces, axial rotation instability, and postural abnormalities.[39,56]

Despite continued debate whether growth or biomechanics play a role in AIS onset, a large consensus agrees they play a role in curve progression.[20,39,56] Those with AIS have been found to be taller post menarche, grow more during adolescent growth spurt, and grow faster during puberty than other adolescents.[56] Although the cause of AIS is still debated and researched, its natural history is well defined.

Natural History

Without treatment, severe scoliosis can be detrimental both physically and psychologically.[39] Early studies indicated that scoliosis caused debilitating back pain and cardiopulmonary compromise and can affect activities of daily living.[39,50] More recent findings conclude that those with early onset scoliosis (EOS) have a high risk for cardiopulmonary complications, whereas patients who present with AIS rarely see severe complications.[50] Despite age of onset, even small curves seem to produce negative pulmonary effect, albeit minor.[51]

The prevalence of back pain in scoliosis patients is still somewhat debated.[50] Some studies indicate that prevalence of back pain is equivalent to that of their peers while others indicate a higher prevalence of chronic back pain in scoliosis populations.[50] While pain severity

does not appear to correlate to curve magnitude, curve pattern indicates correlation with pain.[51] Pain can indicate an underlying or additional abnormality, usually involving the spinal cord.

Whether or not function is compromised by scoliosis, there are physical changes that most often appear as an asymmetric trunk, including uneven shoulders, uneven waist narrowing, uneven hip height, and prominent rib hump.[39,52] This physical deformity, so closely related to the patient's body image, can oftentimes lead to psychological implications.

Mild to moderate psychological concerns tend to become more frequent in severe scoliosis cases. Due to the prominent deformity, self-image was found to be significantly worse for scoliosis patients than that of controls.[51] Studies again, are inconclusive on the correlation of more severe psychological concerns. Reports range from finding no mental health problems in the present population to finding real psychological disturbances in scoliosis populations.[50,51] Many studies have also addressed the quality of life of scoliosis patients. Here again results vary.[50]

The natural history of early onset scoliosis is different than that of adolescent idiopathic scoliosis. Children with EOS have many important stages of growth to pass through while bearing this deformity or while the deformity progresses. Many younger EOS patients have also developed thoracic insufficiency syndrome (TIS), which is characterized by a small lung volume but also by an inability for the rib cage to expand the lung with respiration.[60] This syndrome is life threatening as the deformity that causes the breathing deficit will remain or progress further without intervention. Even with intervention, pulmonary function may permanently be damaged because of the presence of the deformity during key stages of growth.[60–62] Without intervention, curves greater than about 20°, will likely progress into a profound deformity.[62] In short, children

with untreated EOS have a significantly increased mortality rate, with contributions from both pulmonary and cardiac disorders.[63,64]

Classification

Currently, the most accepted classification system for scoliosis is known as the Lenke classification system. This is a relatively recent change from the King classification system used since 1983.[65] Lenke's system, proposed in 2001, more fully describes the deformity and has a higher inter- and intra-observer reliability than the King classification.[65] Using Lenke's system, curves are classified according to location, size, and flexibility and incorporate coronal curves and sagittal balance across the full spine. This level of detail allows for accurate prediction of surgical approach by viewing the curvature as a three dimensional deformity.[39] Because of the nature of the Lenke classification, it is not assigned until side bending radiographs are performed, usually just prior to surgical correction. If a scoliosis patient will undergo more conservative treatment, curves are generally classified only by the posterior-anterior radiographs taken at each follow up visit. The four classifications are single thoracic curve, single lumbar curve, single thoracolumbar curve, and double curve. These classifications are based of the apex location of the primary curve. The apex is the vertebra that is furthest out laterally from the midline of the spine. Primary curve refers to the scoliotic curve with the largest Cobb angle. This curve is always structural. While they do not provide the same level of curvature detail as the Lenke classification system, they are sufficient for conservative treatment uses.

Curve Progression

Likelihood of curve progression is an area of great concern. Skeletal maturity is an important indicator of curve progression, as most curves do not progress after skeletal maturity is

reached.[20] Growth velocity, remaining spinal growth, size of curve, and apex location are considered risk factors for continued curve progression.[50,51] Premenarchal females with 20-30º curves as well as those with curves greater than 50º at maturity are likely to progress.[51] In general, larger curves will develop, regardless of location. However single thoracic curves were found to be most likely to develop.[51] With curve progression comes the possibility for further complications or reduced effectiveness of more aggressive treatment options.

Treatment

Ideally treatment, whether surgical or non-surgical in nature should prevent the negative outcomes associated with the deformity without introducing complications.[50] Traditionally, mild curves (<25º) are monitored, moderate curves (25º-45º) are treated conservatively through bracing and physical therapy, and severe curves (>45º) are treated with surgical correction and spinal fusion.[39,50–52] However, if the AIS patients are not yet skeletally mature, they may be treated with growing or growth-friendly surgical interventions.

Physical Therapy

Although studies have shown that AIS causes asymmetric paraspinal muscles and decreased rotation strength, physical therapy and physiotherapeutic scoliosis specific exercises are not widely prescribed as treatments for AIS in the US.[66,67] However, physical therapy remains the standard of care for small, non-progressing curves in Europe.[50] Physical therapy is especially preferred in France, Germany, and Spain.[50] Many physicians do not recommend physical therapy and exercises because of the lack of evidence supporting the value of these treatments for AIS.[67] Physical therapy is also used in moderate curves to augment the use of a

brace and in such treatments, 54% had improved curvatures.[50,68] Targeted physical therapy for scoliosis patients focuses on improving spinal proprioception and motion control.[50]

Bracing

The goal of bracing is to arrest curve progression through applying external corrective forces to the trunk.[39] This is especially important for younger patients with large amounts of skeletal growth left. Braces are traditionally indicated for skeletally immature patients with moderate curves of 25°-45°.[39,69] Other criteria include Risser grade between 0 and II, less than one year post-menarche, and age of at least ten years.[69]

Although bracing has been used for hundreds of years, the long term benefit of bracing is still debated amongst researchers and clinicians.[51,54] Ideally, brace usage would prevent the need for surgery and restore appropriate sagittal and coronal contour.[39] Although the end goal is to reduce the frequency of surgery, limited curve progression is commonly used metric to determine bracing success. Using this criteria, studies have shown a small but beneficial effect due to bracing.[51] Some studies also report decreased frequency of surgery as well.[51] More recent bracing studies have found positive results of bracing in AIS. Studies showed success rates of 72%-75% with only approximately 12% progressing past set magnitude failure criteria.[69,70] A significant dose response was also found between hours of brace wear and rate of treatment success.[70]

With little proven benefit for the use of bracing, the negative effects of bracing must be examined. Most often, patients report psychosocial effects of wearing the brace. This reduces the compliance of these patients. Other negative effects of brace usage include pain, skin irritation, lung and kidney dysfunction, and nerve irritation.[39] Additionally, brace wear can increase the

stiffness of the spine, thereby increasing the difficulty of surgical correction if it becomes necessary.[39]

Surgical Correction

In the past when curves progressed so that bracing no longer provided any meaningful improvement, there were no further treatment options. Luckily developments in modern medicine provide a surgical treatment option for those severe curves. Major advances in the treatment of scoliosis were made by Drs. Harrington and Moe while treating a mass influx of polio patients who developed scoliosis, many of them adolescents.[51,71] Dr. Harrington developed many designs for surgical spinal instrumentation and consistently achieved 55% correction in his patients. These initial designs were made to correct the spine without arthrodesis; however other researchers proved that arthrodesis greatly improved the outcomes of the scoliosis patients and prevented loss of correction post-operatively.[71] Continued developments, beginning in 1984, produced a three-planar and three-dimensional surgical correction method which is still currently used.[72]

Of these major research areas, the most prolific area of research is on surgical correction methods. The primary objectives of surgical correction are to arrest progression, achieve maximum permanent correction of the three-dimensional deformity, improve appearance through trunk balance and stability, preserve the maximum motion segment, and keep complications to a minimum.[39,50,71] Additional goals of surgery are to preserve as many motion segments as possible and to restore pulmonary function.[39] Three types of treatment outcomes are traditionally reported: radiographic, clinical, and self-reported.[50] Many of these indicators look only to restore the characteristics of natural spine posture without understanding the characteristics of natural spine mobility.

A popular topic currently is the outcomes of growing and growth friendly constructs. As adolescent idiopathic scoliosis as well as early onset scoliosis. There are three main kinds of growth and growth friendly systems: distraction, compression, and guided growth.[73] The distraction systems act as internal brace, applying vertical forces to the ends of the deformity to encourage straightening and continued growth.[73] The compression systems, like vertebral staples and tethers, act to arrest growth at the apex of the convex side of the deformity.[73] The growth guided systems non-rigidly affix apical vertebrae to a rod to allow for vertical expansion while minimizing the deformity.[73] There is no clear superior growth friendly construct option and different constructs excel based on the situation. Modifications on these designs and new perspectives into growth-friendly treatment continue to be explored.

Mobility

As normative adolescent spinal mobility was discussed previously, little detailed information exists regarding thoracic and lumbar mobility in the adolescent. Even less information is available about the spinal mobility in an AIS population. Several studies mentioned earlier in the section on adolescent spine mobility compared typical adolescent mobility and AIS mobility.[41,43,44,47,49] Many others only investigate mobility in an AIS population.[74–78]

Comparative Mobility

Veldhuizen and Scholten: This study investigated flexibility and bending stiffness of a typical and AIS adolescents. The flexibilities and stiffness values of the AIS population were found to be equal to that of the typical population.[49] Values for flexibilities of the AIS participants can be found in Table 5.

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Poussa: This study investigated the thoracic and lumbar mobility in typical and AIS adolescent populations. Thoracic mobility was found to be greater during extension but lesser during flexion compared to typical mobility measures.[43] The lumbar mobility during extension was lower in the AIS group than the control group.[43] Mobility values for the AIS group can be found in Table 5.

Mattson: This study investigated joint flexibilities of adolescents with and without scoliosis. The control group was found to have greater or equal flexibility compared to the AIS group.[47] Spinal flexibility values can be found in Table 5.

Smidt: This study investigated the thoracolumbar mobility of both typical and AIS participants during sitting and standing tasks. The thoracolumbar mobility of the AIS group was found to be approximately equal to that of the control group in all modes of bending.[41] The mobility values for the AIS group can be found in Table 5.

Viola and Andrassy: This longitudinal study investigated the changes in thoracic and lumbar mobility over time in typical and AIS populations. Axial rotation mobility at age fourteen was found to be greater in the AIS group compared to the typical adolescents.[44] Kyphosis was also greater in the AIS group.[44] While mobility behaviors are discussed, mobility values were not presented and are not included in the mobility table.

Table 5. Comparative Control and Adolescent Idiopathic Scoliosis Spinal Mobility Values
Average mobility values are presented with standard deviations in parentheses. Most mobility values are presented in degrees but some are presented in percent, as shown. Dashed are used where no data is available.

Author	Region	Group	Flexion	Extension	Left Bending	Right Bending	Left Rotation	Right Rotation
Smidt	Thoracolumbar	Control	22 (6.2)	42 (6.0)	21.0 (6.3)	18.0 (4.1)	-	-
		Scoliosis	22 (4.6)	43 (10.8)	20 (5.2)	19 (4.4)	-	-
Poussa	Thoracic	Control	62.0 (9.1)	-3.3 (14.1)	34.1 (7.3)	32.2 (7.0)	13.7 (7.0)	17.5 (6.4)
		Scoliosis	53.9 (11.1)	15.9 (15.3)	34.2 (7.5)	32.6 (8.4)	13.7 (7.7)	13.7 (8.8)
	Lumbar	Control	25.7 (5.0)	45.6 (8.9)	20.6 (6.4)	21.8 (5.5)	37.2 (5.3)	36.9 (5.6)
		Scoliosis	26.2 (9.6)	37.4 (11.5)	21.1 (5.3)	23.0 (6.8)	38.9 (10.4)	36.5 (9.7)
Mattson	Full Spine	Control	20.6 (4.0) %	-	27.6 (6.4) %	27.6 (6.2) %	-	-
		Scoliosis	18.9 (3.9) %	-	25.6 (4.7) %	25.3 (4.4) %	-	-
Veldhuizen and Scholten	Full Spine	Control	24.4 (3.9) %	-	31.4 (6.3) %	31.4 (6.4) %	-	-
		Scoliosis	21.1 (4.3) %	-	27.9 (4.6) %	27.6 (4.3) %	-	-

Scoliosis Only Mobility

Engsberg: These two studies investigated the spinal mobility and gait changes pre- and post-operatively in an AIS population (10-18 years).[74,75] The lateral bending of the full spine was asymmetric whereas the axial rotation was symmetric.[74,75] The left axial rotation mobility was not equal for participants set to undergo anterior fusion versus posterior fusion.[74] The mobility values are found in Table 6.

Poussa and Mellin: This study investigated the thoracic and lumbar mobility differences in three stages of curve magnitudes in AIS participants (12-16 years). Thoracic mobility during flexion and right lateral bending was smaller for the group with the largest curve magnitude.[76] During bilateral axial rotation, thoracic mobility decreased with increasing Cobb angle.[76] Lumbar mobility during left lateral bending decreased with increasing Cobb angle.[76] Overall mobility decreased with increasing curve magnitude.[76] Mobility values can be found in Table 6.

Rahmatalla: This study investigated the use of a three dimensional electrogoniometer for measuring full spinal mobility in an AIS population (12-20 years). Using this method, good repeatability between trials was achievable. Large amounts of axial coupling and smaller amounts of sagittal coupling were seen during lateral bending. The mobility values calculated can be found in Table 6.

Hresko: This study investigated the use of three different measurement methods to obtain lumbar flexion mobility values and also correlated lumbar mobility in all planes to curve flexibility values calculated from radiographs in a group of female AIS participants (age 11-19). The three measures of flexion mobility did not produce a significant correlation.[78] The well accepted correlation of decreasing mobility with increasing Cobb angle was not supported by

this study.[78] No mobility measures from the three dimensional electrogoniometer taken in all six modes of bending strongly correlated with curve flexibility measures, though flexion did have a mild correlation.[78] The mobility values for this study can be found in Table 6.

Researchers have established some basic trends seen with mobility in an AIS population: mobility tends to decrease with increasing Cobb angle, mobility can vary with the scoliosis presentation, mobility tends to be less symmetric than in a typical population. While scoliosis is known to be a highly variable deformity of the thoracic and lumbar spine, little attention is given to thoracic mobility or controlling by curve type. Spinal mobility of an AIS population needs to be fully investigated so that surgical and non-surgical treatments alike can benefit from the more complete understanding of AIS.

Table 6. Adolescent Idiopathic Scoliosis Spinal Mobility and Flexibility
Mean range of motion values are presented here with standard deviations in parentheses where available. Dashes represent values that were not available from a given study.

	Group	Region	Flexion	Extension	Left Bending	Right Bending	Left Rotation	Right Rotation
Hresko	Dual Inclinometer	Lumbar	49 (11)	-	-	-	-	-
	3D Goniometer	Lumbar	64 (10)	27 (12)	24 (9)	23 (6)	22 (8)	23 (8)
Engsberg	-	Full Spine	37.9 (9.1)	-	35.4 (5.8)	25.4 (6.2)	47.8 (11.6)	45.3 (14.2)
Engsberg	Anterior	Full Spine	42 (11)	-	30 (8)	24 (8)	49 (7)	42 (14)
	Posterior	Full Spine	37 (7)	-	31 (12)	25 (7)	35 (11)	36 (15)
Rahmatalla	-	Thoracic	28.8	12.1	30.2	28.4	12.0	21.6
	-	Lumbar	31.3	3.12	7.33	10.31	2.0	1.6
Poussa and Mellin	Cobb <25°	Thoracic	58.6 (8.7)	18.2 (14.5)	35.2 (7.9)	33.6 (9.8)	18.3 (5.4)	16.4 (7.0)
	Cobb 25°-35°	Thoracic	59.9 (11.1)	15.9 (15.3)	34.2 (7.5)	32.6 (8.4)	13.7 (7.7)	13.7 (7.7)
	Cobb >35°	Thoracic	50.9 (12.6)	16.5 (19.1)	37.5 (7.8)	25.4 (12.5)	9.4 (7.0)	9.4 (7.0)
	Cobb <25°	Lumbar	27.8 (7.9	39.7 (10.0)	24.1 (6.4)	23.3 (5.5)	37.1 (8.6)	36.8 (8.1)
	Cobb 25°-35°	Lumbar	26.2 (9.6	37.4 (11.5)	21.1 (5.3)	23.0 (6.8)	38.9 (10.4)	36.5 (9.7)
	Cobb >35°	Lumbar	24.6 (7.1	35.1 (12.2)	18.5 (5.4)	23.9 (5.6)	42.9 (9.9)	35.4 (7.3)

Research Gaps

Although developing successful treatments for AIS is the end-goal for researchers and clinicians, developing treatments with a complete understanding of how the deformity affects the spine and trunk biomechanically is preferable. While treatments aim to return the spine to its original form and function, there is no clear target of what normal is. Without a defined target of what a normal adolescent spine looks like and how it performs, there is no way to accurately measure the success of surgical techniques or other treatment methods. Therefore, to isolate and understand the effect of AIS, the limits of motion for the typical adolescent spine must be understood.

While some studies have monitored trunk motion in AIS and TA populations, characterizing the complete motion profile has not been the aim of these studies. Most of the studies only focus on the lumbar spine and view the lumbar spine as a single motion unit and not a compilation of motion segments. This assumption is also made about the thoracic spine; though fewer studies include thoracic mobility at all. The thoracic spine, with the interaction of the rib cage, is more complex than the lumbar spine and the mobility in this region is not well understood from *in vivo* or *in vitro* studies. Detailed mobility information is needed to fully characterize the thoracic and thoracolumbar spine in the typical adolescent spine to develop viable targets for AIS treatment outcomes.

In studies of AIS mobility, similar limitations exist. In these studies, mobility was presented for the entire AIS group and was not controlled for curve type or apex location. The spine behaves differently based on the type and location of deformity; therefore, including multiple curve types masks the effect of the deformity and present the effect of curve type

instead. Most studies present full spine mobility or thoracic and lumbar segments as single units. This fails to recognize the complex changes happening on a smaller scale than the segment or full spine scale. Deformities of the rib cage also effect thoracic mobility therefore special attention should be given to thoracic mobility changes in the AIS population.

Significance

The research previously conducted in these areas investigated lumbar and some thoracic spinal mobility as a comparison to spinal disorders such as AIS to determine possible causes of deformity onset, sources of curve progression, and mobility deviations due to treatment. Adolescent idiopathic scoliosis has a detrimental impact physically and psychologically to those it affects. Although scientists around the globe have been looking for many years, there is no known cause and therefore known no cure.

The best solution for those with severe AIS is surgical intervention. Treatments for skeletally mature AIS patients have not been improved upon in many years. The innovation has stagnated. The current methods are deemed good enough despite inherent correction loss, mobility disparities, and adjacent level degeneration. Treatments could be improved upon if the biomechanical effect of the deformity and surgical correction were better understood, which makes understanding typical spinal biomechanics necessary as well.

While definitive fusion treatments have stagnated treatments for AIS patients who are still able to grow continuously evolve and improve. For the treatments, the biomechanical target of typical adolescent spine biomechanics can aid as a driver for design modifications. Testing methods for these devices could be developed that incorporate the biomechanical differences caused by the deformity and by previous construct designs. From this, better correction outcomes

and fewer complications may result. While this research does not develop or propose these improved treatment methods, understanding the biomechanics of the typical, deformed, and treated adolescent thoracic and lumbar spine is the first step toward such advances and successes.

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Chapter 3 The Age and Gender Effect on Spinal Mobility in Adolescents

This manuscript investigates the typical biomechanics of the non-pathologic adolescent spine

and has been submitted to the *Journal of Applied Biomechanics*.

SN Galvis had primary responsibility of the study design and approval, data collection,

processing, and analysis, and manuscript writing and editing.

The Age and Gender Effect on Spinal Mobility in Adolescents

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Conflict of Interest Disclosure: The authors have no conflict of interest to disclose.

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Running Title: Adolescent Spinal Mobility

Abstract

The effect of gender and age on adolescent spinal mobility is important to investigate in order to characterize normative spine biomechanics. Having established normative adolescent spine biomechanics, deviation from this normal, as caused by such spinal deformities as Adolescent Idiopathic Scoliosis (AIS), can be quantified and used for treatment targets or for means of earlier detection. To characterize adolescent trunk biomechanics, eight electromagnetic sensors were placed along the midline at T1, T3, T6, T10, the sacrum, and the manubrium in thirty-seven adolescents. Range of motion was captured during six full planar and two full off-planar motion tasks for the torso and sub-segments of the thoracic, thoracolumbar, and lumbar spine. No significant differences were found between females and males in thoracic mobility measures. Age was found to be a weak predictor of mobility for both males and females. Lateral bending and axial rotation mobility was found to be symmetric for both genders. From these findings, it appears it may be appropriate to use both male and female adolescents together to characterize thoracic spine mobility.

Word Count: 3,628

Introduction

Adolescent Idiopathic Scoliosis (AIS) is the most common spinal disorder that affects adolescents, causing both lateral and axial deformities of the spine, rib cage, and surrounding tissue.[1–4] However, the effect the structural deformity has on spine mobility is not well characterized. Having a better understanding of extent and nature of this motion abnormality could provide better treatment targets and earlier diagnostic means. Typical trunk biomechanics must be characterized to better understand how AIS affects trunk biomechanics and how this motion deviates from typical trunk biomechanics. Although spine biomechanics have been widely studied and well characterized in adults[5–10], very little effort has focused on the biomechanics of the adolescent spine or on spinal development during adolescence.[11–15] When establishing typical trunk biomechanics, special investigation should be made into the effect of gender and age, as there is a gender disparity in AIS diagnosis[2] and deformities become more severe during pubertal growth spurts.[1,3,16,17]

Some studies have sought to understand the normative kinematics of the adolescent thoracic, thoracolumbar, and lumbar spine.[11–15,18,19] Of these, most focused on the lumbar spine and only one researcher investigated the kinematics of the thoracic spine.[13,14] In that study, the thoracic spine was treated as a rigid structure and detailed kinematics of sub-segmental levels were not performed. As many spinal disorders common in adolescents are not confined to the lumbar spine, it is important to look at both the thoracic and lumbar spine kinematics in detail to develop a complete picture of the spine biomechanics in this population.[14] Special emphasis must be placed on understanding the effect of gender and changes due to spinal maturation, as these both play a role in disease onset and progression, specifically for AIS.

In this study, spinal mobility was measured during all six modes of planar bending and 45˚ anterior-lateral flexion in the thoracic and lumbar spine of adolescents. The purpose of this research was to provide greater understanding of the gender effect and age relationship which exist with spinal mobility and symmetry in the adolescent. It was hypothesized that significant gender differences would be evident in (1) mobility of sub-segments of the thoracic, thoracolumbar, and lumbar spine, (2) relationship of mobility and age, and (3) lateral bending and axial rotation symmetry. From the literature, it was expected that female adolescents have increased mobility in all modes of bending compared to the male adolescents, and that age relationships with mobility show decreased flexion with increasing age. Motion was expected to be symmetric for both genders.

Methods

Thirty-three self-reported healthy adolescents were recruited for this study. Adolescents ranged from age 9-18 to capture the beginning of adolescent growth spurt through skeletal maturity.[17,20,21] The subject population had an average age of 13.8 ± 2.5 years, an average height of 1.60 ± 0.14 m, and an average weight of 52.7 ± 14.6 kg. Two subjects were left handed. The study consisted of twenty-four females (Age = 13.8 ± 2.3 years, Height = 1.51 ± 0.34 m, Weight = 52.3 ± 12.7 kg) and nine males (Age = 13.7 ± 3.0 years, Height = 1.66 ± 0.2 m, Weight = 54.4 ± 12.7 kg). Subjects were excluded if they had any self-reported musculoskeletal deformity, disorders, or a prior history of back pain. This study was approved by the Institutional Research Board at the University of Kansas-Lawrence and written and informed consent and assent was obtained for all subjects. After consent was obtained, participants performed ten repetitions of three symmetric stretching exercises. The participants started with cat/cow exercises to stretch in

the sagittal plane; next were seated twists to stretch in the axial plane; finally, standing side to side bending was used to stretch the coronal plane.

Data Collection

Eight electromagnetic sensors (TrakSTAR, Ascension Technologies Burlington, Vermont) were placed along the midline at the manubrium, T1, T3, T6, T10, L1, L3, and the sacrum (Figure 1). The sensors were placed after warm-up stretches to avoid dislodgement during excessive movement. This electromagnetic motion system, used to measure the position and orientation of the sensors, has an RMS accuracy of 1.4 mm and 0.5 degrees. Kinematic data was collected at 80 Hz and a low pass 4th order Butterworth filter with a 2 Hz cutoff was used to filter the raw position data.
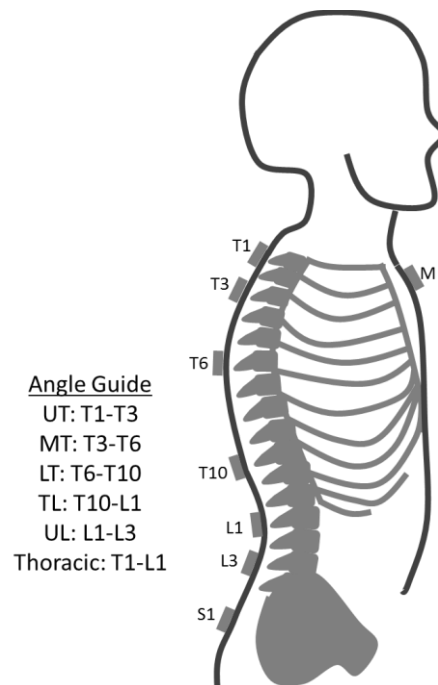
Figure 1. Sensor Placement. Sensors were placed along the midline at the first, third, sixth, and tenth thoracic vertebrae; first and third lumbar vertebrae; sacrum, and manubrium.

Several instructions were given to the subjects to standardize the task procedures. The subjects stood on a platform fitted with a height-adjustable sacrum support. The subjects were instructed to stand in a neutral position, described as having their feet shoulder width apart and parallel to each other, knees straight but not locked, and arms lightly crossed over their chest. After the sensors were placed, subjects were belted into the sacral support to limit sacral motion (Figure 2). Subjects were instructed to remain in the neutral position until the first verbal cue. At that cue, subjects were to begin moving in a prescribed direction, reach maximum voluntary range, and hold that position for approximately five seconds. On a second verbal cue, subjects were to return to neutral standing position. Subjects were instructed to refrain from using the restraint for support during bending tasks.

Figure 2. Experiment Set up and Sacral Restraint. The participants stood on a platform with their backside against a height-adjustable sacral support and were belted in with the accompanying restraint to limit sacral motion. The transmitter was positioned behind the platform.

Subjects were instructed that the goal was to move to their maximal voluntary motion in each of eight full motion tasks. The tasks were flexion (F), extension (E), left lateral bending (LLB), right lateral bending (RLB), left axial rotation (LAR), right axial rotation (RAR), left 45° anterior-lateral flexion (L45), and right 45° anterior-lateral flexion (R45). For LLB and RLB, subjects were instructed to place their hands to their sides and slide their hand along their leg, keeping their shoulders facing forward. For L45 and R45, subjects were instructed to bend toward a mark on the platform, 45˚ off of the sagittal plane. Tasks were demonstrated and the subjects were allowed to practice the motions before data collection began. The order of the tasks was randomized for each subject. Movement to the maximal voluntary range was at a self-selected speed, as to capture the true movement patterns of each subject.

Each task was repeated in five consecutive trials. Trials were excluded where sensors exceeded the collection volume or data recordings were incomplete. For a given motion task, if more than two trials were excluded for analysis, that subject was excluded from analysis for that given task. The last trial of each task was used for analysis to allow for the viscoelastic effect to stabilize during testing.

Data Analysis

From this data, seven spinal motion angles were calculated in the primary plane of motion for each task. Using the position data collected by the electromagnetic system, coordinate systems were established at each sensor by crossing two position vectors. The first position vector was created from the position of the sensor of interest to the position of the sacrum sensor, creating the new z axis, while the second vector was created from the position of the sensor of interest to the position of the manubrium sensor. Crossing these two vectors resulted in the

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formation of the new y axis. By crossing the sacrum vector (z axis) with the new y axis, the x axis was formed, establishing a coordinate system at the sensor of interest.

The rotation matrices were decomposed into Euler angles using the rotation sequence dictated by the motion being performed. The first rotation was about the axis of intended motion, the second rotation was about the axis that has the most coupling with the axis of intended motion, and the third rotation was about the axis with the least coupling with the axis of intended motion. For tasks primarily occurring in the sagittal plane, including flexion, extension, and anterior-lateral flexion, the secondary plane was the coronal plane and the tertiary plane was the transverse plane. Lateral bending tasks primarily occurred in the coronal plane, secondarily in the transverse plane, and thirdly in the sagittal plane. The primary plane for axial rotation was the transverse plane, the secondary plane was the coronal plane, and the third plane was the sagittal plane. Once the coordinate systems were established, the angles were formed by comparing the orientation of the coordinate system of the superior sensor to that of the inferior sensor.

The resulting sub-segmental motion angles were upper thoracic angle (UT) from T1-T3, mid thoracic angle (MT) from T3-T6, lower thoracic angle (LT) from T6-T10, thoracolumbar angle (TL) from T10-L1, upper lumbar angle (UL) from L1-L3, and thoracic curvature angle from T1-L1. Torso angle was calculated by first defining vectors **lu** (lumbar) and **th** (thoracic) and crossing them to create a coordinate system at T10, as described in the previous paragraph (Figure 3). Then the orientation of the T10 coordinate system was compared to the global coordinate system based at the transmitter to create torso angle.[22] Range of motion (ROM) for all motion angles was calculated by subtracting the average angle at the maximum voluntary maximum hold from the average angle at the neutral standing position. Symmetry ratios, derived from the torso ROM for lateral bending and axial rotation, were also calculated. The symmetry

ratios range from entirely left motion (-1) to entirely right motion (1), with zero indicating

perfect symmetry. All of these calculations were completed using customized MATLAB

(MathWorks, Natick, MA, USA) programs.
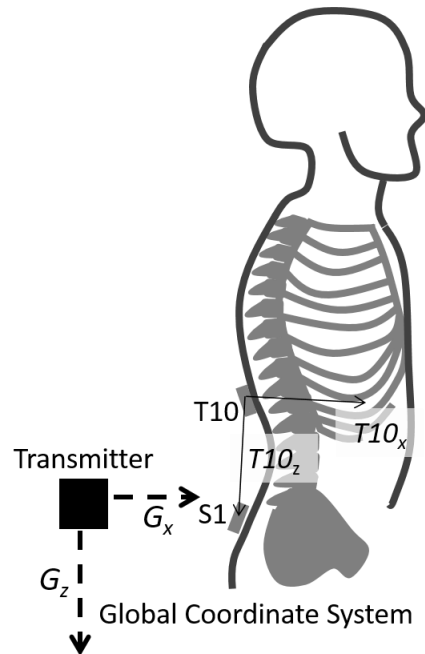
Figure 3. Torso angle calculations. A coordinate system was created at T10, from a lumbar vector (**lu**) from T10 to S1 and a thoracic vector (**th**) from T10 to M. The torso angle is the orientation of the T10 coordinate system relative to the orientation of the global coordinate system centered at the transmitter.

Statistical Analysis

The first hypothesis, which states there is a mobility difference between male and female

adolescents, was tested using unpaired t-tests. For the second hypothesis, the relationship

between age and mobility was analyzed using linear regression analysis. The age-mobility

equation, R^2 value, and p value were calculated. For the last hypothesis, unpaired t-tests were

used to test for a difference in symmetry of motion between genders. Although the use of

statistical corrections remains controversial, none of the analyses are truly independent, therefore

a statistical correction was not used.[23,24] All statistical procedures were performed in MATLAB with a significance level of α=.05.

Results

While most differences in mobility were not significant, torso ROM was significantly higher for females in LLB, RLB, L45, and R45, as was UL ROM during E, LLB, RLB, L45 and R45 (Figure 4). Power calculations of the independent t-test results ranged from 0.025-0.697 for non-significant comparisons and from 0.748-0.980 for significant comparisons. For the non-significant comparisons, only one segment (TL region in RLB) had power greater than 0.515, with most comparisons having power lower than 0.200. Both the male and female groups were normally distributed for height, weight, and age, and there were no significant differences in height, weight, or age between the male and female groups. No significant differences between males and females were seen in UT, MT, LT, or TL or during during F, LAR, or RAR (Table 1). General sub-segmental mobility patterns for adolescents include a cephalocaudal increase in mobility in F, E, LLB, RLB, L45 and R45, though the thoracolumbar mobility did not always follow this pattern. In sagittal plane tasks, including F, E, L45, and R45, the thoracic angle ROM to torso angle ROM mobility ratio was between 29-35%. However, in LLB and RLB the thoracic to torso mobiltiy ratio was nearly twice, at 62%, of the sagittal plane bending modes. The general task-specific adolescent mobility patterns begin with flexion-type tasks having the greatest range of motion. From greatest to least range of torso motion, the tasks are: F; L45 and R45; LAR and RAR; E; and LLB and RLB. Lateral bending and axial rotation mobility was symmetric. These patterns hold true regardless of gender.

Figure 4. Sub-segmental motion angles during Flexion, Extension, Bilateral Bending and Bilateral Anterior-Lateral Flexion. Upper thoracic (UT), mid thoracic (MT), low thoracic (LT), thoracolumbar (TL), upper lumbar (UL), and thoracic sub-segments are presented in sagittal and coronal plane tasks. Ranges of motion are presented as averages of magnitudes. Asterisks denote significant gender differences in mobility.

	F	n	E	n	LLB	n	RLB	n	LAR	n	RAR	n	L45	n	R45	n
Torso ROM (°)	80.6±27.9	17	43.4±17.7	33	27.2±9.2	32	30.3±10.1	32	57.6±15.8	31	56.9±19.4	32	61.7±36.4	23	61.0±41.5	25
Females	87.4±33.7	10	45.6±18.3	24	29.6±8.5*	23	33.2±10.5*	23	60.4±16.5	22	58.6±21.0	23	72.7±35.3*	16	72.6±44.4*	17
Males	70.8±13.2	7	38.8±15.3	9	20.9±7.9	9	23.4±4.2	9	50.6±11.1	9	52.4±14.5	9	36.4±25.9	7	36.5±20.0	8
UT ROM (°)	1.9±1.6		2.5±2.7		1.6±1.1		1.7±1.1		-		-		1.6±1.1		2.3±2.7	
Females	1.5±1.5		2.5±2.2		1.5±1.1		1.6±1.1		-		-		1.5±0.9		2.0±2.9	
Males	2.4±1.6		2.4±4.6		1.8±1.2		2.0±1.3		-		-		1.7±1.6		2.7±2.1	
MT ROM (°)	4.9±1.6		1.9±4.3		4.2±1.1		5.4±1.1		-		-		3.9±1.1		5.1±2.7	
Females	3.9±2.1		2.9±4.6		4.1±1.5		5.3±1.9		-		-		4.1±1.4		5.5±3.4	
Males	6.2±3.6		0.6±2.0		4.5±1.9		5.6±2.8		-		-		3.4±3.3		4.1±4.0	
LT ROM (°)	8.0±4.3		5.3±13.7		6.1±3.0		6.2±3.4		-		-		5.7±4.1		5.8±4.3	
Females	7.0±4.3		7.1±15.6		6.5±3.3		6.5±3.9		-		-		5.3±4.1		6.1±4.8	
Males	9.6±4.0		0.5±4.6		5.1±1.7		5.4±1.7		-		-		6.7±4.3		5.4±3.0	
UTL ROM (°)	14.3±4.2		3.5±6.3		6.7±3.2		5.9±2.6		-		-		9.9±4.5		9.5±4.5	
Females	14.5±4.9		3.9±7.2		6.4±3.1		6.5±2.7		-		-		10.6±4.6		10.1±5.0	
Males	14.1±3.4		2.2±3.2		4.6±1.9		4.5±1.7		-		-		8.5±4.4		8.2±3.0	
LTL ROM (°)	18.0±6.6		7.1±8.5		6.7±3.2		7.6±3.7		-		-		15.5±8.0		13.3±6.5	
Females	18.2±7.8		9.2±8.7*		7.6±3.1*		8.7±3.4*		-		-		18.3±7.8*		15.4±6.4*	
Males	17.8±4.9		1.4±4.6		4.5±2.0		5.0±3.2		-		-		9.0±3.3		8.7±3.9	
Thor ROM(°)	27.7±8.9		12.8±22.1		17.5±6.7		18.9±6.8		-		-		19.5±10.7		21.2±11.4	
Females	26.0±8.8		15.9±24.6		18.3±7.2		19.8±7.5		-		-		19.5±10.4		22.7±12.6	
Males	30.3±9.1		4.3±9.9		15.3±1.7		16.6±1.7		-		-		19.5±4.3		18.2±3.0	

(-) Value not reported

* Denotes statistically significant results (p < .05)

Table 7. Range of motion results for all segments and all bending modes. Range of motion data for each spine motion angle during each bending task are presented for the entire adolescent group, in the shaded rows, as well as gender divided groups. The number of subjects included in each analysis is presented to the right of the torso ROM data in italics. The asterisks indicate statistical difference in mobility between genders. Female adolescents have significantly higher torso ROM than males during left lateral bending (LLB) (p=.014), right lateral bending (RLB) (p=.012), left anterior-lateral flexion (L45) (p=.024), and right anterior-lateral flexion (R45) (p=.040). Significantly higher upper lumbar (UL) ROM was also seen during extension (E) (p=.017), left lateral bending (LLB) (p=.010), right lateral bending (RLB) (p=.010), left anterior-lateral flexion (L45) (p=.007), and right anterior-lateral flexion (R45) (p=.011).

For the gender combined group, there were few significant mobility-age relationships (Table 2). No age relationships were significant in extension, left axial rotation, right axial rotation, or right 45° anterior-lateral flexion. A significant mobility decrease with age was seen in mid thoracic region during L45 ($P = .031$); in the lower thoracic region during LLB ($P = .022$), in the thoracic region during LLB ($P = .034$) and RLB ($P = .040$); in the thoracolumbar region during F ($P = .445$), L45 ($P = .043$), and RLB ($P = .008$); and in the upper lumbar region during F ($P = .003$), L45 ($P = .015$), LLB ($P = .007$), and RLB ($P = .001$). While age did have a significant relationship with mobility for some of the parameters, the coefficient for the age term was small, as shown in the regression coefficients.

Task	Parameter	Mobility-Age-Gender Relationship Equation for Range of Motion	R^2
L45	Mid Thoracic	MT ROM = **-0.05 × Age** − 3.70 × Gender + 0.02 × I_{AG} + 12.51	0.265
LLB	Lower Thoracic	LT ROM = **-0.06 × Age** − 4.51 × Gender + 0.02 × I_{AG} + 15.62	0.253
LLB	Thoracic	Thoracic ROM = **-0.12 × Age** − 4.30 × Gender + 0.01 × I_{AG} + 36.99	0.258
RLB		Thoracic ROM = **-0.11 × Age** − 9.07 × Gender + 0.04 × I_{AG} + 38.29	0.225
F	Upper Thoracolumbar	UTL ROM = **-0.09 × Age** − 11.74 × Gender + 0.06 × I_{AG} + 30.55	0.292
L45		UTL ROM = **-0.09 × Age** + 0.99 × Gender − 0.03 × I_{AG} + 24.54	0.341
RLB		UTL ROM = **-0.05 × Age** − 7.61 × Gender + 0.03 × I_{AG} + 15.37	0.345
F	Lower Thoracolumbar	LTL ROM = **-0.20× Age − 38.63 × Gender + 0.22 × I_{AG}** + 53.12	0.518
L45		LTL ROM = **-0.17 × Age** − 36.41 × Gender + 0.17 × I_{AG} + 45.47	0.493
LLB		LTL ROM = **-0.06 × Age** − 9.55 × Gender + 0.04 × I_{AG} + 17.61	0.397
RLB		LTL ROM = **-0.08 × Age − 15.86 × Gender + 0.08 × I_{AG}** + 22.43	0.463

Table 2. Mobility relationships with age and gender, a linear model. Age (in months), gender (males = 1, females = 0), and the interaction of age and gender (I_{AG}) were used as inputs in the linear regression model for mobility prediction. Bolded entries indicate that input parameter has a significant effect on the mobility outcome. Age consistently showed a negative relationship with mobility, indicating mobility decreased as the age of the subject increased. Significant gender relationships indicate that females had higher mobility than males. The interaction term between age and gender only had a significant effect on mobility when gender also had a significant effect on mobility. This could indicate that the interaction term is heavily driven by the behavior of the gender term.

When considering age and gender as a function of mobility, the relationship between age and mobility changed slightly. Upper lumbar ROM ,which was significant for age alone, also had significant gender specific age relationships with mobility during F and RLB ($P = .020$ and

.049, respectively). In right and left 45˚ anterior-lateral flexion, however, the age effect was masked when the genders were combined. When including gender as a function of mobility, there was a significant age relationship in TL ROM for L45 and R45 (P = .045 and .037, respectively). As upper lumbar ROM in F and RLB had a significant age-mobility relationship regardless of gender, the only significant age and gender mobility relationship differences seen were in upper thoracic ROM in L45 and R45. The power calculations on these regression calculations ranged from .068 - .976 for non-significant analyses and from .680 - .999 for significant analyses.

All subjects presented with symmetric motion. The gender combined group had a symmetry ratio of .06 ± .13 for lateral bending and .00 ± .17 for axial rotation. There was no significant difference in lateral bending or axial rotation symmetry between male and female adolescents. The power for lateral bending symmetry was .095, and for axial rotation symmetry, the power was .053.

Discussion

The purpose of this study was to elucidate differences in spinal motion due to gender and age in a typical adolescent population. It was hypothesized that female adolescents would have increased mobility, earlier age related effects, and decreased symmetry compared to male adolescents. The results presented showed significant gender differences and age relationships in the upper lumbar spine but no significant gender differences in the thoracic spine.

While gender differences have been established in the mature spine [8,25–27], data is sparse and sometimes contradictory for gender differences in the immature spine.[11,13–15] Similar studies of the *in vivo* biomechanics of the immature lumbar spine revealed increased mobility for females compared to males in lateral bending and flexion.[11,13,15] However, not all studies agreed,

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stating males had increased lateral bending lumbar range of motion compared to females.[14] The

dissenting study investigated lumbar mobility at ages near the peak growth age but only account

for chronologic age, not developmental stage. As for thoracic spine kinematics, previous studies

looked at the thoracic spine as a single unit and did not provide details of sub-segmental thoracic

motion. Males were found to have significantly greater thoracic mobility in lateral bending,

flexion, and extension.[13,14] Conversely, the present study found no gender differences in any of

the thoracic mobility parameters during any of the bending tasks. Thoracic spine mobility is

especially important during the adolescent growth spurt as it is near peak height velocity when

females are prone to develop progressive scoliosis. The mechanical behavior of the thoracic

spine differs above and below the apex of kyphosis, making tracking of sub-segmental regions

imperative.

Although the findings of the present study appeared to show a difference in mobility due

to gender in the upper lumbar and torso measures, other factors could influence mobility and be

specific to gender. It has been well established that females reach puberty and peak growth age

approximately two years before males.[17,20] However, the effect of skeletal maturity on mobility

has not yet been determined. It is possible that the 'gender effect' seen in the torso and upper

lumbar angles is an effect of skeletal maturity more so than gender.

As skeletal maturity progresses at different rates across genders, the effect of age on

biomechanical development is also important to explore. Peak growth age occurs at 12 ± 1 year

for females and 14 ± 1 year in males, with anterior spinal column growth stopping around 16-18

years of age.[17,21] The findings of this study showed a trend of decreasing mobility with

increasing age mostly in the lumbar spine, with few significant trends in the thoracic spine.

Similar studies on adolescent lumbar biomechanics found differences between specific age

groups, without consensus as to the age effect in adolescents.[11–13,15,18,19] Two studies found decreasing flexion mobility with age and one found decreasing lateral bending mobility with age but most studies indicate increasing lumbar mobility throughout adolescence.[11–13,15] Other studies cite no age related change during adolescent development after adolescents reach age eleven, approximately.[18,19] In the thoracic spine, an age-mobility relationship was found in one study with extension, lateral bending, and axial rotation mobility decreasing at age twelve and thirteen but returning to previous values by age sixteen.[13] Despite the significant mobility-age relationships in this study, age was a weak predictor of spinal mobility in the adolescent. As the findings of this study suggested, mobility changes have little correlations with changes in chronological age, the question remains as to the relationship between skeletal maturity or growth velocity and spinal mobility.

Sagittal plane postures and movements are most often tied to low back pain and therefore are most often studied, but within the thoracic spine, axial rotation and lateral bending should be further explored. Excluding the atlo-axial joint, the thoracic spine contributes the most to overall axial rotation in the spine.[6,7] However, axial rotation is more difficult to measure than lateral bending and flexion/extension in an *in vivo* model.[37,38] Limited investigation of lumbar axial rotation has been conducted, with only one study indicating significant gender effects exist in the adolescent spine.[13] Although the current study was designed to be the first to investigate axial rotation in the sub-segmental thoracic spine, the Euler method produced significant data variations when applied to the thoracic axial rotation. Therefore, the axial rotation results for the thoracic spine were not presented here; this was a limitation of this study. While few gender or age related changes were identified in the axial rotation of the adolescent lumbar spine, axial

rotation in the thoracic spine could yield additional information about the characterization of the adolescent thoracic spine and should be further investigated.

Potential study limitations of the study population must be considered in *in vivo* studies. The population was self-reportedly non-scoliotic, small, and lop sided in gender. As scoliosis screening was not part of this study, it is possible undiagnosed scoliosis existed in the study population. The sample size of this study was small, limiting the power of the study. While it is possible there were mobility differences across genders in these measures, this study lacked the power necessary to detect these differences. The gender ratios included in the study reflected those found in an adolescent idiopathic scoliosis population but made significant gender differences more difficult to discern. Statistical comparisons used were chosen to allow for different group size, but no specific modifications were made to account for the gender size differences.

Limitations in data collection and analysis also need to be considered. In data collection, data trials were excluded when sensors exceeded the collection volume, which may have eliminated some trials from taller and more flexible participants. Because of the large variation in axial rotation data with use of Euler decomposition, axial rotation data was removed from the study. While the findings presented characterized motion in two planes and an off-planar motion, full characterization would require mobility calculations in axial rotation as well. Based on the calculation methods used, inferior angles, such as upper lumbar angle, were more sensitive to position changes than superior angles, such as upper thoracic angle. This has the potential to over emphasize motion changes in the lower spine. Lastly, due to the use of the sacrum and manubrium markers to establish coordinate systems at the other sensor location, this study was unable to create a coordinate system at S1, which would have allowed for calculation of a lower

lumbar (L3-S1) and lumbar (L1-S1) angle. With the current mobility parameters, comparison to existing studies was limited without data for full lumbar mobility. Further research should include full lumbar mobility as well as pelvic balance. Despite these limitations, this investigation built upon the body of knowledge by presenting thoracic, thoracolumbar, and lumbar mobility for healthy adolescents.

In conclusion, differences in spinal mobility based on gender were investigated, but significant gender differences were only found in torso and upper lumbar ROM. There was no gender based difference in the thoracic sub-segments of the adolescent spine. In the future, it may be possible to group male and female adolescents for analyses of the thoracic spine.

Creating a baseline set of values for adolescent spine kinematics is important to assist in diagnosis and treatment of adolescent spine disorders. Although this was a pilot study, its findings could be used to begin to establish normative mobility values for the thoracic spine in the adolescent. With this research and other similar research investigating normative adolescent spine mobility and pelvic balance, abnormal values of mobility could be identified more easily. Especially in spinal deformities such as adolescent idiopathic scoliosis, detecting variances from normal kinematics and balance is of the utmost importance, as deformities can progress swiftly. Discovering easily detectable ways to diagnose scoliosis, such as a clinical mobility test, could allow for earlier detection or treatment. While results of this pilot study began to provide a baseline measure as to the gender and age effects on spinal kinematics, these need to be further studied in both normal and abnormal adolescents to assist with future diagnosis and treatment advances.

Acknowledgements

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Chapter 4 Correlation of Thoracic Mobility with Adolescent Idiopathic Scoliosis Characteristics

This manuscript investigates the biomechanics of subjects with Adolescent Idiopathic Scoliosis and was prepared for and submitted to the *Journal of Pediatric Orthopaedics*.

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Title Page

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Background

Adolescent idiopathic scoliosis greatly affects spinal form, but how it affects spinal function is not well understood. This research investigates the relationship of age, skeletal maturity, and curve severity on thoracic, thoracolumbar, and lumbar mobility outcomes.

Methods

A Trakstar system (Ascension Technologies Burlington, VT) collected position data at the manubrium, T1, T3, T6, T10, L1, L3, and S1. Eleven adolescents with right thoracic AIS moved to their maximum voluntary range of motion at a self-selected speed in sagittal and coronal plane tasks. The study was approved by the local IRB. Scoliosis curve information for each subject was collected at the time of motion data collection by an orthopedic surgeon and managed using REDCap.

From the position data, seven spinal angles were calculated. The normalized range of motion was calculated using MATLAB (MathWorks, Natick, MA) by subtracting the standing position from the maximum position and dividing by the number of functional spinal units for each angle. Pearson correlation was performed using SAS software (SAS Institute Inc., Cary, NC) to correlate chronologic age, Risser sign, and the Cobb angle of the major curve with spinal mobility parameters, $\alpha = 0.05$.

Results

While age was not expected to have a significant correlation with mobility, it did have a significant, positive correlation with some measures of spinal mobility. Risser sign met expectations, having significant, negative correlations with mobility. Curve severity, however,

showed mixed correlations with mobility, indicating the possibility of differing correlations with apical, periapical, and non-apical regions.

Conclusions

This investigation into the relationship between curve characteristics and mobility provides a better understanding of how this three-dimensional deformity affects all aspects of spinal mobility in a right thoracic AIS model.

Clinical Relevance

By learning more about the relationship between form and function, better methods of isolating areas of deformity and correcting deformities can be developed and implemented.

BACKGROUND

Curve flexibility is an important measure in adolescent idiopathic scoliosis (AIS) treatment planning. Traditionally, curve flexibility is measured from supine side bending radiographs but surgeons are looking for new ways to assess curve flexibility.[1,2] Spinal mobility, an externally measured quantification of movement ability, can be easily applied in a clinical setting and is tied to traditional measures of curve flexibility.[3] Since range of motion measures are a standard part of orthopedic examinations, spinal mobility, as a surrogate for curve flexibility, could be calculated for all AIS patients during routine visits. Therefore, it is important to understand the behaviors of spinal mobility in addition to curve flexibility.

Researchers have investigated age and curve severity as predictors of curve flexibility.[2,4–8] Although strongly correlated with age, skeletal maturity measures, such as Risser sign, have not been investigated as predictors for curve flexibility or mobility.[7] The objective of this pilot study was to correlate known or expected predictors of curve flexibility with externally measured spinal mobility. Specifically, Risser sign, chronologic age, and the major curve Cobb angle were each analyzed as predictors of spinal mobility changes during sagittal and coronal plane bending. It was expected there would be no mobility relationships with age or skeletal maturity and negative relationships with curve severity.

MATERIALS AND METHODS

A Trakstar electromagnetic tracking system (Ascension Technologies, Burlington, VT) was used to collect position data at the manubrium, T1, T3, T6, T10, L1, L3, and S1 in eleven adolescents with right thoracic AIS with apices between T6 and T10. Participants were excluded if they had any musculoskeletal diagnosis other than AIS. This study was approved by the

Institutional Research Board at the University of Kansas Medical Center and written and informed consent was obtained for all participants.

Data Collection

Scoliosis curve information for each subject, including curve severity, apex location, and Risser sign was collected at the time of motion data collection by an orthopedic spine surgeon (DB) with over 20 years of experience and managed using REDCap electronic data capture tools hosted at the University of Kansas-Lawrence.[9]

Participants were instructed that the goal was to move to their maximal bent position at a self-selected speed for each of six full motion tasks. The tasks were flexion (F), extension (E), left lateral bending (LLB), right lateral bending (RLB), left 45° anterior-lateral flexion (L45), and right 45° anterior-lateral flexion (R45), as shown in Figure 1. Instructions were given to reduce out-of-plane motion. Tasks were demonstrated and participants were allowed to practice before data collection. Of the five trials for each task, the last trial was used for analysis.
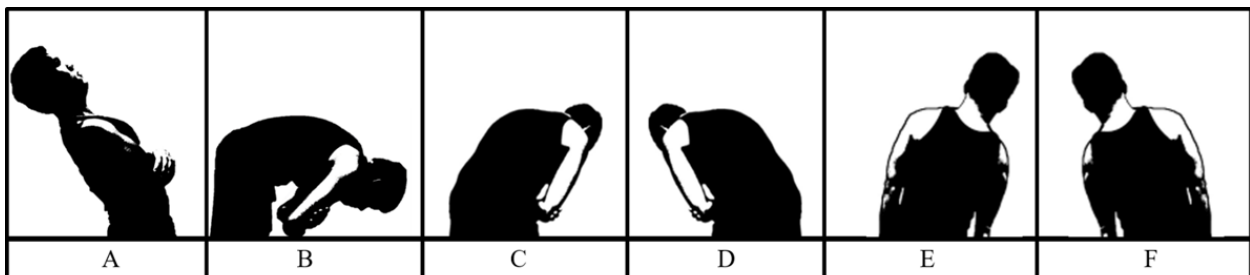
Figure 1. Sagittal and Coronal Plane Motion Tasks
a. Flexion (F), b. Extension (E) c. Right Lateral Bending (RLB) d. Left Lateral Bending (LLB) e. Right 45° Anterior-Lateral Flexion (R45) f. Left 45° Anterior-Lateral Flexion (L45)

Data Analysis

As previously described, position data was used to calculate seven angles: upper thoracic angle from T1-T3, mid thoracic angle from T3-T6, lower thoracic angle from T6-T10, thoracolumbar angle from T10-L1, upper lumbar angle from L1-L3, and thoracic curvature angle from T1-L1 (Galvis, unpublished data).[10] The normalized range of motion (nROM) was calculated using MATLAB (MathWorks, Natick, MA) by subtracting the standing position from the maximum bent position and dividing by the number of functional spinal units for each segment.

Pearson correlation was used to correlate chronologic age, Risser sign, and the Cobb angle of the major curve with spinal mobility parameters. Correlations of 0.0 to 0.49 reflect poor to low, 0.5 to 0.69 moderate, 0.70 to 0.89 good and 0.9 to 1.0 excellent correlations.[11] All statistical procedures were performed with SAS software (SAS Institute Inc., Cary, NC) with a significance level of $\alpha = 0.05$. Table 1 contains all correlations analyzed as a part of this study. Table 2 presents the equations relating significant predictors to mobility measures, as well as correlation coefficients, confidence intervals and statistical power.

RESULTS

The participants had an average age of 15.1 ± 2.0 years, an average height of 1.58 ± 0.18 m, an average weight of 56.1 ± 15.1 kg, and an average major curve Cobb angle of $48.0° \pm 11.6°$ (range 21°- 68°). Three participants were male. Positive correlations indicate increasing mobility with increasing age, Risser sign, or major curve Cobb angle, whereas negative correlations denote decreasing mobility with increasing age, Risser sign, or major curve Cobb angle.

Table 1. Mobility Correlations

(   ) Empty cells denote weak/very weak correlations with mobility. $(0 < |r| < 0.49)$
(- / +) Denotes a moderate correlation with mobility. $(0.50 < |r| < 0.69)$
(- - / + +) Denotes a good correlation with mobility. $(0.70 < |r| < 0.89)$
(- - - / + + +) Denotes an excellent correlation with mobility. $(0.9 < |r| < 1.0)$
Shaded cells have a significant correlation between predictor and mobility. $(p < 0.05)$
Bending Modes: Flexion (F), Extension (E), Left Lateral Bending (LLB), Right Lateral Bending (RLB), Left Anterior-Lateral Flexion (L45), and Right Anterior-Lateral Flexion (R45).

	PREDICTOR	UT (T1-T3)	MT (T3-T6)	LT (T6-T10)	TL (T10-L1)	UL (L1-L3)	THOR (T1-L1)
F (n=5)	AGE					+	
	RISSER	+	-		+ + +	+	+ +
	COBB	+	-		+ + +	+	+ +
E (n=10)	AGE			+			
	RISSER						
	COBB						
LLB (n=11)	AGE						
	RISSER					+	
	COBB	-				+	
RLB (n=11)	AGE						
	RISSER						
	COBB					-	
L45 (n=10)	AGE	-			+		+
	RISSER	- -	-				
	COBB						
R45 (n=8)	AGE	- -		+ +	+	+	+ +
	RISSER	- - -	- -	+		+	
	COBB						

Table 2. Mobility Equations for Significant Correlations

In the clinical records, Risser grades as one of ten levels: 0, 1, 1+, 2, 2+, 3, 3+, 4, 4+, or 5. Risser grade was then coded so it could be correlated such that a Risser grade of zero was coded as a one; Risser grade of one was coded as a two; Risser grade of one plus was coded as a three and so on.

	Correlation Equation	Segment	Task	R	CL$_-$	CL$_+$	Power
Age	Mobility = 0.42 × Age – 45.57	Thoracolumbar	L45	0.64	0.065	0.896	0.40
	Mobility = 0.22 × Age – 27.02	Thoracic	L45	0.66	0.100	0.903	0.43
	Mobility = -0.46 × Age + 98.05	Upper Thoracic	R45	0.88	-0.969	-0.593	0.98
	Mobility = 0.28 × Age – 43.97	Low Thoracic	R45	0.87	0.565	0.966	0.97
	Mobility = 0.27 × Age – 33.00	Thoracic	R45	0.84	0.484	0.957	0.91
Risser	Mobility = 1.93 × Risser – 12.95	Thoracolumbar	F	0.91	0.683	0.977	>0.99
	Mobility = -0.32 × Risser + 3.54	Upper Thoracic	L45	0.75	-0.931	-0.273	0.66
	Mobility = -0.19 × Risser + 3.50	Mid Thoracic	L45	0.67	-0.906	-0.117	0.46
	Mobility = -0.28 × Risser + 37.07	Upper Thoracic	R45	0.93	-0.982	-0.746	>0.99
	Mobility = -0.23 × Risser + 49.66	Mid Thoracic	R45	0.73	-0.925	-0.232	0.60
Cobb	Mobility = 0.07 × Cobb + 0.97	Thoracolumbar	F	0.97	0.885	0.992	>0.99
	Mobility = -0.08 × Cobb + 7.55	Upper Lumbar	RLB	0.64	-0.896	-0.065	0.40

Age and mobility correlations ranged from moderate to good, with positive correlations found in more inferior segments and negative correlations only found in in the upper thoracic region. In flexion, age moderately correlated with increasing upper lumbar mobility but this correlation was not significant (p > 0.05). In extension, age moderately correlated with increasing lower thoracic mobility, which trended towards significance (p = 0.06). There were no correlations of note between age and lateral bending. In L45, mobility moderately decreased with

increasing age in the upper thoracic region. The thoracolumbar and thoracic mobility had a strong, positive correlation with age ($p < 0.05$). In R45, in the upper thoracic mobility had a good, negative correlation with age ($p < 0.01$). Lower thoracic and thoracic mobility had good, positive correlations with age ($p < 0.01$). Thoracolumbar and upper lumbar mobility had moderate, positive correlations with age that trended towards significance ($p = 0.07$, $p = 0.06$).

Correlations between skeletal maturity and mobility ranged from moderate to excellent, with stronger correlations found in L45 and R45. Most correlations were positive, but a few negative correlations were found in in the upper thoracic and mid thoracic mobility In flexion, Risser sign had a good, negative correlation with mid thoracic mobility, which trended towards significance ($p = 0.07$). There was an excellent, positive correlation between Risser sign and thoracolumbar mobility ($p < 0.05$). Upper thoracic and upper lumbar mobility had good, positive correlations, while thoracic mobility had a moderate, positive correlation with Risser sign ($p > 0.05$). In left 45° anterior-lateral flexion, upper thoracic mobility had a good, positive correlation with Risser sign ($p < 0.05$). Likewise, in mid thoracic mobility, there was a moderate, positive correlation with Risser sign ($p < 0.05$). In right 45° anterior-lateral flexion, upper thoracic mobility had an excellent, negative correlation with Risser sign ($p < 0.01$). Similarly, mid thoracic mobility had a good, negative correlation with Risser sign ($p < 0.05$). Lower thoracic and upper lumbar mobility had moderate, positive correlations with Risser sign ($p > 0.05$). In LLB, upper lumbar mobility had a moderate, positive correlation with Risser sign that trended towards significance ($p = 0.08$). In extension as well as RLB, there were no significant correlations between Risser sign and mobility ($p > 0.05$).

Mobility and curve severity correlations ranged from moderate to excellent, with the strongest correlations occurring during flexion. In flexion, there was an excellent, positive

correlation between thoracolumbar mobility and increasing major curve Cobb angle ($p < 0.01$). The upper thoracic and upper lumbar mobility had moderate, positive correlations with the major curve Cobb angle ($p > 0.05$). Thoracic mobility had a good, positive correlation with curve severity, trending towards significance ($p < 0.10$). There is one negative correlation of note however. Mid thoracic mobility had a good, negative correlation with curve severity, which also trended towards significance ($p = 0.07$).

Few notable mobility-severity correlations took place in non-flexion tasks. In extension, increasing major curve Cobb angle did not correlate to any mobility measure ($p > 0.05$). In LLB, upper thoracic mobility had a moderate, negative correlation with the major curve Cobb angle ($p > 0.05$). Upper lumbar mobility had a moderate, positive correlation with the major curve Cobb angle, which trended towards significance ($p = 0.06$). In RLB, upper lumbar mobility had a moderate, negative correlation with the major curve Cobb angle ($p < 0.05$). In L45 and R45, there were no significant correlations between mobility and the major curve Cobb angle ($p > 0.05$).

DISCUSSION

The objective of this study was to investigate the correlation of Risser sign, chronologic age, and the major curve Cobb angle with externally measured thoracic, thoracolumbar, and lumbar mobility, a non-radiographic measure similar to curve flexibility. It was expected that curve severity would be a significant predictor of spinal mobility while chronologic age and skeletal maturity measures would not. Results gathered from the AIS participants with right thoracic curves indicate some expectations hold true. However, correlation of these predictors to mobility greatly depended on the segmental region and bending task.

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Mobility Magnitude Comparisons to Literature

The mobility values of the current study are compared against mobility values from Rahmatalla et al. and Poussa et al. in Table 3.[12,13] The mobility values for extension are similar across studies but those presented for flexion and lateral bending are smaller than those presented in the other studies. While these studies represent the best comparisons available within the current literature, these studies did not collect data, constrain motion, or select participants with the same methodologies as the current study. Because of the differences in methodologies, differences in mobility outcomes were expected. Mobility magnitudes are not the only comparisons made with literature; mobility relationships can also be examined.

Table 3. Comparison of Thoracic Mobility to Literature
Average mobility values are presented. Standard deviation values are presented in parentheses where available.

	Author	Galvis et al.	Rahmatalla et al.	Poussa et al.	Poussa et al.	Poussa et al.
	(Curve Size)	*(20° - 68°)*	*(None Stated)*	*(< 25˚)*	*(25˚- 35˚)*	*(>35˚)*
Flexion	N	5	9	20	29	22
	Thoracic	18.1 (6.0)	28.8	58.6 (8.7)	59.9 (11.1)	50.9 (12.6)
Extension	N	10	9	20	29	22
	Thoracic	11.4 (9.4)	12.1	18.2 (14.5)	15.9 (15.3)	16.5 (19.1)
L. Bending	N	11	9	20	29	22
	Thoracic	13.1 (5.4)	30.2	35.2 (7.9)	34.2 (7.5)	37.5 (7.8)
R. Bending	N	11	9	20	29	22
	Thoracic	16.8 (5.4)	28.4	33.6 (9.8)	32.6 (8.4)	25.4 (12.5)

Age, Risser sign, and the Cobb angle of the major curve had not been examined as predictors of spinal mobility but most were investigated as predictors of curve flexibility.[3] Similar mobility relationships, from the current study, and curve flexibility relationships, from

literature, were seen with age and curve severity. However, curve flexibility is only measured during lateral bending, therefore comparisons between relationships can only be drawn within that constraint.

Age Correlation Comparisons to Literature

While age was a significant predictor of curve flexibility when including both adults and adolescents, age was not a significant predictor in an adolescent only population.[2,5] This agreed with the current study, as no correlation between age and lateral bending mobility were found. However, there were significant, positive relationships between age and mobility in L45 and R45, a combined sagittal and coronal plane bending task.

Skeletal Maturity Correlation Comparisons to Literature

To the author's knowledge, no study has correlated Risser sign to curve flexibility or spinal mobility. However, curve flexibility differences have been evaluated between skeletally mature and immature groups, as defined by Risser sign. In that study, the flexibility in the skeletally immature group (Risser <5) was significantly less than the flexibility of the skeletally mature group (Risser = 5).[7] While in the current study, UL mobility during LLB had a non-significant, moderate correlation with Risser sign, it is unclear if there is a true correlation between skeletal maturity measures and mobility during lateral bending. Due to the lack of variability in Risser sign for this study population, discerning true correlations is difficult.

Comparison of Age to Skeletal Maturity

Mobility relationships with age and Risser sign were expected to be similar, as age and Risser sign have been found to have a significant positive correlation.[7] While it is obvious Risser

sign is a better measure of skeletal maturity than chronologic age alone, it is unclear whether Risser sign provides any additional clinical insight that analysis of age overlooks.[14] In the current study, the significance of the age and skeletal maturity relationships with mobility did not always agree. Age significantly and positively correlated with mobility in more inferior regions of the spine more often while Risser sign significantly and negatively correlated with mobility in more superior regions of the spine more often. Poussa suggests that as the scoliotic curve progresses, it begins to cause decreases in flexion mobility.[13] The Risser sign seems to agree with this trend while age does not. This difference could be because Risser sign accounts for the chronologically later skeletal maturity found in males. Peak growth age in males occurs approximately two years after females on average.[14] While age and skeletal maturity are strongly correlated with each other, age appears to be a poor predictor of functional outcomes affected by skeletal maturation. These findings would suggest that age may not be a sensitive enough indicator for maturity in mixed gender adolescent populations.

Curve Severity Correlation Comparisons to Literature

Curve severity is a significant predictor of curve flexibility, with an inverse relationship between flexibility and curve magnitude.[2,5,7] This is likely cause by impingement of the rib or pelvis during movement. One study found increasing thoracic curve severity decreased lumbar spine flexibility.[3] These studies looked at the entire scoliotic curve and did not investigate segments of the spine individually. In the current study, both positive and negative correlations were found with curve severity. Based on the locations of the positive versus negative correlations, it is possible that the negative correlations occurred in regions where AIS had induced increased rigidity, limiting range of motion; whereas the areas of positive correlation were in regions where the spine was able to compensate for rigidity elsewhere. This could

indicate the amount of compensatory motion is correlated with the curve severity. These results have important implications for treatment and merit future research.

Study Considerations

This pilot study was designed to investigate the correlation of curve and participant characteristics to spinal mobility in an AIS population. Sagittal balance is another important consideration when determining correction but was not investigated here as sagittal radiographs were not available for all subjects. However, this should be investigated in the future to better inform the correction decision process. As gender was not found to have a significant effect on curve flexibility and thoracic mobility in other research, a mixed gender population was used (Galvis, Unpublished data).[2] Because curve location and direction affects flexibility, only right thoracic curves with apices between T6-T10 were chosen.[4,6–8,15] Although brace wear has been shown to affect curve flexibility, the group was not sub-divided to accommodate for this effect, which was a limitation of the study.[16] Another limitation was the lack of variation in the Risser sign of the participants. This tight spread makes true correlations more difficult to identify. The small sample size in this pilot study also made it difficult to elucidate significant trends, which is why Pearson r values and confidence intervals, as a representation of effect size, were used in combination with traditional p values. Furthermore, human subject testing is subject to many inherent limitations, such as subject motivation and interpretation of instruction. Despite these limitations, significant correlations were identified with age, Risser sign, and curve severity in this pilot study.

The objective of this study was to investigate the relationship between age, Risser sign, and curve severity with spinal mobility in both the sagittal and coronal planes. Based on this

design, there are several innovative aspects of this study. None of these factors had been correlated with a non-radiographic, clinically assessable measures of spinal mobility. Furthermore, Risser sign, had never been used as a predictor of curve flexibility, though it is a common tool to assess skeletal maturity and risk of scoliosis progression.[14] The data collection methods used in this study allowed for natural body loading in sagittal and coronal plane bending tasks, unlike typical curve flexibility measures taken from supine side bending radiographs. Lastly, all mobility and curve flexibility studies investigating the thoracic, thoracolumbar, and lumbar spine do not analyze motion in small segments. Using small spinal segments provides a level of detail regarding spinal mobility that was unavailable until now and is vital when investigating scoliosis.

In conclusion, chronologic age, skeletal maturity, and curve severity were correlated with thoracic, thoracolumbar, and lumbar mobility in an AIS population to determine the presence of significant relationships. Age had significant, positive correlations with some measures of spinal mobility. Risser sign had significant, negative correlations with some mobility measures. Curve severity, however, showed mixed correlations with mobility, indicating the possibility of differing correlations with compensating regions versus regions of increased rigidity. This investigation into the relationship between curve characteristics and mobility provides a better understanding of how this three-dimensional deformity affects all aspects of thoracic, thoracolumbar, and lumbar mobility in a right thoracic AIS model. Scoliosis is a highly variable deformity; further work should be performed to investigate similar relationships in other curve types. Future work should also analyze other factors that may affect spinal mobility, such as ligament laxity, hyper and body habitus. By learning more about the relationship between form and function, better treatments can be developed and implemented.

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Chapter 5 The Effect of Scoliotic Deformity on Spine Biomechanics in Adolescents

This manuscript investigates the similarities and differences in the spine biomechanics of the non-pathologic and scoliotic adolescent groups and has been accepted to *Scoliosis and Spine Disorders.* The KU Open Access Authors Fund has awarded funds to SN Galvis towards the publication of this manuscript in *Scoliosis and Spine Disorders*.

SN Galvis had primary responsibility of the study design and approval, data collection, processing, and analysis, and manuscript writing and editing.

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Abstract

Background

While Adolescent Idiopathic Scoliosis (AIS) produces well characterized deformation in spinal form, the effect on spinal function, namely mobility, is not well known. Better understanding of scoliotic spinal mobility could yield better treatment targets and diagnoses.

The purpose of this study was to characterize the spinal mobility differences due to AIS. It was hypothesized the AIS group would exhibit reduced mobility compared to the typical adolescent (TA) group.

Methods

Eleven adolescents with right thoracic AIS, apices T6-T10, and eleven age- and gender-matched TAs moved to their maximum bent position in sagittal and coronal plane bending tasks. A Trakstar (Ascension Technologies Burlington, VT) was used to collect position data. The study was approved by the local IRB.

Using MATLAB (MathWorks, Natick, MA) normalized segmental angles were calculated for upper thoracic (UT) from T1-T3, mid thoracic (MT) from T3-T6, lower thoracic (LT) from T6-T10, thoracolumbar (TL) from T10-L1, upper lumbar (UL) from L1-L3, and thoracic from T1-L1 by subtracting the standing position from the maximum bent position and dividing by number of motion units in each segment. Mann Whitney tests ($\alpha = 0.05$) were used to determine mobility differences.

Results

Results indicate the AIS group had comparatively increased mobility in the periapical

regions of the spine. The AIS group had an increase of 1.2° in the mid thoracic region (p = 0.01) during flexion, an increase of 1.0° in the mid thoracic region (p = 0.01), 1.5° in the thoracolumbar region (p = 0.02), and 0.7° in thoracic region (p = 0.04) during left anterior-lateral flexion, an increase of 6.0° in the upper lumbar region (p = 0.02) during right anterior-lateral flexion, and an increase of 2.2° in the upper lumbar region during left lateral bending (p < 0.01).

Conclusions

Participants with AIS did not have reduced mobility in sagittal or coronal motion. Contrarily, the AIS group often had a greater mobility, especially in segments directly above and below the apex. This indicates the scoliotic spine is flexible and may compensate near the apex.

Keywords

Adolescent Idiopathic Scoliosis, spinal mobility, thoracic spine, motion analysis, kinematics

Background

While Adolescent idiopathic scoliosis (AIS) produces well characterized deformation in spinal form, the effect on spinal function, specifically mobility, is not well characterized. A better understanding on the effect of AIS on spinal mobility could yield better treatment targets and earlier diagnostic means. Therefore, it is important to identify and quantify the mobility disparities caused by AIS. While this area of research is important, very little has focused on the spinal mobility in typical adolescents (TA) and those with AIS.[1–4] Of these studies, none investigate mobility differences found in segments of the spine and instead rely on measures of thoracic and lumbar mobility as a whole to characterize mobility differences cause by AIS.

In this study, spinal mobility was measured during six sagittal and coronal plane bending activities in the thoracolumbar spine of adolescents with and without AIS. The purpose of this pilot study is to define the spinal mobility differences caused by AIS. It was hypothesized that the AIS group will exhibit reduced mobility in all modes of bending compared to the TA group.

Methods

Eleven adolescents with right thoracic AIS and eleven age- and gender-matched typical adolescents (TA) were included this study. Subjects who met the inclusion criteria were recruited at scoliosis clinic visits. Inclusion criteria included diagnosis of adolescent idiopathic scoliosis at age ten or later, primary Cobb angle of at least 15°, and no previous history of spinal surgery,. Subjects were excluded if they had any musculoskeletal diagnoses other than AIS. For this study, only scoliosis patients with

Lenke type 1 curves (right thoracic curves) were included to mitigate the effect of curve location and type on the outcomes of the study. Eight subjects in each group were female. The average Cobb angle of the primary curve was $48° ± 12°$ for the scoliosis group. This study was approved by the Institutional Research Board at the University of Kansas-Lawrence and University of Kansas-Medical Center and written and informed consent and assent was obtained for all subjects.

A Trakstar system (Ascension Technologies, Burlington, VT) was used to collect position data at the manubrium, T1, T3, T6, T10, L1, L3, and S1. Participants were instructed the goal was to move to their maximal bent position at a self-selected speed for each of six full motion tasks. The tasks were flexion (F), extension (E), left lateral bending (LLB), right lateral bending (RLB), left 45° anterior-lateral flexion (L45), and right 45° anterior-lateral flexion (R45), as depicted previously.[5] Additional instructions were given to reduce out of plane motion. Tasks were demonstrated and participants were allowed to practice before data collection. Of the five trials for each task, the last trial was used for analysis to allow for the viscoelastic effect to stabilize during testing.

Scoliosis curve information for each subject was collected at the time of motion data collection by an orthopedic surgeon (DB) with over 20 years of experience and managed using REDCap electronic data capture tools hosted at the University of Kansas-Lawrence.[6]

With the position data, seven angles were calculated as previously described: upper thoracic angle (UT) from T1-T3, mid thoracic angle (MT) from T3-T6, lower thoracic angle (LT) from T6-T10, thoracolumbar angle (TL) from T10-L1, upper lumbar

angle (UL) from L1-L3, and thoracic curvature angle from T1-L1.[5] The normalized range of motion (nROM) was calculated by subtracting the standing position from the maximally bent position and dividing by the number of functional spinal units for each segmental region. All calculations were performed using customized MATLAB (MathWorks, Natick, MA) programs.

Statistical tests were used to determine the mobility differences between the AIS and TA group. A Mann-Whitney was used to determine statistical differences in the ROM of the AIS and TA groups. Statistical analysis was not conducted when either group had less than five subjects. Although the use of statistical corrections remains controversial, none of the analyses are truly independent, therefore a statistical correction was not used.[7,8] All statistical procedures were performed with a significance level of $\alpha = 0.05$.

Results

The AIS group had an average age of 15.1 ± 2.0 years, an average height of 1.58 ± 0.18 m, and an average weight of 56.1 ± 15.1 kg while the TA group had an average age of 15.2 ± 2.2 years, an average height of 1.62 ± 0.12 m, and an average weight of 55.2 ± 10.8 kg. The control and scoliosis groups had statistically similar ages, heights, and weights ($p > 0.05$). Both groups demonstrated statistically symmetric mobility in symmetric motion tasks ($p > 0.05$). It was hypothesized that the TA group would experience greater mobility than the AIS group. The results from this study did not support the hypothesis. Instead it seems the AIS group frequently demonstrates greater mobility than the TA group in the thoracolumbar region. While data was collected for all

eleven subjects from each group, some mobility results could not be calculated as sensors occasionally exceeded the collection volume in flexion and flexion-type tasks. The following statistical results were obtained from trials where all data was recorded within the collection volume.

While no significant differences were found during extension, consistent mobility patterns can be seen during the flexion and flexion-type tasks. During flexion (Figure 1), the AIS group was more mobile in the mid thoracic region and trended towards increased mobility in the upper lumbar segmental region ($p = 0.01$, $p = 0.07$). In L45 (Figure 2), the AIS group had greater mobility than the TA group in the mid thoracic, thoracolumbar, and thoracic segmental regions ($p = 0.01$, $p = 0.02$, $p = 0.04$). In R45 (Figure 2), the AIS group had greater mobility than the TA group in upper lumbar segmental region ($p = 0.02$). One interesting result of note is that the TA group had greater mobility than the AIS group in the upper thoracic segmental region during R45 ($p = 0.02$). Power for sagittal plane analyses ranged from 2.6 to 36.2 for non-significant comparisons and from 53.6 to 98.7 for significant comparisons.

Figure 1. Comparison of Functional Spine Unit normalized ROM of thoracic and thoracolumbar segments of the AIS group to the same segments in the TA group during sagittal plane tasks (Flexion and Extension). The asterisk denotes the significantly greater nROM in the AIS group compared to the TA group in mid thoracic and upper lumbar motion (p = 0.01 p = 0.07) during flexion.
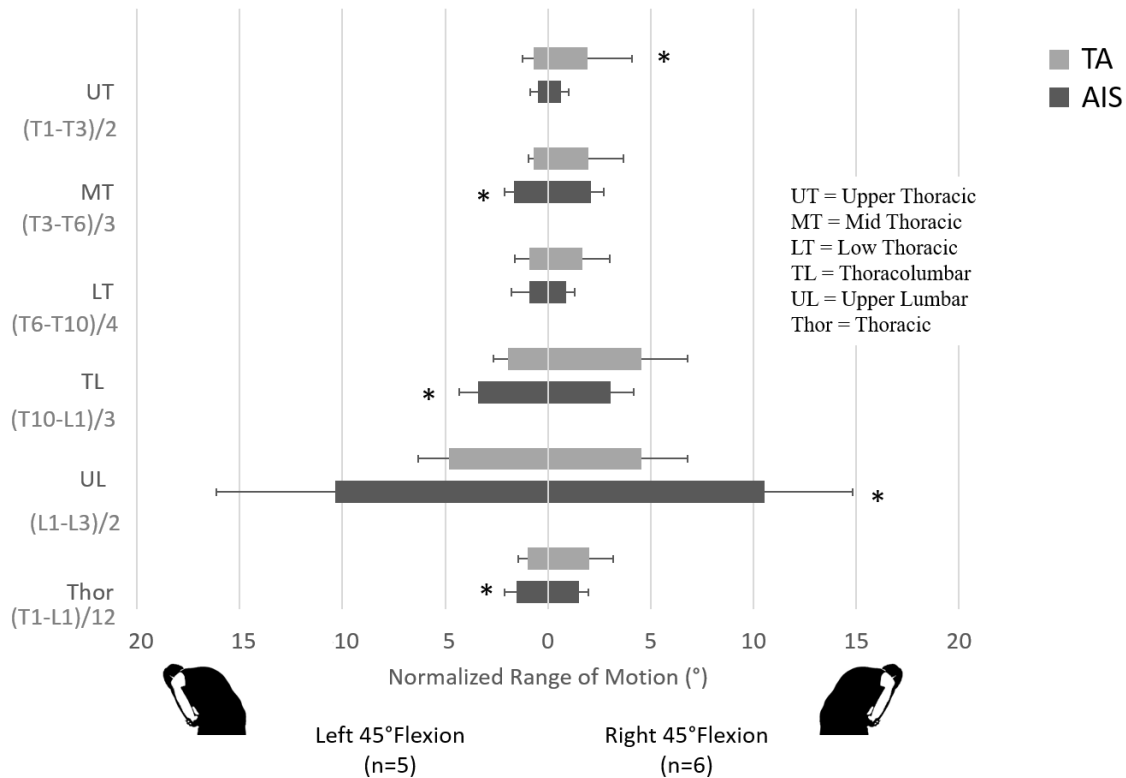
Figure 2. Comparison of Functional Spine Unit normalized ROM of thoracic and thoracolumbar segments of the AIS group to the same segments in the TA group during Left and Right 45° Anterior-Lateral Flexion. The asterisk denotes the significantly greater nROM in the AIS group in mid thoracic (p = 0.01), thoracolumbar (p = 0.02), and thoracic (p = 0.04) motion during L45 and significantly greater nROM in the TA group in upper thoracic motion during R45 (p = 0.02).

Mobility in the lateral bending tasks follows slightly different patterns (Figure 3). The only instance where the TA group had greater mobility than the AIS group was in the upper thoracic region during left lateral bending (p = 0.02). However, in the same bending task, the upper lumbar mobility was greater for the AIS group (p < 0.01). In RLB, there were no significant mobility differences between the two groups. As all of the AIS participants have right thoracic curves, the asymmetric mobility results are to be expected. Power for coronal plane analyses ranged from 5.1 to 30.4 for non-significant comparisons. Power of significant comparisons was 72.2 for UT and 98.9 for UL during LLB.
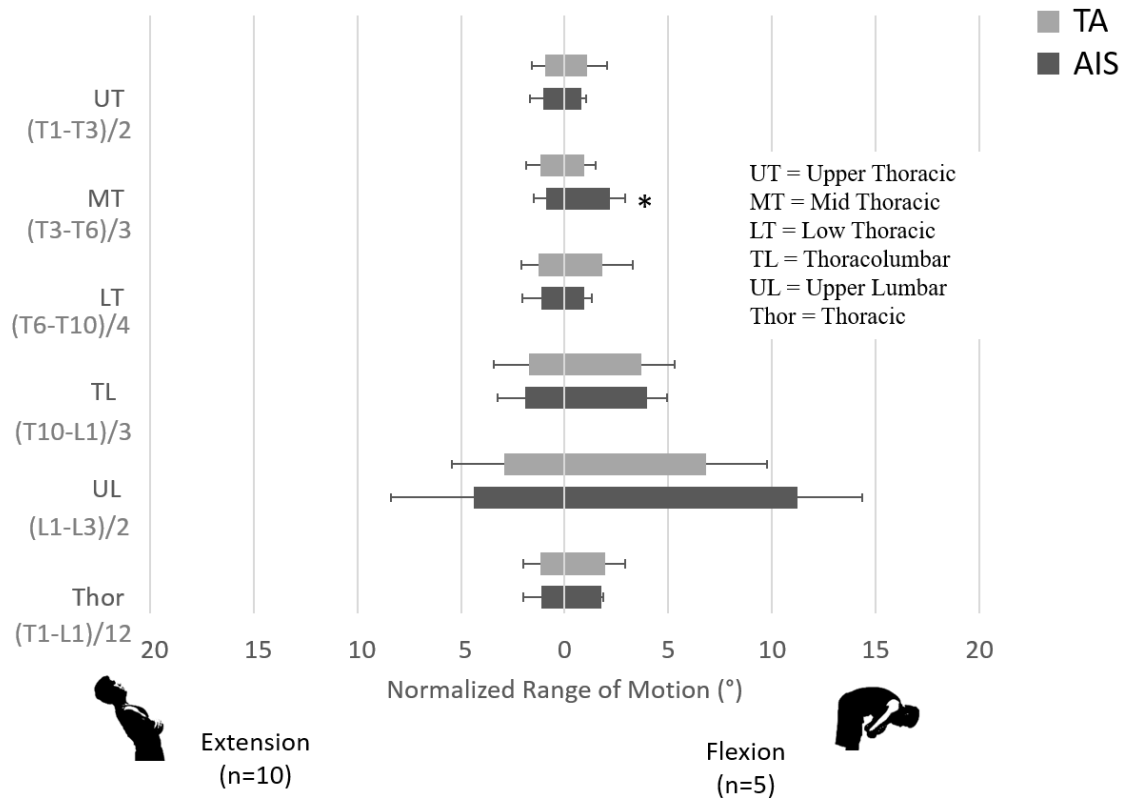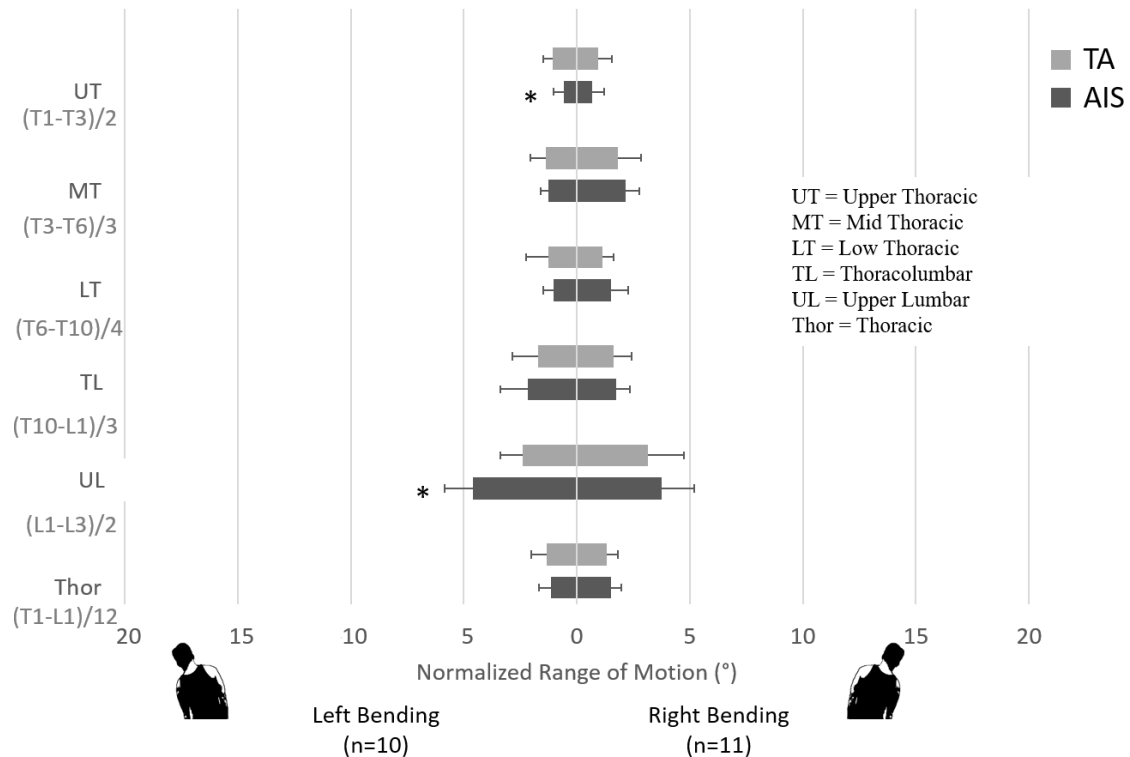
Figure 3. Comparison of Functional Spine Unit normalized ROM of thoracic and thoracolumbar segments of the AIS group to the same segments in the TA group during coronal plane tasks (Left and Right Lateral Bending). The asterisk denotes the significantly greater nROM in the AIS group compared to the TA group in upper lumbar motion ($p < 0.01$) and significantly lower nROM in upper thoracic motion ($p = 0.02$) during left lateral bending.

Discussion

The goal of this research was to characterize the spinal mobility differences caused by AIS, as this has not been done before with segmental detail. It was hypothesized that the AIS group would exhibit reduced mobility in all modes of bending compared to the TA group, but this was not supported. In almost all cases, the mobility of the AIS group was statistically equivalent or significantly greater than the mobility of the TA group.

Mobility values of the current study are compared to literature values for scoliotic adolescents and typical adolescents in Table 1. The mobility values for extension were

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similar across studies but those presented for flexion and lateral bending were smaller

than those presented in the other studies for both TA and AIS populations. Mellin and

Poussa use an inclinometer method that has been shown to have a 15° range of motion

difference and no correlation with values calculated by the electrogoniometer method, as

was used in this study.[9] While these studies shown in Table 1 represent the best

comparisons available within the current literature, these studies did not collect data,

constrain motion, or select participants with the same methodologies as the current study.

Because of the differences in methodologies, differences in mobility outcomes were to be

expected.

Table 1. Thoracic Mobility in Control and Scoliosis Subjects

Group	Author	Flexion	Extension	Left Bending	Right Bending
Control	Galvis et al	23.2 (11.8)	14.1 (10.1)	15.9 (8.2)	21.9 (12.2)
	Poussa et al	62.0 (9.1)	-3.3 (14.1)	34.1 (7.3)	32.2 (7.0)
	Mellin and Poussa	62.2-70.3	-4.0 -13.0	65.8-82.6	
	Mellin et al	62.0-69.2	-3.3- -2.6	34.1-37.2	32.2-35.5
Scoliosis	Galvis et al	18.1 (6.0)	11.4 (9.4)	13.1 (5.4)	16.8 (5.4)
	Poussa et al (G1)	58.6 (8.7)	18.2 (14.5)	35.2 (7.9)	33.6 (9.8)
	Poussa et al (G2)	59.9 (11.1)	15.9 (15.3)	34.2 (7.5)	32.6 (8.4)
	Poussa et al (G3)	50.9 (12.6)	16.5 (19.1)	37.5 (7.8)	25.4 (12.5
	Rahmatalla et al	28.8	12.1	30.2	28.4

Values presented are mean range of motion values with standard deviation values presented in parentheses where available. The number of subjects varied by bending mode in Galvis et al: Flexion (n=5), extension (n=10), and left and right lateral bending (n=11). The groups presented for Poussa et al represented divisions by Cobb angle, with Group 1 having <25° Cobb angles, Group 2 having 25°-35° Cobb angle, and Group 3 having Cobb angles >35°.

Near the primary curve apex in the AIS group, it was expected the spine would be more rigid than a typical spine. While there was no significant difference between the mobility of the groups, the average range of motion was lower in the scoliosis group compared to the control. One study found the four periapical spinal units experience "structural tethering" where the spinal units demonstrate decreased range of motion.[10] This same effect could be causing the non-significantly lower mobility in the AIS group since the apical effects could have been dampened by the inclusion of "non-tethered" individual motion levels in the lower thoracic region. While structural tethering at the apex was not definitively demonstrated in this study, it has been shown in similar studies and could be the underlying cause of the mobility assessed here but further research is needed.

Results indicate the AIS group had increased nROM in the periapical regions of the spine, particularly in flexion and flexion-type tasks. Many possibilities exist to explain this phenomenon. The segments could be more mobile due to a compensation for reduced mobility near the apex, hypokyphosis in the thoracic spine (though degree of kyphosis was unknown) which would allow for improved rotation about the spinal column, or hyperlaxity of the spine in scoliosis patients which could contribute to deformity progression. The AIS group had greater mobility in the MT region during flexion, in MT, TL, and Thoracic during left anterior-lateral flexion, and in UL during right anterior-lateral flexion. The AIS group had significantly higher UL in left lateral bending. In some bending modes, significant mobility differences were seen between the lower thoracic (apical) region and the periapical regions ($p < 0.05$). Without controlling for thoracic kyphosis and with some studies indicating those with scoliosis are no more flexible than their non-pathologic counterparts, compensatory motion may be the mechanism causing the increased mobility. While these results indicate greater mobility above and below the theoretically tethered apical region, this contradicts related findings which indicate mobility above and below long fusions is significantly reduced.[11–13] Since previous research does not agree with the current findings, further study is needed to confirm the increased mobility and its cause.

Other research has shown that thoracic mobility in an AIS population is rarely different compared to controls.[1–4] In this pilot study, there was no statistical difference between the two groups for overall thoracic flexion but there were significant differences in smaller segments of the spine. This showed evaluating thoracic and thoracolumbar mobility to the segmental level is necessary to fully characterize thoracic mobility in an

AIS population, as full segmental analyses alone can miss significant mobility differences.

Although there were innovative aspects of this work, there were several limitations to consider as well. Existing three dimensional images were not available; therefore a three dimensional description of the deformity, including degree of kyphosis and axial rotation, was unknown. Though the current study was designed to be the first to investigate axial rotation in the thoracic spine in an AIS population, the Euler method produced significant data variations when applied to axial rotation. Therefore spinal motion was not compared in the three primary modes of bending, which would have yielded a three dimensional characterization of adolescent spinal motion. Despite research indicating brace wear can affect curve flexibility, the group was not sub-divided to accommodate for this effect, which is a limitation of the study.[14] This study design did not control for age, Risser grade, or curve severity, which have the potential to effect mobility outcomes in this population and therefore is a limitation. Motion effect from effort, diurnal, sensor placement, soft tissue, and selection variability can obfuscate the true motion and true differences between groups. Trials were the sensors exceeded the collection volume were excluded, which may have eliminated some trials from taller and more flexible participants. With such a small sample size and low power, it was difficult to discern significant differences between groups. Future research should be designed to mitigate against these limitations.

This pilot study was designed to characterize the spinal mobility differences caused by AIS. As gender was not found to have a significant effect on curve flexibility, a mixed gender population was used.[15] Although no gender differences were noted in

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curve flexibility, subjects were age and gender matched across groups to eliminate any possible cofounding effects. Because curve location and direction affects flexibility, only right thoracic curves with apices between T6-T10 were chosen.[2,16–19] The age range was limited to isolate the pubertal phase in adolescent subjects to investigate motion differences prior to skeletal maturity. Of the five trials collected for each task, the last trial was used to allow for the viscoelastic effect to stabilize during testing and fatigue effect was not expected as the trials had a high level of repeatability ($r > 0.9$) for all measures in all tasks.

Very little research has focused on comparing spinal function, as measured by spinal mobility, in adolescents both with and without AIS. Of these studies, only one presented range of thoracic mobility and none provided information about near apex mobility.[2] While scoliosis affects large portions of the spine, the deformity varies throughout its length and greatly affects thoracic and lumbar biomechanics. This pilot study was the first to examine spinal function in segmental regions of the thoracic and thoracolumbar spine in adolescents with and without AIS. This investigation shed light on mobility differences caused by the deformity and opened the door for further exploration in this area.

Future work could expand on the research in this study. Three dimensional characterization of the posture and motion would be beneficial. Future studies should control for skeletal maturity and curve severity. As shown by the low power in this study, a larger number of participants would be needed to discern significant mobility differences. This would allow for investigation into segmental mobility differences

between scoliosis and control groups with the ability to discern significant differences and isolate the causes of these mobility differences.

Conclusion

Participants with AIS did not have reduced range of motion in sagittal or coronal motion. On the contrary, the AIS group often had a greater range of motion, especially in segments directly above and below the apex. This indicates the scoliotic spine is flexible and may compensate for any "structural tethering" seen near the apex of curvature. Further work should be pursued to explore the causes of the mobility effect near the apex.

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Chapter 6 Biomechanical Evaluation of a Growth Friendly Rod Construct

This manuscript investigates the changes in biomechanics that occur after implantation of a unilateral growing rod construct and was prepared for and submitted to the *Spine Deformity* journal. An expanded portion of this work was presented at the 2016 Orthopaedic Research Society Conference.

SN Galvis had primary responsibility of the data processing, data analysis, manuscript writing, and editing for this study.

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Background

Distraction type rods mechanically stabilize the thorax and improve lung growth and function by applying distraction forces at the rib, spine, pelvis, or a combination of locations. However, the amount of stability the rods provide and the amount the thorax needs is unknown.

Methods

Five freshly frozen and thawed cadaveric thoracic spine specimens were tested lateral bending, flexion/extension, and axial rotation in displacement control (1°/sec) to a load limit of ± 5 Nm for five cycles after which a growth-friendly unilateral rod was placed in a simulated rib-to-lumbar attachment along the right side. The specimens were tested again the same modes of bending. From the seven Optotrak Orthopedic Research Pin markers (Northern Digital Inc., Waterloo, ON, Canada) inserted into the top potting to denote T1, and the right pedicles at T2, T4, T5, T8, T9, and T11 and the Standard Needle Tip Pressure Transducers (Gaeltech, Isle of Skye, Scotland) inserted into the T4/T5 and T8/T9 discs, motion, stiffness, and pressure data were calculated. Parameters from the third cycle of the intact case and the construct case were compared using two-tailed paired t-tests with 0.05 as the level of significance.

Results

With the construct attached, the T4-T8 segment had a 11% decrease in ROM and the T8-T12 segment had a 44% ROM decrease during extension (p = 0.04); the T8-T12 segment experienced a 63% ROM reduction during flexion (p = 0.04); the T4-T8 segment had a significant decrease of

58   12% in EZ ROM during axial rotation (p = 0.04); and the out-of-plane motion in the sagittal

59   plane during lateral bending significantly increased by 293% (p = 0.04).

60   **Conclusions**

61   It is clear the device as tested here does not produce large biomechanical changes, but the

62   balance between providing desired changes while preventing complications remains

63   difficult.

64   **Clinical Relevance**

65   Investigating the biomechanical effect growth-friendly rods have on the thoracic spine

66   could lead to better understanding of treatment outcomes, both positive and negative.

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BACKGROUND

Growth preserving spine implants are commonly used in the surgical treatment of early onset scoliosis (EOS).[1] Because these patients are still growing, EOS is often a challenge to treat.[2] Currently, distraction based spine implants are the most commonly used in EOS treatment.[2–4]

Distraction based implants mechanically stabilize the spine and/or thorax in the hope of preventing spinal deformity progression while allowing for pulmonary development in a growing child.[5] Traditional "growing rods" utilize anchors on the spine, both cephalad and caudal to the curve apex. More recently, the use of ribs as cephalad anchor sites has been described as a hybrid to the traditional system.[6] The first description of a rib based distraction system, however, was by Campbell.[7,8] The VEPTR®/VEPTR II™ Vertically Expandable Prosthetic Titanium Rib Vertical Expandable Prosthetic Titanium Rib (VEPTR) was designed to treat children with thoracic insufficiency syndrome, defined as the inability of the thorax to support normal respiration or lung growth.[9]

A well- known challenge to surgeons and engineers alike is finding the right balance between having enough stability to prevent deformity progression and implant failure, and an acceptable amount of motion to prevent autofusion of the thoracic spine.[10–13]

Sankar described the law of diminishing returns with subsequent lengthening of growing rods, which was felt to likely be secondary to autofusion.[14] Cahill et al. reported an 89% incidence of autofusion in their series of 9 patients treated with growing rods.[15] Although rib based distraction is felt to maintain spinal growth,[16] the occurrence of unwanted ossification is still an issue with rib-based distraction systems [7,8] This problem complicates the effort of obtaining additional improvements in spinal balance at the time of definitive fusion.

While very little is known about the exact cause of autofusion, most feel it is the direct result of the spine being somewhat immobilized by rigid implants. Currently, there is little

93 biomechanical data regarding in-plane range of motion, out-of-plane range of motion, stiffness,

94 motion symmetry, or disc pressure within the thoracic spine under the constraint of a pediatric

95 unilateral distraction rod.[17–20] Motion, stiffness, and pressure experienced at an intervertebral joint

96 are all clinically rooted biomechanical measures that can be used to monitor the integrity of the

97 joint and the spine as a system.[21–24] By evaluating the implant biomechanics more closely, it may

98 be possible to improve clinical success and reduce complications and the need for multiple

99 procedures.

100 The goal of this study was to determine how a unilateral growth-friendly distraction rod

101 construct implanted in a simulated rib-to-lumbar attachment affects the kinematics, stiffness, and

102 loading of the thoracic spine. With this information, inferences regarding clinical performance

103 can be made. It was hypothesized that the implantation of the construct leads to (i) an increase in

104 in-plane elastic zone stiffness (EZS), in-plane neutral zone stiffness (NZS), out-of-plane range of

105 motion, and in-plane motion asymmetry, and (ii) a decrease in in-plane range of motion (ROM),

106 in-plane elastic zone range of motion (EZ), and in-plane neutral zone range of motion (NZ)

107 within the construct region compared to the intact cadaver specimen. As disc pressure increases

108 have been found adjacent to long constructs, increased disc pressure was expected adjacent to the

109 construct region.[25] However, no significant pressure differences were expected within the

110 construct region, based on the findings of Mahar et al.[26] Increased out-of-plane range of motion

111 was expected above the construct region, but no other biomechanical changes were expected.

MATERIALS AND METHODS

113 Five freshly frozen and thawed cadaveric thoracic spine specimens, three male, were

114 prepared to include vertebrae, intact rib cage, intervertebral discs, sternum, and stabilizing

115 ligaments from T1-T12. Mean age was 68 ± 3.6 years. Exclusion criteria included vertebral

116 fractures, severe scoliosis or kyphosis, and a history of spine surgery.

117   Potting parallel to the vertebral endplates at the superior (T1) and inferior (T12) ends of

118   the specimen allowed for secure attachment to the test machine. Seven Optotrak Orthopedic

119   Research Pin markers (Northern Digital Inc., Waterloo, ON, Canada) were inserted into the top

120   potting to denote T1, and the right pedicles at T2, T4, T5, T8, T9, and T11. Standard Needle Tip

121   Pressure Transducers (Gaeltech, Isle of Skye, Scotland) were inserted into the T4/T5 and T8/T9

122   discs. Implementation of the pressure transducers was based on Cripton et al.[27] Disc pressure data

123   was recorded using LabVIEW (National Instruments, Austin, TX, United States). A follower load

124   of 400 N was applied by threading a cable from the T1 potting through ball joint rod ends

125   connected to threaded rods inserted at T3-T11 vertebral body centers and hung off the T12 base

126   from pulleys, as first described by Sis et al.[28] (Unpublished data) A six degree component AMTI

127   MC5-6-5000 (AMTI, Inc., Watertown, MA) was mounted at the T12 specimen base to verify that

128   the resultant force acting on the spine was in the direction of the cable.

129   The FS20 Biomechanical Spine Test System (Applied Test Systems, Butler, PA) was

130   used to test specimens in lateral bending, flexion/extension, and axial rotation in displacement

131   control (1°/sec) to a load limit of ± 5 Nm for five cycles. The intact spines (T1-T12) were tested

132   first in all modes of bending. A unilateral VEPTR system was then proximally attached to the

133   right T5 rib, approximately 2.5 cm right lateral to the costotransverse joint. The distal attachment

134   was secured to the inferior potting, simulating a rigid attachment to the lumbar spine. The

135   specimen with VEPTR system attached was then tested in all modes of bending again. A

136   schematic of the setup is shown in Figure 1.

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142 T1
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144 T4
T5
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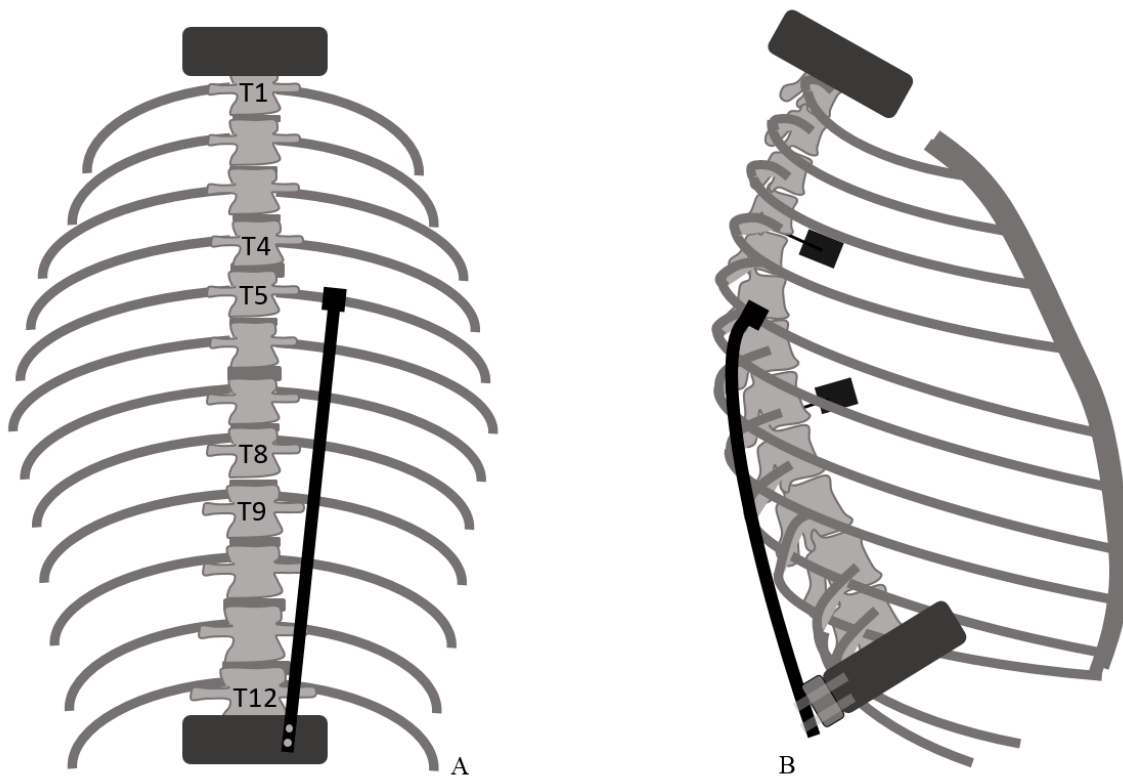
Figure 1a: Posterior View of Cadaver Specimen Setup. The specimen was potted at T1 and T12 with rib cage intact. Rod construct was proximally placed approximately 2.5cm right laterally to the costotransverse joint at the T5 level. The distal attached was rigidly affixed to the inferior potting, simulating a lumbar attachment.

Figure 1b: Lateral View of Cadaver Specimen Setup. Specimen were positioned such that the potting was parallel to the vertebral endplates. Needle tip pressure transducers we inserted into the intervertebral space at the T4/T5 level and T8/T9 level, as shown.

Customized MATLAB (MathWorks, Natick, MA, USA) programs were used to calculate stiffness and motion parameters using Euler decomposition techniques for both the intact and construct case. In-plane ROM and stiffness parameters and out-of-plane ROM were computed for all modes of bending in the T1-T4, T4-T8, and T8-T12 spinal segments and for the T1/T2, T4/T5, and T8/T9 spinal motion units.[29] Parameters from the third cycle of the intact case and the construct case were compared using two-tailed Wilcoxon Signed Ranks tests with 0.05 as the level of significance.

Results

165   The objective of this study was to determine the biomechanical differences caused by a growth-

166   friendly construct implanted in the thorax. Although significant differences between the intact

167   case and the construct case were expected in many parameters, very few significant differences

168   were found. The in-plane and out-of-plane ROM values are shown for spinal segments and spinal

169   motion units in Tables 1-3 for axial rotation, lateral bending, and flexion/extension, respectively.

170   In-plane stiffness values for both spinal segments and motion units are found in Table 4. Where

171   motion sensors were blocked by the construct or the sensor resolution was too low to accurately

172   capture the motion, biomechanical parameters could not be calculated.

173   The hypotheses proposed for the areas above and within the construct region were not

174   supported by the data. Of all the parameter comparisons between the intact and construct case,

175   only four were statistically significant. With the construct attached, the T4-T8 segment had an

176   11% decrease in ROM and the T8-T12 segment had a 44% ROM decrease during extension ($p =$

177   0.04); the T8-T12 segment experienced a 63% ROM reduction during flexion ($p = 0.04$); the T4-

178   T8 segment had a significant decrease of 12% in EZ ROM during axial rotation ($p = 0.04$); and

179   the out-of-plane motion in the sagittal plane during lateral bending significantly increased by

180   293% ($p=0.04$). No significant differences were found in the other in-plane motion, in-plane

181   stiffness, out-of-plane motion, disc pressure, or symmetry between the intact and construct case

182   for either segments or motion units.

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Table 1. Intact and Construct In-plane and Out-of-plane Range of Motion Averages for Spinal Segments during Axial Rotation

In-plane and out-of-plane range of motion for the upper, mid, and lower thoracic regions of axial rotation are presented here. During axial rotation, the primary plane is the axial plane; the secondary plane is the coronal plane; and the tertiary plane is the sagittal plane. The averages are of the intact and construct cases as groups; however, the statistical analysis was a paired difference test between individual specimens within the group. All ROM values are presented in degrees.

Region/Level	State	RIGHT ROTATION			LEFT ROTATION		
		Axial	Coronal	Sagittal	Axial)	Coronal	Sagittal
T1-T4	Intact	7.02 ± 4.22	1.18 ± 0.78	5.76 ± 1.45	1.91 ± 1.40	1.31 ± 0.88	5.97 ± 1.42
	Construct	7.35 ± 5.45	1.43 ± 0.32	4.63 ± 1.95	7.27 ± 5.41	1.47 ± 0.33	4.71 ± 1.91
T4-T8	Intact	7.09 ± 2.30	2.48 ± 1.68	3.02 ± 0.89	7.17 ± 2.28	2.43 ± 1.76	2.99 ± 0.85
	Construct	6.37 ± 2.45	2.37 ± 1.49	2.78 ± 1.00	6.39 ± 2.45	2.38 ± 1.54	2.82 ± 0.97
T8-T12	Intact	11.39 ± 3.22	4.96 ± 2.12	3.91 ± 3.16	11.47 ± 4.18	4.81 ± 1.94	3.85 ± 2.85
	Construct	11.20 ± 4.12	5.83 ± 2.75	4.86 ± 3.91	11.17 ± 4.17	5.68 ± 2.78	4.86 ± 3.98

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Table 2. Intact and Construct In-plane and Out-of-plane Range of Motion Averages for Spinal Segments during Lateral Bending

In-plane and out-of-plane range of motion for the upper, mid, and lower thoracic regions of lateral bending are presented here. During lateral bending, the primary plane is the coronal plane; the secondary plane is the axial plane; and the tertiary plane is the sagittal plane. The averages are of the intact and construct cases as groups; however, the statistical analysis was a paired difference test between individual specimens within the group. All ROM values are presented in degrees.

Region/ Level	State	RIGHT BENDING			LEFT BENDING		
		Coronal	Axial	Sagittal	Coronal	Axial	Sagittal
T1-T4	Intact	0.69 ± 0.41	5.80 ± 5.19	1.96 ± 2.22	-	-	-
	Construct	1.04 ± 0.56	6.98 ± 4.29	1.91 ± 2.12	-	-	-
T4-T8	Intact	0.70 ± 0.81	3.07 ± 1.92	0.46 ± 0.58	0.63 ± 0.64	2.51 ± 1.93	0.45 ± 0.48
	Construct	0.58 ± 0.44	2.86 ± 1.45	0.62 ± 0.53	0.47 ± 0.38	2.40 ± 1.61	0.59 ± 0.48*
T8-T12	Intact	5.98 ± 3.25	1.94 ± 1.35	2.36 ± 0.94	5.01 ± 3.46	1.54 ± 1.17	1.95 ± 1.33
	Construct	6.35 ± 3.29	1.95 ± 1.51	2.46 ± 1.51	5.40 ± 3.50	1.61 ± 1.46	1.94 ± 1.70

Table 3. Intact and Construct In-plane and Out-of-plane Range of Motion Averages for Spinal Segments during Flexion/Extension

In-plane and out-of-plane range of motion for the upper, mid, and lower thoracic regions of flexion/extension are presented here. During flexion/extension, the primary plane is the sagittal plane; the secondary plane is the coronal plane; and the tertiary plane is the axial plane. The averages are of the intact and construct cases as groups; however, the statistical analysis was a paired difference test between individual specimen within the group. The asterisk denotes a significant paired differences in the paired comparison of the range of motion between intact and construct case. All ROM values are presented in degrees.

Region/ Level	State	FLEXION			EXTENSION		
		Sagittal	Coronal	Axial	Sagittal	Coronal	Axial
T1-T4	Intact	4.12 ± 3.39	7.27 ± 6.05	3.32 ± 4.80	1.91 ± 1.40	7.25 ± 6.14	3.41 ± 4.94
	Construct	3.53 ± 2.77	7.05 ± 6.00	3.29 ± 4.35	1.93 ± 0.94	6.84 ± 6.09	3.65 ± 5.14
T4-T8	Intact	1.75 ± 1.30	3.18 ± 1.87	1.08 ± 1.23	1.18 ± 0.95	3.16 ± 1.89	1.09 ± 1.22
	Construct	1.28 ± 1.64	3.25 ± 1.93	0.92 ± 0.91	$1.05 \pm 0.92*$	3.05 ± 2.06	1.01 ± 1.04
T8-T12	Intact	3.01 ± 1.69	4.62 ± 1.91	1.42 ± 1.24	2.44 ± 1.21	4.57 ± 1.99	1.38 ± 1.28
	Construct	$1.14 \pm 1.38*$	4.03 ± 2.20	1.35 ± 1.93	$1.37 \pm 1.13*$	3.84 ± 2.40	1.48 ± 1.95

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Table 4. Intact and Construct Stiffness Averages

Elastic zone stiffness (EZS) and neutral zone stiffness (NZS) for the upper, mid, and lower thoracic regions and motion units T1/T2, T4/T5, and T8/T9 are presented here. The asterisk denotes a significant paired differences in the stiffness between pre- and post- implantation of the rod system. All stiffness values are presented in degrees per Newton-meter (°/Nm).

Region /Level	State	RIGHT ROTATION		LEFT ROTATION		RIGHT BENDING		LEFT BENDING		FLEXION		EXTENSION	
		EZS	NZS	EZS	NZS	EZS	NZS	EZS	NZS	EZS	NZS	EZS	NZS
T1-T4	Intact	2.4 ± 1.4	1.5 ± 0.8	4.4 ± 3.9	1.5 ± 0.9	8.5 ± 5.1	-	-	-	2.6 ± 2.2	1.9 ± 1.2	4.6 ± 2.5	0.8 ± 0.6
	Construct	1.9 ± 1.4	1.6 ± 1.2	3.9 ± 3.0	1.5 ± 1.0	8.7 ± 1.3	-	-	-	2.1 ± 2.4	1.8 ± 1.3	3.0 ± 1.3	1.0 ± 0.6
T4-T8	Intact	2.0 ± 1.2	1.2 ± 0.4	5.3 ± 7.2	1.1 ± 0.3	-	-	-	-	5.1 ± 6.1	3.1 ± 1.3	5.7 ± 4.1	3.9 ± 5.0
	Construct	2.1 ± 0.4	1.1 ± 0.4	2.2 ± 0.4	1.1 ± 0.4	-	-	-	-	3.5 ± 1.6	3.3 ± 1.4	8.3 ± 3.9	5.4 ± 4.8
T8-T12	Intact	2.3 ± 2.1	0.7 ± 0.3	3.1 ± 3.3	0.7 ± 0.3	0.9 ± 0.4	2.6 ± 1.2	4.0 ± 5.9	3.3 ± 2.2	1.3 ± 0.3	1.6 ± 1.0	1.9 ± 1.1	1.0 ± 0.7
	Construct	1.6 ± 0.5	0.7 ± 0.4	1.8 ± 0.9	0.7 ± 0.4	1.4 ± 0.7	2.1 ± 0.9	1.8 ± 0.6	4.4 ± 3.4	3.9 ± 2.9	2.3 ± 0.8	5.0 ± 2.0	2.9 ± 2.7

DISCUSSION

The purpose of the growth-friendly rod construct is to provide stability to the thorax during development while preventing negative biomechanical changes; however, the ideal amount of stability for the construct to provide has not been determined. The challenge is to balance the distractive forces of the implant with the forces progressing the deformity. Too little rigidity and force could mean too little correction or retracting correction, perpetuating a poor quality of life; too much rigidity and force can lead to ossifications, rib dislocations, rib fracture, and subsidence.[6,12,30–35]

Understanding the biomechanical effect corrective constructs have on the thoracic system provides a better understanding of the clinical effect as well. Because the spine is a linked system, the rod attachment and simulated lumbar attachment altered biomechanical parameters outside and within the construct region. Because of the comparably flexible nature of rib-attached constructs, few changes occurred near and between attachment sites than initially expected. It is well known that the type of construct affects the resulting biomechanical parameters, with more rigid constructs causing greater biomechanical differences. Rod material, number of rods, addition of cross connectors, and rod attachment types have all been shown to increase the stiffness and/or decrease the mobility of the spine.[17–20,36,37] Other studies have shown that a less rigid construct produces fewer adjacent level changes.[20] This study utilized a rod construct with a simulated rib-to-lumbar attachment, producing a comparably flexible system, which had not been tested previously.

Very few studies have been conducted to determine the biomechanical effect of VEPTR system. The two major innovations of this study, inclusion of the rib cage and the unconstrained superior motion, were implemented to create testing conditions more similar to clinical conditions. The inclusion of the rib cage has significant effect on the thoracic biomechanics.[38,39] With rib attached constructs, including or at least simulating the rib cage is vital in biomechanical

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251 tests. While trends with previous research may be similar, it is difficult to draw direct

252 comparisons due to the inclusion of the rib cage in the present study. For example, a study by

253 Rodriguez-Martinez et al. implemented four variations of long rod constructs in the thoracic spine

254 and found the greatest motion variation in the sagittal plane.[40] Similarly, the present study also

255 found the greatest motion changes occurred in the sagittal plane. However, the 75%-76% loss of

256 sagittal motion in that study is not similar to the 24%-58% loss of sagittal motion that was found

257 in the present study.[40] While implementing this innovation prohibits direct comparisons to other

258 research in the field, it provides a better mechanism for studying biomechanical changes in

259 deformities and treatments of the thoracic spine.

260   Intradiscal pressure has not previously been investigated in a growth-friendly distraction rod

261 model, but has been shown to be an important indicator for disc degeneration and therefore is

262 important to investigate.[24] Some studies found significant intradiscal pressure changes in single

263 level fusions and others found significant trends that suggest these pressure changes increase with

264 increasing construct length.[25,41,42] However, this is not the case for all studies. One study

265 investigated the disc pressure at two levels between attachment points in long rod constructs

266 meant for definitive fusions, one level directly adjacent to the superior attachment and one level

267 in the midpoint between the two attachment sites. At both disc locations, no significant pressure

268 changes were noted, which agrees with the findings of the current study.[26] Another study showed

269 that at the level adjacent to the superior attachment, intradiscal pressure was reduced when a less

270 rigid construct was implemented.[43] Despite the length of the construct, more flexible systems are

271 able to avoid pressure changes at the adjacent level. The construct used in the current study

272 allowed for more similar loading above the construct and between construct attachment points,

273 resulting in no significant intradiscal pressure changes at the level adjacent to the superior

274 attachment site or within the construct region.

275   Clinically, many construct variations have provided the needed rigidity to stabilize the thorax

276   during childhood development, but have resulted in complications caused by biomechanical

277   changes to the adjacent levels and the region as a whole. Ossifications at the attachment sites,

278   along the implant, between ribs, and between vertebrae have been found with differeing level of

279   incidence.[10–12,30,31,34] These ossifications are thought to contribute to curve stiffening.[11,12,30,35]

280   Anchor point migration is a common occurrence with these devices,[6,12,30–35] and in some cases rib

281   fracture or dislocation has occurred.[30,32–35] These issues are seen in rib-to-rib, rib-to-lumbar, and

282   rib-to-pelvis variations of these constructs to varying degrees. Because the prevalence varies

283   based on the type or configuration of the construct, there seems to be an underlying

284   biomechanical cause for these complications. Ossifications most often occurred at attachments at

285   the lumbar spine and were more prevalent when the construct had a high rate of load sharing and

286   when the curve correctability was lower, indicating a stiffer thoracic curve.[10,12] By design,

287   repeated pressure is applied at attachment sites. This allows for flexibility of the construct, which

288   mitigates rib fracture and dislocation, but leaves the periosteum suseptible to injury and

289   subsequent ossification.[12]

290   To the authors' knowledge, this pilot study was the first of its kind to investigate the in-plane

291   and out-of-plane motion biomechanics, as well as intradiscal pressure, of a growth-friendly

292   construct in a thoracic spine and rib cage model. While this type of investigation helps to

293   characterize the biomechanical changes brought on through this type of treatment, there are

294   limitations of this study design. The spines used were not representative of an early onset

295   scoliosis population, both in terms of age and deformity characteristics. Bone quality as well as

296   anatomic geometry would have an effect on the biomechanical parameters, and these were not

297   appropriately simulated in an older adult cadaveric model. This type of device is typically

298   tensioned to apply a distraction force and no such force was applied in this study. Applying

299   clinically relevant tension could affect the biomechanics of the region. A more accurate model,

300 including rod tensioning should be investigated in the future. With the sample size in this pilot

301 study, true differences between the intact and construct case were difficult to discern.

302   From the interpretations of this data, several interesting areas of further investigation emerge.

303 As rib migration and dislocation occurs clinically, tracking the movement of both the construct

304 and rib head could provide insight as to what biomechanical changes cause these clinical

305 complications. Further work could expand upon this study to investigate the motion and stiffness

306 differences at the costovertebral joint and pressure changes at the rib fixation point. The motion

307 and pressure at these sites are more directly tied to complications seen clinically. Additionally,

308 distraction forces similar to those applied during surgery should be used for further

309 biomechanical investigation.

310   In conclusion, understanding the biomechanical effect of implants within the body is

311 paramount, as it helps to improve treatments and reduce complications. This study investigated

312 the biomechanics of a unilateral growth-friendly construct in a simulated rib-to-lumbar

313 attachment and found very few biomechanical changes above or within the construct region.

314 Research suggests the biomechanical changes seen here are primarily caused by the type of

315 construct used, as more flexible constructs are less disruptive of native spinal biomechanics. It is

316 clear the device as tested here does not produce large biomechanical changes, but the balance

317 between providing desired changes while preventing complications remains difficult.

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Chapter 7 Conclusion

This research sought to develop a set of kinematic parameters for development and validation of an analogue AIS spine model, representing both the anatomy and biomechanics of the deformity. This model could be used for medical education and treatment development and testing. To provide a full set of kinematic parameters, the effect of deformity and treatment needed to be characterized. This was accomplished through (i) characterization of typical adolescent spine biomechanics in Chapter 4, (ii) characterization of AIS spine biomechanics in right thoracic curves only in Chapter 5, (iii) comparison of the TA and AIS spine kinematics in Chapter 6, and (iv) biomechanical assessment of a growth-friendly scoliosis correction construct in Chapter 7.

In Chapter 4 the thoracic and thoracolumbar mobility of a typical adolescent population was characterized. While it was hypothesized that gender differences in mobility, age relationships with mobility, and motion symmetry would exist, few differences were significant. Both males and females had symmetric motion and there were no gender-based significant differences in thoracic mobility measures. This suggests that males and females can be combined when performing analyses of thoracic biomechanics in adolescents.

In Chapter 5 AIS mobility in the thoracic and thoracolumbar regions was characterized. Correlations between mobility and chronological age, skeletal maturity, and curve severity were investigated. While age had some significant positive correlations with mobility, skeletal maturity measures, which correlate positively with age, had significant negative correlations with mobility. Curve severity had mixed correlations with mobility, indicating motion may depend on

the location within the deformity. This should be further investigated in a larger population of AIS patients with right thoracic curves.

Chapter 6 compared thoracic and thoracolumbar mobility in the TA and AIS populations. Though it was expected the AIS participants would have a comparatively reduced spinal mobility, this was not the case. In several instances, the AIS group had greater mobility, mostly in regions directly above or below the curve apex. This suggests a possible compensation effect where the areas around the curve apex exhibit increased mobility to compensate for reduced motion at the apex. While other studies have observed a tethering effect near the apex, no significant difference was seen here.

In Chapter 7, the biomechanical change brought on by scoliosis treatment was evaluated in an *in vitro* model. Range of motion, stiffness, and intradiscal pressure were compared in an intact thoracic spine with rib cage before and after implantation of a rib-to-spine unilateral rod construct. Above the construct, no changes were expected, but a significant increase in stiffness was noted in the upper thoracic segment. There was also a significant decrease in range of motion, during flexion, and a significant decrease in stiffness, during left axial rotation, between the attachment sites. Overall there were very few significant changes with implantation of the growth-friendly system. This is most likely due to the relatively flexible nature of the construct and its rib attached design, which allows for additional flexibility at the superior end. Other scoliosis correction systems should be tested in a complete thoracic model to provide accurate kinematic parameters with which to quantify the biomechanical effect of treatment.

These studies provided a database for normative and AIS mobility in the thoracic and thoracolumbar spine. The final study specifically provided information about the biomechanics of treatment with a scoliosis correction rod construct. The kinematic information about normal, deformed, and treated spines can be used to develop and/or validate an analogue spine model depicting an adolescent with or without AIS. A biomechanically and anatomically accurate model is vital for medical education and development and testing for medical devices specific to an adolescent population. Future work can expand on the research completed by investigating axial rotation and lumbar mobility in all populations, expanding the AIS research into other curve types, and testing other scoliosis correction constructs or braces in cadavers. This would supplement the database of kinematic information established in these studies and work to full characterize the adolescent spinal mobility of those both with and without scoliosis.

Chapter 8 Appendices

Appendix A. IRB Approval Documents

A1. University of Kansas IRB Approval Letter

11/30/11
HSCL #19432

Nikki Johnson
MECH ENG
3139 Learned Hall

The Human Subjects Committee Lawrence has received your response to its full IRB review of your research project,

19432 Johnson/Wilson (MECH ENG) Lumbar-Pelvic Motion Analysis in Children with Scoliosis

and found that it complied with policies established by the University for protection of human subjects in research. The subjects will be at minimal risk. Unless renewed, approval lapses one year after approval date.

The Office for Human Research Protections requires that your consent form must include the note of HSCL approval and expiration date, which has been entered on the consent form sent back to you with this approval.
HSCL also approves your flyer.

1.   At designated intervals until the project is completed, a Project Status Report must be returned to theHSCL office.

2.   Any significant change in the experimental procedure as described should be reviewed by this Committee prior to altering the project.

3.   Notify HSCL about any new investigators not named in original application. Note that new investigators must take the online tutorial at http://www.rcr.ku.edu/hscl/hsp_tutorial/000.shtml.

4.	Any injury to a subject because of the research procedure must be reported to the Committee immediately.

5.	When signed consent documents are required, the primary investigator must retain the signed consent documents for at least three years past completion of the research activity. If you use a signed consent form, provide a copy of the consent form to subjects at the time of consent.

6.	If this is a funded project, keep a copy of this approval letter with your proposal/grant file.

Please inform HSCL when this project is terminated. You must also provide HSCL with an annual status report to maintain HSCLapproval. Unless renewed, approval lapses one year after approval date. If your project receives funding which requests an annual update approval, you must request this from HSCL one month prior to the annual update. Thanks for your cooperation. If you have any questions, please contact me.

Sincerely,

Jan Butin
Associate Coordinator
Human Subjects Committee -
Lawrence
cc: Sara Wilson

A2. University of Kansas Consent Form

PARENT-GUARDIAN INFORMED CONSENT STATEMENT

Lumbar-Pelvic Motion Analysis in Children with Scoliosis

INTRODUCTION

The Department of Mechanical Engineering at the University of Kansas supports the practice of protection for human subjects participating in research. The following information is provided for you to decide whether you wish your child to participate in the present study. You may refuse to sign this form and not allow your child to participate in this study. You should be aware that even if you agree to allow your child to participate, you are free to withdraw at any time. If you do withdraw your child from this study, it will not affect your relationship with this unit, the services it may provide to you, or the University of Kansas.

PURPOSE OF THE STUDY

The purpose of this study is to see how children and young adults coordinate their low back motion during different activities and the effects of scoliosis on this coordination. A better understanding of dynamic back motion and the effect of scoliosis on this motion will help physicians to better understand scoliosis and to design methods to treat it.

PROCEDURES

Your child's participation in this study will involve a single session of approximately one and a half hours in duration. Children with and without scoliosis are being recruited in order to understand the differences between these two groups. If you and your child choose to participate, your child will have markers placed along her/his back and at the base of his/her collar. These markers are a magnetic system that measure movement of the back. They will be attached to your child's skin using tape. Your child will be asked to do a series of movements while wearing these markers. These movements may include:

1. Your child will be asked to flex and extend his/her low back as much as possible in up to three bending positions.
2. Full range motions. Your child will be asked to flex, extend, rotate, and laterally bend her/his trunk as far as possible up to thirty times.
3. Flexion Relaxation. Your child will be asked to flex his/her back and hold it in position for up to ten minutes up to three times.
4. Lifting. Your child will lift a crate with up to 15% of his/her body weight. This will be done at both a fast and slow speed up to twelve times.

For both participant populations, height, weight, age and gender will be recorded. For the scoliosis population, medical information including: Lenke type, Cobb angle, past treatment, and previous x-rays will be recorded and matched to a participant number. For the control population, no medical records will be obtained from physicians. All data will be kept confidential and will be stored by participant number. No identifying information will be kept or linked to each individual participant.

RISKS

There are few risks involved in this experiment. It is possible that your child might be allergic to tape and react to the tape used in the experiment. If your child is allergic to band-aids or similar adhesives, please let the investigator know and alternate methods (such as elastic or Velcro straps) will be used to attach the markers. It is also possible that your child may experience muscle soreness such as might occur after normal exercise. As with any physical task there is a small possibility of low back injury.

BENEFITS

There are no direct benefits to you or your child from participating in this experiment. We expect that this study should be reasonably fun for the children and young adults participating. Our improved understanding of scoliosis from this study will be of benefit to orthopedic surgeons in learning more about scoliosis in general.

PAYMENT TO PARTICIPANTS

There will be no payments made to participants.

PARTICIPANT CONFIDENTIALITY

Your child's name will not be associated in any way with the information collected about your child or with the research findings from this study. The researcher(s) will use a study number or a pseudonym instead of your name.
Some persons or groups that receive your health information as described above may not be required to comply with the Health Insurance Portability and Accountability Act's privacy regulations, and your health information may lose this federal protection if those persons or groups disclose it.

The researchers will not share information about your child with anyone not specified above unless (a) it is required by law or university policy, or (b) you give written permission.

Permission granted on this date to use and disclose your information remains in effect indefinitely. By signing this form you give permission for the use and disclosure of your information for purposes of this study at any time in the future.

INSTITUTIONAL DISCLAIMER STATEMENT

In the event of injury, the Kansas Tort Claims Act provides for compensation if it can be demonstrated that the injury was caused by the negligent or wrongful act or omission of a state employee acting within the scope of his/her employment.

REFUSAL TO SIGN CONSENT AND AUTHORIZATION

You are not required to sign this Consent and Authorization form and you may refuse to do so without affecting your right to any services you are receiving or may receive from the University of Kansas or to participate in any programs or events of the University of Kansas. However, if you refuse to sign, your child cannot participate in this study.

CANCELLING THIS CONSENT AND AUTHORIZATION

You may withdraw your consent to allow participation of your child in this study at any time. You also have the right to cancel your permission to use and disclose further information collected about your child, in writing, at any time, by sending your written request to:

Sara E. Wilson, Ph.D.   OR   Lisa Friis, PhD
3013 Learned Hall   3134 Learned Hall
Mechanical Engineering   Mechanical Engineering
University of Kansas   University of Kansas
Lawrence, KS 66045   Lawrence, KS 66045
(785) 864-2103   (785) 864-2104

If you cancel permission to use your child's information, the researchers will stop collecting additional information about your child. However, the research team may use and disclose information that was gathered before they received your cancellation, as described above.

QUESTIONS ABOUT PARTICIPATION

I have read the information in this form. The investigators have answered my and your child's questions to our satisfaction. We know if we have any more questions after signing this form, we may contact Sara E. Wilson, Ph.D. (785) 864-2103, Dr. Anderson, Dr. Schwinn, or Dr. Price. If I have any questions about your child's rights as a research subject, I may call (913) 588-1240 or write the Human Subjects Committee, University of Kansas, 2385 Irving Hill Rd. Lawrence, KS 66045-7563

PARTICIPANT CERTIFICATION:

I have read this Consent and Authorization form. I have had the opportunity to ask, and I have received answers to, any questions I had regarding the study. I understand that if I have any additional questions about your child's rights as a research participant, I may call (785) 864-7429, write to the Human Subjects Committee Lawrence Campus (HSCL), University of Kansas, 2385 Irving Hill Road, Lawrence, Kansas 66045-7568, or email irb@ku.edu.

I agree to allow your child to take part in this study as a research participant. By my signature I affirm that I have received a copy of this Consent and Authorization form.

_____   _____

Type/Print Participant's Name Date

_____

Parent/Guardian Signature

Researcher Contact Information

Sara E. Wilson, Ph.D. Lisa Friis, Ph.D.

3013 Learned Hall 3134 Learned Hall

Mechanical Engineering Mechanical Engineering

University of Kansas University of Kansas

Lawrence, KS 66049 Lawrence, KS 66049

(785) 864-2103 785-864-2104

KU Lawrence IRB # 19432 | Approval Period 11/18/2013 – 11/30/2014

A3. University of Kansas Assent Form

Lumbar-Pelvic Motion Analysis in Children with Scoliosis
Children's Assent

I am interested in finding out how your back moves so I would like you to take part in some activities that will today that will last about an hour and a half. I will tape little plastic cubes on your back that act like cameras so I can record the way your back moves when you bend and twist. If you don't want to do the activities, you don't have to, and you can stop doing them at anytime and that will be all right. I will be happy to answer any questions you may have now or during the activities. Do you want to take part in this project?

_____

Signature of Child/Adolescent Subject

KU Lawrence IRB # 19432 | Approval Period 11/18/2013 – 11/30/2014

A4. University of Kansas HIPPA Authorization

Authorization to Use or Disclose (Release) Health Information that Identifies Your Child for a Research Study

1. Purpose. Your child has been asked to be part of a research study under the direction of , Drs. Lisa Friis and Sara Wilson, and her research team. If you sign this document, you give permission to Dr. Lisa Friis, Dr. Wilson and their research team at the University of Kansas and researchers at Children's Mercy Hospital to use or disclose (release) your child's health information that identifies your child for the research study described here:

The lumbar motion study will compare the spinal movements of adolescents with and without scoliosis to better understand how this condition affects the spine.

2. Health Information to be used or Disclosed. The health information that may be used or disclosed (released) for this research includes: For both participant populations, height, weight, age and gender will be recorded. For the scoliosis population, medical information including: Lenke type, Cobb angle, past treatment, and previous x-rays will be obtained.

3. Recipient(s) of the Health Information. The health information listed above may be used by and/or disclosed (released) to: Dr. Lisa Friis, Dr. Wilson and their research team at the University of Kansas and researchers at Children's Mercy Hospital working on this project. Your child's health information may be shared with others outside of the research group for purposes directly related to the conduct of this research study or as required by law, including but not limited to: researchers at the University of Kansas and Children's Mercy Hospital.

Your child's information may also be shared with individuals or entities responsible for general administration, oversight and compliance of research activities. Examples include internal oversight staff, Safety Monitoring Boards, an Institutional Review Board, or certain government oversight agencies that have authority over the research. Your child's information may also be shared with other entities as required by law. No publication or public presentation about the research described above will reveal your child's identity without another authorization from you. If all information that does or can identify your child is removed from your health information, the remaining information will no longer be subject to this authorization and may be used or disclosed for other purposes.

4. Potential for Redisclosure. The University of Kansas and Children's Mercy Hospital are required by law to protect your child's health information. By signing this document, you

authorize The University of Kansas and Children's Mercy Hospital to use and/or disclose (release) your child's health information for this research. Those persons who receive your health information may not be required by Federal privacy laws (such as the Privacy Rule) to protect it and may share your information with others without your permission, if permitted by laws governing them.

5. Expiration Date. This Authorization does not have an expiration date.

6. Right to Refuse to Sign this Authorization. You do not have to sign this authorization, but if you do not, your child may not be allowed to participate in this study or receive any research related treatment that is provided through the study. Your decision not to sign this authorization will not affect any other treatment, payment, or enrollment in health plans or eligibility for benefits.

7. Right to Revoke this Authorization. Please note that you may change your mind and revoke (take back) this Authorization at any time, except to the extent that the University of Kansas and Children's Mercy Hospital have already acted based on this Authorization. To revoke this Authorization, you must write to:

Sara E. Wilson, Ph.D.　　　　OR　　　　　Lisa Friis, PhD
3013 Learned Hall　　　　　　　　　　　　3134 Learned Hall
Mechanical Engineering　　　　　　　　　 Mechanical Engineering
University of Kansas　　　　　　　　University of Kansas
Lawrence, KS 66045　　　　　　　　Lawrence, KS 66045
(785) 864-2103　　　　　　　　　　　　(785) 864-2104

If you revoke this Authorization, your child may no longer be allowed to participate in the research described in this Authorization.

_____
Signature of participant or participant's personal representative

_____
Date

_____
Printed name of participant or participant's personal representative

_____
If applicable, a description of the personal representative's authority to sign for the participant

INFORMED CONSENT STATEMENT

Characterization of Trunk Motion in an Adolescent Idiopathic Scoliosis (AIS) Population

You are being asked to join a research study because you have adolescent idiopathic scoliosis. You do not have to participate in this research study. The main purpose of research is to create new knowledge for the benefit of future patients and society in general. Research studies may or may not benefit the people who participate.

Research is voluntary, and you may change your mind at any time. There will be no penalty to you if you decide not to participate, or if you start the study and decides to stop early. Either way, you can still get medical care and services at the University of Kansas Medical Center (KUMC) and/or Children's Mercy Hospitals (CMH).

This consent form explains what you will have to do if you are in the study. It also describes the possible risks and benefits. Please read the form carefully and ask as many questions as you need to, before deciding about this research.

You can ask questions now or anytime during the study. The researchers will tell you if they receive any new information that might cause you to change your mind about participating.

This research study will take place at the University of Kansas Medical Center (KUMC) and at Children's Mercy Hospital (CMH) with Dr. Doug Burton (KUMC) , Dr. John Anderson (CMH), Dr. Nigel Price (CMH), and Dr. Richard Schwend (CMH) and Nikki Galvis as the researchers. About 40 people will be in the study at KUMC and up to 120 people will be in the study at CMH. A total of about 160 people will be in the study at 2 centers across the United States.

BACKGROUND

Scoliosis is known to profoundly affect normal trunk motion and balance. However, current findings in the field provide an incomplete understanding of how the structural asymmetry affects specific spinal motions. Therefore normal trunk motion of the scoliosis population must be established to identify the changes due solely to the structural changes of scoliosis. Specifically, we will investigate the symmetry of motion, range of motion, and motion mechanics of this population. Learning more about the limitations and changes caused by scoliosis will help researchers development better treatment options in the future.

PURPOSE OF THE STUDY

The purpose of this study is to see how children and young adults coordinate their low back motion during different activities and the effects of scoliosis on this coordination. A better understanding of dynamic back motion and the effect of scoliosis on this motion will help physicians to better understand scoliosis and to design methods to treat it.

PROCEDURES

Your participation in this study will involve a single session of approximately one hour in duration.
This research study will take place at the following locations:

Testing Location	Parent's Initials	Child's Initials
1. University of Kansas Medical Center (KUMC)	_____	_____
2. Children's Mercy Hospital (CMH)	_____	_____
3. Other _____	_____	_____

Other testing locations include the patient's home or an affiliated KUMC clinic.
Children with and without scoliosis are being recruited in order to understand the differences between these two groups. If you choose to participate, you will have markers placed along your back and at the base of your collar. These markers are a magnetic system that measure movement of the back. They will be attached to your skin using tape. You will be asked to do a series of movements while wearing these markers. These movements will include:
1. Flexion/Extension: Subjects are asked to bend as far as possible in each direction while keeping their knees straight.
2. Lateral Bending: Subjects are asked to bend as far as possible to each side while keeping their knees straight and feet flat on the ground

3. Torsion: Subjects are asked to twist as far as possible in each direction while keeping their knees and hips straight

4. Asymmetrical bending: Subjects are asked to bend as far as possible towards a mark on the platform, 45 degrees off mid-line, while keeping their knees and hips straight.

For the scoliosis population, medical information including the type and severity of the scoliosis and treatment history for your scoliosis will be given to the research team by your physician. For the control population, no medical records will be obtained from physicians. All data will be kept confidential and will be identified by subject number rather than by name.

RISKS

There are few risks involved in this experiment. It is possible that you might be allergic to tape and react to the tape used in the experiment. If you are allergic to band-aids or similar adhesives please let the investigator know and alternate methods will be used to attach the markers. It is also possible that you may experience muscle soreness such as might occur after normal exercise. As with any physical task there is a small possibility of low back injury. Although we have established protections against it, there is still a slight risk of a breach of confidentiality. To prevent this from occurring, all data is stored under encryption and identified with subject number rather than name wherever possible.

BENEFITS

There are no direct benefits to you from participating in this experiment. We expect that this study should be reasonably fun for the children and young adults participating. Our improved understanding of scoliosis from this study will be of benefit to orthopedic surgeons in learning more about scoliosis in general.

ALTERNATIVES

Your participation in this study is voluntary. This information is provided for you to decide whether you wish to participate in the present study. You may refuse to sign this form and choose not to participate in this study. You should be aware that even if you agree to participate, you are free to withdraw at any time. If you do withdraw from this study, it will not affect your relationship with this unit, the services it may provide to you, or the University of Kansas or Children's Mercy Hospital.

COSTS/PAYMENT

There is no cost for being in this study. There is no payment for this study.

IN THE EVENT OF INJURY
If you have a serious side effect or other problem during this study, you should immediately contact Dr. Sara Wilson at 785 864 2103. A member of the research team will decide what type of treatment, if any, is best for you at that time.

INSTITUTIONAL DISCLAIMER STATEMENT

If you think you have been harmed as a result of participating in research at the University of Kansas Medical Center (KUMC), you should contact the Director, Human Research Protection Program, Mail Stop #1032, University of Kansas Medical Center, 3901 Rainbow Blvd., Kansas City, KS 66160. Under certain conditions, Kansas state law or the Kansas Tort Claims Act may allow for payment to persons who are injured in research at KUMC.

In the case of illness or injury resulting from this study, treatment is available at The Children's Mercy Hospitals & Clinics, but will be provided at the usual charge. Payment for this treatment will be your responsibility. The hospital may not bill insurance or other third party payers for this care. The Children's Mercy Hospitals & Clinics does not have funds set aside to pay research participants if the research results in injury. By signing this form, you, or your child, are not giving up any legal rights to seek compensation for injury.

CONFIDENTIALITY AND PRIVACY AUTHORIZATION

The researchers will protect your information, as required by law. Absolute confidentiality cannot be guaranteed because persons outside the study team may need to look at your study records. The researchers may publish the results of the study. If they do, they will only discuss group results. Your name will not be used in any publication or presentation about the study.

Your health information is protected by a federal privacy law called HIPAA. By signing this consent form, you are giving permission for KUMC or CMH to use and share your health information. If you decide not to sign the form, you cannot be in the study.

The researchers will only use and share information that is needed for the study. To do the study, they will collect health information from the study activities and from your medical record. You may be identified by information such as name, address, phone, date of birth, social security number, or other identifiers. Your health information will be used at KU Medical

Center by Dr. Burton, at CMH by Dr. Anderson, Dr. Price, or Dr. Schwend, members of the research team, the University of Kansas Hospital Medical Record Department, the CMH Medical records Department, the KUMC Human Subjects Committee, the CMH Human Subjects Committee, and other committees and offices that review and monitor research studies. Study records might be reviewed by government officials who oversee research, if a regulatory review takes place.

All study information that is sent outside KU Medical Center or the Children's Mercy Hospital will have your name and other identifying characteristics protected through encryption, so that your identity will not be known to those outside the study, unless required by law. Because identifiers will be encrypted, child's health information will not be re-disclosed by outside persons or groups and will not lose its federal privacy protection

Your permission to use and share your health information remains in effect until the study is complete and the results are analyzed. After that time, researchers will remove personal information from study records.

Questions

Before you sign this form, Dr. Burton, Dr. Anderson, Dr. Schwend, Dr. Price, or other members of the study team should answer all your questions. You can talk to the researchers if you have any more questions, suggestions, concerns or complaints after signing this form. If you have any questions about your rights as a research subject, or if you want to talk with someone who is not involved in the study, you may call the Human Subjects Committee at (913) 588-1240 or the CMH Human Subjects Committee at (816) 701-1348. You may also write the Human Subjects Committee at Mail Stop #1032, University of Kansas Medical Center, 3901 Rainbow Blvd., Kansas City, KS 66160 or write the CMH Human Subjects Committee at Director, Research Integrity Program, at 2401 Gillham Road Kansas City, MO 64108.

Subject Rights and Withdrawl from the Study

You may stop being in the study at any time. Your decision to stop will not prevent you from getting treatment or services at KUMC. The entire study may be discontinued for any reason without your consent by the investigator conducting the study.

You have the right to cancel your permission for researchers to use yourhealth information. If you want to cancel your permission, please write to Dr. Doug Burton. The mailing address is Dr. Doug Burton, University of Kansas Medical Center, 3901 Rainbow Boulevard, Kansas City, KS 66160. If you want to cancel your permission after testing at CMH, please write to Dr. Anderson, Dr. Schwend, or Dr. Price at 2401 Gillham Road Kansas City, MO 64108. If you cancel

permission to use your health information, you will be withdrawn from the study. The research team will stop collecting any additional information about you. The research team may use and share information that was gathered before they received your cancellation.

CONSENT

Dr. Burton, Dr. Anderson, Dr. Price, Dr. Schwend, or the research team has given you information about this research study. They have explained what will be done and how long it will take. They explained any inconvenience, discomfort or risks that may be experienced during this study.

By signing this form, you say that you freely and voluntarily consent to participate in this research study. You have read the information and had your questions answered.

You will be given a signed copy of the consent form to keep for your records.

_____

Print Participant's Name

_____   _____   _____

Signature of Participant   Time   Date

_____

Print Name of Person Obtaining Consent

_____   _____

Signature of Person Obtaining Consent   Date

A6. University of Kansas Medical Center Consent Form (Over 18)

INFORMED CONSENT STATEMENT

Characterization of Trunk Motion in an Adolescent Idiopathic Scoliosis (AIS) Population

You are being asked to join a research study because you have adolescent idiopathic scoliosis. You do not have to participate in this research study. The main purpose of research is to create new knowledge for the benefit of future patients and society in general. Research studies may or may not benefit the people who participate.

Research is voluntary, and you may change your mind at any time. There will be no penalty to you if you decide not to participate, or if you start the study and decides to stop early. Either way, you can still get medical care and services at the University of Kansas Medical Center (KUMC) and/or Children's Mercy Hospitals (CMH).

This consent form explains what you will have to do if you are in the study. It also describes the possible risks and benefits. Please read the form carefully and ask as many questions as you need to, before deciding about this research.

You can ask questions now or anytime during the study. The researchers will tell you if they receive any new information that might cause you to change your mind about participating.

This research study will take place at the University of Kansas Medical Center (KUMC) and at Children's Mercy Hospital (CMH) with Dr. Doug Burton (KUMC) , Dr. John Anderson (CMH), Dr. Nigel Price (CMH), and Dr. Richard Schwend (CMH) and Nikki Galvis as the researchers. About 40 people will be in the study at KUMC and up to 120 people will be in the study at CMH. A total of about 160 people will be in the study at 2 centers across the United States.

BACKGROUND

Scoliosis is known to profoundly affect normal trunk motion and balance. However, current findings in the field provide an incomplete understanding of how the structural asymmetry affects specific spinal motions. Therefore normal trunk motion of the scoliosis population must be established to identify the changes due solely to the structural changes of scoliosis. Specifically, we will investigate the symmetry of motion, range of motion, and motion mechanics of this population. Learning more about the limitations and changes caused by scoliosis will help researchers development better treatment options in the future.

PURPOSE OF THE STUDY

The purpose of this study is to see how children and young adults coordinate their low back motion during different activities and the effects of scoliosis on this coordination. A better understanding of dynamic back motion and the effect of scoliosis on this motion will help physicians to better understand scoliosis and to design methods to treat it.

PROCEDURES

Your participation in this study will involve a single session of approximately one hour in duration.
This research study will take place at the following locations:

Testing Location	Parent's Initials	Child's Initials
4. University of Kansas Medical Center (KUMC)	_____	
5. Children's Mercy Hospital (CMH)	_____	
6. Other _____	_____	_____

Other testing locations include the patient's home or an affiliated KUMC clinic.
Children with and without scoliosis are being recruited in order to understand the differences between these two groups. If you choose to participate, you will have markers placed along your back and at the base of your collar. These markers are a magnetic system that measure movement of the back. They will be attached to your skin using tape. You will be asked to do a series of movements while wearing these markers. These movements will include:
5. Flexion/Extension: Subjects are asked to bend as far as possible in each direction while keeping their knees straight.
6. Lateral Bending: Subjects are asked to bend as far as possible to each side while keeping their knees straight and feet flat on the ground
7. Torsion: Subjects are asked to twist as far as possible in each direction while keeping their knees and hips straight
8. Asymmetrical bending: Subjects are asked to bend as far as possible towards a mark on the platform, 45 degrees off mid-line, while keeping their knees and hips straight.

For the scoliosis population, medical information including the type and severity of the scoliosis and treatment history for your scoliosis will be given to the research team by your physician. For the control population, no medical records will be obtained from physicians. All data will be kept confidential and will be identified by subject number rather than by name.

RISKS

There are few risks involved in this experiment. It is possible that you might be allergic to tape and react to the tape used in the experiment. If you are allergic to band-aids or similar adhesives please let the investigator know and alternate methods will be used to attach the markers. It is also possible that you may experience muscle soreness such as might occur after normal exercise. As with any physical task there is a small possibility of low back injury. Although we have established protections against it, there is still a slight risk of a breach of confidentiality. To prevent this from occurring, all data is stored under encryption and identified with subject number rather than name wherever possible.

BENEFITS

There are no direct benefits to you from participating in this experiment. We expect that this study should be reasonably fun for the children and young adults participating. Our improved understanding of scoliosis from this study will be of benefit to orthopedic surgeons in learning more about scoliosis in general.

ALTERNATIVES

Your participation in this study is voluntary. This information is provided for you to decide whether you wish to participate in the present study. You may refuse to sign this form and choose not to participate in this study. You should be aware that even if you agree to participate, you are free to withdraw at any time. If you do withdraw from this study, it will not affect your relationship with this unit, the services it may provide to you, or the University of Kansas or Children's Mercy Hospital.

COSTS/PAYMENT

There is no cost for being in this study. There is no payment for this study.

IN THE EVENT OF INJURY

If you have a serious side effect or other problem during this study, you should immediately contact Dr. Sara Wilson at 785 864 2103. A member of the research team will decide what type of treatment, if any, is best for you at that time.

INSTITUTIONAL DISCLAIMER STATEMENT

If you think you have been harmed as a result of participating in research at the University of Kansas Medical Center (KUMC), you should contact the Director, Human Research Protection Program, Mail Stop #1032, University of Kansas Medical Center, 3901 Rainbow Blvd., Kansas City, KS 66160. Under certain conditions, Kansas state law or the Kansas Tort Claims Act may allow for payment to persons who are injured in research at KUMC.

In the case of illness or injury resulting from this study, treatment is available at The Children's Mercy Hospitals & Clinics, but will be provided at the usual charge. Payment for this treatment will be your responsibility. The hospital may not bill insurance or other third party payers for this care. The Children's Mercy Hospitals & Clinics does not have funds set aside to pay research participants if the research results in injury. By signing this form, you, or your child, are not giving up any legal rights to seek compensation for injury.

CONFIDENTIALITY AND PRIVACY AUTHORIZATION

The researchers will protect your information, as required by law. Absolute confidentiality cannot be guaranteed because persons outside the study team may need to look at your study records. The researchers may publish the results of the study. If they do, they will only discuss group results. Your name will not be used in any publication or presentation about the study.

Your health information is protected by a federal privacy law called HIPAA. By signing this consent form, you are giving permission for KUMC or CMH to use and share your health information. If you decide not to sign the form, you cannot be in the study.

The researchers will only use and share information that is needed for the study. To do the study, they will collect health information from the study activities and from your medical record. You may be identified by information such as name, address, phone, date of birth, social security number, or other identifiers. Your health information will be used at KU Medical Center by Dr. Burton, at CMH by Dr. Anderson, Dr. Price, or Dr. Schwend, members of the research team, the University of Kansas Hospital Medical Record Department, the CMH Medical records Department, the KUMC Human Subjects Committee, the CMH Human Subjects Committee, and other committees and offices that review and monitor research studies. Study records might be reviewed by government officials who oversee research, if a regulatory review takes place.

All study information that is sent outside KU Medical Center or the Children's Mercy Hospital will have your name and other identifying characteristics protected through encryption, so that your identity will not be known to those outside the study, unless required by law. Because identifiers will be encrypted, child's health information will not be re-disclosed by outside persons or groups and will not lose its federal privacy protection

Your permission to use and share your health information remains in effect until the study is complete and the results are analyzed. After that time, researchers will remove personal information from study records.

Questions

Before you sign this form, Dr. Burton, Dr. Anderson, Dr. Schwend, Dr. Price, or other members of the study team should answer all your questions. You can talk to the researchers if you have any more questions, suggestions, concerns or complaints after signing this form. If you have any questions about your rights as a research subject, or if you want to talk with someone who is not involved in the study, you may call the Human Subjects Committee at (913) 588-1240 or the CMH Human Subjects Committee at (816) 701-1348. You may also write the Human Subjects Committee at Mail Stop #1032, University of Kansas Medical Center, 3901 Rainbow Blvd., Kansas City, KS 66160 or write the CMH Human Subjects Committee at Director, Research Integrity Program, at 2401 Gillham Road Kansas City, MO 64108.

Subject Rights and WIthdrawal from the Study

You may stop being in the study at any time. Your decision to stop will not prevent you from getting treatment or services at KUMC. The entire study may be discontinued for any reason without your consent by the investigator conducting the study.

You have the right to cancel your permission for researchers to use yourhealth information. If you want to cancel your permission, please write to Dr. Doug Burton. The mailing address is Dr. Doug Burton, University of Kansas Medical Center, 3901 Rainbow Boulevard, Kansas City, KS 66160. If you want to cancel your permission after testing at CMH, please write to Dr. Anderson, Dr. Schwend, or Dr. Price at 2401 Gillham Road Kansas City, MO 64108. If you cancel permission to use your health information, you will be withdrawn from the study. The research team will stop collecting any additional information about you. The research team may use and share information that was gathered before they received your cancellation.

CONSENT

Dr. Burton, Dr. Anderson, Dr. Price, Dr. Schwend, or the research team has given you information about this research study. They have explained what will be done and how long it will take. They explained any inconvenience, discomfort or risks that may be experienced during this study.

By signing this form, you say that you freely and voluntarily consent to participate in this research study. You have read the information and had your questions answered.

You will be given a signed copy of the consent form to keep for your records.

_____

Print Participant's Name

_____   _____   _____

Signature of Participant   Time   Date

_____

Print Name of Person Obtaining Consent

_____   _____

Signature of Person Obtaining Consent   Date

A7. Testing Script

WARM UP

First we will start with a set of warm up exercises.

The first is the flexion exercise. You will get on all fours. This is the table top position. Then you will arch your back slowly. Then return to table top. Next bow your back. Return to table top. Repeat this 10 times.

-Pause-

The second exercise is the seated twist. Sit Indian style with your arm in front of you. Slowly twist to the left, keeping your hips facing forward. Then slowly twist to the right. Repeat this 10 times.

-Pause-

The last exercise is side bending. Stand up straight with your arms to your side. Bend to the left, sliding your arm down your arm towards your knee. Come out of the bend and stand up straight before bending to the right, sliding your right arm towards your knee. Try not to twist your shoulders while you are doing this. Repeat 10 times.

-Pause-

Now you may go change into the testing smock.

Now we will place the sensors on your back.

TESTING INSTRUCTIONS

There are 8 motions total. For each motion, we will do 5 trials. Each trial takes 10 second. Testing will take about 30 minutes.

The neutral position means to stand straight with your feet shoulder width apart, parallel to one another. Your knees should be straight but not locked. Your arms should be lightly crossed in front of you.

For the testing, when I say ARE YOU READY?, you need to get into the neutral testing position. Once you are in the neutral position, then you will say YES. Wait for me to say GO before you move. When I say STOP (or you hear the timer), you may relax until I ask ARE YOU READY? Again.

Let's practice it once together.

I say ARE YOU READY?
You get ready and say YES
You stay still until I say GO
You do the motion until I say STOP or you hear the timer.

The next motion is **flexion**. This is forward bending. Before we begin, let me check your sensors to make sure they haven't moved. For this motion you will bend forward as far as you can. Keep your knees straight, but not locked, and your feet flat on the ground. If you start to feel light headed, stand up. Bend as far as you can in this direction. If you feel that you are unbalanced, adjust your stance or scoot your feet forward. Don't rely on the belt to hold you. For this motion you will bend forward as far as you can. Do you understand?

The next motion is **extension.** This is backward bending. Before we begin, let me check your sensors to make sure they haven't moved. For this motion you will bend backward as far as you can. Keep your knees straight, but not locked, and your feet flat on the ground. If you start to feel light headed, stand up. You can hold your head up or you can drop it back. How you hold your head doesn't matter. Bend as far as you can in this direction. Do you understand?

The next motion is **left bending**. Before we begin, let me check your sensors to make sure they haven't moved. For this motion, drop your arms to your sides and bend as far as you can to the left. Try not to twist your shoulders. Keep your knees straight, but not locked, and your feet flat on the ground. Bend as far as you can in this direction. Do you understand?

The next motion is **right bending**. Before we begin, let me check your sensors to make sure they haven't moved. For this motion, drop your arms to your sides and bend as far as you can to the right. Try not to twist your shoulders. Keep your knees straight, but not locked, and your feet flat on the ground. Bend as far as you can in this direction. Do you understand?

The next motion is **left torsion**. This is twisting to the left. Before we begin, let me check your sensors to make sure they haven't moved. For this motion, you will twist as far as you can to the left. Keep your hips to the front, your knees straight, but not locked, and your feet flat on the ground. Twist as far as you can in this direction. Do you understand?

The next motion is **right torsion**. This is twisting to the right. Before we begin, let me check your sensors to make sure they haven't moved. For this motion, you will twist as far as you can to the right. Keep your hips to the front, your knees straight, but not locked, and your feet flat on the ground. Twist as far as you can in this direction. Do you understand?

The next motion is **left 45 degree bending**. Before we begin, let me check your sensors to make sure they haven't moved. For this motion you will bend toward this mark on the ground. Pretend as if your nose is really long and you are trying to touch your nose to the mark. You can change your stance for balance but keep your hips facing forward. Keep your knees straight, but not locked, and your feet flat on the ground. Bend as far as you can in this direction. Do you understand?

The next motion is **right 45 degree bending**. Before we begin, let me check your sensors to make sure they haven't moved. For this motion you will bend toward this mark on the ground. Pretend as if your nose is really long and you are trying to touch your nose to the mark. You can change your stance for balance but keep your hips facing forward. Keep your knees straight, but not locked, and your feet flat on the ground. Bend as far as you can in this direction. Do you understand?

Appendix B Data Analysis Code

Pre	**Pre_AnalysisRevB.m** Input: Raw Position Output: Quality and Time points
	LoadtoSensors.m Input: dat or mat files Output: raw data as sensors
	QualityCheck.m Input: Outputs from Pre_AnalysisRevB.m and subject Output: good_trial decision and timepoints
Prep	**YnegFix.m** Input: sensor data (raw positions) Output: 'fixed' sensor position data
	filterme.m Input: 'fixed sensor positions Output: 'fixed' and filtered sensor positions
	newOOBadjustments.m Input: F&F sensor positions Output: time indices for each sensor during OOB
Meat	**CoordinateSystemAngles.m** Input: F&F sensor positions and task Output: 3D Orientations of all vertebrae wrt the global
Fix	**JumpFixes.m** Input: 3D vertebrae orientations Output: 'Fixed' 3D vertebrae orientations
	OOBchop.m Input: 3D vertebrae orientations Output: 3D vertebrae orientations w/ NaN during OOB
	Analysis_RevAU.m *(in part)* Input: OOB timepoints for torso Output: quality decision
Fish	**ROMCalculations.m** Input: 'Fixed' 3D vertebrae orientations and timepoints Output: ROM for all angles
	DynamicCalculations.m Input: 'Fixed' 3D vertebrae orientations and timepoints Output: All angles during bending
Dessert	**Analysis_RevAU.m** *(in part)* Input: good_trial Output: trial to analyze statistically

B1. AnalysisRev_AV.m

```
% Full Analysis for Motion Analysis project
% Purpose
% The purpose of this analysis code is to bring in raw position and
% orientation data from the eight TrakSTAR sensors and convert them
% into motions, specifically flexion, extension, bilateral bending, and
% bilateral torsion for both gross and fine spinal motion. This
% analysis code implements several user defined functions to carry out
% these tasks, including:
% LoadtoSensors,
% LoadTaskTrialThings,
% YnegFix,
% JumpFixes,
% FilterMe,
% ROMcalcs,
% DynamicCalcs,
%
% The primary functions of this analysis code are as follows:
% Load in raw data files
% Using a thresholding method, select the initiation of the task and
% all positioning and orientation at that time
% Calculate range of motion of every parameter
% Print range of motion data to excel file
% Create a symmetry ratio for lateral bending and torsion parameters
% Plot engagement mechanics data

% Inputs
% X, Y, and Z position with reference to the global frame (transmitter)
% A, E, and R orientation with reference to the global frame (transmitter)
%
% Outputs
% Range of Motion for all parameters
% Symmetry ratios for all bending and torsion parameters
% Engagement Mechanics plots

%Example File Name
%Subj3Task2Trial1Sensor4.dat

%Task Definitions
%Task 1 = Flexion
%Task 2 = Extension
%Task 3 = Left Bending
%Task 4 = Right Bending
%Task 5 = Left Torsion
%Task 6 = Right Torsion
%Task 7 = Left 45 Bending (Currently not analyzed)
%Task 8 = Right 45 Bending (Currently not analyzed)
%Sensor Placement
%Sensor 1 = S1
%Sensor 2 = L3
%Sensor 3 = L1
%Sensor 4 = T10
%Sensor 5 = T6
%Sensor 6 = T3
```

```matlab
%Sensor 7 = T1
%Sensor 8 = Manubrium

%% Clear variables and command window
close all
clear all
clc
tic
%% Assign subject, task, trial, and sensor numbers
isubject = [1,3:4,6:10,13,16:48,50,52:57]; %Control subject numbers
%[19,20,21,22,29,34,46:48,50,52:57]; %Scoliosis subject numbers

for i = 1:length(isubject)
itxt = num2str(isubject(i));

%Bring in subject specific checks for existence, and good pattern, stand,
bend, and hold
[good_trial,ktxt,jtxt,htxt,standstart,standend,holdstart,holdend,path] =
QualityCheck(isubject,i);
good_trial_allsubjects(:,:,isubject(i)) = good_trial; %set good trial for all
subjects

for itask = 1:8
if itask == 1 || itask == 2 || itask == 7 || itask == 8
plane = 1;
oop1 = 2; %OOP = Out of Plane motion. %Check crawford for correct OOP2 and
OOP3 per task
oop2 = 3;
elseif itask == 3 || itask == 4
plane = 2;
oop1 = 1;
oop2 = 3;
elseif itask == 5 || itask == 6
plane = 3;
oop1 = 1;
oop2 = 2;
end
for itrial = 1:5
if good_trial_allsubjects(itask,itrial,isubject(i)) == 1
%do all the things
%Load in data from all sensors
for isens = 1:8
file_original = [path itxt,'_',num2str(itask), '_', num2str(itrial),'_',
num2str(isens),'.mat'];
if exist(file_original) == 2;
s{isens} = load(file_original);
end
end

%Seperate out the data for each sensor (xyzaer)
s1 = struct2cell(s{1});
s1 = s1{1}(:,1:3);
sensor = zeros(length(s1),3,8); sensor(:,:,1) = s1;
s2 = struct2cell(s{2}); s2 = s2{1}(:,1:3); sensor(:,:,2) = s2;
s3 = struct2cell(s{3}); s3 = s3{1}(:,1:3); sensor(:,:,3) = s3;
s4 = struct2cell(s{4}); s4 = s4{1}(:,1:3); sensor(:,:,4) = s4;
```

```
s5 = struct2cell(s{5}); s5 = s5{1}(:,1:3); sensor(:,:,5) = s5;
s6 = struct2cell(s{6}); s6 = s6{1}(:,1:3); sensor(:,:,6) = s6;
s7 = struct2cell(s{7}); s7 = s7{1}(:,1:3); sensor(:,:,7) = s7;
s8 = struct2cell(s{8}); s8 = s8{1}(:,1:3); sensor(:,:,8) = s8;

%Fix Negative Y errors
[s1,s2,s3,s4,s5,s6,s7,s8] = YnegFixAlt(s1,s2,s3,s4,s5,s6,s7,s8); %check this
to make sure it does what I want

% Filter
[s1,s2,s3,s4,s5,s6,s7,s8,sensors_filtered] =
filterme(s1,s2,s3,s4,s5,s6,s7,s8);

% Return OOB time indeces for each sensor
[oob_loc_s1,oob_loc_s2,oob_loc_s3,oob_loc_s4,oob_loc_s5,oob_loc_s6,oob_loc_s7
,oob_loc_s8] = newOOBadjustments(s1,s2,s3,s4,s5,s6,s7,s8);

%Create new coordinate systems at each vertebrae
[T1,T3,T6,T10,L1,L3] = CoordinateSystemAngles(itask,s1,s2,s3,s4,s5,s6,s7,s8);

%Fix the jumps created by gimble lock
[T1,T3,T6,T10,L1,L3] = JumpFixesLoop(T1,T3,T6,T10,L1,L3);

%Replace data with NaNs when sensors are OOB
[T1,T3,T6,T10,L1,L3,oobtime_T10] =
OOBchop(T1,T3,T6,T10,L1,L3,oob_loc_s1,oob_loc_s2,oob_loc_s3,oob_loc_s4,oob_lo
c_s5,oob_loc_s6,oob_loc_s7,oob_loc_s8);

%% Define timepoints
stand_start = standstart(itask,itrial);
stand_end = standend(itask,itrial);

hold_start = holdstart(itask,itrial);
hold_end = holdend(itask,itrial);

%% Offset values by the stand phase average position
T1 = T1 - ones(length(T1),1) * mean(T1(stand_start:stand_end+1,:));
T3 = T3 - ones(length(T3),1) * mean(T3(stand_start:stand_end+1,:));
T6 = T6 - ones(length(T6),1) * mean(T6(stand_start:stand_end+1,:));
T10 = T10 - ones(length(T10),1) * mean(T10(stand_start:stand_end+1,:));
L1 = L1 - ones(length(L1),1) * mean(L1(stand_start:stand_end+1,:));
L3 = L3 - ones(length(L3),1) * mean(L3(stand_start:stand_end+1,:));

%% Calculate angles
utang = T1-T3;
mtang = T3-T6;
ltang = T6-T10;
utlang = T10-L1;
ltlang = L1-L3;
thorang = T1 - L1;
torsoang = T10;

%% Add in quality info for torso (to match quality criteria for dynamic
analysis)
bending_time_pts = stand_end:1:hold_start;
```

```matlab
oob_bending_time_pts = intersect(oobtime_T10,bending_time_pts);
if isempty(oob_bending_time_pts) == 0
good_trial_allsubjects(itask,itrial,isubject(i)) = 0;
else
end

%% Do a click check
if stand_end > stand_start && hold_start > stand_end && hold_end > hold_start
stand_time{itask,itrial} = {(stand_start:1:stand_end)'};
bend_time{itask,itrial} = {(stand_end:1:hold_start)'};
hold_time{itask,itrial} = {(hold_start:1:hold_end)'};

%% Calculate new angle parameters based on coordinate method
[ROM_temp] =
ROMcalculations(torsoang,utang,mtang,ltang,utlang,ltlang,thorang,stand_time,h
old_time,plane,itask,itrial);
if max(ROM_temp) >= 180 ||  min(ROM_temp) <= -180
good_trial_allsubjects(itask,itrial,isubject(i)) = 0;
else
end

%% Torso Sign Quality Check
if itask == 2
if sign(ROM_temp(1,1)) == 1
good_trial_allsubjects(itask,itrial,isubject(i)) = 0;
else
end
if isubject(i) == 9 && itrial == 5
good_trial_allsubjects(itask,itrial,isubject(i)) = 0;
else
end
elseif itask == 3
if sign(ROM_temp(1,1)) == 1
good_trial_allsubjects(itask,itrial,isubject(i)) = 0;
else
end
elseif itask == 5
if sign(ROM_temp(1,1)) == 1
good_trial_allsubjects(itask,itrial,isubject(i)) = 0;
else
end
elseif itask == 1
if sign(ROM_temp(1,1)) == -1
good_trial_allsubjects(itask,itrial,isubject(i)) = 0;
else
end
elseif itask == 4
if sign(ROM_temp(1,1)) == -1
good_trial_allsubjects(itask,itrial,isubject(i)) = 0;
else
end
elseif itask == 6
if sign(ROM_temp(1,1)) == -1
good_trial_allsubjects(itask,itrial,isubject(i)) = 0;
else
end
```

```matlab
elseif itask == 7
if sign(ROM_temp(1,1)) == -1
good_trial_allsubjects(itask,itrial,isubject(i)) = 0;
else
end
elseif itask == 8
if sign(ROM_temp(1,1)) == -1
good_trial_allsubjects(itask,itrial,isubject(i)) = 0;
else
end
end

%% Calculate Output Parameters
ROM_all{itask,itrial,isubject(i)} = (ROM_temp);

[dynamic_bending_temp] =
DynamicCalculations(torsoang,utang,mtang,ltang,utlang,ltlang,thorang,bend_tim
e,plane,itask,itrial);
dynamic_bending{itask,itrial,isubject(i)} = (dynamic_bending_temp);

clearvars stand_time bend_time hold_time ROM_temp dynamic_bending_temp
else
good_trial_allsubjects(itask,itrial,isubject(i)) = 0;
end
else
%do nothing
end
end

%Create trial_keep file
if good_trial_allsubjects(itask,5,isubject(i)) == 1
trial_keep(isubject(i),itask) = 5;
elseif good_trial_allsubjects(itask,4,isubject(i)) == 1
trial_keep(isubject(i),itask) = 4;
elseif good_trial_allsubjects(itask,3,isubject(i)) == 1
trial_keep(isubject(i),itask) = 3;
else
trial_keep(isubject(i),itask) = 0;
end

end
end
toc

%% Save output parameters to mat files
save('ROM_data','ROM_all');
save('dynamic_bending.mat','dynamic_bending');
save('good_trial.mat','good_trial_allsubjects');
save('trial_keep','trial_keep');
```

B2. PreAnalysis_RevB.m

```matlab
%PreAnalysis
clear all
close all
clc

for isubject = 23
for itask = 1%1:8
for itrial = 3%1:5

run = ((itask-1)*5)+itrial;

[s1 s2 s3 s4 s5 s6 s7 s8 fail] = LoadtoSensors(isubject,itask,itrial);

[s1 s2 s3 s4 s5 s6 s7 s8] = YnegFix(s1,s2,s3,s4,s5,s6,s7,s8);

[OOB] = TrialCheckFunction(itask, itrial, s1, s2, s3, s4, s5, s6, s7, s8);

[Flexion Bending Torsion] = RawToFlexion(s1,s4,s8);

[Flexion Bending Torsion] = JumpFixes(Flexion, Bending, Torsion);

%Assign In-Plane and Out-of-Plane Motions
F = 0; %In-plane Flexion is fal se
B = 0; %In-plane Bending is false
T = 0; %In-plane Torsion is false

%Generalize global parameters into motion angles
if itask == 1 || itask == 2 || itask ==7 || itask == 8
F = 1; %For Task 1 or Task 2, in-plane flexion is true
motion = Flexion;
elseif itask == 3 || itask == 4
B = 1; %For Task 3 or Task 4, in-plane bending is true
motion = Bending;
elseif itask == 5 || itask == 6
T = 1; %For Task 5 or Task 6, in-plane torsion is true
motion = Torsion;
end

%Check to see that the data is actually there
if isnan(motion)==1
break
else

%Modify Motion Pattern
if itask == 2 || itask == 3 || itask == 5
motion = -motion;
else
end
if min(motion) < 0
motion = motion + abs(min(motion));
end
```

```matlab
[m,n] = size(motion);

[stand_start,stand_end,hold_start,hold_end,stnd_start,stnd_end,pattern,stand1
,bending,maxhold,unbending,stand2] = breakpoints(Flexion,Bending,
Torsion,motion);

stand_start1(itrial,itask) = stand_start;
stand_end1(itrial,itask) = stand_end;
hold_start1(itrial,itask) = hold_start;
hold_end1(itrial,itask) = hold_end;
stand_start2(itrial,itask) = stnd_start;
stand_end2(itrial,itask) = stnd_end;
OOB1(itrial,itask) = OOB;
pattern1(itrial,itask) = pattern;
stand11(itrial,itask) = stand1;
bending1(itrial,itask) = bending;
maxhold1(itrial,itask) = maxhold;
unbending1(itrial,itask) = unbending;
stand21(itrial,itask) = stand2;
end
end
end
%     xlswrite('QualityResults.xlsx',OOB1',['Subject '
num2str(isubject)],'B2:F9');
%     xlswrite('QualityResults.xlsx',pattern1',['Subject '
num2str(isubject)],'H2:L9');
%     xlswrite('QualityResults.xlsx',stand11',['Subject '
num2str(isubject)],'B11:F18');
%     xlswrite('QualityResults.xlsx',bending1',['Subject '
num2str(isubject)],'H11:L18');
%     xlswrite('QualityResults.xlsx',maxhold1',['Subject '
num2str(isubject)],'B20:F27');
%     xlswrite('QualityResults.xlsx',unbending1',['Subject '
num2str(isubject)],'H20:L27');
%     xlswrite('QualityResults.xlsx',stand21',['Subject '
num2str(isubject)],'B29:F36');
%
%
%     xlswrite('PreAnalysisResults.xlsx',stand_start1',['Subject '
num2str(isubject)],'B2:F9');
%     xlswrite('PreAnalysisResults.xlsx',stand_end1',['Subject '
num2str(isubject)],'H2:L9');
%     xlswrite('PreAnalysisResults.xlsx',hold_start1',['Subject '
num2str(isubject)],'B11:F18');
%     xlswrite('PreAnalysisResults.xlsx',hold_end1',['Subject '
num2str(isubject)],'H11:L18');
%     xlswrite('PreAnalysisResults.xlsx',stand_start2',['Subject '
num2str(isubject)],'B20:F27');
%     xlswrite('PreAnalysisResults.xlsx',stand_end2',['Subject '
num2str(isubject)],'H20:L27');
end
```

B3. QualityCheck.m

```matlab
function
[good_trial,ktxt,jtxt,htxt,standstart,standend,holdstart,holdend,path] =
QualityCheck(isubject,i)

%itxt = subject num
%jtxt = trial num
%ktxt = task num
%% PATTERN, STAND, BEND, AND HOLD GOOD CHECK FOR TASK AND TRIAL
for itask = 1:8
for itrial = 1:5
ktxt = num2str(itask);
jtxt = num2str(itrial);
itxt = num2str(isubject(i));

path =
['\\people.soecs.ku.edu\s\s563j986\Home\Documents\Research\NewDataMethods\Dat
a\MATfiles\'];

%% DATA QUALITY CHECK (commented out below)
Qfilename = [itxt '_Q.mat'];
Qfull_filename = [path Qfilename];
datacheck = exist(Qfull_filename,'file');
if datacheck == 2
data = load(Qfull_filename);
data = struct2cell(data);
OOB = data{1}(1:8,1:5);
pattern = data{1}(1:8,7:11);
stand = data{1}(10:17,1:5);
bend = data{1}(10:17,7:11);
holdd = data{1}(19:26,1:5);
unbend = data{1}(19:26,7:11);
stand2 = data{1}(28:35,1:5);
clear data
else
%Create the files for the task/trial
Xfilename = ['QualityResults.xlsx'];  %Create naming system for control data
file
Xfull_filename = [path Xfilename];
data = xlsread (Xfull_filename);
%Attempts to read in the data from the file
filename = [itxt,'_Q.mat'];
save (filename, 'data') ;
OOB = data(1:8,1:5);
pattern = data(1:8,7:11);
stand = data(10:17,1:5);
bend = data(10:17,7:11);
holdd = data(19:26,1:5);
unbend = data(19:26,7:11);
stand2 = data(28:35,1:5);
clear data
end

%% TIME DATA CHECK (commented out below)
```

```matlab
Tfilename = [itxt '_T.mat'];
Tfull_filename = [path Tfilename];
datacheck = exist(Tfull_filename,'file');
if datacheck == 2
data = load(Tfull_filename);
data = struct2cell(data);
standstart = data{1}(1:8,1:5);
standend = data{1}(1:8,7:11);
holdstart = data{1}(10:17,1:5);
holdend = data{1}(10:17,7:11);
standstart2 = data{1}(19:26,1:5);
standend2 = data{1}(19:26,7:11);
clear data
else
%upload the sway trials for selected subject numbers
clear Xfilename
Xfilename = ['QualityResults.xlsx'];  %Create naming system for control data
file
Xfull_filename = [path Xfilename];
data = xlsread (Xfull_filename);
%Attempts to read in the data from the file
filename = [itxt,'_T'];
save (filename, 'data') ;
standstart = data(1:8,1:5);
standend = data(1:8,7:11);
holdstart = data(10:17,1:5);
holdend = data(10:17,7:11);
standstart2 = data(19:26,1:5);
standend2 = data(19:26,7:11);
clear data
end

if pattern(itask,itrial) == 1
pattern_good = 1;
else
pattern_good = 0;
end

if stand(itask,itrial) == 1
stand_good = 1;
else
stand_good = 0;
end

if bend(itask,itrial) == 1
bend_good = 1;
else
bend_good = 0;
end

if holdd(itask,itrial) == 1
hold_good = 1;
else
hold_good = 0;
end
%% SENSOR FILES EXIST CHECK
```

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```matlab
for isens = 1:8
htxt = int2str(isens);
filename_mat = [itxt,'_',ktxt, '_', jtxt,'_', htxt,'.mat'];
full_filename_mat = [path filename_mat];
datacheck = exist(full_filename_mat,'file');
if datacheck == 2 %if the mat file exists,
data_exist(isens) = 1;
else
data_exist(isens) = 0;
end
end
all_sensors_exist = prod(data_exist);
good_trial(itask,itrial) =
all_sensors_exist*pattern_good*stand_good*bend_good*hold_good; %1 is good, 0
is bad
end
end
end
```

B4. YnegFixAlt.m

```matlab
function[s1, s2, s3, s4, s5, s6, s7, s8] =
YnegFixAlt(s1,s2,s3,s4,s5,s6,s7,s8) %add S1 back in
all_sensors(:,:,1) = s1;
all_sensors(:,:,2) = s2;
all_sensors(:,:,3) = s3;
all_sensors(:,:,4) = s4;
all_sensors(:,:,5) = s5;
all_sensors(:,:,6) = s6;
all_sensors(:,:,7) = s7;
all_sensors(:,:,8) = s8;

%Check for jumps in the y position
for sensor = 1:size(all_sensors,3)
y_pos = all_sensors(:,2,sensor);
%% Check for Jumps
AAA = diff(y_pos);
ajump = find(AAA > 5 | AAA < -5); %check that this threshold works
ajump_ht = AAA(ajump);
if isempty(ajump) == 0
for ii = 1:length(ajump)
for iii = ajump(ii)+1:length(y_pos)
y_pos(iii) = y_pos(iii) - ajump_ht(ii);
end
end
end
sensor_fixed(:,2,sensor) = y_pos;
end

s1 = sensor_fixed(:,:,1);
s2 = sensor_fixed(:,:,2);
s3 = sensor_fixed(:,:,3);
s4 = sensor_fixed(:,:,4);
s5 = sensor_fixed(:,:,5);
s6 = sensor_fixed(:,:,6);
s7 = sensor_fixed(:,:,7);
s8 = sensor_fixed(:,:,7);
end
```

B5. Filterme.m

```matlab
function [s1,s2,s3,s4,s5,s6,s7,s8,sensors_filtered] =
filterme(s1,s2,s3,s4,s5,s6,s7,s8)
%definitions
fsample = 80;

%low pass filter info
order = 4;
fnyquist = fsample/2;
fcutoff = 2; %annaria approved this cutoff, or 1Hz
fnormalized_cutoff = fcutoff/fnyquist;

%filter data
[b,a] = butter(order,fnormalized_cutoff,'low');
sensor_grouped = {s1 s2 s3 s4 s5 s6 s7 s8};
for sensor_num = 1:8
for column = 1:3
filtme = sensor_grouped{1,sensor_num}(:,column);
sensors_filtered(:,column,sensor_num) = filtfilt(b,a,filtme);
end
end
clear vars s1 s2 s3 s4 s5 s6 s7 s8
s1 = sensors_filtered(:,:,1);
s2 = sensors_filtered(:,:,2);
s3 = sensors_filtered(:,:,3);
s4 = sensors_filtered(:,:,4);
s5 = sensors_filtered(:,:,5);
s6 = sensors_filtered(:,:,6);
s7 = sensors_filtered(:,:,7);
s8 = sensors_filtered(:,:,8);
end
```

B6. newOOBadjustment.m


```matlab
function
[oob_loc_s1,oob_loc_s2,oob_loc_s3,oob_loc_s4,oob_loc_s5,oob_loc_s6,oob_loc_s7
,oob_loc_s8] = newOOBadjustments(s1,s2,s3,s4,s5,s6,s7,s8)

sx_mode = 35.9956;

%%Isolate x values of the sensors
s1x = s1(:,1);
s2x = s2(:,1);
s3x = s3(:,1);
s4x = s4(:,1);
s5x = s5(:,1);
s6x = s6(:,1);
s7x = s7(:,1);
s8x = s8(:,1);


%% Find what time points are OOB timepoints

[oob_loc_s1] = find(s1x >= sx_mode);
[oob_loc_s2] = find(s2x >= sx_mode);
[oob_loc_s3] = find(s3x >= sx_mode);
[oob_loc_s4] = find(s4x >= sx_mode);
[oob_loc_s5] = find(s5x >= sx_mode);
[oob_loc_s6] = find(s6x >= sx_mode);
[oob_loc_s7] = find(s7x >= sx_mode);
[oob_loc_s8] = find(s8x >= sx_mode);

end
```

B7. *CoordinateSystemAngles.m*

```matlab
function [T1,T3,T6,T10,L1,L3] =
CoordinateSystemAngles(itask,s1,s2,s3,s4,s5,s6,s7,s8)

%create inferior vector (sacrum to vertebrae)
S_T1 = s1 - s7;
S_T3 = s1 - s6;
S_T6 = s1 - s5;
S_T10 = s1 - s4;
S_L1 = s1 - s3;
S_L3 = s1 - s2;
S_to_vert = {S_T1,S_T3,S_T6,S_T10,S_L1,S_L3};
%create anterior vector (manubrium to vertebrae)
M_T1 = s8 - s7;
M_T3 = s8 - s6;
M_T6 = s8 - s5;
M_T10 = s8 - s4;
M_L1 = s8 - s3;
M_L3 = s8 - s4;
M_to_vert = {M_T1,M_T3,M_T6,M_T10,M_L1,M_L3};
clearvars -except itask latang flexang twistang Flexion Bending Torsion
S_to_vert M_to_vert

for i = 1:6
v1 = M_to_vert{i};       %superior vector (manubrium to vertebrae)
v2 = S_to_vert{i};       %inferior vector (sacrum to vertebrae)
%Turn time vectors into unit vectors
for time_index = 1:length(S_to_vert{i});
vector1 = v1(time_index,:);
vector2 = v2(time_index,:);
vector1 = vector1/sqrt(dot(vector1,vector1));
vector2 = vector2/sqrt(dot(vector2,vector2));

%Create first orthogonal vector
newvector1 = cross(vector2,vector1,2); %cross inferior vector into superior
vector
n1 = newvector1/sqrt(dot(newvector1,newvector1)); %change to unit vector

%Create second orthogonal vector
newvector2 = cross(n1,vector2,2); %cross new vector with inferior vector
n2 = newvector2/sqrt(dot(newvector2,newvector2)); %change to unit vector

%Place coordinate system vectors into inverted rotation matrix
ainv(3,1:3) = vector2; %place in row 3, all columns
ainv(2,1:3) = n1; %palce in row 2, all columns
ainv(1,1:3) = n2; %place in row 1, all columns

%Invert to obtain true rotation matrix
A = inv(ainv);

%Pull out cells of the rotation matrix
a11 = A(1,1);
a12 = A(1,2);
```

```matlab
a13 = A(1,3);
a21 = A(2,1);
a22 = A(2,2);
a23 = A(2,3);
a31 = A(3,1);
a32 = A(3,2);
a33 = A(3,3);

%Crawford rotation sequence stuff (Body 2-1-3 Rotation)
lat = atan(a13./a33);
flex = asin(-a23);
twist = atan(a21./a22);

latang(time_index) = lat;
flexang(time_index) = flex;
twistang(time_index) = twist;

%% Output Parameters
Flexion = (-flexang)*180/3.14159;
%Calculated flexion angle for the position data
Bending = (latang)*180/3.14159;
%Calculated lateral bending angle for the position data
Torsion = (twistang)*180/3.14159;
%Calculated torsion angle for the position data
%        [Flexion Bending Torsion] = JumpFixes180(Flexion, Bending,
Torsion,itask);
end

if i == 1 %T1 angle
T1(:,1) = Flexion';
T1(:,2) = Bending';
T1(:,3) = Torsion';
elseif i == 2 %T3 angle
T3(:,1) = Flexion';
T3(:,2) = Bending';
T3(:,3) = Torsion';
elseif i == 3 %T6 angle
T6(:,1) = Flexion';
T6(:,2) = Bending';
T6(:,3) = Torsion';
elseif i == 4 %T10 angle %AKA torso angle
T10(:,1) = Flexion';
T10(:,2) = Bending';
T10(:,3) = Torsion';
elseif i == 5  %L1 angle
L1(:,1) = Flexion';
L1(:,2) = Bending';
L1(:,3) = Torsion';
elseif i == 6 %L3 angle
L3(:,1) = Flexion';
L3(:,2) = Bending';
L3(:,3) = Torsion';
end
end
end
```

B8. *JumpFixesLoop.m*

```matlab
function[T1,T3,T6,T10,L1,L3] = JumpFixesLoop(T1,T3,T6,T10,L1,L3) %add S1 back
in
all_parameters(:,:,1) = T1;
all_parameters(:,:,2) = T3;
all_parameters(:,:,3) = T6;
all_parameters(:,:,4) = T10;
all_parameters(:,:,5) = L1;
all_parameters(:,:,6) = L3;
% all_parameters(:,:,7) = S1;

for parameter = 1:size(all_parameters,3)
for plane = 1:size(all_parameters,2)
angle = all_parameters(:,plane,parameter);
%% Check for Jumps
AAA = diff(angle);
ajump = find(AAA > 160 | AAA < -160);
ajump_ht = AAA(ajump);
if isempty(ajump) == 0
for ii = 1:length(ajump)
if sign(ajump_ht(ii)) == 1
ajump_ht(ii) = 180;
elseif sign(ajump_ht(ii)) == -1
ajump_ht(ii) = -180;
end
for iii = ajump(ii)+1:length(angle)
angle(iii) = angle(iii) - ajump_ht(ii);
end
end
end
parameter_fixed(:,plane,parameter) = angle;
end
end

T1 = parameter_fixed(:,:,1);
T3 = parameter_fixed(:,:,2);
T6 = parameter_fixed(:,:,3);
T10 = parameter_fixed(:,:,4);
L1 = parameter_fixed(:,:,5);
L3 = parameter_fixed(:,:,6);
% S1 = parameter_fixed(:,:,7);
end
```

B9. OOBchop.m

```
function [T1,T3,T6,T10,L1,L3,oobtime_T10] =
OOBchop(T1,T3,T6,T10,L1,L3,oob_loc_s1,oob_loc_s2,oob_loc_s3,oob_loc_s4,oob_lo
c_s5,oob_loc_s6,oob_loc_s7,oob_loc_s8);

%Replace OOB time point data with NaNs

%Every vertebrae data set need to look at the sensor that is at that
%vertebra, the manubrium sensor and the sacrum sensor, as the manubrium and
%sacral sensor are used for all parameter calculations.

%Create full oob time for each vertebrae
oobtime_T1 = cat(1,oob_loc_s1,oob_loc_s7,oob_loc_s8);
oobtime_T1 = unique(oobtime_T1);

oobtime_T3 = cat(1,oob_loc_s1,oob_loc_s6,oob_loc_s8);
oobtime_T3 = unique(oobtime_T3);

oobtime_T6 = cat(1,oob_loc_s1,oob_loc_s5,oob_loc_s8);
oobtime_T6 = unique(oobtime_T1);

oobtime_T10 = cat(1,oob_loc_s1,oob_loc_s4,oob_loc_s8);
oobtime_T10 = unique(oobtime_T1);

oobtime_L1 = cat(1,oob_loc_s1,oob_loc_s3,oob_loc_s8);
oobtime_L1 = unique(oobtime_T1);

oobtime_L3 = cat(1,oob_loc_s1,oob_loc_s2,oob_loc_s8);
oobtime_L3 = unique(oobtime_T1);

%Replace oob time points with NaNs
T1(oobtime_T1) = NaN;
T3(oobtime_T3) = NaN;
T6(oobtime_T6) = NaN;
T10(oobtime_T10) = NaN;
L1(oobtime_L1) = NaN;
L3(oobtime_L3) = NaN;
end
```

B10. ROMcalculations.m

```matlab
function [ROM_temp] =
ROMcalculations(torsoang,utang,mtang,ltang,utlang,ltlang,thorang,stand_time,h
old_time,plane,itask,itrial)


for rows =
stand_time{itask,itrial}{1}:length(stand_time{itask,itrial}{1})+stand_time{it
ask,itrial}{1}-1
rows_start = rows - stand_time{itask,itrial}{1}(1)+1;

utang_stand(rows_start,:) = utang(rows,plane);
mtang_stand(rows_start,:) = mtang(rows,plane);
ltang_stand(rows_start,:) = ltang(rows,plane);
utlang_stand(rows_start,:) = utlang(rows,plane);
ltlang_stand(rows_start,:) = ltlang(rows,plane);
thorang_stand(rows_start,:) = thorang(rows,plane);
torsoang_stand(rows_start,:) = torsoang(rows,plane);
end

mean_utang_stand = mean(utang_stand);
mean_mtang_stand = mean(mtang_stand);
mean_ltang_stand = mean(ltang_stand);
mean_utlang_stand = mean(utlang_stand);
mean_ltlang_stand = mean(ltlang_stand);
mean_thorang_stand = mean(thorang_stand);
mean_torsoang_stand = mean(torsoang_stand);

clear rows rows_start

for rows =
hold_time{itask,itrial}{1}:length(hold_time{itask,itrial}{1})+hold_time{itask
,itrial}{1}-1
rows_start = rows - hold_time{itask,itrial}{1}(1)+1;

utang_hold(rows_start,:) = utang(rows,plane);
mtang_hold(rows_start,:) = mtang(rows,plane);
ltang_hold(rows_start,:) = ltang(rows,plane);
utlang_hold(rows_start,:) = utlang(rows,plane);
ltlang_hold(rows_start,:) = ltlang(rows,plane);
thorang_hold(rows_start,:) = thorang(rows,plane);
torsoang_hold(rows_start,:) = torsoang(rows,plane);

end

mean_utang_hold = mean(utang_hold);
mean_mtang_hold = mean(mtang_hold);
mean_ltang_hold = mean(ltang_hold);
mean_utlang_hold = mean(utlang_hold);
mean_ltlang_hold = mean(ltlang_hold);
mean_thorang_hold = mean(thorang_hold);
mean_torsoang_hold = mean(torsoang_hold);

utang_static = mean_utang_hold - mean_utang_stand;
```

```
mtang_static = mean_mtang_hold - mean_mtang_stand;
ltang_static = mean_ltang_hold - mean_ltang_stand;
utlang_static = mean_utlang_hold - mean_utlang_stand;
ltlang_static = mean_ltlang_hold - mean_ltlang_stand;
thorang_static = mean_thorang_hold - mean_thorang_stand;
torsoang_static = mean_torsoang_hold - mean_torsoang_stand;


ROM_temp = [torsoang_static utang_static mtang_static ltang_static
utlang_static ltlang_static thorang_static];

end
```

B11. DynamicCalculations.m

```
function [dynamic_bending_temp] =
DynamicCalculations(torsoang,utang,mtang,ltang,utlang,ltlang,thorang,bend_tim
e,plane,itask,itrial)

for rows =
bend_time{itask,itrial}{1}:length(bend_time{itask,itrial}{1})+bend_time{itask
,itrial}{1}-1
rows_start = rows - bend_time{itask,itrial}{1}(1)+1;

utang_bend(rows_start,:) = utang(rows,plane);
mtang_bend(rows_start,:) = mtang(rows,plane);
ltang_bend(rows_start,:) = ltang(rows,plane);
utlang_bend(rows_start,:) = utlang(rows,plane);
ltlang_bend(rows_start,:) = ltlang(rows,plane);
thorang_bend(rows_start,:) = thorang(rows,plane);
torsoang_bend(rows_start,:) = torsoang(rows,plane);

end

dynamic_bending_temp = [torsoang_bend utang_bend mtang_bend ltang_bend
utlang_bend ltlang_bend thorang_bend];
```

Appendix C Data Analysis Methods

The analysis techniques described below are standard analysis techniques in the field of human motion (HM) tracking particularly as it relates to tracking and analysis of spine motion. This document explains two methods for analyzing data collected from a TrakSTAR motion tracking system. The first method assumes that the orientations and positions given by the TrakSTAR will be used and the rotation sequence needs to be altered for analysis and comparisons. The method focuses on the decomposition of Euler angles into vectors. The second method assumes that only the position data from the TrakSTAR will used and explains how to create new orientation vectors from the position data. Once both methods have established appropriate vectors, they use the same method to convert the vectors into the desired Euler angles. Before the two methods are explained, the coordinate system setup will be discussed.

Global and Local Coordinate Systems

Raw data collected consists of three positions (x, y, and z) and three orientations (a, e, and r) relative to the transmitter for each of the eight sensors. The global coordinate system (*G*) as defined by the TrakSTAR transmitter with the positive x-axis pointing along a line from posterior to anterior, the positive y-axis pointing along a line from left to right, and the positive z-axis pointing along a line from superior to inferior (Figure 1).
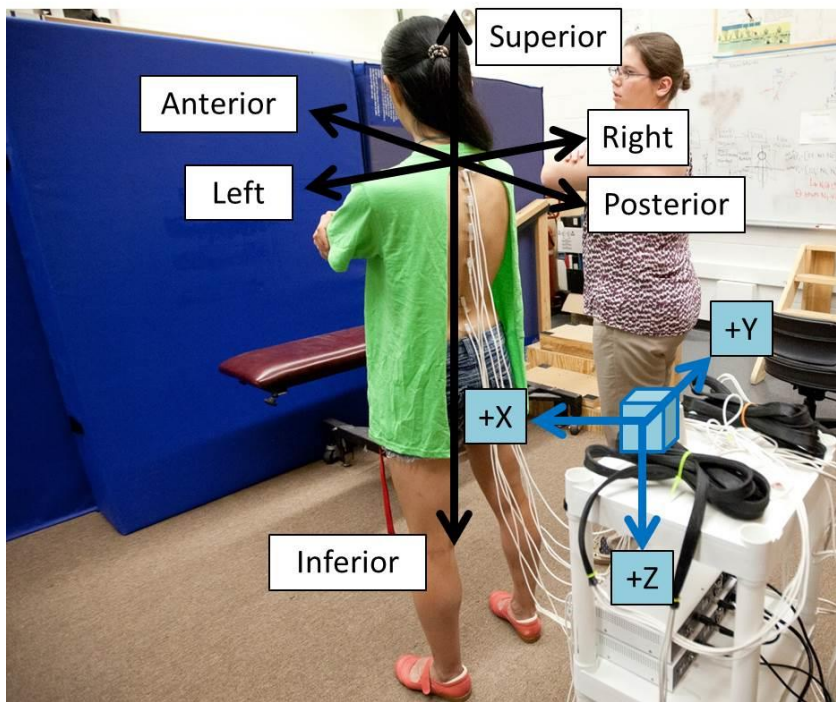
Figure   1: Coordinate System in terms of Anatomic Directions

The local (sensor) coordinate system (*L*) is defined with the positive x-axis pointing up from the top of the sensor, the positive y-axis pointing to the right of the sensor, and the positive z-axis pointing to the front of the sensor (Figure 2).
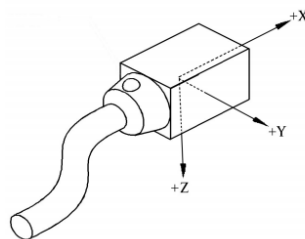

Figure   2: Local (Sensor) Coordinate System

Euler angles, presented as azimuth (ψ_{HM}), elevation (θ_{HM}), and roll (φ_{HM}), are used to determine the orientation of any local coordinate system (*L*) with respect to the global coordinate

system (**G**). Azimuth is the rotation about the global z-axis. Elevation is the rotation about the global x-axis. Roll is the rotation about the global y-axis.

Table   1: Euler Angles and Axes of Rotation

Axis of Rotation	Euler Angle	Symbol
Global Z Axis	Azimuth	ψ_{HM}
Global X Axis	Elevation	φ_{HM}
Global Y Axis	Roll	θ_{HM}

Although the TrakSTAR provides the sensor orientation in Euler angles, it is useful to decompose these Euler angles in to vector components in order to create and compare new coordinate systems.

Method 1: Decomposing Euler Angles

As shown in Figure 3, X-Y-Z define the global reference system (**G**) while x-y-z define a local coordinate system (**L**). As the raw data is reported in Euler angles, the correct rotation sequence used to produce the given Euler angles is needed to decompose the angles into vectors. The rotation sequence, as established by Ascension, is z-y-x.
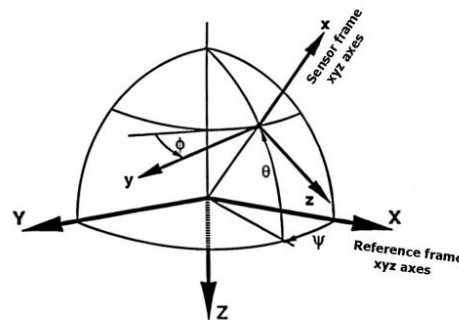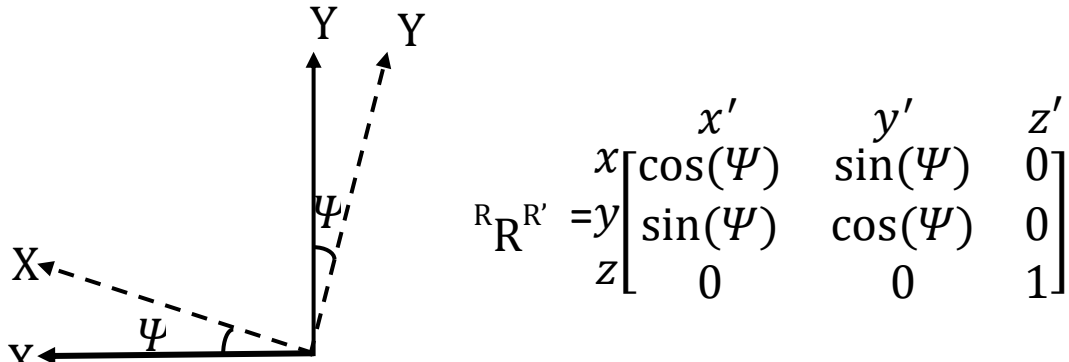

Figure   3: Sensor coordinate system within the global reference frame

For this body 3-2-1 rotation, the first rotation (Ψ) is about the z axis. The rotation and the cosine

matrix are shown in Figure 4.

$${}^{R}R^{R'} = \begin{array}{c} \\ x \\ y \\ z \end{array}\begin{array}{ccc} x' & y' & z' \\ \left[\begin{array}{ccc} \cos(\Psi) & \sin(\Psi) & 0 \\ \sin(\Psi) & \cos(\Psi) & 0 \\ 0 & 0 & 1 \end{array}\right] \end{array}$$

Figure   4: Rotation about the Z axis

The second rotation (θ) is about the y axis. The rotation and the cosine matrix are shown in

Figure 5.

$${}^{R'}R^{R''} = \begin{array}{c} \\ x \\ y \\ z \end{array}\begin{array}{ccc} x'' & y'' & z'' \\ \left[\begin{array}{ccc} \cos(\theta) & 0 & \sin(\theta) \\ 0 & 1 & 0 \\ \sin(\theta) & 0 & \cos(\theta) \end{array}\right] \end{array}$$
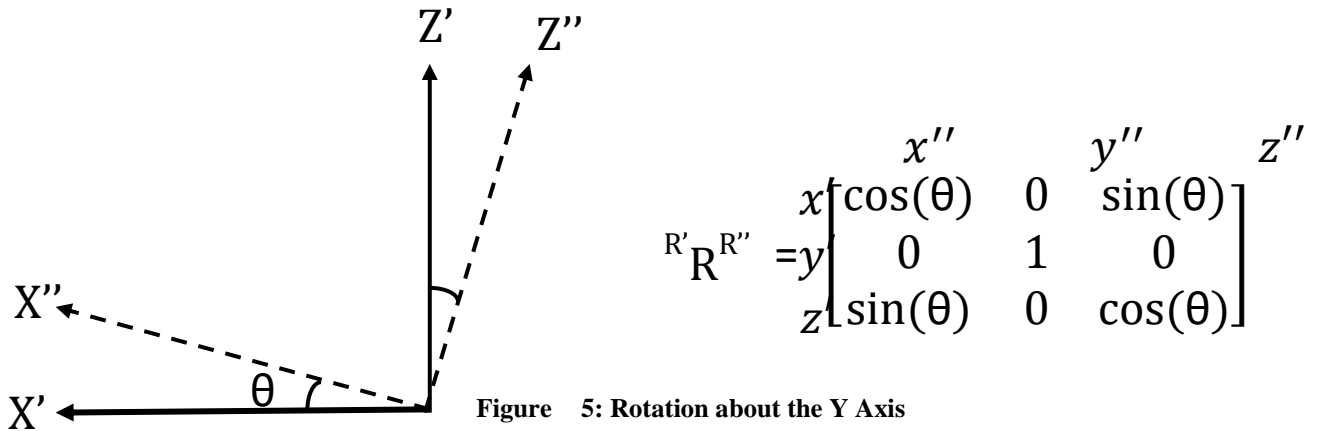
Figure   5: Rotation about the Y Axis

The third and final rotation (φ) is about the x axis. The rotation and the cosine matrix are shown

in Figure 6.

$${}^{R''}R^{R'''} = \begin{array}{c} \\ x'' \\ y'' \\ z'' \end{array}\begin{array}{ccc} x''' & y''' & z''' \\ \left[\begin{array}{ccc} 1 & 0 & 0 \\ 0 & \cos(\varphi) & \sin(\varphi) \\ 0 & \sin(\varphi) & \cos(\varphi) \end{array}\right] \end{array}$$
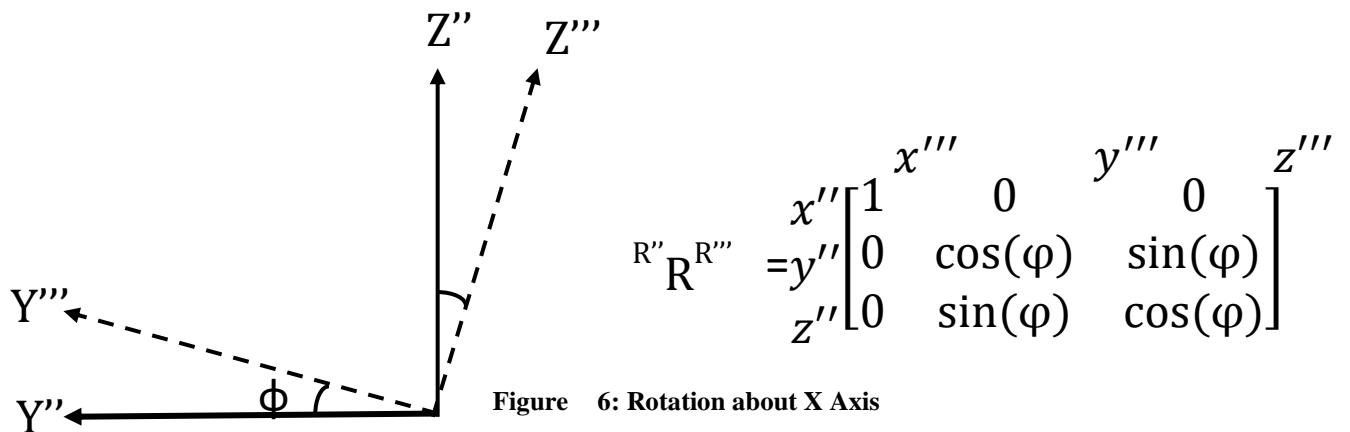
Figure   6: Rotation about X Axis

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The body 3-2-1 rotation is accomplished by multiplying the cosine matrices together, as shown symbolically in Equation 1.

Equation 1: Body 3-2-1 Rotation

$$^R R^{R'''} = {}^R R^{R'} \text{ x } {}^{R'} R^{R''} \text{ x } {}^{R''} R^{R'''}$$

The cosine matrices are multiplied together in the order of the rotation sequence. Equation 2 shows this multiplication. It is an expansion of Equation 1.

Equation 2: Expanded Multiplication of the Three Cosine Matrices

$$\begin{bmatrix} r11 & r12 & r13 \\ r21 & r22 & r23 \\ r31 & r32 & r33 \end{bmatrix} = \begin{bmatrix} \cos\Psi & \sin\Psi & 0 \\ \sin\Psi & \cos\Psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & \sin\varphi \\ 0 & \sin\varphi & \cos\varphi \end{bmatrix}$$

In symbolic form, the rotation matrix between the global reference frame and the local reference frame is as stated below in Equation 3.

Equation 3: Symbolic Rotation Matric for Body 3-2-1 Rotation

$$\begin{pmatrix} \cos(\psi)\cos(\theta) & \cos(\psi)\sin(\varphi)\sin(\theta)-\cos(\varphi)\sin(\psi) & \sin(\varphi)\sin(\psi)+\cos(\varphi)\cos(\psi)\sin(\theta) \\ \cos(\theta)\sin(\psi) & \cos(\varphi)\cos(\psi)+\sin(\varphi)\sin(\psi)\sin(\theta) & \cos(\varphi)\sin(\psi)\sin(\theta)-\cos(\psi)\sin(\varphi) \\ -\sin(\theta) & \cos(\theta)\sin(\varphi) & \cos(\varphi)\cos(\theta) \end{pmatrix}$$

By substituting the Euler angles (outputs from TrakSTAR equipment) into the equation described above, the given local coordinate system can be represented as a numeric value for each time point. Using the identity matrix to represent the three orthogonal axes defining the global coordinate system, the above listed rotation matrices from Equation 3 is equivalent to the vectors describing the sensor orientation.

With the sensor data decomposed into a coordinate system, any rotation sequence can be applied to the data to obtain Euler angles again. This can be useful when comparing data sets from two

studies that did not assume the same rotation sequence. By decomposing the Euler angles with the known rotation sequence and recomposing the Euler angles using the new rotation sequence, data may be compared across studies.

Method 2: Establishing Orientation Vectors from Position

In some cases, it may not be possible to use the orientation data collected from the TrakSTAR. In those instances, position data can be used to create a surrogate orientation for each sensor location. This is a two-step process: the first is to establish coordinate systems at each sensor and the second is to calculate the orientation of those coordinate systems in the global space. This process while can be modified for other applications is described in detail below for spinal motion tracking. Further detail is provided in the user defined MATLAB function CoordinateStystemAngles.m.

Coordinate System Creation

The idea behind this process is to establish a coordinate system centered at the sensor's location. The location of the 'sensor of interest' are the origin the new coordinate system will be coincident. For this example, the sensor of interest is T3 and the angle bring created is the upper thoracic angle.

1. Vector 1 (v1) is created by subtracting the position of the sacral sensor (the most inferior sensor) from the position of the sensor of interest. This is the inferior vector. (Figure 7a)

2. Vector 2 (v2) is created by subtracting the position of the sternal sensor (the most anterior sensor) from the position of the sensor of interest. This is the anterior vector. (Figure 7a)

3. Take the magnitude of vector 1 and vector 2.

4. A new vector is created by crossing vector 2 into vector 1. This new vector is orthogonal to the original vectors. For the example given in Figure 7b, this new vector is $T3_y$. Take the magnitude of $T3_y$.

5. A second new vector is created by crossing vector 1 into the first new vector. This vector is orthogonal to vector 1 and the first new vector. In Figure 7b, the second new vector is shown as $T3_x$. Take the magnitude of $T3_x$.

6. Together, $T3_x$, $T3_y$, and $T3_z$ establish the coordinate system at the T3 sensor. Each T3 vector has three components: one component in the global x direction, one component in the global y direction, and one component in the global z direction.
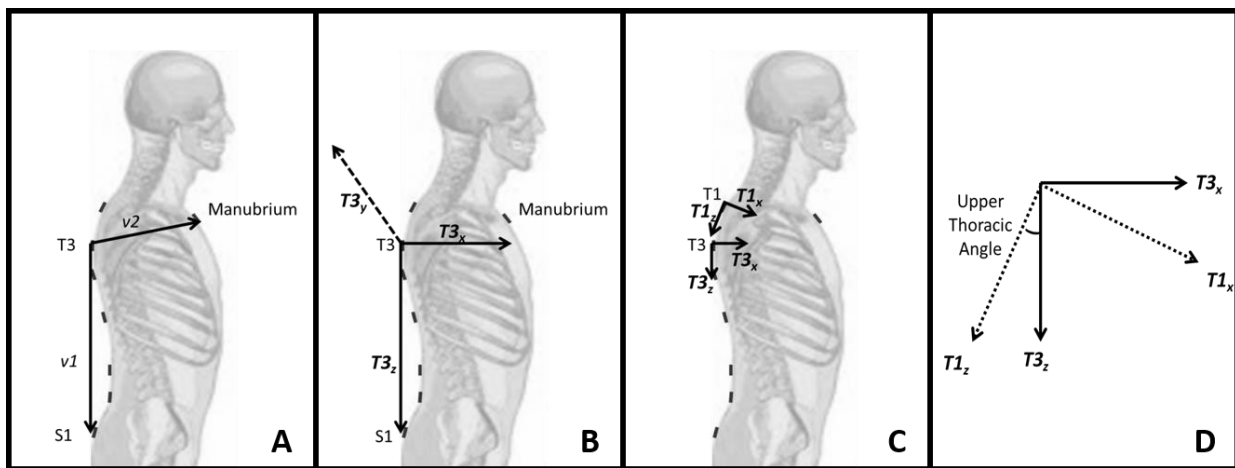

Figure   7: Creating Coordinate Systems at Sensor Locations

Method 3: Combined Methods for Euler Angle Calculation

To calculate the Euler angles, the rotation sequence must first be established. Then the rotation matrices can be formed and decomposed into Euler angles.

Numeric Rotation Matrices Creation

1. Having established the coordinate system, the three coordinate system vectors ($\mathbf{n_2}$, $\mathbf{n_1}$, and $\mathbf{v_2}$) for a single sensor are placed into an inverted rotation matrix.

2. Continuing the original example, $\mathbf{v_2}$ ($T3_z$) is placed in the third row. The first new vector ($\mathbf{n_1}$), T3y, is placed in the second row. The second new vector ($\mathbf{n_2}$), $T3_x$, is placed in the first row.

3. Invert this matrix to obtain the numeric rotation matrix.

4. Set the inverted numeric matrix equal to the symbolic rotation matrices.

7. Isolate each of the rotations (ψ, φ, θ) from the rotation sequence and use the numeric matrix to solve for the angle value.

Symbolic Rotation Matrices Creation

The resulting spine motion can deviate based on the rotation sequence used. For planar motions, the outcome does not change greatly but the rotation sequence becomes important when looking at spinal coupling.[79] There are two widely accepted rotation sequences used in spine motion analysis: one from the International Biomechanics Society and a second from Crawford et al. From the work of Crawford et al., it is proposed that there is a best rotation sequence to use for spine motion analysis. Therefore, analysis of each planar motion should use unique rotation sequences. The ISB sequence is sagittal-axial-lateral. The Crawford sequence is axial-lateral-sagittal. A third sequence has been historically used within the Human Motion Control laboratory. The HMC sequence is sagittal-lateral-axial. For this analysis, the HMC sequence was chosen to maintain standard analysis practices within the lab. In the future, especially when conducting coupling analyses consideration should be given to adopting the ISB or Crawford sequence.

Having presented the sequence used here, these Euler angles can be decomposed into their

vectors again and reformed using alternative rotation sequences if so desired. The rotation

sequences used here, as well as the two most common sequences, are summarized in Table 2.

Table   2: Summary of Rotation Sequences by Motion Type

Rotation Sequence	First Rotation	Second Rotation	Third Rotation
HMC Lab	Sagittal	Coronal	Axial
Crawford	Axial	Coronal	Sagittal
IBS	Sagittal	Axial	Lateral

With the coordinate systems established at each vertebra, the axes are oriented in the same

manner as the global coordinate system, such that: the x axis points from posterior to anterior;

the y axis points from medial to lateral to the right; and the z axis points from superior to

inferior. Therefore, lateral bending is a rotation about the x axis; flexion and extension are

rotations about the y axis; and axial rotation is a rotation about the z axis. The general cosine

matrices for single rotations are shown in Equation 4.

Equation 4: Rotation Matrix Calculations for Flexion/Extension

$$Body1\ Rotation = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi & \cos\varphi \end{bmatrix}, \quad about\ X\ axis$$

$$Body2\ Rotation = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}, \quad about\ Y\ axis$$

$$Body3\ Rotation = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad about\ Z\ axis$$

For **all motion** tasks, the sagittal-lateral-axial rotation sequence was used. Therefore, the rotation

sequence is a 2-1-3 Body rotation, as shown in Equation 5.

Equation 5: Rotation Matrix Calculations for a Body 213 Rotation

$$Body\ 2-1-3 = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi & \cos\varphi \end{bmatrix} \times \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$Body\ 213 = \begin{bmatrix} \cos\theta\cos\psi + \sin\theta\sin\varphi\sin\psi & \cos\psi\sin\theta\sin\varphi - \cos\theta\sin\psi & \cos\varphi\sin\theta \\ \cos\varphi\sin\psi & \cos\varphi\cos\psi & -\sin\varphi \\ \cos\theta\sin\varphi\sin\psi - \cos\psi\sin\theta & \sin\theta\sin\psi + \cos\theta\cos\psi & \cos\theta\cos\varphi \end{bmatrix}$$

By setting the symbolic rotation matrix from each motion task equal to the numeric rotation

matrix, the angles (θ, φ, and ψ) can be calculated, where theta is the rotation about the y axis

(Flex/Ext); phi is the rotation about the x axis (Lateral Bending); and psi is the rotation about the

z axis (Axial Rotation).

Equation 6: Angle Calculations for a Body 213 Rotation

$$\varphi = \sin^{-1}(-a_{23}) = Lateral\ Bending$$

$$\theta = \tan^{-1}\left(\frac{a_{13}}{a_{33}}\right) = Flexion/Extension$$

$$\psi = \tan^{-1}\left(\frac{a_{21}}{a_{22}}\right) = Axial\ Rotation$$

Creating Anatomic Angles from Euler Angles

Having utilized the correct rotation sequence, the position and orientation of each sensor is

established. There are three types of anatomic angles: global, segmental, and normalized. The

global angle refers to the torso angle. It is a measured used to quantify the movement of the torso

as a whole as approximated from the movement of a specific sensor, in this case T10. Segmental

angles are the angles measured between two vertebrae. Normalized angles are segmental angles divided by the number of functional spine units exist within that segment.

Torso Angle

The global parameters are representative of motion of the entire trunk including flexion, bending, and torsion. This analysis technique is adapted from the work of Wilson et al. and is a standard in the field of human motion tracking.[80,81] For this technique, the vertebra T10 is used as a representation of the entire spine. The torso typically has one lordotic and one kyphotic curve in the sagittal plane. The T10 vertebra is chosen because it lies in a neutral position between these curves. To track the motion at T10, a coordinate system must be established. Like in Figure 7, the coordinate system is established at T10. The coordinate system established at T10 is shown in Figure 8.
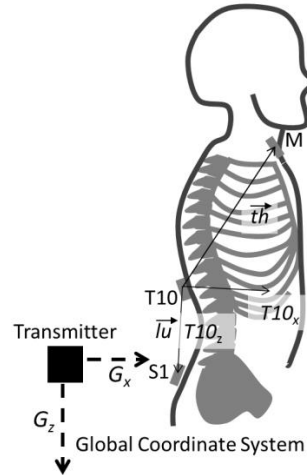

Figure   8: Establishing a Coordinate System at T10 for the Torso Angle Measurement

Using the sensors at T10, the sacrum, and the manubrium, two vectors, the lumbar vector and the thoracic vector, are created and used to create three orthogonal vectors centered at T10 (Figure 8). Before defining the other vectors for the coordinate system, the lumbar and thoracic vectors

are converted to unit vectors. Crossing the lumbar motion unit vector with the thoracic motion unit vector will result in a new unit vector (n_1) orthogonal to the lumbar and thoracic motion vectors. Crossing the resultant unit vector with the lumbar motion unit vector will result in a second unit vector (n_2), orthogonal to the lumbar motion unit vector and the first resultant unit vector (Figure 8). The resulting trunk coordinate system (T) can be used to determine motion angles of the trunk with respect to the transmitter in all planes of bending.

Segmental Angles

Segmental angles represent the angle of one vertebral sensor with respect to another. In Figure 7d, the upper thoracic angle is shown. The upper thoracic segment lies between T1 and T3. To calculate the angle, the orientation of the T1 coordinate system is compared (substracted from) to the orientation of the T3 coordinate system. The difference in orientation is the upper thoracic angle. These segmental angles can be measures in all three planes but are typically only measured in the plane of intended motion. For this study, six segmental angles were calculated: upper thoracic (T1-T3), mid thoracic (T3-T6), lower thoracic (T6-T10), thoracolumbar (T10-L1), upper lumbar (L1-L3), and thoracic (T1-L1). To calculate these angles, the motion of the inferior vertebra is usually subtracted from the superior vertebra, such that the motion is the motion of the superior vertebra with respect to the inferior vertebra. This is due to the similarity of the spine to an inverted pendulum.

Normalized Segmental Angles

Normalized segmental angles are segmental angles, calculated as described above, divided by the number of functional spine units (or levels) in each segment. This normalization is based on the idea that the contribution for each functional spine unit within a segment is equal. The normalized segmental angle is then the representative motion contribution of a single functional

spine unit within that segment. The upper thoracic segment has two levels; the mid thoracic

segment has three levels; the lower thoracic segment has four levels; the thoracolumbar segment

has three levels, the upper lumbar segment has two levels; and the thoracic segment has twelve

levels. A guide for segmental and normalized angle is provided in Table 3.

Table   3: Quick Guide for Anatomic Angles

Angles	Location	FSUs	Normalized Angle	
Upper Thoracic (UT)	T1-T3	2	$\dfrac{T_1 - T_3}{2}$	UT nROM
Mid Thoracic (MT)	T3-T6	3	$\dfrac{T_3 - T_6}{3}$	MT nROM
Lower Thoracic (LT)	T6-T10	4	$\dfrac{T_6 - T_{10}}{4}$	LT nROM
Thoracolumbar (TL)	T10-L1	3	$\dfrac{T_{10} - L_1}{3}$	TL nROM
Upper Lumbar (UL)	L1-L3	3	$\dfrac{L_1 - L_3}{2}$	UL nROM
Thoracic (Thor)	T1-L1	12	$\dfrac{T_1 - L_1}{12}$	Thor nROM

Jump Fixes

Because these analysis methods utilize trigonometric functions, they are susceptible to gimble

lock. This occurs when the trigonometric function has the same value in more than one quadrant.

Without knowing which quadrant the resulting angle should be in, the program makes a best

guess, which sometimes shifts the data into a new quadrant. To identify these problem spots, the

angle data is plotted over time. Anywhere the data suddenly jumps by approximately 180

degrees, a gimble lock error has occurred. To mathematically identify these jumps, the derivative

is of the motion over time is taken. A threshold is set near the height of the jump. In this case,

160 was used. When the derivative exceeds the threshold, a jump is identified. To fix the jump,

the data needs to be shifted back to the appropriate quadrant. By determining if the derivative is positive or negative, the data can be shifted up or down by 180 degrees. These steps are repeated for all angles for all bending modes.