In Vivo Characterization of Thoracolumbar Range of Motion in Healthy Populations

By

Eileen S. Cadel

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Chairperson Dr. Elizabeth Friis

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Dr. Carl Luchies

_____

Dr. Sara Wilson

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The Thesis Committee for Eileen Cadel

Certifies that this is the approved version of the following thesis:

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Chairperson Elizabeth Friis

Data approved: _____

Abstract

The long term objective of this research was to investigate thoracolumbar mobility *in vivo* and develop a method that allows for the comparison of motion data between *in vivo* and cadaveric models. Many research studies have investigated *in vivo* motion and the effects of aging on the lumbar spine, but little has been done for the thoracic and thoracolumbar spine. The thoracolumbar spine is commonly affected by adult deformities, resulting in chronic back pain, osteoarthritis, and osteoporosis. The goal of treating these deformities is to return the spine to native condition. In order to accomplish this, research must be conducted on how the native thoracolumbar spine functions in the representative patient population.

The first objective of this study was to quantify the effect of aging on the thoracolumbar spine. The *in vivo* thoracolumbar mobility of healthy adolescents and healthy older adults was compared to investigate how the non-pathologic thoracolumbar spine changes with age. The study results quantified that the healthy adolescent spine has significantly more motion than the healthy older adult spine in three modes of bending.

The second study objective was to develop a method that allows for the comparison of spinal motion data in different physiological models and to frame *in vivo* motion data in a way that is meaningful to clinicians. The analysis technique developed allowed for clinical parameters to be investigated in an *in vivo* motion model that previously was difficult to measure.

The results from this work found that the healthy adolescent spine is more mobile than the healthy older adult spine. The next steps are to directly compare cadaveric and

in vivo spinal motion models for healthy older adults. It is important to be able to compare the data from these two models, particularly when designing medical devices. Pediatric and adolescent spinal devices are tested on older adult cadavers. If pediatric and adolescent *in vivo* motion cannot be compare to older adult cadaveric motion, the use of older adult cadavers cannot be validated.

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List of Abbreviations

C1 – C7	cervical spine levels 1 through 7
T1 – T12	thoracic spine levels 1 through 12
L1 – L5	lumbar spine levels 1 through 5
FSU	functional spine unit
ROM	range of motion
F	flexion
E	extension
RLB	right lateral bending
LLB	left lateral bending
RAR	right axial rotation
LAR	left axial rotation
R45	right 45° anterior – lateral flexion
L45	left 45° anterior – lateral flexion
UT	upper thoracic segment (T1 – T3)
MT	middle thoracic segment (T3 – T6)
LT	lower thoracic segment (T6 – T10)
UTL	upper thoracolumbar segment (T10 – L1)
LTL	lower thoracolumbar segment (L1 – L3)
Thor	thoracic segment (T1- L1)
TL	thoracolumbar segment (T1 – L3)
nROM	normalized range of motion
%ROM	percent of thoracolumbar range of motion

Chapter 1: Introduction

Many research studies have been conducted to investigate the *in vivo* motion in the lumbar spine. This is because it is often associated with low back pain, a common ailment in adults and typically a sign of a spinal disorder. However, it is just as important to investigate the thoracic spine. Adult spinal deformity is prevalent in the thoracic and thoracolumbar regions of the spine. The long term implications of these deformities are chronic back pain, osteoarthritis, and osteoporosis. The goal of treating these deformities is to return the spine to native condition. In order to accomplish this, research must be conducted on how the native thoracolumbar spine functions.

Previous studies have been conducted on lumbar mobility in a healthy aging population. However, the same cannot be said for thoracic and thoracolumbar mobility. In order to treat patients with adult deformities, it is important to understand the kinematics of the thoracolumbar spine so that clinical steps can be taken to restore their spinal function.

In addition to characterizing the thoracolumbar spine *in vivo*, it is important to be able to compare the *in vivo* motion to cadaveric motion. Currently, methods do not exist to accurately compare these models. This is primarily due to the differences in data collection. In cadaveric models, motion is commonly reported for individual functional spine units while *in vivo* models commonly report motion for longer segments in the spine. It is important to be able to compare the data from these two models, particularly when designing medical devices. Pediatric and adolescent spinal devices are tested on

older adult cadavers. If pediatric and adolescent *in vivo* motion cannot be compared to older adult cadaveric motion, the use of older adult cadavers cannot be validated.

The following chapter discusses background knowledge and the significance for this research. First the relevant human anatomy will be discussed, followed by a discussion on spinal mobility and the effects aging have on the spine. Finally, comparing cadaveric and *in vivo* spinal motion data will be discussed.

The third chapter contains a study that compares *in vivo* thoracolumbar spinal range of motion between healthy adolescents and healthy older adults. It was hypothesized that differences in spinal motion with exist between these two subject groups.

The fourth chapter contains a study that proposes a method to evaluate the *in vivo* contribution of a single representative spinal motion unit in the thoracolumbar spine for healthy adults. The motion in a spinal segment was normalized by the number of functional spine units so the individual motion units can be investigated.

The final chapter summarizes the conclusion from this research and proposes areas for further investigation.

Chapter 2: Background and Significance

2.1 Basic Spinal Anatomy

2.1.1 Anatomical References

The human body is commonly described using a series of anatomic references. Superior and inferior describe movement along the vertical plane in an upwards and downwards directions respectively. Lateral and medial describe movement in the horizontal plan where lateral is moving away from the center of the body and medial is moving towards the center. Anterior and posterior refer to the front and back of the body respectively. The human body is also commonly divided into three two-dimensional planes that describe movement in reference to the spinal column (Figure 1). The coronal plane runs horizontally and divides the front and back of the body. The sagittal plane runs vertically and divides the left and right sides of the body. The transverse plane runs horizontally and divides the top and bottom of the body through the waist.[1]

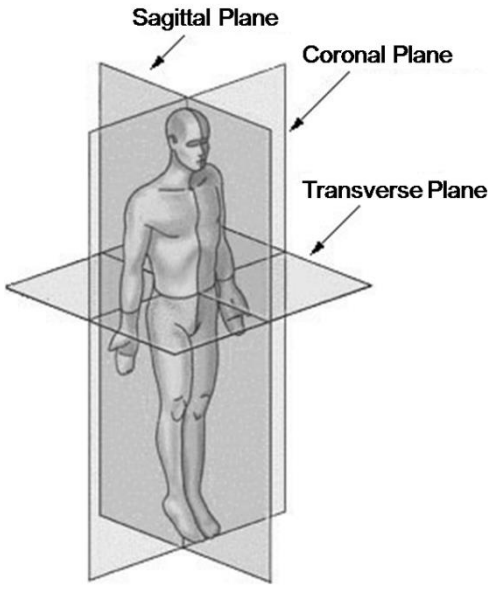

Figure 1. Anatomical Reference Planes (Public Domain)

2.1.2 Spinal Anatomy Overview

The human spine is comprised of both hard and soft tissue constructs that allows for the protection of the spinal cord and its branching nerves, the ability to undergo compressive loads, and the facilitation of movement by providing anchorage for muscle attachments. The spine is divided into four regions: cervical, thoracic, lumbar, and the sacrum (Figure 2).

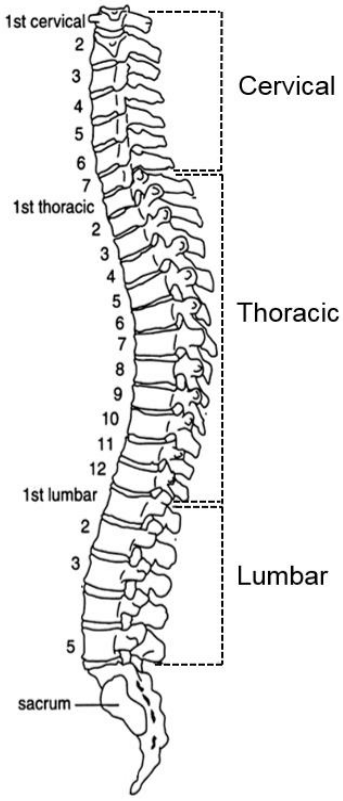

Figure 2. Anatomy of the Spine (Public Domain)

The cervical region is the most superior region and contains the first seven vertebrae, C1 to C7 (superior to inferior). The thoracic region is directly inferior to the cervical region. It contains the next twelve vertebrae, T1 to T12. The thoracic vertebrae differ from the cervical vertebrae to provide a connection point to for the ribs and to

provide increased support and protection to the organs contained in the chest cavity resulting in the most stable and stiff region of the spine. The lumbar region is directly inferior to the thoracic region. It contains the next five vertebrae, L1 to L5. These five vertebrae are the largest and strongest vertebrae due to the immense forces and moments they are subjected to. The thoracic and lumbar regions together can be referred to as the thoracolumbar region. The most inferior portion of the spine is comprised of the sacrum. It attaches L5 to the iliac bones of the pelvis. The vertebrae in the sacral region are fused together and form what is commonly referred to as the tailbone.[1]

Another common way to refer to the spine is by its individual functional spine units (FSUs). A single FSU is composed of two adjacent vertebrae, the disc between them, and their connecting soft tissue. This is a useful way to describe the motion of a single join in the spine. For example, the T1/T2 FSU represents the motion that is due to the interaction of the T1 vertebra and the T2 vertebra.

The curvature of the spine can be expressed in the three anatomical reference planes. When viewing the spine in the frontal plane, it is straight. When viewing the spine in the sagittal plane, the lordosis (the posterior concavity) in the cervical and lumbar region can be seen as well as the kyphosis (the anterior concavity) in the thoracic region.[1]

2.2 Spinal Mobility

2.2.1 Range of Motion

Range of motion (ROM) is one of the most common parameters that represent spinal mobility. White and Panjabi define spinal ROM as the difference between two

positions that represent the range of physiological motion.[2] This parameter is extremely versatile because it can measure the how spinal segments, regions, or the entire spinal column moves.

2.2.2 Modes of Bending

Typically, ROM is presented as an angular measure of displacement during a bending task. There are three primary modes of bending of the human spine (Figure 3). Flexion (bending anteriorly) and extension (bending posteriorly) both have primary motion within the sagittal plane. Right and left lateral bending have primary motion within the frontal plane. Right and left axial rotation have primary motion within the transverse plane.[1] However, not all bending tasks are purely flexion, extension, lateral lending, or axial rotation. Additional mobility often comes from out-of-plane bending.

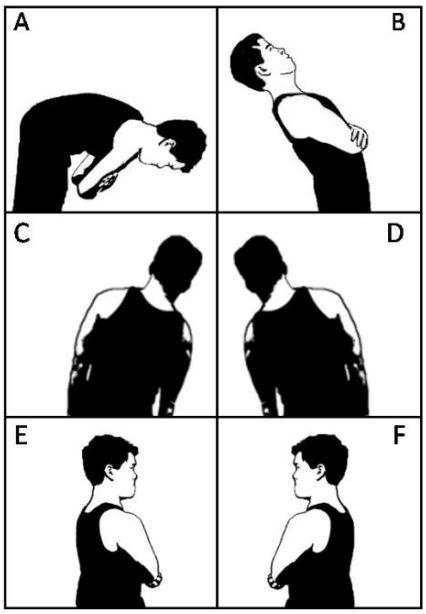

Figure 3. Modes of Bending
A) Flexion B) Extension
C) Right Lateral Bending D) Left Lateral Bending
E) Right Axial Rotation F) Left Axial Rotation

2.2.3 In Vivo Testing of Spinal Mobility

There are several methods of measuring *in vivo* spinal ROM. They range from electromagnetic[3–5] and optical tracking[6–12] to using radiographic images[13,14] to using a device that traces spinal curvature[15,16] to using a ruler or inclinometer to physically measure the change.[17–21]

The principle behind each of these measurement techniques is the same; measure the angular change of a vertebra from a neutral position to a bent position.

- Electromagnetic tracking:
    - Hajibozorgi et al. measured thoracic, thoracic segments, lumbar, lumbar segments, pelvic, and entire trunk ROM during flexion in young adults.[3]
    - Mc Gill et al. measured lumbar ROM during flexion, lateral bending, and axial rotation in older adults.[4]
    - Bull and McGregor measured lumbar and pelvic ROM during rowing in young adults.[5]
- Optical Tracking
    - Al-Eisa et al. measured lower thoracic and lumbar ROM during lateral flexion and axial rotation in young to middle aged adults.[6]
    - Edmondston et al. measured thoracic segments ROM during flexion and extension in young adults.[7]
    - Gercek et al. measured lower thoracic and upper lumbar vertebrae ROM during flexion, extension, lateral bending, and axial rotation in young adults. Data was collected at individual vertebra by inserting K–wires into the spinous processes.[8]
    - Larivière et al. measured thoracic and lumbar ROM during flexion, extension, and lateral bending in middle aged adults with and without chronic lower back pain.[9]

    - Lee et al. measured thoracic segments and lumbar segments ROM during flexion, anterior-lateral bending, and lateral bending in young adults and older adults with degenerative spine disease.[10]
    - Noh et al. measured thoracic segments and lumbar segments ROM during lateral bending in a young adult with mild scoliosis and compared results against x–ray images.[11]
    - Tojima et al. measured lumbar ROM during flexion, extension, lateral bending, and axial rotation in middle aged adults.[12]
- Radiographic Images
    - Miyasaka et al. measured lumbar ROM during flexion and extension in middle aged adults. Measurements were made from functional radiographs.[13]
    - Morita et al. measured thoracic vertebrae ROM during flexion and extension in middle aged and older adults. Measurements were made from CT images.[14]
- Spinal Tracing Devices
    - Granacher et al. measured thoracolumbar ROM during flexion, extension, and lateral bending in older adults using the MediMouse system.[16]
    - Mannion et al. measured thoracic and lumbar vertebrae ROM during flexion in middle aged adults using a Spinal Mouse.[15]
- Measuring by Hand
    - Alaranta et al. measured cervical, lumbar, and entire trunk ROM during flexion, extension, and axial rotation in middle aged adults with and without neck or low back pain. Data was collected with a liquid inclinometer on the subjects' head.[18]
    - Burton et al. measured lumbar ROM during flexion and extension in school children, young adults, middle aged adults, and older adults. Data was collected using the flexicurve technique.[19]
    - Fitzgerald et al. measured lumbar ROM during flexion, extension, and lateral flexion in young adults, middle aged adults, and older adults. Data

was collected using the Shöber methods that measures the amount of distraction between two marked points with a ruler.[20]

- Ng et al. measured lumbar ROM during flexion, extension, and lateral bending in young adults. Data was collected using an inclinometer.[21]

With the electromagnetic and optical tracking systems, the markers or sensors placed a desired vertebrae collect position data. A method to extract angular ROM from position data has been established in the field of spinal mobility testing.[22] The position data obtained can be used to create coordinate systems centered at each vertebra. To calculate ROM angles from this coordinate data, the Euler method is often used to extract the angle of the coordinate system centered at each vertebra in relation to a globally defined coordinate system. The order of the rotation sequences is dictated by the primary motion axis, primary coupled axis, and secondary coupled axis.[23]

2.2.4 Overall Torso and Segment Motion Techniques

The angular ROM data outputted from these measurement and analysis methods allow motion from desired anatomical locations to be recorded. Studies have investigated the overall torso ROM during a particular bending task. Granata and Sanford have demonstrated that the movement of the T10 vertebra relative to upright posture is a good representation for overall torso motion.[24] In addition to torso ROM, researchers will often separate the spinal column into segments to further analyze parameters and to isolate trends. There are many different ways to segment the thoracolumbar region spine.

One common method is to divide the thoracolumbar spine into two segments, the thoracic and lumbar segments. However, these are long segments and the spinal

kinematics may not be uniform throughout the entire segment due to anatomical differences in the vertebrae such as angle of the facet joints and height of the vertebral body.[2]

Therefore, it is common to divide these long segments into smaller ones. It is common throughout the literature to have thoracic segments (upper thoracic, middle thoracic, lower thoracic) and lumbar segments (upper lumbar, lower lumbar). However, there is not uniformity in where these smaller segments begin and end. For example, Lee et al. defined segments from C7 – T3, T3 – T6, T6 – T9, T9 – T12, T12 – L3, and L3 – S1 for upper thoracic, mid-upper thoracic, mid-lower thoracic, lower thoracic, upper lumbar, and lower lumbar respectively.[10] Alqhtani et al. defined segments from T1 – T4, T4 – T8, T8 – T12, T12 – L3, and L3 – S1 for upper thoracic, middle thoracic, lower thoracic, upper lumbar, and lower lumbar respectively.[25]

2.2.5 Sensor Placement for Present Studies

In the present studies, electromagnetic tracking was used and sensors were places on the subject's manubrium and spinous processes of T1, T3, T6, T10, L1, L3, and at the top of the sacrum (Figure 4). Therefore, the segments were defined from T1 – T3, T3 – T6, T6 – T10, T10 – L1, and L1 – L3 for upper thoracic, middle thoracic, lower thoracic, upper thoracolumbar, and lower thoracolumbar. Additionally, the thoracic segment was defined from T1 to L1 to ensure that every thoracic FSU was captured in the segment. Overall torso angle was defined as the orientation of T10 in reference to the globally defined coordinate system.

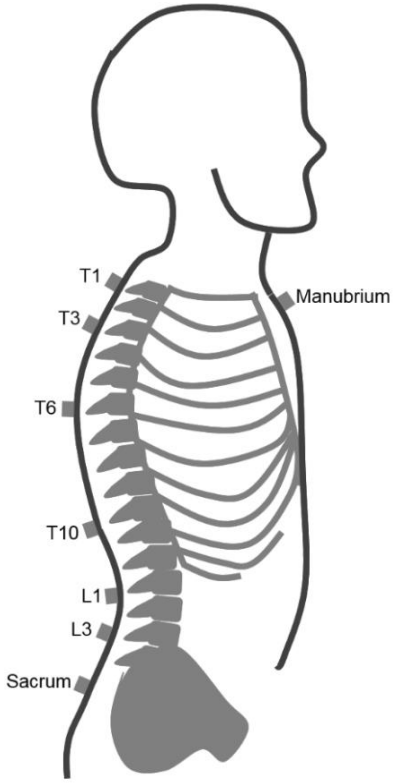

Figure 4. Sensor Placement for Present Studies

Careful thought was put into the selection of the sensor locations. Sensors were placed at the first vertebra in both the thoracic, lumbar, and sacral regions. A sensor was placed at T10 in order to capture overall torso motion[24]. A sensor was placed at T6 to measure motion at the apex of thoracic kyphosis and at L3 to measure the motion at the apex of lumbar lordosis.[26] In order to create three thoracic segments, a sensor was placed at T3. The last sensor was placed at the manubrium to allow for the vector creation of a coordinate system centered at each vertebra.

2.2.6 Calculating Spinal Angles

To calculate spinal angles for a segment or region, the general protocol is to take the motion of the most superior vertebra relative to the most inferior vertebra in the

desired segment. In many *in vivo* studies, this is done by subtracting the angle the most inferior vertebrae from the most superior vertebrae in the segment. For example, the angle for a segment ranging from T1 to T12 would be the angle of T1 minus the angle of T12. Once this segment has been created, its ROM can be calculated by subtracting the neutral position angle from the bent position angle.

The problem with this technique is the slight variations between analysis methods found in the literature. For example, researchers in one study measured lumbar angle from T12 to L5.[9] In a similar study, researchers measured lumbar angle in two segments, one from T12 to L3 and the second from T3 to S1[25].

If you sum the T12 to L3 segment with the T3 to S1 segment, these two methods may not seem that different. However, the first study is reporting motion from a segment that has one less vertebra. The shorter segment has one less FSU. One limitation of measuring ROM with an electromagnetic or optical tracking system is that a sensor or marker cannot be placed at every vertebra due to anatomical space constraints. Therefore, ROM is typically reported for segments. Collecting data at different starting or ending vertebrae or having varying number of FSUs in the segments may affect the ROM reported. This would be less of an issue if there were to be a way to normalize the motion in each segment by the number of FSUs. However, there is not a standardized way to do this.

2.3 The effect of Spinal Aging

2.3.1 Range of Motion and Aging

Many researchers have investigated the effect of aging on spinal motion and it has been shown that aging significantly decreases an individual's motion

characteristics.[4,10,18–20,27,28] Alaranta et al., McGill et al., Saidu et al., Fitzgerald et al., and Troke et al. have studied lumbar ROM in a healthy aging population[4,18,20,27,28]. Alaranta found that cervical and lumbar ROM decreased for subjects aged 35 through 54 binned into groups during flexion, extension, lateral bending, and axial rotation.[18] McGill found that lumbar ROM decreased between young adults (21 years ± 3.4) compared to older adults (69 years ± 3.5) during flexion and lateral bending.[4] Saidu found that lumbar ROM decreased for subjects aged 20 through 76 binned into groups during flexion, extension, and lateral bending.[27] Similarly, Fitzgerald found that lumbar ROM decreased for subjects ranging from 20 to 82 years old during flexion, extension, and lateral bending.[20] In addition, Troke found that lumbar ROM decreased for subjects ranging from 16 to 90 years old during flexion, extension, and lateral bending.[28]

Burton et al. studied lumbar ROM in a healthy young population compared to an older population with low back trouble. Burton found that lumbar ROM decreased for subjects aged 10 through 84 binned into groups during flexion and extension. The groups were binned according whether the subject was currently having low back trouble, had low back trouble in the past, or never experiences low back trouble.[19] Lee et al. studied both thoracic and lumbar ROM in a healthy younger population compared to an older population with degenerative spine diseases. Lee found that lumbar and thoracic ROM decreased between young adults (26.5 years ± 1.8) compared to older adults (71.7 years ± 4.0). The older adults all had been diagnosed with degenerative spine diseases and must have an osteoarthritis grade 2 to 4.[10] This study conducted by Lee is the only study that compares thoracic ROM in young and older adults.

The decrease in spinal mobility with age can be attributed to several physiological changes. As the body ages, it loses muscle mass.[29] This reduction in muscle mass is due to adipose tissue infiltration and overall atrophy.[30] Previous studies have investigated the effect of such physiological changes on the spine. The lumbar spine undergoes the greatest forces and moments and is commonly associated with low back pain.[31] This has resulted in literature focusing on the lumbar spine.[4,12,19–21,28,32–34]

For the aging adult population, many studies have been conducted to investigate the effect of age on the lumbar ROM due to the large number of spine disorders that affect the lumbar region particularly low back pain [31]. While the lumbar region of the spine undergoes the greatest forces and moments, it is still important to study the other regions of the spine. In particular, the thoracic region of the spine in regards to ROM is not studied thoroughly in the literature.

2.3.2 Importance of the Thoracic Spine

Spinal disorders and deformities affect all regions of the spine, not just the lumbar.[35–38] More than 65% of all adults over 60 years of age have developed some form of adult spinal deformity.[39] Adult spinal deformity predominantly affects the thoracic and thoracolumbar regions of the spine. The long-term implications of adult spinal deformities are chronic back pain as well as osteoporosis and osteoarthritis in the vertebrae affected by the deformity.[40–42] Additionally, the amount of kyphosis in the thoracic spine is of particular interest. The exaggeration of the kyphosis curvature in this region is associated with many conditions and illnesses including hyperkyphosis,

Scheuermann disease, congenital spine defects and abnormalities, vertebral facture, and osteoporosis.[43,44]

The general goal for treating spinal disorders and deformities is to reduce a patient's pain and hopefully regain the function and mobility found in a native spine. To accomplish this, it is imperative to understand how a healthy spine ages. Preliminary studies have been conducted on the thoracic spine with the goal of better understanding the kinematics of the native spine. However, the subjects in these studies are not of an age representative of the patients experiencing thoracic-related spinal disorders and deformities.[6–11,45–47] This is an important distinction because back pain, osteoporosis, and osteoarthritis are ailments experienced typically by the older population.[48–51]

While it is important to understand thoracic and thoracolumbar spinal mobility in a young adult and adult population, it does not provide the necessary kinematics for the older adult population. Previous studies have shown that lumbar spinal mobility does change with age in a healthy population. If thoracic spinal mobility is affected by age similar to the lumbar spine, then it is just as important to study thoracic spinal mobility in a healthy population.

2.4 Comparing Cadaveric and *In Vivo* Motion Analysis Methods

2.4.1 Comparing Range of Motion between Models

Historically, it has been difficult to compare ROM measured in cadaveric studies to ROM measured in *in vivo* models. This is primarily due to cadaveric ROM being measured in terms of FSUs while *in vivo* ROM is measured in segments. It is advantageous to measure ROM in terms of FSUs for a few reasons. The first is that the spine can be considered as one structure made up of multiple FSUs connected in

series.[2] This indicates that the behavior of the entire spine is merely a composite of each FSUs added in series.

Oda et al., Oxland et al., and Sran et al. have studied ROM in thoracic spine FSUs.[52–54] They all record ROM for FSUs as the relative motion of the superior vertebra to the inferior vertebra. Oda measured ROM for six sets of FSUs: T3/T4, T4/T5, T5/T6, T6/T7, T7/T8, and T8/T9.[52] Oxland measured ROM for two sets of FSUs: T11/T12 and T12/L1.[53] Sran measured ROM for three sets of FSUs: T5/T6, T6/T7, and T7/T8.[54] Busscher et al. measured ROM for individual vertebra: T1, T2, T3, and L1.[55]

It is beneficial to study an individual FSU because it direct motion from a single joint can be characterized.[52–56] This is advantageous for surgeons because they are primarily concerned with the specific vertebra or FSU where a problem is originating. The downside to studying only individual FSUs is that the motion of a spinal segment, consisting of several FSUs in series, is much more indicative of *in vivo* spinal motion.[2]

In vivo models are limited to measuring ROM in segments. This is due to the anatomical space constraints on a subject's back. Typically, markers or sensors will be placed on the spinous process of vertebrae of interest. Particularly in the cervical and thoracic regions, the heights of these vertebral bodies limit the number of sensors that can be physically placed. Therefore, researchers must be judicious when selecting particular vertebrae in which they want to measure ROM.

Both cadaveric and *in vivo* models each have strengths and limitations. A strength of a cadaveric model is the ability to measure ROM for adjacent vertebrae. However, cadaveric studies are incredibly expensive and the ROM measured is not as representative of native bending. While a strength of an *in vivo* model is that is better

characterizes native movement of the spine during bending, accurately measuring ROM for adjacent vertebrae is not feasible. If a method to the segment ROM for an *in vivo* model and normalize it to the number of FSUs in that segment, then *in vivo* ROM data could be directly compared to cadaveric ROM data. This innovative technique has not previously been presented in the literature.

Another difference between measuring ROM in cadaveric and *in vivo* studies is how each specimen or subject reaches their maximum bent position. In cadaveric studies, specimens will bend to a machine designated load limit.[57–60] However, in the *in vivo* studies mentioned above, subject will bend to their voluntary maximum. This difference may explain why cadaveric data seems to be higher than *in vivo* data, due to a machine pushing a specimen beyond what their voluntary maximum bend would have been.[6,8,9,13,23,25,54,55,59,61,62]

2.4.2 Testing Pediatric Spinal Devices

Researchers can measure how the ROM from an *in vivo* spine changes with age. However, this is not possible in cadaveric spine due to the age of typical cadaveric specimens. This results in pediatric and adolescent thoracic spinal devices being tested for efficacy on older adult cadaver models. If researchers want to validate the use of an older adult cadaver to test pediatric and adolescent thoracic spinal devices, two critical steps must take place. The first is to show that the thoracic *in vivo* adolescent spine is similar to the thoracic *in vivo* older adult spine. The second is to quantify that the thoracic older adult *in vivo* and thoracic older adult cadaveric spine have similar spine kinematics. If these can be shown, then is may be plausible to say the thoracic *in vivo*

adolescent spine is similar to the thoracic older adult cadaveric spine, validating the testing of pediatric and adolescent spinal devices on an older adult cadaver.

Erickson et al. is assessing pedicle screws in cadaveric models.[63] These pedicle screws are designed for use the Luque – Galveston fixation system for pediatric spinal deformities. However, the study is being conducted on cadaveric specimens aged 45 to 60. While the study showed that adding pedicle screws increases the strength and stiffness of the fixation system, all data was collected on specimens not of a representative age of the patients who would be getting the Luque – Galveston system. It is unknown if the same results would hold true in a pediatric or adolescent model.

2.5 Summary

Understanding basic spine anatomy, spinal mobility, the effect of spinal aging, and how cadaveric and *in vivo* motion analysis methods can be compared provides the background knowledge needed to understand the importance of the two studies to be presented. The first study will compare *in vivo* thoracolumbar spinal range of motion between healthy adolescents and healthy older adults. The second study will propose a method to evaluate the *in vivo* contribution of a single representative spinal motion unit in the thoracolumbar spine for healthy adults. Both of these studies aim to further expand the research in thoracolumbar spinal mobility and its clinical importance.

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CHAPTER 3:

A Comparison of *in vivo* Thoracic and Thoracolumbar Range of Motion between Healthy Adolescents and Healthy Older Adults

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This study compares spinal range of motion in healthy adolescents and healthy older adults. Eileen Cadel had primary responsibility for the data collection, data analysis, writing of the manuscript, and editing as recommended by her fellow co-authors.

A Comparison of *in vivo* Thoracic and Thoracolumbar Range of Motion between Healthy Adolescents and Healthy Older Adults

Eileen S. Cadel[1]
Sarah N. Galvis[1]
William M. Eboch[3]
Paul M. Arnold[2]
Sara E. Wilson[1,3]
Elizabeth A. Friis[1,3]

[1]University of Kansas, Bioengineering, 1530 W 15th Street, Learned Hall Room 3135A, Lawrence, KS, 66045, USA
[2]University of Kansas Medical Center, Department of Neurosurgery, 3901 Rainbow Bvld., MS 3021, Kansas City, KS, 66160, USA
[3]The University of Kansas, Mechanical Engineering, 1530 W 15th Street, Learned Hall Room 3138, Lawrence, KS, 66045, USA

Please address all correspondences to:

Elizabeth Friis
The University of Kansas, Department of Mechanical Engineering
1530 W. 15th St., Learned Hall Room 3138
Lawrence, KS 66045
Phone: 785-864-2104
Fax: 785-864-5254
Email: lfriis@ku.edu

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Abstract

The aim of this study was to compare *in vivo* range of motion values for overall spinal movement and segment motion in the thoracic and thoracolumbar regions between healthy adolescents aged 9-18 and healthy older adults aged 55-81. Researchers have investigated the effects of aging on spinal flexibility for the lumbar spine. However, the same has not been done for the thoracic spine. In this study, subject motion was captured in six modes of planar bending. Range of motion for torso angle, upper thoracic, middle thoracic, lower thoracic, upper thoracolumbar, middle thoracolumbar, and thoracic were calculated for all bending tasks. Results showed a decrease in range of motion in flexion, extension, and right lateral bending with age for torso angle. In the adolescents, there was a relatively steady increase in range of motion for the segments traveling inferiorly down the spine in flexion and right and left 45° anterior-lateral flexion. The same pattern was not found in the older adults. The thoracic and thoracolumbar regions contribute differently to overall torso angle between the two age groups. The results of this study indicate that age does effect spinal flexibility and that older adults are not an appropriate model for adolescents and vice versa. Future studies investigating the effect of illnesses, disorders, or activities that are predominantly found in the older population and rely on flexion, extension, or lateral bending tasks should take steps to ensure that their subjects are in the older adult age range.

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Introduction

Many research studies have investigated the impact of aging on *in vivo* spinal mobility (Alaranta et al., 1994; Burton et al., 1989; Faulkner et al., 2007; Kienbacher et al., 2015; Saidu et al., 2011). Muscle mass decreases while adipose tissue infiltration into the spinal muscles increase naturally as the spine ages. These phenomena may reduce spinal mobility over time (Hiepe et al., 2015; Simpson et al., 2008). The lumbar spine was the primary focus of these studies due to the association with low back pain (Burton et al., 1989; Esola et al., 1996; Lehman, 2004; Saidu et al., 2011; Troke et al., 2001). However, diseases associated with aging can involve the thoracic and thoracolumbar regions (Arden et al., 1996; Edmondston and Singer, 1997; Osman et al., 1994).

Some *in vivo* research has been conducted on thoracic spinal mobility (Edmondston et al., 2011; Gercek et al., 2008; Lee et al., 2013; Noh et al., 2014). A limitation of this research is the age of the subjects. Back pain, osteoporosis, and osteoarthritis are ailments predominantly found in the older population (Riggs and Melton III, 1995; Weiner et al., 2006). Yet the results from these studies regarding thoracic spinal mobility came from a young population, less representative of the patients with these ailments. Researchers have conducted studies on thoracic spinal mobility and found differences between a younger healthy population and an older diseased population (Larivière et al., 2000; Lee et al., 2013). However, researchers express a need to examine spinal kinematics in healthy older adults (Kienbacher et al., 2015; Lee et al., 2013).

Differences in spinal mobility have been reported between different age and health populations, particularly in the lumbar region. However, thoracic and thoracolumbar spinal mobility comparing healthy adolescents to healthy older adults has not yet been investigated. The aim of this study was to compare spinal range of motion (ROM) values for overall spinal movement and segment motion in the thoracic and thoracolumbar regions between healthy adolescents and healthy older adults. With this comparison, it may be determined if the use of younger healthy subjects can be used as a model for older healthy adults. It is hypothesized that differences in ROM exist between healthy adolescents and healthy older adults in all modes of bending. Additionally it is hypothesized that symmetry ratios for symmetric tasks are not different between the groups. Analyzing symmetry ratios along with ROM can further validate if a healthy adolescent spine is biomechanically similar to a healthy older adult spine (Ng et al., 2001; Stokes et al., 1981).

Methods

2.1 Subjects

Thirty-three adolescents aged 9-18 years and eighteen older adults aged 55-81 years were recruited for this study. The adolescent group consisted of nine males and twenty-four females, ages 13.7 ± 2.53 years, heights of 1.59 ± 0.14 m, and masses of 52.7 ± 14.6 kg. The older adult group consisted of fourteen males and four females, ages 70.0 ± 8.31 years, heights of 1.71 ± 0.11 m, masses of 78.59 ± 17.90 kg. All participants were in good physical condition, able to stand for one hour, and had no known spinal disease. Exclusion criteria for adolescents were any patient-reported musculoskeletal deformities or prior history of back pain. Exclusion criteria for older

adults were patient-reported spinal disorders and deformities, previous spinal surgery, steroid injections in the back, recent trauma, and the presence of broken ribs. All participants signed consent forms and this study was approved by the Institutional Review Board at the University of Kansas – Lawrence.

2.2 Data Collection

Prior to data collection, each subject performed ten iterations of three trunk stretches. Afterwards, eight six-degree-of-freedom electromagnetic sensors were placed along the midline using double-sided tape at the manubrium, the spinous processes of T1, T3, T6, T10, L1, L3, and at the sacrum (Fig. 1). Each subject stood on a platform with an isometric restraint around their hips to prevent sacral motion. The subjects were asked to stand in a neutral standing position with their feet shoulder width apart and parallel to each other, knees loose, and arms lightly crossed in front of them.

Data was collected in ten second intervals as each subject performed eight different bending tasks: flexion (F), extension (E), right lateral bending (RLB), left lateral bending (LLB), right axial rotation (RAR), left axial rotation (LAR), right 45° anterior-lateral flexion (R45), and left 45° anterior-lateral flexion (L45) as represented in Fig. 2. The order of the bending tasks was randomized for each subject. For each task the subject was instructed to stand in their neutral standing position, then bend maximally at a self-paced velocity in the given direction and hold until directed to return to the neutral standing position. Each bending task was demonstrated to the subjects and they were given time to practice before beginning data collection. Each task was repeated for five consecutive trials. Trials were considered unacceptable if the subject did not have a complete bending task or if a sensor went outside the collection volume of the motion

monitoring system. If a sensor went outside the collection volume, no parameters were calculated for that subject in that bending task. Tasks with at least three acceptable trials were approved for analysis and the last acceptable trial (either 5, 4, or 3) was used for analysis.

An electromagnetic motion monitoring system (TrakSTAR, Ascension Technologies, Burlington, VT, USA) was used to measure the position and orientation of the sensors. These sensors have a reported RMS accuracy of 1.4 mm and 0.5 degrees at a rate of 80 Hz. A low pass 4^{th} order Butterworth filter with a cutoff frequency of 2 Hz was used to filter and minimize phase shifting of the raw position data.

2.3 Data Analysis

Angular Range of Motion (ROM) is defined as the change in angle from each subject's neutral standing position to the maximally bent position. From the data collected, ROM for overall torso angle and for motion segment angles were calculated. The motion segments were upper thoracic from T1-T3 (UT), middle thoracic from T3-T6 (MT), lower thoracic from T6-T10 (LT), upper thoracolumbar from T10-L1 (UTL), lower thoracolumbar from L1-L3 (LTL), and thoracic angle from T1-L1.

To calculate spinal motion angles, a coordinate system was established at each vertebral sensor. First, a superior-inferior vector was created from the vertebra of interest down to the sacrum sensor and a posterior-anterior vector was created from the vertebra of interest out to the manubrium sensor. Then, the cross product of these two vectors was taken to create a new vector. Finally, the cross product of the superior-inferior vector and the new vector was taken to create the final vector for the coordinate system (Fig.3). Euler rotation sequence was used to extract the angles of the sensors'

coordinate systems in relation to the global coordinate system established at the TrakSTAR transmitter. The first rotation was about the primary motion axis. The second was about the primary coupled axis. The third was about the secondary coupled axis. For F, E, R45, and L45 the order was: sagittal, coronal, transverse. For RLB and LLB the order was: coronal, transverse, sagittal. For RAR and LAR the order was: transverse, coronal, sagittal (Wilke et al., 1998).

Torso angle was defined as the orientation of the sensor at T10 in comparison to the global coordinate system (Fig. 3). The angles of the motion segments were defined as the difference in angular rotation between the superior and inferior vertebrae of the segment. For both angles, ROM was only calculated in the primary plane of motion for each bending task.

Bending symmetry ratio was calculated between RLB and LLB where a value of -1 indicates the subject bent laterally 100% to the left, a value of 0 indicated the subject had symmetrical ROM between their right and left lateral bending, and a value 1 indicated the subject bent laterally 100% to the right. A twisting symmetry ratio was calculated between RAR and LAR in a similar manner to the bending symmetry ratio.

All calculations were performed in MATLAB (MathWorks, Natick, MA) using customized programs for data collection, analysis, and statistics.

2.4 Statistics

The ROM for torso and spinal motion segment angles (UT, MT, LT, UTL, LTL, and thoracic) between the adolescents and older adults were analyzed using unpaired t-tests in MATLAB with significance considered to be $\alpha = 0.05$. The use of a multiple

comparison correction remains controversial and was not implemented to maintain consistency with the literature (Nakagawa, 2004; Perneger, 1998).

Symmetry ratios for bending and torsion tasks were analyzed using unpaired t-tests between the left and right bending tasks as well as between the older adult and adolescent groups in MATLAB with a significance level of $\alpha = 0.05$.

The effect of gender on torso ROM was analyzed for both the adolescent and older adult populations separately using unpaired t-tests between males and females with a significance level of $\alpha = 0.05$.

The sample sizes for F, E, RLB, LLB, RAR, LAR, R45, and L45 for the adolescents were 17, 33, 31, 32, 32, 32, 25, and 23 respectively. The sample sizes for F, E, RLB, LLB, RAR, LAR, R45, and L45 for the older adults were 13, 18, 16, 17, 17, 18, 18, and 18 respectively.

Results

3.1 Torso Range of Motion

The overall motion of the spine is characterized by the ROM of the torso angle. There was a significant decrease in this measure in F ($p = 0.006$), E ($p = 0.002$) and RLB ($p = 0.004$) between the adolescents and the older adults (Table 1). In the adolescent group, F had the greatest ROM followed by 45° anterior-lateral flexion. In the older adult group, LAR had the greatest ROM followed by F, RAR, and 45° anterior-lateral flexion. In both groups, lateral bending had the lowest ROM.

3.2 Segment Range of Motion (ROM)

By calculating the ROM for the individual spinal motion segments, the contribution of the thoracic and thoracolumbar regions of the spine can be investigated

(Figure 4). In the adolescents, there was a relatively steady increase in ROM from UT, MT, LT, UTL, and LTL traveling inferiorly down the spine in F, R45, and L45 tasks. The same pattern was not found in the older adults; E and LLB had an increase in ROM from UT, MT, LT, and UTL but not in LTL.

Table 1 compares the angular ROM in each of the eight bending tasks between the older adults and adolescents. Both UTL ($p < 0.01$) and thoracic ($p < 0.01$) ROM are significantly different in F and LTL ROM ($p = 0.01$) is significantly different in E between age groups. The LT ($p < 0.01$), UTL ($p = 0.03$), and thoracic ($p < 0.01$) ROM are significantly different between age groups in RLB. The LT ($p < 0.01$), UTL ($p = 0.04$), and thoracic ($p = 0.02$) ROM are significantly different in LLB between age groups. The MT ($p = 0.02$), UTL ($p < 0.01$), and thoracic ($p < 0.01$) ROM are significantly different between age groups in R45. The LT ($p = 0.02$), UTL ($p < 0.01$), and thoracic ($p < 0.01$) ROM are significantly different between age groups in L45. In all ROM measures with significance, the older adults had a lower ROM than the adolescents.

3.3 Symmetry Ratios

The symmetry ratios for both groups in bending and twisting were not significantly different and were very close to zero, indicating symmetry in the tasks. Additionally, right and left ROM in lateral bending and axial rotation tasks had no significant difference ($p <<< 0.01$). Symmetry ratios were only calculated for the bending tasks that have been shown to be symmetric in previous research (Ng et al., 2001).

3.4 Gender

Due to recruiting difficulties, gender distribution was unbalanced. T-tests were performed comparing torso angle ROM between genders for the two age groups for all

eight bending tasks. There was no significance between genders in the older adult groups ($p > 0.05$). In the adolescent group, there was a difference in RLB, LLB, R45 and L45 ($p = 0.01$, $p = 0.01$, $p = 0.04$, $p = 0.02$ respectively).

Discussion

The purpose of this study was to compare spinal ROM in the thoracic and thoracolumbar regions between healthy adolescents and healthy older adults. This research is innovative because this is the first time these two groups have been compared in terms of thoracic kinematics. Previous studies have shown that ROM changes with age in the spine, but there are conflicting reports regarding which parameters, bending modes, and regions of the spine show significant changes. Previous studies that compare healthy young adults to older adults with degenerative spine disease showed significant decreases in spinal mobility for F, E, and LB tasks in both the thoracic and lumbar regions with the aging process. However, these previous studies were not able to isolate the effect of aging on a healthy spine (Kondratek et al., 2007; Lee et al., 2013).

4.1 Axial Rotation for Torso Angle Range of Motion

In axial rotation, previous research has shown that the lumbar region experiences decreased ROM with age but the thoracic region does not (Alaranta et al., 1994; Kondratek et al., 2007; Lee et al., 2013). The results from the current study support the notion that axial rotation ROM does not significantly change with age. However, only torso ROM was calculated for axial rotation. This lack of motion segment ROM does not inform which regions of the thoracolumbar spine are responsible for the significant change between age groups (Kondratek et al., 2007).

The lack of significance in torso angle during axial rotation could be attributed to the method of obtaining torso angle. This and prior studies have used the change between neutral standing position and maximum bending position of T10 in relation to the global coordinate system as a measure of torso angle (Granata and Sanford, 2000; Maduri et al., 2008). The analysis method assumes that T10 ROM is representative of the entire torso, of which the lumbar spine contributes the majority of mobility. The lack of significance found in this study for ROM during axial rotation may imply that the motion of the T10 acts more similar to a thoracic measure than a lumbar measure. Torso angle ROM in axial rotation is driven more by the rotation of the T10-M vector than the T10-sacrum vector (Fig. 3). The T10-M vector incorporates deformation of vertebrae superior to T10 during bending while still accounting for lumbar motion. Because of this, the resulting coordinate system created at T10, which tracks torso angle, may be more representative of and driven by thoracic motion.

4.2 Torso Angle Patterns

The overall spine biomechanics are governed by soft tissue effects for F, RLB, LLB, R45, and L45 while RAR and LAR are governed by the intervertebral discs. This is seen in the pattern of torso angle (Markolf, 1972; White and Panjabi, 1990; Zatsiorsky, 1998). The pattern found in torso angle ranging from largest to smallest ROM in adolescents was F, L45, R45, LAR, RAR, E, RLB, and LLB while in the older adults the pattern was LAR, F, RAR, L45, R45, E, RLB, and LLB. These two patterns may at first seem dissimilar. However, this is because the rank of the axial rotation changes between the adolescent and the older adult groups.

This pattern may indicate that the muscles and ligaments controlling F, RLB, LLB, R45, and L45, such as the superior costotransverse, radiate, and intraarticular ligaments, stiffen due to the natural structural changes elastin undergoes as it ages (Pasquali-Ronchetti and Baccarani-Contri, 1997). Markolf found that the intervertebral discs are responsible for controlling axial rotation more than any other bending task (Markolf, 1972). This may indicate that intervertebral discs change with age at a different rate than spinal ligaments and muscles causing reduced muscle strength and lower ROM.

4.3 Coupled Bending

In 45° anterior-lateral flexion, there was approximately a 25% reduction in the torso angle ROM between the adolescents and older adults for both right and left tasks. Due to the high variability in this measure, the two groups were not significantly different. Lee et al. found that this bending task is a coupled motion and is primarily driven by the spinal mobility in the sagittal plane (Lee et al., 2013). Kondratek et al. found that flexion tasks show the greatest variability (Kondratek et al., 2007). Because primary motion for 45° anterior-lateral flexion occurs in the sagittal plane, it may be a contributing factor to the high variability in this task. However, because lateral bending in the coronal plane and axial rotation in the transverse plane are highly coupled motions, it is difficult to distinguish which is the secondary motion in off-plane anterior-lateral flexion. Subjects may have interpreted the instructions differently, resulting in different amounts of coupling. The large variability in this motion could also be due to the compounding effect of variability in the sagittal, coronal, and transverse planes. Further exploration into the motion in these three planes during 45° anterior-lateral

flexion would provide more insight into what the secondary motion is. This is important to understand because coupled bending motions are an integral part of people's daily lives (Fujiwara et al., 2000; Shum et al., 2006).

4.4 Thoracic Contribution to Range of Motion

A unique attribute of this study was the ability to directly compare thoracic and thoracolumbar contributions in terms of ROM. Thoracic ROM remains relatively constant throughout all modes of bending within each age group. In both RLB and LLB for adolescents and older adults, the ratio of thoracic ROM to overall torso angle ROM was approximately 60%. However, this ratio was 18-38% in all other bending tasks for both groups. This may indicate that the maximum lumbar ROM is reached sooner during the bend in lateral bending as compared to thoracic ROM, allowing for the thoracic region to contribute more mobility. The iliac crest may be preventing the lumbar region from contributing more to torso angle ROM than in the other modes of bending (Schafer, 1986). Confirming this anatomical restriction on lateral bending could further explain the change in thoracic contribution in lateral bending. A further investigation into the effect the mobility for each functional spine unit on the ROM for each motion segment could provide a more complete comparison between relative motion in the thoracic and thoracolumbar regions.

4.5 Limitations

This study was designed to make direct comparisons between adolescents and older adults' ROM during planar and non-planar bending tasks. However, there were a number of limitations. The most apparent limitation was the inability to accurately

calculate ROM for motion segments in axial rotation. This is because the posterior-anterior vector from the vertebra of interest to the manubrium dictates the primary motion within the axial plane. This vector was short in comparison to the superior-inferior vector, causing these small angles measured to be obscured by the noise of the measurement. This prevented the comparison of any motion segments to axial rotation.

Another limitation was the unbalanced number of subjects for each gender in both age groups. While no gender differences were found within the older adult group, there were some gender differences found within the adolescent group. Torso angle ROM in RLB showed a significant increase for females compared to males in the adolescent group and also a significant decrease with age. For this one measure, it is unclear if the decrease in RLB ROM found between the adolescent group and the older adult group is due to an effect of age or gender. It would advantageous to further investigate the effects of gender on spinal mobility.

Another limitation was the study methodology. All sensors were placed on the spinal processes of the vertebrae by palpating the spine and subjects were instructed to bend to their own voluntary maximum. Because maximum ROM was determined from each subject's voluntary maximum, it is unknown if each subject truly reached their maximum. Additionally, due to soft tissue artifact, the sensors may not have captured the precise movement of the spinal processes throughout the entire duration of the bending task. Additionally, a subject's voluntary maximal bend may be considerably less than their physiological maximum (Schinkel-Ivy et al., 2014). However, the voluntary maximum ROM was of the measure of interest throughout this study.

A final limitation was the screening of the subjects for healthy spines, particularly in the older adults. The survey conducted only screened for subject's known spinal disorders and deformities; no radiographs were collected. While subjects may claim to be in good health without back pain or mobility restrictions, underlying conditions such as degenerative disc disease and osteophytes can be present without the subject's knowledge (Fujiwara et al., 2000).

4.6 Future Work

This study investigated the changes in spinal ROM between healthy adolescents and healthy older adults and discovered that the flexibility of the spine does change with age in clinically important ways. The changes in ROM can be attributed to many factors such as muscle atrophy, fat infiltration, and loss of elastin, all of which increase with age (Faulkner et al., 2007; Hiepe et al., 2015). Additionally, the thoracic and thoracolumbar regions contribute differently to overall torso angle between the two groups. The primary result of this study is that in F, E, and RLB, the spine of an adolescent behaves differently than that of an older adult resulting in increased ROM for the adolescents. This suggests that studies investigating the effect of illnesses, disorders, or activities that are predominantly found in the older population and rely on flexion, extension, or lateral bending tasks should take steps to ensure that their subjects are in the older adult age range. Additionally, adolescent spinal devices are tested on older adult cadavers. If the older adult cadavers behave similar to *in vivo* subjects, using the cadaveric model to test adolescent devices may not be an appropriate model.

Conflict of Interest Statement

The authors stated that they have no conflict of interest to disclose.

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Tables

Table 1: Summary of motion segments mean Range of Motion (± standard deviation) measured in primary plane of motion.

		F	E	RLB	LLB	RAR	LAR	R45	L45
Torso	Adolescents	80.6 ± 27.9*	-43.7 ± 17.7*	30.3 ± 10.1*	-27.2 ± 9.20	56.9 ± 19.4	-57.6 ± 15.8	61.0 ± 41.5	61.7 ± 36.4
	Older Adults	53.2 ± 21.6	-25.2 ± 12.3	21.3 ± 9.17	-22.2 ± 8.14	52.2 ± 17.4	-53.6 ± 16.2	45.5 ± 24.8	48.6 ± 28.2
UT T1-T3	Adolescents	0.56 ± 2.45	-2.06 ± 3.06	1.41 ± 1.49	-1.39 ± 1.34	-	-	0.97 ± 3.39	0.60 ± 1.89
	Older Adults	-1.26 ± 2.97	-1.01 ± 0.64	1.49 ± 1.58	-1.35 ± 1.43	-	-	0.20 ± 1.71	0.29 ± 2.07
MT T3-T6	Adolescents	4.80 ± 3.09	-1.91 ± 4.29	5.37 ± 2.14	-4.17 ± 1.59	-	-	5.07 ± 3.55*	3.61 ± 2.50
	Older Adults	5.03 ± 4.38	-1.20 ± 1.99	4.55 ± 2.70	-3.88 ± 1.43	-	-	2.45 ± 3.95	3.57 ± 2.77
LT T6-T10	Adolescents	8.04 ± 4.25	-5.33 ± 13.7	6.13 ± 3.47*	-6.07 ± 3.01*	-	-	5.74 ± 4.40	5.34 ± 4.57*
	Older Adults	4.43 ± 8.74	-1.42 ± 3.24	3.23 ± 3.21	-3.65 ± 3.01	-	-	4.16 ± 5.75	2.09 ± 3.34
UTL T10-L1	Adolescents	14.3 ± 4.19*	-3.46 ± 6.35	5.95 ± 2.61*	-5.86 ± 2.90*	-	-	9.46 ± 4.47*	9.92 ± 4.52*
	Older Adults	4.32 ± 5.88	-1.48 ± 4.23	3.99 ± 3.29	-4.18 ± 1.89	-	-	3.22 ± 4.81	2.97 ± 4.98
LTL L1-L3	Adolescents	18.0 ± 6.61*	-7.09 ± 8.53*	7.63 ± 3.68	-6.71 ± 3.19	-	-	13.3 ± 6.48	15.5 ± 8.00
	Older Adults	8.83 ± 8.25	-1.54 ± 3.92	5.39 ± 6.07	-5.09 ± 2.05	-	-	9.74 ± 9.25	11.8 ± 12.2
Thoracic T1-L1	Adolescents	27.7 ± 8.91*	-12.8 ± 22.1	18.9 ± 6.78*	-17.5 ± 6.73*	-	-	21.2 ± 11.4*	19.5 ± 10.7*
	Older Adults	12.5 ± 7.10	-5.11 ± 7.18	13.3 ± 5.62	-13.3 ± 4.76	-	-	10.0 ± 7.85	8.9 ± 9.2

(-) Value not reported
* Denotes statistical difference between adolescent and adult ROM values ($p < 0.05$)

Figures

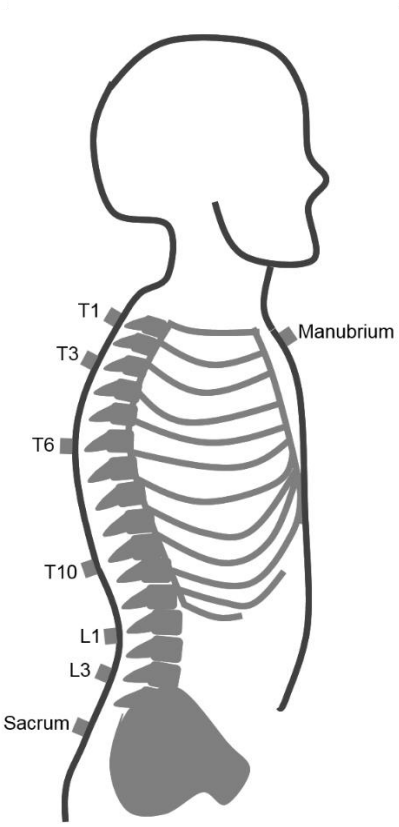

Figure 1: Sensor Placement. Eight six-degree-of-freedom sensors were placed on each subject at the spinous process of T1, T3, T6, T10, L1, L3, and S1 as well as at the superior notch of the manubrium (M).

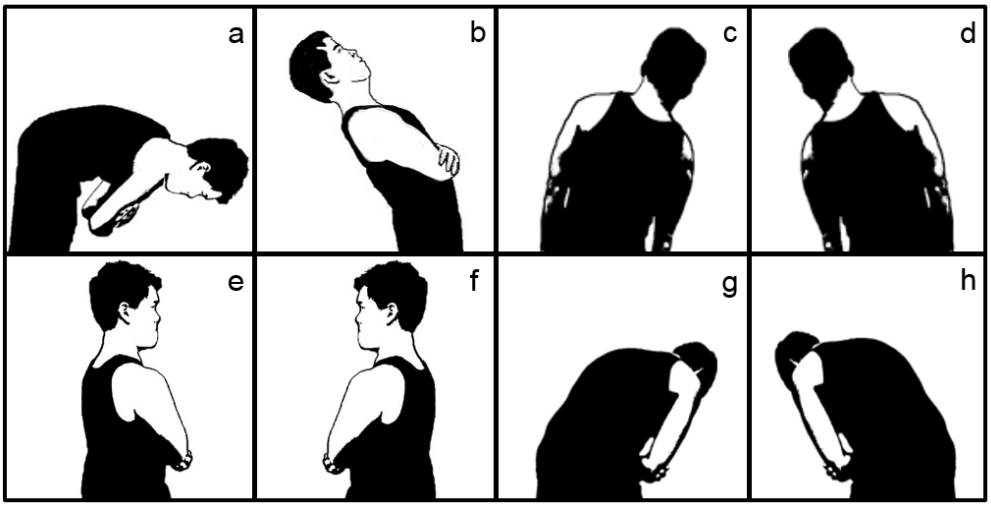

Figure 2: Bending Tasks. a) Flexion b) Extension c) Right Lateral Bending d) Left Lateral Bending e) Right Axial Rotation f) Left Axial Rotation g) Right 45˚ Anterior-Lateral Flexion h) Left 45˚ Anterior-Lateral Flexion.

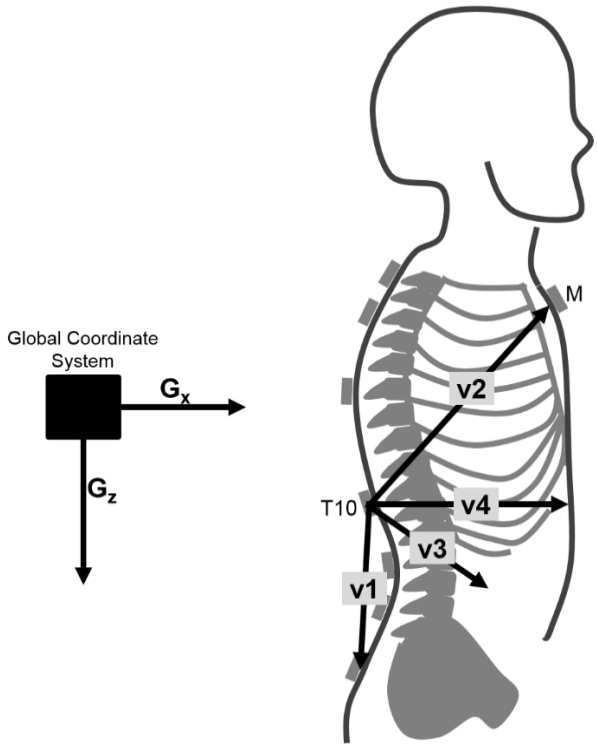

Figure 3: Torso Inclination Calculation. Torso inclination angle is the angle of the T10 coordinate system relative to global coordinate system in the intended plane of motion for a given bending task. The coordinate system at T10 is created by using a superior-inferior vector to S1 (v1) and a posterior-anterior vector to the manubrium (v2). First, v1 was crossed v2 resulting in v3. Then v1 was crossed with v3 resulting in v4. The coordinate system at T10 is dictated by v1, v3, and v4. A rotation sequence was used to extract Euler angles depending on the intended plane of motion.

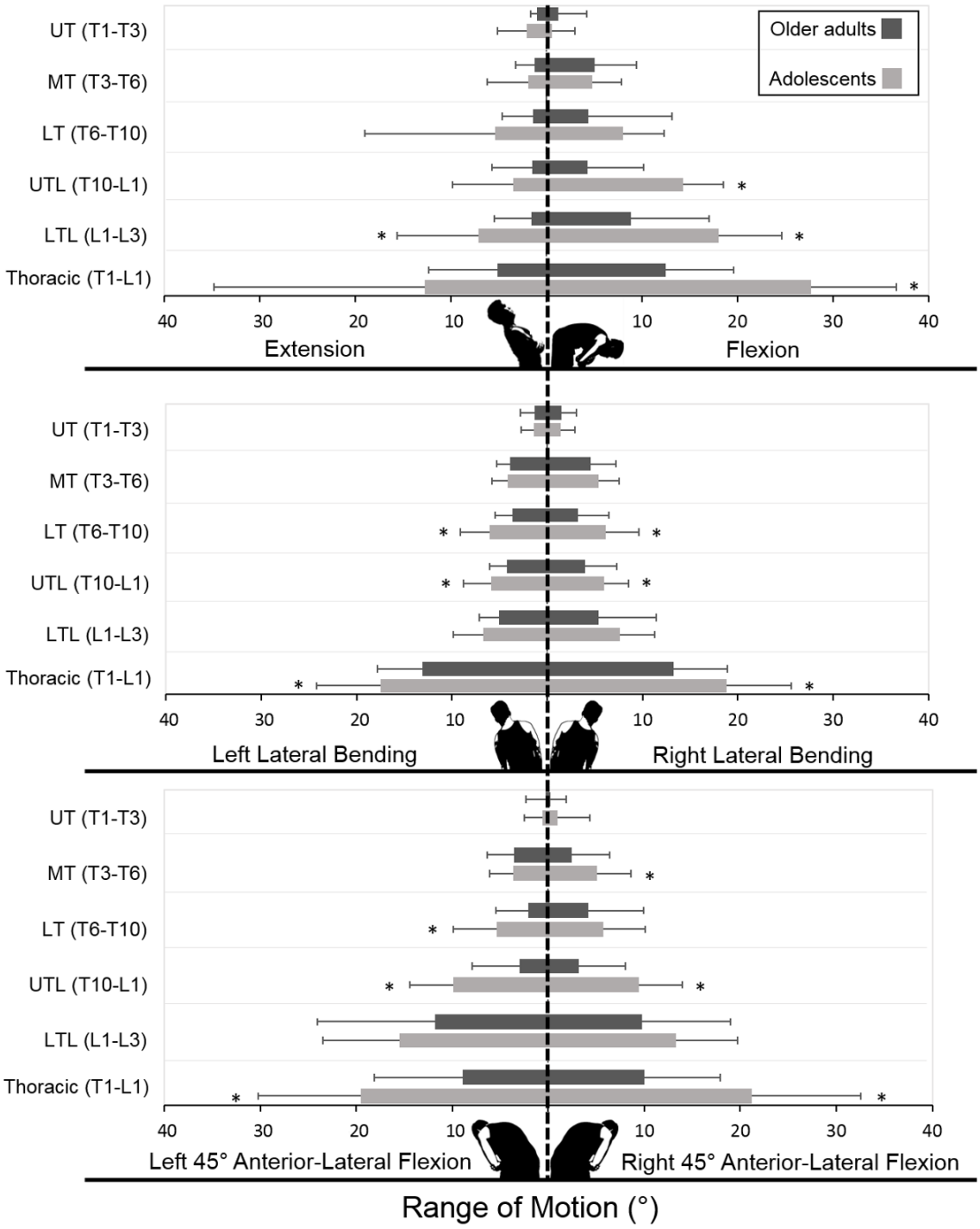

Figure 4: Range of Motion bar plots. Range of motion (ROM) for upper thoracic (UT), middle thoracic (MT), lower thoracic (LT), upper thoracolumbar (UTL), lower thoracolumbar (LTL), and thoracic motion segments. All ROM angles are represented as magnitudes.

CHAPTER 4:

In vivo Thoracolumbar Motion in Healthy Adults Analyzed by Individual Motion Units

Manuscript currently under revision for eventual submission to Spine, Submission planned for January 2016

This study develops a method to investigate the contribution of a representative functional spine unit to thoracolumbar motion in a given spinal segment. Eileen Cadel had primary responsibility for the data collection, data analysis, writing of the manuscript, and eventual editing as recommended by her fellow co-authors.

In vivo Thoracolumbar Motion in Healthy Adults Analyzed by Individual Motion Units

Eileen S. Cadel[1]
Sarah N. Galvis[1]
William M. Eboch[3]
Paul M. Arnold[2]
Sara E. Wilson[1,3]
Elizabeth A. Friis[1,3]

[1]University of Kansas, Bioengineering, 1530 W 15th Street, Learned Hall Room 3135A, Lawrence, KS, 66045, USA
[2]University of Kansas Medical Center, Department of Neurosurgery, 3901 Rainbow Bvld., MS 3021, Kansas City, KS, 66160, USA
[3]The University of Kansas, Mechanical Engineering, 1530 W 15th Street, Learned Hall Room 3138, Lawrence, KS, 66045, USA

Abstract

The aim of this study was to develop a method that allows for the comparison of spinal motion data in cadaveric and *in vivo* models and to frame *in vivo* motion data in a way that is meaningful to surgeons. Cadaveric motion data is often presented in terms of individual motion units while *in vivo* motion data is presented in segments. In order to better compare these two models, a method was developed to investigate the *in vivo* contribution of motion from an individual representative functional spine unit in a segment during bending tasks. The results from this study indicated that the motion contributed by each functional spine unit was consistent between bending tasks and that the presence of a single lumbar vertebra does not typically make a segment more flexible. Additionally, it was found that the lumbar spine is responsible for a large percentage of thoracolumbar motion, but the contribution of the thoracic spine should not be discounted. This information can provide surgeons with specific biomechanical information regarding the movement of representative functional spine units in the living spine, and hopefully aid in making surgical planning decisions for adult deformity cases. The methods presented could allow future studies to directly compare cadaveric and *in vivo* spinal motion models for healthy older adults. It is important to be able to compare the data from these two models, particularly when designing medical devices.

Introduction

The lumbar region of the spine is often the focus of many studies regarding spinal mobility due to its association with low back pain.[1–10] However, understanding the mobility of the thoracic region is imperative, especially due to its involvement in adult spinal deformity.[11–14] More than 65% of all adults over 60 years of age are affected by spinal deformity.[15] Corrective surgery is often needed to alleviate pain, improve balance, and regain spinal function.[16] Multilevel fusion systems are used to treat adult spinal deformities. Previous studies have recognized the benefit of maximizing the number of unfused motion segments in order to retain the most spinal mobility.[17–20] It is also known that the majority of spinal mobility can be attributed to the lumbar region,[21–24] resulting in less conservative surgical approaches to fusion in the thoracic spine.

Much of the research investigating spinal mobility is either conducted using cadaveric functional spine units (FSUs) or *in vivo* spinal segments. The data produced by these two models are difficult to directly compare. The aim of this study was to develop a method to investigate the contribution of a representative FSU in a spinal segment. The proposed method used to calculate the range of motion of a representative FSU in a given spinal segment will allow for an improved comparison of *in vivo* and cadaveric range of motion measures. Learning more about the *in vivo* motion of individual FSUs will help to provide surgeons with specific biomechanical information. This information will better inform surgeons and hopefully allow for improved surgical planning in adult deformity cases.

Methods

2.1 Subjects

Eighteen older adults aged 55-81 years were recruited for this study. This group consisted of fourteen males and four females, with an average age of 70.0 ± 8.31 years, height of 1.71 ± 0.11 m, mass of 78.59 ± 17.90 kg. All participants were required to able to stand for one hour, be in good physical condition, and have no known spinal disease. Exclusion criteria were patient-reported spinal or musculoskeletal disorders and deformities, previous spinal surgery, steroid injections in the back, recent trauma, and the presence of broken ribs. All participants signed consent forms and this study was approved by the Institutional Review Board at the University of Kansas – Lawrence.

2.2 Data Collection

Data collection was performed according to methods described in Chapter 3. Briefly, six-degree-of-freedom electromagnetic sensors (0.313” x 0.771” x 0.317”) were placed at the manubrium, the spinous processes of T1, T3, T6, T10, L1, L3, and at the sacrum. An electromagnetic motion monitoring system (TrakSTAR, Ascension Technologies, Burlington, VT, USA) was used to measure the position and orientation of the sensors. Subjects performed a series of eight different bending tasks: flexion (F), extension (E), right lateral bending (RLB), left lateral bending (LLB), right 45° anterior-lateral flexion (R45), and left 45° anterior-lateral flexion (L45) (Figure 1). Data was collected over ten seconds. For each task, subjects began in a neutral standing position then bent maximally in the given direction, and held that position until instructed to return to the neutral position. The order of the bending tasks was randomized for each subject and each task was repeated for five consecutive trials. Trials were considered

acceptable is the subject performed a complete bend and if all sensors remained within the collection volume of the motion monitoring system. Tasks with at least three acceptable trials were approved for analysis and the last acceptable trial (either 5, 4, or 3) was used for analysis. A low pass 4^{th} order Butterworth filter with a cutoff frequency of 2 Hz was used to filter and minimize phase shifting of the raw position data.

2.3 Data Analysis

Angular Range of Motion (ROM) as defined in Chapter 3 was calculated for each subject in each mode of bending. Mean ROM over the entire subject group for five motion segments were calculated: upper thoracic from T1-T3 (UT), middle thoracic from T3-T6 (MT), lower thoracic from T6-T10 (LT), upper thoracolumbar from T10-L1 (UTL), and lower thoracolumbar from L1-L3 (LTL). The number of functional spine units (FSUs) within each motion segment was noted in Figure 2. FSUs are composed of two adjacent vertebrae and their connecting soft tissue. Based on the number of FSUs in each segment, a normalized ROM (nROM) value was calculated by dividing the ROM in each motion segment by the number of FSUs in that given segment (Table 1). The nROM represents the average motion for a single FSU within a given motion segment.

The percent contribution of an FSU (%ROM) in each segment was calculated as a percentage of thoracolumbar (TL) ROM. TL ROM was calculated by summing the ROM for all motion segments in a particular bending task. The %ROM was calculated by dividing each nROM value by the TL ROM for each bending task. The %ROM represents the average contribution of an FSU within a given motion segment.

Table 1 summarizes the data that was collected and the naming system used to describe each data set.

All calculations were performed in MATLAB (MathWorks, Natick, MA) using customized programs for data collection, analysis, and statistics.

2.4 Statistics

Two sets of statistical comparisons were performed on the %ROM data from each segment and bending task. The first set of comparisons investigated the %ROM for all six bending tasks in a single normalized FSU motion segment. The second set of comparisons investigated the %ROM for all five normalized FSU motion segments in a single bending task. ANOVAs were used followed by a Tukey-Kramer post-hoc test to determine which comparisons were significant.

All analyses were conducting in MATLAB with significance at $\alpha = 0.05$. The sample sizes for F, E, RLB, R45, and L45 were 13, 18, 16, 17, 18, and 18 respectively.

Results

3.1 Normalized Range of Motion

The nROM characterized the angular motion of a representative FSU in a given motion segment (Table 2). The greatest nROM was found in the LTL segment.

3.2 Percent Contribution of Thoracolumbar Motion – Comparing Bending Tasks

Comparing the %ROM between all six bending tasks in a single normalized FSU motion segment determined if the percent contribution from a normalized FSU in a given motion segment changed depending on the bending task (Figure 3). Fifteen combinations of different bending tasks were required to evaluate all possibilities of bending tasks in a given segment. From these seventy-five combinations, only one yielded significance. The MT %ROM in RLB was found to be significantly larger than the MT %ROM in E ($p = 0.0078$).

3.3 Percent Contribution of Thoracolumbar Motion – Comparing Motion Segments

Comparing the %ROM between all five normalized FSU motion segments in a single bending task determined if the percent contribution from a normalized FSU changed depending on which motion segment it was located in (Figure 4). Ten comparisons of different normalized FSUs were required to evaluate all possibilities of normalized FSUs in a given bending task. The LTL %ROM was significantly greater than UT %ROM, MT %ROM, LT %ROM, and UTL %ROM in all six modes of bending ($p < 0.02$). In LLB, MT %ROM and UTL %ROM were significantly greater than UT %ROM ($p < 0.01$).

Discussion

The purpose of this study was to develop a method to investigate the contribution of representative FSUs within segments of the spine during *in vivo* bending tasks. This analysis of spinal ROM is beneficial for two primary reasons. The first is that *in vivo* spinal mobility is typically measured angular ROM of the torso or defined spinal segments. In cadaveric studies, ROM is typically measured in terms of individual FSUs. This difference in mobility measurement makes it difficult to compare *in vivo* mobility to cadaveric mobility. The current study proposes a way to calculate the ROM of a representative FSU in a given spinal segment to allow for an improved comparison of *in vivo* and cadaveric ROM measures. The second benefit of this study is its application to surgical planning for adult deformity cases. If the specific motion of an FSU can be account for *in vivo*, surgeons may be able to better understand the biomechanical effects their procedures will have on spinal mobility.

4.1 Normalized Range of Motion – Comparisons to in vivo Literature

This method of normalizing the ROM according to the number of FSUs is a simple calculation that extracts the motion of a representative FSU from a given segment. One benefit of presenting nROM is that motion of segments with varying lengths can be compared.

The nROM data from the present study was compared to ROM data from two other studies. Alqhtani et al. and Mannion et al. both investigated the *in vivo* ROM in the thoracolumbar spine during flexion.[26,24] Alqhtani et al. used triaxial accelerometers to measure the ROM of five motion segments: upper thoracic (T1 – T4), middle thoracic (T4 – T8), lower thoracic (T8 – T12), upper lumbar (T12 – L3), and lower lumbar (L3 – S1). The segments by Alqhtani et al. contain different FSUs than the segments used in the current study. By normalizing the segment ROM by the number of FSUs in each segment, the upper thoracic, middle thoracic, lower thoracic, and upper lumbar data presented Alqhtani et al. study can be compared to the nROM data presented in the present study.

Mannion et al. used the Spinal Mouse system to measure the ROM of individual FSUs from T1/2 through L5/S1. The normalized data sets from the current study and the Alqhtani et al. study were presented against the ROM data of individual segments from T1/2 through L2/3 in the Mannion et al. study (Figure 5). In all three studies, the most inferior segment or FSU where data was collected had the greatest ROM. White and Panjabi reported that the lumbar region of the spine has a greater ROM than the thoracic region.[21] This pattern was found in all three studies, validating the method of normalizing segment ROM by the number of FSUs.

The magnitudes of the nROM between the present study, the Alqhtani et al. study, and the Mannion et al. study are not identical. This difference between data sets can most likely be attributed to the age of the subjects and the different data collection methods. The average age from the present study, Alqhtani et al. study, and Mannion et al. study were 70.0 years, 30.6 years, and 41.8 years respectively. Previous studies have shown that the ROM in flexion does decrease with age, supporting the difference in the three data sets.[1,2,6,8,9,25,27] Both the present study and the Alqhtani et al. study measured spinal ROM using sensors placed at specific vertebrae while the Mannion et al. study used the Spinal Mouse system to calculate the relative positions of vertebral bodies. This difference in ROM measurement supports the differences between the data sets.

4.2 Normalized Range of Motion – Comparisons to Cadaveric Literature

Another benefit of presenting nROM is the ability to compare the results presented to cadaveric studies. Many cadaveric studies present ROM data from individual FSUs[28,29,22,30–32] while *in vivo* ROM is typically calculated over segments in the spine.[3,7,24,33,34] The studies that present ROM from cadaveric thoracolumbar FSUs reported higher ROM than what was calculated in this study. The lower nROM found *in vivo* could be attributed to two factors. The first is that the living subjects only bent to their voluntary maximum, as opposed to a machine-designated load limit. The second factor is the presence of a soft tissue artifact. In the cadaveric studies, skin, adipose tissue, and muscles were removed from the specimens. In living subjects, previous studies have shown that the presence of soft tissue influences ROM.[35–37] While the ROM angles were not the same, cadaveric and *in vivo* studies did report that the ROM

increased in the lumbar region as compared to the thoracic region. This pattern in both cadaveric and *in vivo* studies indicate a similarity in the biomechanics between these two models.

4.3 Percent Contribution of a FSU to Thoracolumbar Motion

The %ROM represents the contribution of a FSU to total TL ROM in a given segment. These %ROM measures can be compared across segments or bending tasks. However, these results were first verified that they made physiological sense. To do this, a simple calculation was performed to ensure that the sum of all %ROM values added up to 100%. Each segment %ROM was multiplied by the number of FSUs in that segment, then summed for single bending task. This indicated that all motion from T1 to L3 was accounted for in the TL ROM.

The first set of ANOVAs that compared %ROM a single normalized FSU motion segment between all six bending tasks only yielded one significant comparison out of fifteen (Figure 3). This indicates that the motion contributed by a representative FSU was independent of the bending task being performed. For F, E, R45, and L45, the primary motion occurred in the sagittal plane while the primary motion for RLB and LLB occurred in the coronal plane. The results from the present study indicate that the plane of primary motion does not affect the ability for an FSU in a given segment to contribute to spinal motion.

The second set of ANOVAs that compared %ROM in a single bending task between all five normalized FSU motion segments found much more significance (Figure 4). In all six bending tasks, the LTL %ROM was significantly greater than every other segment's %ROM. This indicates that the increased motion contributed by a

representative LTL FSU was independent of the bending task being performed. While the UTL segment contained a single lumbar vertebra, the UTL %ROM was significantly greater than the UT %ROM and MT %ROM in only LLB. This indicates that the presence of a single lumbar vertebra does not typically make that segment more flexible.

4.4 Clinical Impact of Representative FSU Range of Motion

Adults with severe spinal deformities will often require surgical intervention[11–14]. Surgeons are typically less conservative in placing fusion systems in the thoracic region because it is believed that the region contributes very little to spinal flexibility. Previous studies have found that the lumbar region contributes more to spinal mobility than the thoracic region, particularly in motions that occur in the sagittal plane.[24,21–23,38] The results of this study support the existing literature that the thoracic spine, compared to the lumbar spine, contributes less to spinal mobility. However, the mobility contributed by the thoracic spine should not be discounted.

For example, for every FSU that gets fused in the LT segment, the patient will lose 1.3° of mobility in flexion. Fusing the vertebrae in the LT segment may not initially seem like it will have severe implications. However, if you compare that to the 53° of motion in an older adult's torso during flexion[25], the LT is responsible for approximately 10% of their torso mobility. This biomechanical information about the spine would be very useful to surgeons during the surgical planning process in adult deformity cases. Knowing how small or large the motion of a FSU in a specific segment is could greatly influence where fusions begin, end, and how many FSU they will span.

4.4 Limitations

This study presents a new way to analyze spinal motion from segments. However, there were several limitations. The sensors placed were intended to track a specific spinous process during each subject's bending task. But as with all *in vivo* ROM data collected by sensors or markers placed on the skin, the skin's movement over the spinous process of a vertebra during bending cannot be avoided. This soft tissue artifact is less in the spine than in other areas of the body due to the firm attachment of the fascia to the spinous processes.[39] Additionally, the ability to reliably collect ROM angles for the small segments is difficult with the electromagnetic sensor because the noise of the measurement can easily mask the ROM of these very small angles. However, the small size of the sensors used increased the accuracy of the measurement and helped to mitigate this problem.

Another limitation was the inability to calculate ROM for the entire lumbar region. The method used to calculate the motion angles required an inferior-superior vector that originated from below the sensor of interest up to the sensor. Due to the sensor placement, this inferior-superior vector always originated from the one placed at the top of the sacrum. This eliminated the ability to create a vector that would point up to the sensor at the top of the sacrum, allowing for the inclusion of a lower lumbar segment.

A final limitation was the process of normalizing ROM in a segment. Some information within a segment gets lost as the nROM is calculated. The assumption made when using this method is that significant physiological and biomechanical changes do not occur in the segments used. The segment where this assumption may not be valid is UTL because this segment incorporates vertebrae with false ribs, floating

ribs, and a lumbar vertebra without any rib attachment. Additionally, this method may not valid over a long segment, such as the entire thoracic region from T1 to L1.

4.5 Future Work

This study investigated the contribution of representative FSUs within spinal segments of the spine during *in vivo* bending tasks. The results of this study indicate that the lumbar region is responsible for a large percentage of thoracolumbar motion, but the contribution of the thoracic region should not be discounted. Additionally, the motion contributed by each FSU is consistent between bending tasks.

This analysis method is beneficial because it allows for an improved comparison between *in vivo* and cadaveric spinal mobility models. It also provides surgeons with specific biomechanical information regarding the movement of representative FSUs in the living spine. This information will hopefully become an important decision making tool during planning for adult deformity surgeries. Having an increased biomechanical understanding about the spine can only help to better inform surgeons and spinal device designers.

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Tables

Table 1: Summary of the data collected and the naming system used to describe each data set.

Motion Segment	Vertebrae	Number of FSUs	Normalized ROM (nROM)	Percent Contribution (%ROM)
Upper Thoracic (UT)	T1 – T3	2	UT nROM $= \frac{UT}{2}$	UT %ROM $= \frac{UT\ nROM}{TL} * 100$
Middle Thoracic (MT)	T3 – T6	3	MT nROM $= \frac{MT}{3}$	MT %ROM $= \frac{MT\ nROM}{TL} * 100$
Lower Thoracic (LT)	T6 – T10	4	LT nROM $= \frac{LT}{4}$	LT %ROM $= \frac{LT\ nROM}{TL} * 100$
Upper Thoracolumbar (UTL)	T10 – L1	3	UTL nROM $= \frac{UTL}{3}$	UTL %ROM $= \frac{UTL\ nROM}{TL} * 100$
Lower Thoracolumbar (LTL)	L1 – L3	2	LTL nROM $= \frac{LTL}{2}$	LTL %ROM $= \frac{LTL\ nROM}{TL} * 100$
Thoracolumbar (TL)	T1 – L3	14	–	–

Table 2: Summary of mean range of motion (± standard deviation) for both normalized range of motion (nROM) and percent contribution of total thoracolumbar motion (%ROM). All motions were measured in the primary plane of motion for each bending task.

Segment nROM contribution	Bending Tasks					
	F	E	RLB	LLB	R45	L45
UT nROM (UT %ROM)	1.1° ± 1.1 (3.8%)	0.5° ± 0.3 (5.1%)	0.9° ± 0.7 (5.1%)	0.8° ± 0.6 (4.1%)	0.6° ± 0.6 (2.6%)	0.9° ± 0.6 (3.6%)
MT nROM (MT %ROM)	1.7° ± 1.5 (6.4%)	0.5° ± 0.6 (4.0%)	1.5° ± 0.9 (8.4%)	1.3° ± 0.5 (7.3%)	1.2° ± 0.9 (5.4%)	1.2° ± 0.9 (5.3%)
LT nROM (LT %ROM)	1.3° ± 2.1 (4.5%)	0.7° ± 0.6 (5.8%)	0.9° ± 0.7 (4.4%)	0.9° ± 0.5 (4.8%)	1.2° ± 1.3 (4.3%)	0.8° ± 0.6 (3.8%)
UTL nROM (UTL %ROM)	2.1° ± 1.2 (7.6%)	1.1° ± 1.0 (8.6%)	1.4° ± 1.1 (6.8%)	1.4° ± 0.6 (7.5%)	1.5° ± 1.3 (6.8%)	1.6° ± 1.0 (6.1%)
LTL nROM (LTL %ROM)	4.7° ± 3.8 (16.2%)	1.6° ± 1.3 (14.4%)	2.8° ± 3.0 (13.1%)	2.6° ± 1.0 (14.1%)	5.3° ± 4.1 (20.5%)	6.4° ± 5.6 (21.7%)

Figures

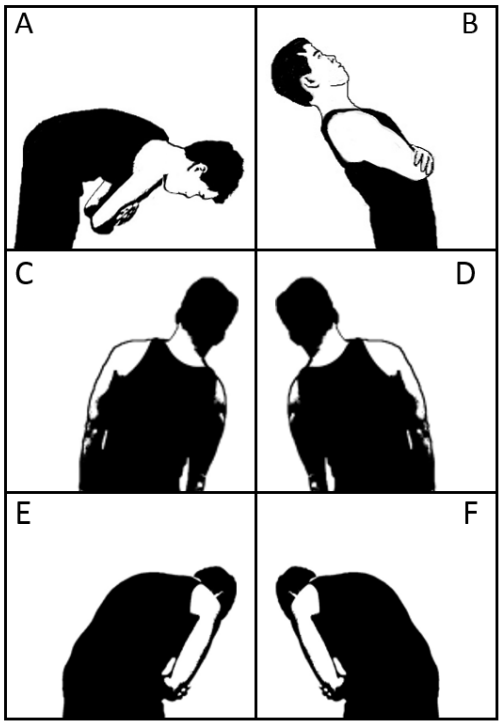

Figure 1: Bending Tasks. Visual representation of each bending task performed by all subjects. a) Flexion b) Extension c) Right Lateral Bending d) Left Lateral Bending e) Right 45° Anterior-Lateral Flexion f) Left 45° Anterior-Lateral Flexion

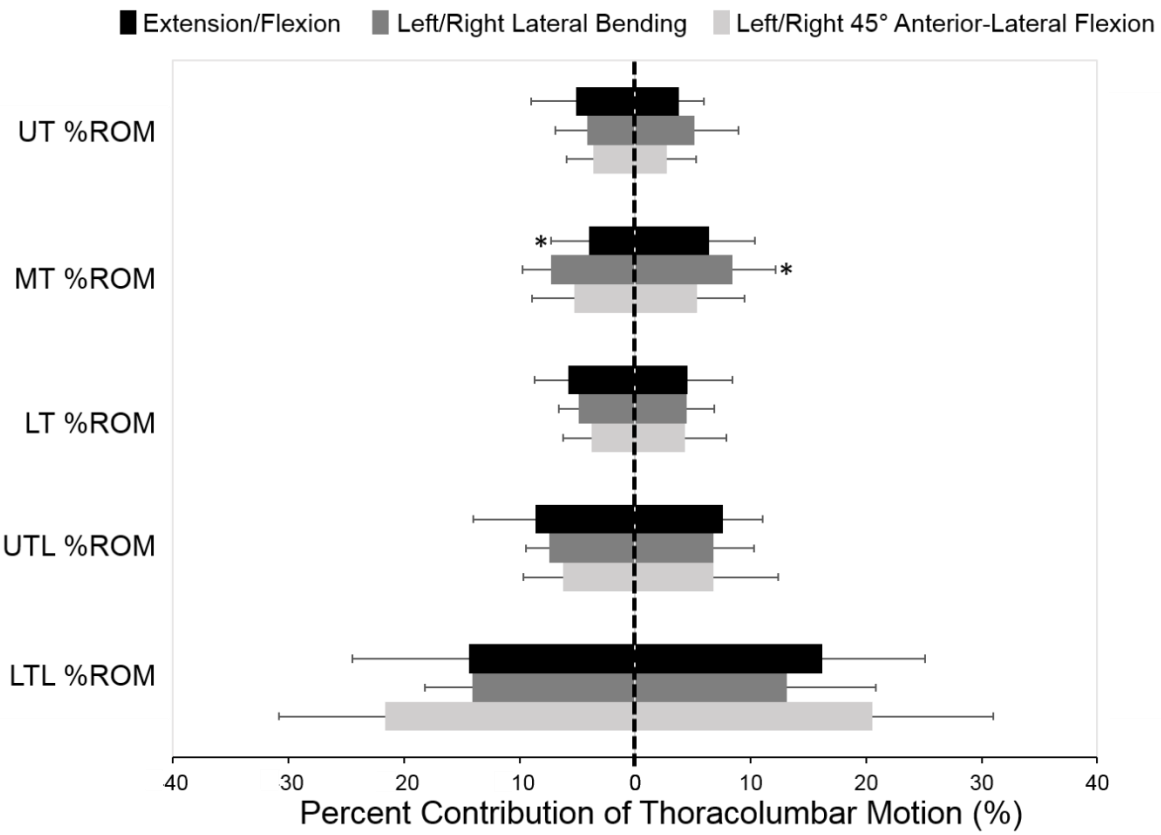

Figure 2: Range of Motion Bar Plots – Comparing Segments. Range of Motion for the contribution of a representative FSU in each spinal segment: upper thoracic (UT), middle thoracic (MT), lower thoracic (LT), upper thoracolumbar (UTL), and lower thoracolumbar (LTL). All values are reported as magnitudes of percent total motion from T1 to L3.
* Denotes statistical difference between bending tasks ($p < 0.05$)

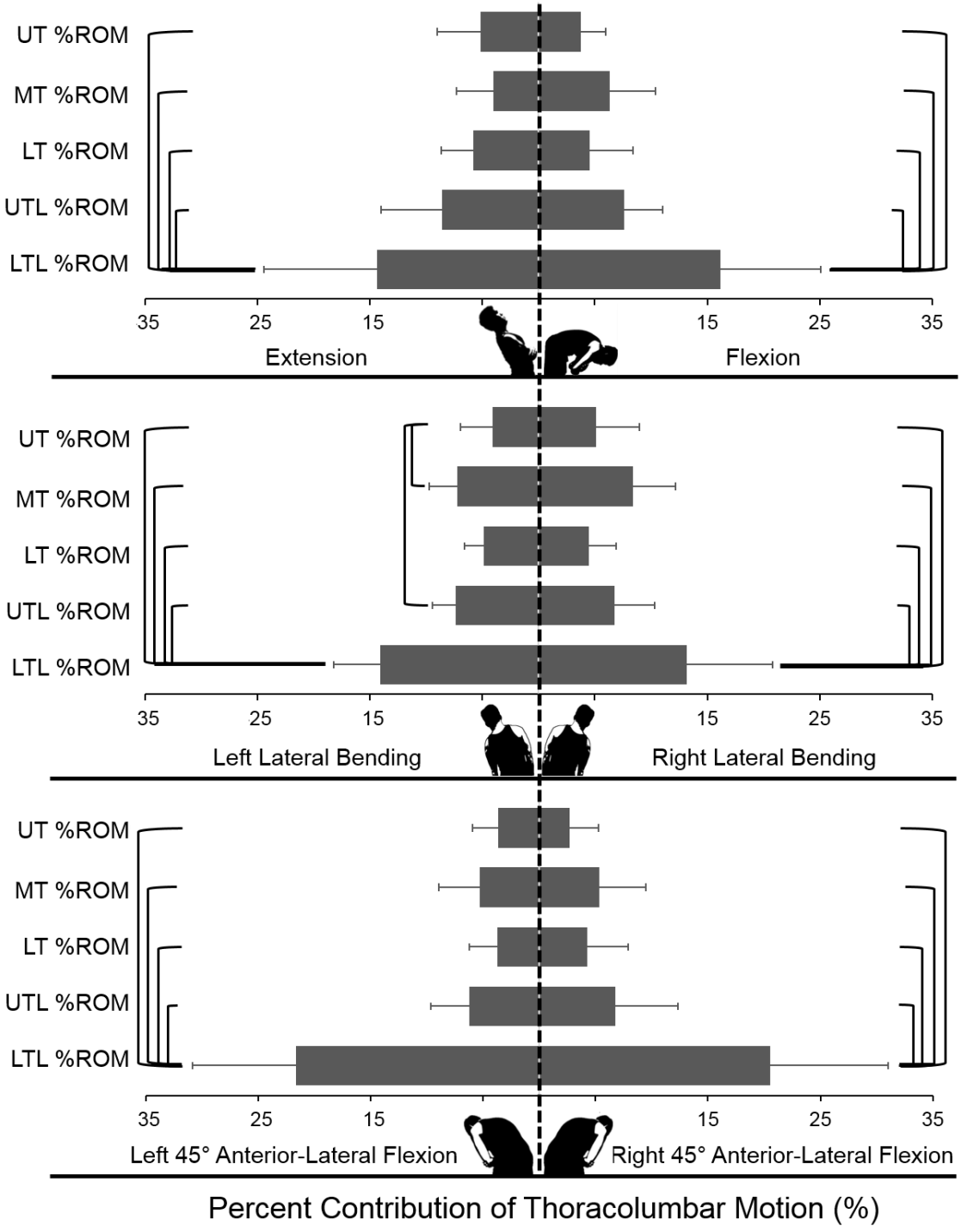

Figure 3: Range of Motion Bar Plots – Comparing Bending Tasks. Range of Motion for the contribution of a representative FSU in each spinal segment: upper thoracic (UT), middle thoracic (MT), lower thoracic (LT), upper thoracolumbar (UTL), and lower thoracolumbar (LTL). All values are reported as magnitudes of percent total motion from T1 to L3. Comparisons shown indicate a statistical increase from the superior FSU to the inferior FSU ($p < 0.05$).

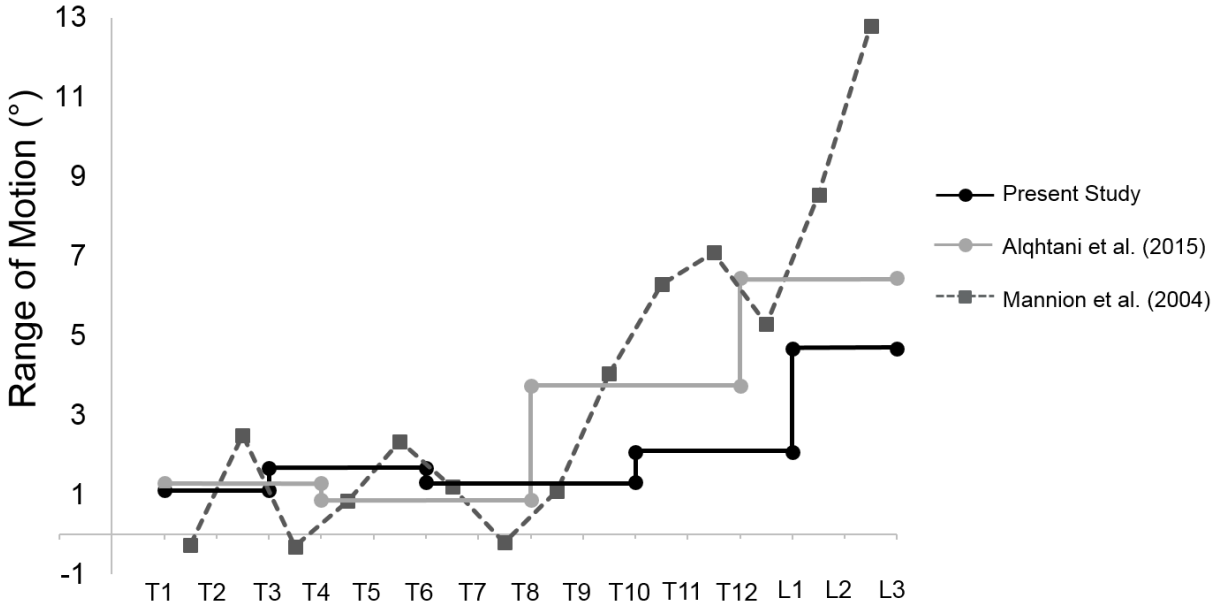

Figure 4: Comparison to Literature in Flexion. The normalized range of motion was calculated for spinal segments from the Alqhtani et al study[24] to compare to the present study. All normalized range of motion data was presented against the FSU data from Mannion et al.[26]

CHAPTER 5: Conclusions and Future Work

The overall goal of this research was to further investigate thoracolumbar mobility *in vivo*. The first objective was to quantify the effect of aging on the thoracolumbar spine. The first study investigated the changes in thoracolumbar spinal mobility between healthy adolescents and healthy older adults. It was found that the flexibility of the thoracolumbar spine does change with age. The primary result of this study was that the healthy adolescent spine has significantly more range of motion than the healthy older adult spine during flexion, extension, and right lateral bending. The implication of these results are that if older adult cadaveric spines biomechanically act like *in vivo* older adult spines, then using a cadaveric model to test spinal instrumentation directed for pediatric and adolescent use might not be an appropriate model.

The second objective was to develop a method that allows for the comparison of spinal motion data in cadaveric and *in vivo* models and to frame *in vivo* motion data in a way that is meaningful to clinicians. Cadaveric motion data is often presented in terms of FSUs while *in vivo* data is presented in segments. In order to better compare these two models, the second study investigated the *in vivo* contribution of motion from an individual representative FSU in a segment during bending tasks. The results from this study indicate that the motion contributed by each FSU was consistent between bending tasks and that the presence of a single lumbar vertebra does not typically make a segment more flexible. Additionally, it was found that while the lumbar spine is responsible for a large percentage of thoracolumbar motion, but the contribution of the thoracic spine should not be discounted. This information can provide surgeons with specific biomechanical information regarding the movement of representative FSUs in

the living spine, and hopefully aid in making surgical planning decisions for adult deformity cases.

The results from this work lay the framework for a study that can directly compare motion obtained from *in vivo* and cadaveric models. The normalization method presented is a good first step, but more in depth analysis and data processing will be required to more accurately compare these models. In addition, future studies investigating the effect of motion due to spinal disorders can be accomplished. By defining healthy adolescent and healthy older adult spinal motion, disorders that affect both populations can be further investigated.

APPENDIX A: Testing Documentation

A.1 IRB Approval

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

A.2 Adult Consent Form

INFORMED CONSENT STATEMENT

ADULT SPINE MOTION ANALYSIS

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 to participate in the present study. You may refuse to sign this form and not choose 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.

PURPOSE OF THE STUDY

The purpose of this study is to see how adults coordinate their back motion during different activities. A better understanding of dynamic back motion can aid in future research studies.

PROCEDURES

Your participation in this study will involve a single session of approximately one and a half hours in duration. Adults without spinal problems are being recruited in order to understand the differences their spine motion. 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. Flex and extend your back as much as possible in up to ten times.

2. Rotate and laterally bend your trunk as far as possible up to thirty times.

For this study, no medical records will be obtained from physicians. All data will be kept confidential and will be stored in a de-identified fashion.

RISKS

There are few risks involved in this experiment. It is possible that you may 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.

We do not know of any risks to an unborn child from this experiment

BENEFITS

There are no direct benefits to you from participating in this experiment.

PAYMENT TO PARTICIPANTS

Payment will be $10. Investigators may ask for your social security number in order to comply with federal and state tax and accounting regulations.

PARTICIPANT CONFIDENTIALITY

Your name will not be associated in any publication or presentation with the information collected about or with the research findings from this study. Instead, the researcher(s) will use a study number or a pseudonym rather than your name in order to de-identify the information. Your identifiable information will not be shared unless required by law or unless you give written permission.

The investigators will keep secret all research related records and information from this study. However, sometimes the investigators will need to let others look at records of your participation. By signing this consent form, you are agreeing to let the investigators and individuals from the IRB committee see your records of participation in the study. The investigators will not reveal your identity if they publish the results of this study.

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

de-identified information, excluding your name, 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, you cannot participate in this study.

CANCELLING THIS CONSENT AND AUTHORIZATION

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

Sara E. Wilson, Ph.D.	OR	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

If you cancel permission to use your information, the researchers will stop collecting additional information about you. However, the research team may use and disclose

information that was gathered before they received your cancellation, as described above.

QUESTIONS ABOUT PARTICIPATION

Having read the consent form, please direct any questions you have to any of the research personnel. If you have questions after signing this form, please contact the faculty advisor for this study: Sara E. Wilson, Ph.D. (785) 864-2103.

PARTICIPANT CERTIFICATION:

I have read this Consent and Authorization form and agree to participate in the study as described. 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 my 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.

_____ _____

Type/Print Participant's Name Date

_____

Participant Signature

DO NOT FILL OUT

_____ _____

Print Name Obtaining Consent Date

_____

Signature of Person Obtaining Consent

A.3 Adolescent Assent Form

Approved by the Human Subjects Committee University of Kansas, Lawrence Campus (HSCL) on 10/26/2012.
Approval expires one year from 11/30/2012. HSCL#19432

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

A.4 Parent/Guardian Consent Form

Approved by the Human Subjects Committee University of Kansas, Lawrence Campus (HSCL) on 10/26/2012.
Approval expires one year from 11/30/2012. HSCL#19432

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

A.5 HIPPA Authorization

Approved by the Human Subjects Committee University of Kansas, Lawrence Campus (HSCL) on 10/26/2012.
Approval expires one year from 11/30/2012. HSCL#19432

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

A.6 Screening Questions

Hello,

Thank you for your interest in participating in this study. This screening will help us determine if you qualify to be in our study. Stop me if you have any questions.

1. How old are you? (Continue IF between 55 and 85)
2. Are you able to perform light exercise? (Continue IF yes)
3. Are you able to stand for 30 minutes? (Continue IF yes)
4. Do you have any spinal deformity or disorder such as scoliosis, slipped or bluging disc, degenerative disc disease, kypophsis, etc that you are aware of? (Continue IF no)
5. Have you had any spinal surgery or steroid injections in your back? (Continue IF no)
6. Have you had any traumatic injuries in the last 6 months? (Continue IF no)
7. Are any of your vertebra (spinal bones) fused that you know of? (Continue IF no)
8. Are any of your ribs broken that you are aware of? (Continue IF no)

(If failed) Thank you for answering the screening questions; however you are not eligible to participate in our study. Biomedical research thrives because of people like you. Thank you for your support.

(If passed) Thank you for answering the screening questions. You are eligible to participate in our study. Do you have any questions about participating in this study? When would you like to schedule your testing sessions.

A.7 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-

INSERT SIT AND REACH TASK HERE(EILEEN)

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 Techniques

B.1 Rainbow Plotter

This code plots the raw sensor data collected by the trackSTAR sensors. These plots verified that the sensors were placed in the correct order and that the data seemed physiologically reasonable.

```
function [] = RainbowPlotter(isubject,i,itask, itrial, s1, s2, s3, s4, s5,
s6, s7, s8)
%Ends try loop

%Creates motion plot of all sensor positions
if itask == 1
    fnum = (isubject(i)*100+(itask*10)+itrial);
    a = figure(fnum);
    plot3(s1(:,1),s1(:,2),-s1(:,3))
    hold all
    plot3(s2(:,1),s2(:,2),-s2(:,3))
    plot3(s3(:,1),s3(:,2),-s3(:,3))
    plot3(s4(:,1),s4(:,2),-s4(:,3))
    plot3(s5(:,1),s5(:,2),-s5(:,3))
    plot3(s6(:,1),s6(:,2),-s6(:,3))
    plot3(s7(:,1),s7(:,2),-s7(:,3))
    plot3(s8(:,1),s8(:,2),-s8(:,3))
    xlabel('X Axis');
    ylabel('Y Axis');
    zlabel('Z Axis');
    legend('S1','L3','L1','T10','T6','T3','T1','M');
    fignum = ['Subject_' int2str(isubject(i)) 'TaskTrial_' int2str(fnum)];
    view([0 1 0]) %X-Z Plane, Flex/Ext
    hold off
    export_fig(fignum,'-tif');
    close (a)
    clear a
elseif itask == 2
    fnum = (isubject(i)*100+(itask*10)+itrial);
    a = figure(fnum);
    plot3(s1(:,1),s1(:,2),-s1(:,3))
    hold all
    plot3(s2(:,1),s2(:,2),-s2(:,3))
    plot3(s3(:,1),s3(:,2),-s3(:,3))
    plot3(s4(:,1),s4(:,2),-s4(:,3))
    plot3(s5(:,1),s5(:,2),-s5(:,3))
    plot3(s6(:,1),s6(:,2),-s6(:,3))
    plot3(s7(:,1),s7(:,2),-s7(:,3))
    plot3(s8(:,1),s8(:,2),-s8(:,3))
    xlabel('X Axis');
    ylabel('Y Axis');
    zlabel('Z Axis');
    legend('S1','L3','L1','T10','T6','T3','T1','M');
    fignum = ['Subject_' int2str(isubject(i)) 'TaskTrial_' int2str(fnum)];
    view([0 1 0]) %X-Z Plane, Flex/Ext
    hold off
```

```
    export_fig(fignum,'-tif');
    close (a)
    clear a
elseif itask == 7
    fnum = (isubject(i)*100+(itask*10)+itrial);
    a = figure(fnum);
    plot3(s1(:,1),s1(:,2),-s1(:,3))
    hold all
    plot3(s2(:,1),s2(:,2),-s2(:,3))
    plot3(s3(:,1),s3(:,2),-s3(:,3))
    plot3(s4(:,1),s4(:,2),-s4(:,3))
    plot3(s5(:,1),s5(:,2),-s5(:,3))
    plot3(s6(:,1),s6(:,2),-s6(:,3))
    plot3(s7(:,1),s7(:,2),-s7(:,3))
    plot3(s8(:,1),s8(:,2),-s8(:,3))
    xlabel('X Axis');
    ylabel('Y Axis');
    zlabel('Z Axis');
    legend('S1','L3','L1','T10','T6','T3','T1','M');
    fignum = ['Subject_' int2str(isubject(i)) 'TaskTrial_' int2str(fnum)];
    view([0 1 0]) %X-Z Plane, Flex/Ext
    hold off
    export_fig(fignum,'-tif');
    close (a)
    clear a
elseif itask == 8
    fnum = (isubject(i)*100+(itask*10)+itrial);
    a = figure(fnum);
    plot3(s1(:,1),s1(:,2),-s1(:,3))
    hold all
    plot3(s2(:,1),s2(:,2),-s2(:,3))
    plot3(s3(:,1),s3(:,2),-s3(:,3))
    plot3(s4(:,1),s4(:,2),-s4(:,3))
    plot3(s5(:,1),s5(:,2),-s5(:,3))
    plot3(s6(:,1),s6(:,2),-s6(:,3))
    plot3(s7(:,1),s7(:,2),-s7(:,3))
    plot3(s8(:,1),s8(:,2),-s8(:,3))
    xlabel('X Axis');
    ylabel('Y Axis');
    zlabel('Z Axis');
    legend('S1','L3','L1','T10','T6','T3','T1','M');
    fignum = ['Subject_' int2str(isubject(i)) 'TaskTrial_' int2str(fnum)];
    view([0 1 0]) %X-Z Plane, Flex/Ext
    hold off
    export_fig(fignum,'-tif');
    close (a)
    clear a
    %Creates motion plot of all sensor positions
elseif itask == 3
    fnum = (isubject(i)*100+(itask*10)+itrial);
    a = figure(fnum);
    plot3(s1(:,1),s1(:,2),-s1(:,3))
    hold all
    plot3(s2(:,1),s2(:,2),-s2(:,3))
    plot3(s3(:,1),s3(:,2),-s3(:,3))
    plot3(s4(:,1),s4(:,2),-s4(:,3))
    plot3(s5(:,1),s5(:,2),-s5(:,3))
```

```
    plot3(s6(:,1),s6(:,2),-s6(:,3))
    plot3(s7(:,1),s7(:,2),-s7(:,3))
    plot3(s8(:,1),s8(:,2),-s8(:,3))
    xlabel('X Axis');
    ylabel('Y Axis');
    zlabel('Z Axis');
    legend('S1','L3','L1','T10','T6','T3','T1','M');
    fignum = ['Subject_' int2str(isubject(i)) 'TaskTrial_' int2str(fnum)];
    view([1 0 0]) %Y-Z Plane, Lateral Bending
    hold off
    export_fig(fignum,'-tif');
    close (a)
    clear a
elseif itask == 4
    fnum = (isubject(i)*100+(itask*10)+itrial);
    a = figure(fnum);
    plot3(s1(:,1),s1(:,2),-s1(:,3))
    hold all
    plot3(s2(:,1),s2(:,2),-s2(:,3))
    plot3(s3(:,1),s3(:,2),-s3(:,3))
    plot3(s4(:,1),s4(:,2),-s4(:,3))
    plot3(s5(:,1),s5(:,2),-s5(:,3))
    plot3(s6(:,1),s6(:,2),-s6(:,3))
    plot3(s7(:,1),s7(:,2),-s7(:,3))
    plot3(s8(:,1),s8(:,2),-s8(:,3))
    xlabel('X Axis');
    ylabel('Y Axis');
    zlabel('Z Axis');
    legend('S1','L3','L1','T10','T6','T3','T1','M');
    fignum = ['Subject_' int2str(isubject(i)) 'TaskTrial_' int2str(fnum)];
    view([1 0 0]) %Y-Z Plane, Lateral Bending
    hold off
    export_fig(fignum,'-tif');
    close (a)
    clear a
elseif itask == 5
    %Creates motion plot of all sensor positions
    fnum = (isubject(i)*100+(itask*10)+itrial);
    a = figure(fnum);
    plot3(s1(:,1),s1(:,2),-s1(:,3))
    hold all
    plot3(s2(:,1),s2(:,2),-s2(:,3))
    plot3(s3(:,1),s3(:,2),-s3(:,3))
    plot3(s4(:,1),s4(:,2),-s4(:,3))
    plot3(s5(:,1),s5(:,2),-s5(:,3))
    plot3(s6(:,1),s6(:,2),-s6(:,3))
    plot3(s7(:,1),s7(:,2),-s7(:,3))
    plot3(s8(:,1),s8(:,2),-s8(:,3))
    xlabel('X Axis');
    ylabel('Y Axis');
    zlabel('Z Axis');
    legend('S1','L3','L1','T10','T6','T3','T1','M');
    fignum = ['Subject_' int2str(isubject(i)) 'TaskTrial_' int2str(fnum)];
    view([0 0 1]) %X-Y Plane, Torsion
    hold off
    export_fig(fignum,'-tif');
    close (a)
```

```
    clear a
elseif itask == 6
    %Creates motion plot of all sensor positions
    fnum = (isubject(i)*100+(itask*10)+itrial);
    a = figure(fnum);
    plot3(s1(:,1),s1(:,2),-s1(:,3))
    hold all
    plot3(s2(:,1),s2(:,2),-s2(:,3))
    plot3(s3(:,1),s3(:,2),-s3(:,3))
    plot3(s4(:,1),s4(:,2),-s4(:,3))
    plot3(s5(:,1),s5(:,2),-s5(:,3))
    plot3(s6(:,1),s6(:,2),-s6(:,3))
    plot3(s7(:,1),s7(:,2),-s7(:,3))
    plot3(s8(:,1),s8(:,2),-s8(:,3))
    xlabel('X Axis');
    ylabel('Y Axis');
    zlabel('Z Axis');
    legend('S1','L3','L1','T10','T6','T3','T1','M');
    fignum = ['Subject_' int2str(isubject(i)) 'TaskTrial_' int2str(fnum)];
    view([0 0 1]) %X-Y Plane, Torsion
    hold off
    export_fig(fignum,'-tif');
    close (a)
    clear a
end


end
```

B.2 Analysis ROM code

This code processes the data from the trackSTAR sensors and calls functions to ensure good quality, adjust the data when gimbal locks occur, converts position data to angles, and calculates range of motion for all tasks, trials, and segments. Data was collected over a series of eight tasks (F, E, RLB, LLB, RAR, LAR, R45, L45). For each task, five trials of data were collected and range of motion was calculated for the desired segments. All data was analyzed in-plane. Plane 1 (sagittal) was the primary plane for flexion, extension, and 45° anterior-lateral bending. Plane 2 (coronal) was the primary plane for lateral bending. Plane 3 (transverse) was the primary plane for axial rotation. Additionally, this code identifies which trial to keep for further data analysis. The code begins with trial 5, if it is good, that becomes trial keep. If it is not good or doesn't exist, trial 4 is looked at. If it is good, that becomes trial keep. If it is not good or doesn't exist, trial 3 is looked at. If it isn't good, no trials can be identifies as good for that subject in that bending task.

```
% 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,
% RawtoFlex_Crawford,

% 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
%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 = [100:117];

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;
            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
            %%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            %good_trial(task_,trial_) = trial you want it to be

            %Remove line below when running for real if running all trials
            %             good_trial(1,5) = 1;
            %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            if good_trial_allsubjects(itask,itrial,isubject(i)) == 1
                %do all the things
                %Load in data from all sensors
                for isens = 1:8
                    filename_sensor = [itxt,'_',num2str(itask), '_',...
                        num2str(itrial),'_', num2str(isens),'.mat'];
                    full_filename_sensor = [path filename_sensor];
                    s{isens} = load(full_filename_sensor);
                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;
                if isubject(i) == 51
                    s7 = s1;
                else
                    s7 = struct2cell(s{7}); s7 = s7{1}(:,1:3); sensor(:,:,7)
= s7;
                end
                s8 = struct2cell(s{8}); s8 = s8{1}(:,1:3); sensor(:,:,8) =
s8;

                %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
                %create and save rainbow plots
                %RainbowPlotter(isubject,i,itask, itrial, s1, s2, s3, s4, s5,
s6, s7, s8);

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

                %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
                % 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);
                %                   Plot vertebrae to vertify angles make
sense
                %                   fignum =
(isubject(i)*100)+(itask*10)+itrial;
                %                                       figure(fignum);
                %                                       plot(T1(:,plane),'b.');
                %                                       hold on;
                %                                       plot(T3(:,plane),'r.');
                %                                       plot(T6(:,plane),'k.');
                %                                       plot(T10(:,plane),'g.');
                %                                       plot(L1(:,plane),'c.');
                %                                       plot(L3(:,plane),'m.');
                %
legend('T1','T3','T6','T10','L1','L3')

                %Fix the jumps created by gimble lock
                [T1,T3,T6,T10,L1,L3] = JumpFixesLoop(T1,T3,T6,T10,L1,L3);
                %                   Plot vertebrae to verify jump fixes worked
                %                   fignum =
(isubject(i)*100)+(itask*10)+itrial+1;
                %                                       figure(fignum);
                %                                       plot(T1(:,plane),'b.');
                %                                       hold on;
                %                                       plot(T3(:,plane),'r.');
                %                                       plot(T6(:,plane),'k.');
                %                                       plot(T10(:,plane),'g.');
                %                                       plot(L1(:,plane),'c.');
                %                                       plot(L3(:,plane),'m.');
                %
legend('T1','T3','T6','T10','L1','L3'

                %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
                % Calculate flexion, bending, and torsion parameters
                %Calculate parameters for the entire torso. The torso
                %angle is defined as Dr. Wilson (SE Wilson) defines torso
                %inclination. Rotation sequence is defined by Crawford and
                %is determined seperately for each task

                %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_loc_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,:));
                % Plot vertebrae to ensure the they are offset correctly
                %  fignum = (isubject(i)*100)+(itask*10)+itrial;
                %  figure(fignum);
                %  plot(T1(:,plane),'b');
                %  hold on;
                %  plot(T3(:,plane),'r');
                %  plot(T6(:,plane),'k');
                %  plot(T10(:,plane),'g');
                %  plot(L1(:,plane),'c');
                %  plot(L3(:,plane),'m');
                %  legend('T1','T3','T6','T10','L1','L3')

                %% Calculate angles
                utang = T1-T3;
                mtang = T3-T6;
                ltang = T6-T10;
                utlang = T10-L1;
                ltlang = L1-L3;
                thorang = T1 - L1;
                torsoang = T10;
                %  Plot segments to ensure they make physiological sense
                %  figure(2);
                %  plot(utang(:,plane),'b--');
                %  hold on;
                %  plot(mtang(:,plane),'r');
                %  plot(ltang(:,plane),'g');
                %  plot(utlang(:,plane),'k--');
                %  plot(ltlang(:,plane),'r.');
                %  legend('ut','mt','lt','utl','ltl','thor')

                %% Add in quality info for torso
                bending_time_pts = stand_end:1:hold_start;
                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,hold_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
                    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
                    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_time,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_all.mat','ROM_all');
save('ROM_all_Adults.mat','ROM_all');
```

```
save('dynamic_bending_adults.mat','dynamic_bending');
save('good_trial.mat','good_trial_allsubjects');
save('trial_keep_Adults.mat','trial_keep');
```

B.3 Quality check

This function was called during the Analysis ROM code. Quality was defined as having data for all eight sensors remaining in the collection volume of the transmitter during the hold and bend phases and having a complete bending task (starting in the neutral position, bending, holding that bent position, and then returning to the neutral position). A trial was only good if both these criteria were met. The good trials were saved and used in the duration of the Analysis ROM code.

```
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 = ['F:\KU\Friis Lab\Adult Motion Study\Data\'];

        %% 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)
        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
        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
```

B.4 Y negative Fix

When the sensors went behind the transmitter during extension tasks, the y position was recorded as negative values. This function manually changes them from negative to positive magnitudes.

```
%% Fixes jumps in position data

%Data collected behind the origin (in the negative y range) is not
%accurate. This is an artifact of the equipment. Therefore when sensors do
%go behind the transmitter and into the negative y range, they need to be
%manually corrected. That correction is below.

function [s1 s2 s3 s4 s5 s6 s7 s8] = YnegFix(s1,s2,s3,s4,s5,s6,s7,s8)
sensors.s1 = s1(:,:);
sensors.s2 = s2(:,:);
sensors.s3 = s3(:,:);
sensors.s4 = s4(:,:);
sensors.s5 = s5(:,:);
sensors.s6 = s6(:,:);
sensors.s7 = s7(:,:);
sensors.s8 = s8(:,:);
sensorname = fieldnames(sensors);

[x,y] = size(s1);
x = 1:x;
y = 1:y;
for iii = 1:8
    data = sensors.(sensorname{iii});
%     figure(iii)
%     plot(x,data(:,1),'k.');
%     hold on
%     plot(x,data(:,2),'c.');
%     plot(x,data(:,3),'m.');

    yneg = find(data(:,2) < 0); %Looks for negative y data
    if isempty(yneg) == 0 %if negative y data is found, do the following.
        for ii = yneg(1):yneg(end)
            if yneg(1) == 1
            else
                if (sign(data(yneg(1)-1,1)) + sign(data(yneg(1),1))) == 0;
                    data(ii,1) = abs(data(ii,1)); %if the sign is different
before versus at yneg(1)
                end
                if (sign(data(yneg(1)-1,2)) + sign(data(yneg(1),2))) == 0;
                    data(ii,2) = abs(data(ii,2));
                end
                if (sign(data(yneg(1)-1,3)) + sign(data(yneg(1),3))) == 0;
                    data(ii,3) = abs(data(ii,3));
                end
            end
        end
    else
```

```
    end

%     plot(x,data(:,1),'k+');
%     plot(x,data(:,2),'c+');
%     plot(x,data(:,3),'m+');
%
    if iii == 1
        s1 = data;
    elseif iii == 2
        s2 = data;
    elseif iii == 3
        s3 = data;
    elseif iii == 4
        s4 = data;
    elseif iii == 5
        s5 = data;
    elseif iii == 6
        s6 = data;
    elseif iii == 7
        s7 = data;
    else
        s8 = data;
    end
end
end
```

B.5 Filterme

To remove some noise from the data, a 4th order butterworth filter was used on the position data from the sensors.

```
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
```

B.6 Coordinate System Angles

This function transforms the position data collected by the sensors into angles in reference to the global coordinate system of the transmitter. This was done by establishing a local coordinate system centered at each sensor. To do this, two vectors were created from the position data: 1) v1 = a vector from the sensor of interest down to the s1 (the sensor at the top of the sacrum), and 2) v2 = a vector from the sensor of interest out to the s8 (the sensor on the manubrium). The cross product of v1 and v2 was n1. Next, the cross product of n1 and v1 was performed resulting in n2. The coordinate system centered at each sensor was v1, n1, n2 (corresponding to x,y,z).

Then, a three-body Euler rotation was performed to transform the position data into angles. The order was dictated by the primary motion axis, primary coupled axis, and secondary coupled axis. For F, E, R45, and L45 the order was: sagittal, coronal, transverse. For RLB and LLB the order was: coronal, transverse, sagittal. For RAR and LAR the order was: transverse, coronal, sagittal.

```
function [T1,T3,T6,T10,L1,L3,S1] =
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_T10 = s1 - s4;

S_to_vert = {S_T1,S_T3,S_T6,S_T10,S_L1,S_L3,S_T10};

%create superior 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 - s2;
M_S  = s8 - s1;

M_to_vert = {M_T1,M_T3,M_T6,M_T10,M_L1,M_L3,M_S};


clearvars -except itask latang flexang twistang Flexion Bending Torsion
S_to_vert M_to_vert
```

```
for i = 1:7
    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);
        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
        if itask == 1 || 2 || 7 || 8
            lat = asin(-a23);
            flex = atan(a13./a33);
            twist = atan(a21./a22);
        elseif itask == 3 || 4
            lat = atan(a32./a22);
            flex = atan(a13./a11);
            twist = asin(-a12);
        elseif itask == 5 || 6
            lat = asin(a32);
            flex = atan((-1)*a31./a33);
            twist = atan((-1)*a12./a22);
```

```
        end
        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 %S1 angle
        T1(:,1) = Flexion';
        T1(:,2) = Bending';
        T1(:,3) = Torsion';
    elseif i == 2 %S2 angle
        T3(:,1) = Flexion';
        T3(:,2) = Bending';
        T3(:,3) = Torsion';
    elseif i == 3 %S3 angle
        T6(:,1) = Flexion';
        T6(:,2) = Bending';
        T6(:,3) = Torsion';
    elseif i == 4 %S4 angle
        T10(:,1) = Flexion';
        T10(:,2) = Bending';
        T10(:,3) = Torsion';
    elseif i == 5  %S5 angle
        L1(:,1) = Flexion';
        L1(:,2) = Bending';
        L1(:,3) = Torsion';
    elseif i == 6 %S6 angle
        L3(:,1) = Flexion';
        L3(:,2) = Bending';
        L3(:,3) = Torsion';
    elseif i == 7 %S6 angle
        S1(:,1) = Flexion';
        S1(:,2) = Bending';
        S1(:,3) = Torsion';
    end
end
end
```

B.7 Jump Fixes

As sensors moved between quadrants of the transmitter, a gimbal lock would occur causing the angles of the sensors to jump 90° or 180°. To fix this, this function identified when this occurred and shifted the necessary data by 90° or 180°.

```
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
```

B.8 OOB chop

This function replaces any out of bounds (OOB) data with the value NaN. This would take into effect if the subject's hold position was right at the boundary of the transmitter (3 feet). By replacing these OOB with NaN, the average hold angle can still be calculated.

```
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
```

B.9 ROM calculations

This function calculates the ROM for the desired segments from the angle data of the sensors. An average angle was calculated for the stand phase (subject in the neutral position) and the hold phase (the subject in their maximally bent position). Then, the stand angle was subjected from the hold angle to output a ROM for a segment for each task and each good trial.

```
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
```

B.10 Post Processing code for statistics

This code takes the processed ROM angles to perform statistics. First, data from the good trials is combined. Then, symmetry ratios are calculated and the data is normalized by the number of FSUs in the particular segment. Then, functions are called that calculate the means and standard deviations of the original data, symmetry ratio data, and normalized data and will also perform independent t-tests. A final function is called that performs ANOVA on the normalized data. Additionally, these functions and this code format the data to be exported into excel spreadsheet. If any data was missing, NaNs were put in its place.

```
%Post Processing ROM data
clc
close all
clear all

%Inputs
%ROM_all = all ROM values for all trials of all task for all subjects
%trial_keep = the trial number to keep and analyze for each task and subj

%Outputs
%To excel
%ROM_keep = the ROM values for all the kept trials of all tasks and subject
%norm_all_time_keep = data normalized by time for all data points on kept
%trials
%bending_ratio = ratio of left vs right bending for the kept trial of all
%tasks and subjects
%twisting_ratio = ratio of left vs right bending for the kept trial of all
%tasks and subjects

%% Load in ROM_all and trial_keep for Adults and Kids
A = open('ROM_all_Adults.mat');
B = struct2cell(A(1));
ROM_all_adults = B{1,1};

C = open('trial_keep_Adults.mat');
D = struct2cell(C(1));
trial_keep_adults = D{1,1};

E = open('ROM_all_Kids.mat');
F = struct2cell(E(1));
ROM_all_kids = F{1,1};

G = open('trial_keep_Kids.mat');
H = struct2cell(G(1));
trial_keep_kids = H{1,1};

clear A B C D E F G H
```

```
%% Create ROM_keep from ROM_all and trial_keep
%ROM_keep_adults
for m = 1:117 %for all subjects
    ROM_subj = ROM_all_adults(:,:,m); %The ROM values for one subject
    for n = 1:8 %for all tasks
        keep = zeros(5,7);
        trial = trial_keep_adults(m,n); %The trial for each subject and task
that is the good trial
        if trial ~= 0
            keep(trial,:) = 1;
            temp_ROM_keep = cell2mat(ROM_subj(n,trial));
            temp_ROM_keep(temp_ROM_keep==0) = NaN;
            %Outputs
            ROM_keep_adults(m,:,n) = temp_ROM_keep;
            clear temp_ROM_keep
        else
            ROM_keep_adults(m,:,n) = NaN(1,7);
            clear temp_ROM_keep
        end
        clear trial
    end
    clear ROM_subj
end

%ROM_keep_kids
for m = 1:57 %for all subjects
    ROM_subj = ROM_all_kids(:,:,m); %The ROM values for one subject
    for n = 1:8 %for all tasks
        keep = zeros(5,7);
        trial = trial_keep_kids(m,n); %The trial for each subject and task
that is the good trial
        if trial ~= 0
            keep(trial,:) = 1;
            temp_ROM_keep = cell2mat(ROM_subj(n,trial));
            temp_ROM_keep(temp_ROM_keep==0) = NaN;
            %Outputs
            ROM_keep_kids(m,:,n) = temp_ROM_keep;
            clear temp_ROM_keep
        else
            ROM_keep_kids(m,:,n) = NaN(1,7);
            clear temp_ROM_keep
        end
        clear trial
    end
    clear ROM_subj
end
adult_all = [1:117];
kid_controls =
[1,3,4,6,7,8,9,10,13,16,17,18,23,24,25,26,27,28,30,31,32,33,35,36,37,38,39,40
,41,42,43,44,45];
% kid_control_girls =
[1,7,8,10,13,17,23,24,28,27,30,32,33,35,36,37,38,39,40,41,42,43,44,45];
% kid_control_boys = [3,4,6,9,16,18,25,26,31];
% kid_scoli = [19,20,21,29,29,34,46,47,48,52,53,54,55,56,22,50,51,57];
% kid_scoli_girls = [19,20,21,29,29,34,46,47,48,52,53,54,55,56];
```

```
% kid_scoli_boys = [22,50,51,57];

ROM.adults = ROM_keep_adults(adult_all,:,:);
ROM.kids = ROM_keep_kids(kid_controls,:,:);
% ROM.kids_girls = ROM_keep_kids(kid_control_girls,:,:);
% ROM.kids_boys = ROM_keep_kids(kid_control_boys,:,:);
% ROM.scoli = ROM_keep_kids(kid_scoli,:,:);
% ROM.scoli_girls = ROM_keep_kids(kid_scoli_girls,:,:);
% ROM.scoli_boys = ROM_keep_kids(kid_scoli_boys,:,:);



symmetry.kids(:,1,1) = (ROM.kids(:,1,4) + ROM.kids(:,1,3))./(ROM.kids(:,1,4)
- ROM.kids(:,1,3)); %Bending ratio
symmetry.kids(:,1,2) = (ROM.kids(:,1,6) + ROM.kids(:,1,5))./(ROM.kids(:,1,6)
- ROM.kids(:,1,5)); %Twisting ratio

symmetry.adults(:,1,1) = (ROM.adults(:,1,4) +
ROM.adults(:,1,3))./(ROM.adults(:,1,4) - ROM.adults(:,1,3)); %Bending ratio
symmetry.adults(:,1,2) = (ROM.adults(:,1,6) +
ROM.adults(:,1,5))./(ROM.adults(:,1,6) - ROM.adults(:,1,5)); %Twisting ratio

ROM_keep_adults = ROM.adults;
ROM_keep_kids = ROM.kids;
bRatio_adults = symmetry.adults(:,1,1);
tRatio_adults = symmetry.adults(:,1,2);
bRatio_kids = symmetry.kids(:,1,1);
tRatio_kids = symmetry.kids(:,1,2);
%% Calculate T1->L3 segment
ROM_keep_adults = abs(ROM_keep_adults);
ROM_keep_kids = abs(ROM_keep_kids);

for itask = 1:8
    for parameter = 1:7
        TL_adults =
ROM_keep_adults(:,2,:)+ROM_keep_adults(:,3,:)+ROM_keep_adults(:,4,:)...
            +ROM_keep_adults(:,5,:)+ROM_keep_adults(:,6,:);
        TL_kids =
ROM_keep_kids(:,2,:)+ROM_keep_kids(:,3,:)+ROM_keep_kids(:,4,:)...
            +ROM_keep_kids(:,5,:)+ROM_keep_kids(:,6,:);
    end
end

%% Normalize for FSUs
ROM_keep_adults_norm = ROM_keep_adults;
ROM_keep_kids_norm = ROM_keep_kids;
for parameter = 1:7
    if parameter == 2 || parameter == 6
        ROM_keep_adults_norm(:,parameter) = ROM_keep_adutls(:,parameter)./2;
        ROM_keep_kids_norm(:,parameter) = ROM_keep_kids(:,parameter)./2;
    elseif parameter == 3 || parameter == 5
        ROM_keep_adults_norm(:,parameter) = ROM_keep_adutls(:,parameter)./3;
        ROM_keep_kids_norm(:,parameter) = ROM_keep_kids(:,parameter)./3;
    elseif parameter == 4
        ROM_keep_adults_norm(:,parameter) = ROM_keep_adutls(:,parameter)./4;
```

```
        ROM_keep_kids_norm(:,parameter) = ROM_keep_kids(:,parameter)./4;
    elseif parameter == 7
        ROM_keep_adults_norm(:,parameter) = ROM_keep_adutls(:,parameter)./9;
        ROM_keep_kids_norm(:,parameter) = ROM_keep_kids(:,parameter)./9;
    end
end

%% Create spreadsheet with mean and std values for ROM
[ROM_mean_matrix1,ROM_std_matrix1,ROM_mean_matrix2,ROM_std_matrix2] =...
    ROMdataNorm(ROM_keep_adults_norm,ROM_keep_kids_norm,TL_adults,TL_kids);

%% Statistics
%Call statistics subfunction [] =
ManuscriptA_ttest(ROM_keep,twisting_ratio,bending_ratio);
[h1,p1,h2,p2,h3,p3,h4,p4,h5,p5,h6,p6,women_ROM,women_tRatio,women_bRatio,men_
ROM,men_tRatio,men_bRatio] = ...

GenStatsRevD(ROM_keep_adults,tRatio_adults,bRatio_adults,ROM_keep_kids,tRatio
_kids,bRatio_kids);

[h7,p7] = GenStatsNorm(ROM_keep_adults_norm,ROM_keep_kids_norm);

[p_F_adults,c_F_adults,p_E_adults,c_E_adults,p_LLB_adults,c_LLB_adults,p_RLB_
adults,c_RLB_adults,...
    p_L45_adults,c_L45_adults,p_R45_adults,c_R45_adults] =
AnovaNormAdults(ROM_keep_adults_norm,TL_adults);

[p_F_kids,c_F_kids,p_E_kids,c_E_kids,p_LLB_kids,c_LLB_kids,p_RLB_kids,c_RLB_k
ids,...
    p_L45_kids,c_L45_kids,p_R45_kids,c_R45_kids] =
AnovaNormKids(ROM_keep_kids_norm,TL_kids);

% %% ttest stats
[h11,p11] = GenStatsNorm_A(ROM_keep_adults_norm,ROM_keep_kids_norm);

%h1 and p1 --> adult women ROM vs adult men ROM
%h2 and p2 --> adult women bRatio vs adult men bRatio
%h3 and p3 --> adult women tRatio vs adult men tRatio
%h4 and p4 --> adults vs kids
%h5 and p5 --> adults bRatio vs kids bRatio
%h6 and p6 --> adults tRatio vs kids tRatio

save('h1.mat','h1');
save('p1.mat','p1');
save('h2.mat','h2');
save('p2.mat','p2');
save('h3.mat','h3');
save('p3.mat','p3');
save('h4.mat','p4');
save('p4.mat','p4');
save('h5.mat','p5');
save('p5.mat','p5');
save('h6.mat','p6');
save('p6.mat','p6');
```

```
xlswrite('ttest_results',h1,'h1');
xlswrite('ttest_results',p1,'p1');
xlswrite('ttest_results',h2,'h2');
xlswrite('ttest_results',p2,'p2');
xlswrite('ttest_results',h3,'h3');
xlswrite('ttest_results',p3,'p3');
xlswrite('ttest_results',h4,'h4');
xlswrite('ttest_results',p4,'p4');
xlswrite('ttest_results',h5,'h5');
xlswrite('ttest_results',p5,'p5');
xlswrite('ttest_results',h6,'h6');
xlswrite('ttest_results',p6,'p6');

% xlswrite('ROM_data',ROM_keep_adults,'ROM_keep_adults');
% xlswrite('ROM_data',bRatio_adults,'bRatio_adults');
% xlswrite('ROM_data',tRatio_adults,'tRatio_adults');
% xlswrite('ROM_data',ROM_keep_kids,'ROM_keep_kids');
% xlswrite('ROM_data',bRatio_kids,'bRatio_kids');
% xlswrite('ROM_data',tRatio_kids,'tRatio_kids');

% flexion = ROM_keep_adults(100:117,:,1);
% extension = ROM_keep_adults(100:117,:,2);
% left_LB = ROM_keep_adults(100:117,:,3);
% right_LB = ROM_keep_adults(100:117,:,4);
% left_AR = ROM_keep_adults(100:117,:,5);
% right_AR = ROM_keep_adults(100:117,:,6);
% left_45 = ROM_keep_adults(100:117,:,7);
% right_45 = ROM_keep_adults(100:117,:,8);
%
% xlswrite('ROMadults_data',flexion,'flexion');
% xlswrite('ROMadults_data',extension,'extension');
% xlswrite('ROMadults_data',left_LB,'left_LB');
% xlswrite('ROMadults_data',right_LB,'right_LB');
%
% clear flexion extension left_LB right_LB left_AR right_AR left_45 right_45
%
% flexion = ROM_keep_kids(100:117,:,1);
% extension = ROM_keep_kids(100:117,:,2);
% left_LB = ROM_keep_kids(100:117,:,3);
% right_LB = ROM_keep_kids(100:117,:,4);
% left_AR = ROM_keep_kids(100:117,:,5);
% right_AR = ROM_keep_kids(100:117,:,6);
% left_45 = ROM_keep_kids(100:117,:,7);
% right_45 = ROM_keep_kids(100:117,:,8);
%
% xlswrite('ROMkids_data',flexion,'flexion');
% xlswrite('ROMkids_data',extension,'extension');
% xlswrite('ROMkids_data',left_LB,'left_LB');
% xlswrite('ROMkids_data',right_LB,'right_LB');
```

B.11 ROMdataNorm

This function takes the normalized data and performs means and standard deviations and formats it to be able to easily create bar charts in excel.

```
function [ROM_mean_matrix1,ROM_std_matrix1,ROM_mean_matrix2,ROM_std_matrix2]
=...
    ROMdataNorm(ROM_keep_adults_norm,ROM_keep_kids_norm,TL_adults,TL_kids)

%calculate means and std for 8 trials, 9 parameters in 3 planes
for itask = 1:8
    for parameter = 2:7 %All 7 parameters (torso, ut, mt, lt, utl, ltl, thor)
        ROMnorm_mean_adults(parameter,itask) =
nanmean(ROM_keep_adults_norm(:,parameter,itask));
        ROMnorm_std_adults(parameter,itask) =
nanstd(ROM_keep_adults_norm(:,parameter,itask));

        ROM_adults_norm(:,parameter,itask) =
ROM_keep_adults_norm(:,parameter,itask)./TL_adults(:,1,itask);
        ROM_kids_norm(:,parameter,itask) =
ROM_keep_kids_norm(:,parameter,itask)./TL_kids(:,1,itask);

        %mean and std for all ADULTS
        ROM_all_mean_adults(parameter,itask) =
nanmean(ROM_adults_norm(:,parameter,itask));
        ROM_all_std_adults(parameter,itask) =
nanstd(ROM_adults_norm(:,parameter,itask));

        %mean and std for all KIDS
        ROM_all_mean_kids(parameter,itask) =
nanmean(ROM_kids_norm(:,parameter,itask));
        ROM_all_std_kids(parameter,itask) =
nanstd(ROM_kids_norm(:,parameter,itask));
    end
end
ROM_all_mean_adults = ROM_all_mean_adults(:,:).*100;
ROM_all_mean_kids = ROM_all_mean_kids(:,:).*100;

ROM_all_std_adults = ROM_all_std_adults(:,:).*100;
ROM_all_std_kids = ROM_all_std_kids(:,:).*100;

for itask = 1:8
    if itask == 2 || itask == 3 || itask == 7
        ROM_all_mean_adults(:,itask) = ROM_all_mean_adults(:,itask).*-1;
        ROM_all_mean_kids(:,itask) = ROM_all_mean_kids(:,itask).*-1;
    end
end

%remove torso and thoracic parameters
ROM_adults_noTorso_mean(1:5,:) = ROM_all_mean_adults(2:6,:);
ROM_adults_noTorso_std(1:5,:) = ROM_all_std_adults(2:6,:);
```

```
ROMnorm_adults_noTorso_mean(1:5,:) = ROMnorm_mean_adults(2:6,:);
ROMnorm_adults_noTorso_std(1:5,:) = ROMnorm_std_adults(2:6,:);

ROM_kids_noTorso_mean(1:5,:) = ROM_all_mean_kids(2:6,:);
ROM_kids_noTorso_std(1:5,:) = ROM_all_std_kids(2:6,:);


ROM_mean_matrix1 = ROM_adults_noTorso_mean;
ROM_std_matrix1 = ROM_adults_noTorso_std;

ROM_mean_matrix2 = ROMnorm_adults_noTorso_mean;
ROM_std_matrix2 = ROMnorm_adults_noTorso_std;

%% Create Spreadsheet for all mean ROM values
%Rearrange adult and kid group ROM data for writing to excel
% ROM_mean_matrix = zeros(9,8);
% ROM_mean_matrix(1,:) = ROM_adults_noTorso_mean(1,:);
% ROM_mean_matrix(3,:) = ROM_adults_noTorso_mean(2,:);
% ROM_mean_matrix(5,:) = ROM_adults_noTorso_mean(3,:);
% ROM_mean_matrix(7,:) = ROM_adults_noTorso_mean(4,:);
% ROM_mean_matrix(9,:) = ROM_adults_noTorso_mean(5,:);
%
% ROM_std_matrix = zeros(9,8);
% ROM_std_matrix(1,:) = ROM_adults_noTorso_std(1,:);
% ROM_std_matrix(3,:) = ROM_adults_noTorso_std(2,:);
% ROM_std_matrix(5,:) = ROM_adults_noTorso_std(3,:);
% ROM_std_matrix(7,:) = ROM_adults_noTorso_std(4,:);
% ROM_std_matrix(9,:) = ROM_adults_noTorso_std(5,:);

ROM_mean_matrix1 = flipud(ROM_mean_matrix1);
ROM_std_matrix1 = flipud(ROM_std_matrix1);

ROM_mean_matrix2 = flipud(ROM_mean_matrix2);
ROM_std_matrix2 = flipud(ROM_std_matrix2);

%Writing ROM to Excel files
header1 = {'Flexion','Extension','LLB','RLB','LAR','RAR','L45','R45'};
header2 = flipud({'UT (T1-T3)';'MT (T3-T6)';'LT (T6-T10)';'UTL (T10-L1)';'LTL
(L1-L3)'});

xlswrite('ROMdataNorm.xlsx',header1,'ROM_data','B1:I1');
xlswrite('ROMdataNorm.xlsx',header2,'ROM_data','A2:A6');
xlswrite('ROMdataNorm.xlsx',header1,'ROM_data','B13:I13');
xlswrite('ROMdataNorm.xlsx',header2,'ROM_data','A14:A18');
xlswrite('ROMdataNorm.xlsx',ROM_mean_matrix1,'ROM_data','B2:I6');
xlswrite('ROMdataNorm.xlsx',ROM_std_matrix1,'ROM_data','B14:I18');

xlswrite('ROMdataNorm.xlsx',header1,'ROMnorm_data','B1:I1');
xlswrite('ROMdataNorm.xlsx',header2,'ROMnorm_data','A2:A6');
xlswrite('ROMdataNorm.xlsx',header1,'ROMnorm_data','B13:I13');
xlswrite('ROMdataNorm.xlsx',header2,'ROMnorm_data','A14:A18');
xlswrite('ROMdataNorm.xlsx',ROM_mean_matrix2,'ROMnorm_data','B2:I6');
xlswrite('ROMdataNorm.xlsx',ROM_std_matrix2,'ROMnorm_data','B14:I18');

end
```

B.12 GenStats

This functions generates statistics for the original data. Independent t tests were ran comparing the adolescent and older adult data.

```
function
[h1,p1,h2,p2,h3,p3,h4,p4,h5,p5,h6,p6,women_ROM,women_tRatio,women_bRatio,men_
ROM,men_tRatio,men_bRatio] = ...

GenStatsRevD(ROM_keep_adults,tRatio_adults,bRatio_adults,ROM_keep_kids,tRatio
_kids,bRatio_kids);
%counters
counter_women = 0;
counter_men = 0;

for isubject = [100:117]
    %Load in Demographic Data
    output(isubject,1:8,1) = [isubject,DemographicData(isubject)];
    %separate out women
    if output(isubject,3,1) == 1
        counter_women = counter_women + 1;
        women_ROM(counter_women,:,:) = ROM_keep_adults(isubject,:,:);
        women_tRatio(counter_women,:,:) = tRatio_adults(isubject,:,:);
        women_bRatio(counter_women,:,:) = bRatio_adults(isubject,:,:);
    elseif output(isubject,3,1) == 2
        counter_men = counter_men + 1;
        men_ROM(counter_men,:,:) = ROM_keep_adults(isubject,:,:);
        men_tRatio(counter_men,:,:) = tRatio_adults(isubject,:,:);
        men_bRatio(counter_men,:,:) = bRatio_adults(isubject,:,:);
    end
end

%calculate means and std for 8 trials, 9 parameters in 3 planes
for itask = 1:8
    for parameter = 1:7 %All 7 parameters (torso, ut, mt, lt, utl, ltl, thor)
        %calculate mean and std for adults, kids, women, and men

        %mean and std for all ADULTS for ROM, bending, and twisting
        ROM_all_mean_adults(parameter,itask) =
nanmean(ROM_keep_adults(:,parameter,itask));
        ROM_all_std_adults(parameter,itask) =
nanstd(ROM_keep_adults(:,parameter,itask));
        bending_all_mean_adults = nanmean(bRatio_adults);
        bending_all_std_adults = nanstd(bRatio_adults);
        twisting_all_mean_adults = nanmean(tRatio_adults);
        twisting_all_std_adults = nanstd(tRatio_adults);

        %mean and std for all KIDS for ROM, bending, and twisting
        ROM_all_mean_kids(parameter,itask) =
nanmean(ROM_keep_kids(:,parameter,itask));
        ROM_all_std_kids(parameter,itask) =
nanstd(ROM_keep_kids(:,parameter,itask));
        bending_all_mean_kids = nanmean(bRatio_kids);
        bending_all_std_kids = nanstd(bRatio_kids);
```

```
        twisting_all_mean_kids = nanmean(tRatio_kids);
        twisting_all_std_kids = nanstd(tRatio_kids);

        %mean and std for WOMEN for ROM, bending, and twisting
        ROM_women_mean(parameter,itask) =
nanmean(women_ROM(:,parameter,itask));
        ROM_women_std(parameter,itask) =
nanstd(women_ROM(:,parameter,itask));
        bending_women_mean = nanmean(women_bRatio);
        bending_women_std = nanstd(women_bRatio);
        twisting_women_mean = nanmean(women_tRatio);
        twisting_women_std = nanstd(women_tRatio);

        %mean and std for MEN for ROM, bending, and twisting
        ROM_men_mean(parameter,itask) = nanmean(men_ROM(:,parameter,itask));
        ROM_men_std(parameter,itask) = nanstd(men_ROM(:,parameter,itask));
        bending_men_mean = nanmean(men_bRatio);
        bending_men_std = nanstd(men_bRatio);
        twisting_men_mean = nanmean(men_tRatio);
        twisting_men_std = nanstd(men_tRatio);

        %% perform ttests
        alpha1 = 0.05/1;  %divide by 1 because there is one output parameter
(ROM)
        alpha2 = 0.05/2;  %divide by 2 because there are two output
parameters (bRatio and tRatio)



        %t-test 1 -> ADULTS, women ROM to men
        [h1(parameter,itask),p1(parameter,itask)] =
ttest2(women_ROM(:,parameter,itask),men_ROM(:,parameter,itask),'alpha',alpha1
);
        %t-test 2 -> ADULTS, bending ratio women to men
        [h2(parameter,itask),p2(parameter,itask)] =
ttest2(women_bRatio(:,1),men_bRatio(:,1),'alpha',alpha2);
        %t-test 3 -> ADULTS, twisting ratio women to men
        [h3(parameter,itask),p3(parameter,itask)] =
ttest2(women_tRatio(:,1),men_tRatio(:,1),'alpha',alpha2);
        %t-test 4 -> adults ROM to kids
        [h4(parameter,itask),p4(parameter,itask)] =
ttest2(ROM_keep_adults(:,parameter,itask),ROM_keep_kids(:,parameter,itask),'a
lpha',alpha1);
        %t-test 5 -> adults bending ratio to kids
        [h5(parameter,itask),p5(parameter,itask)] =
ttest2(bRatio_adults(:,1),bRatio_kids(:,1),'alpha',alpha2);
        %t-test 6 -> adults twisting ratio to kids
        [h6(parameter,itask),p6(parameter,itask)] =
ttest2(tRatio_adults(:,1),tRatio_kids(:,1),'alpha',alpha2);
    end
end
%%
%Rearrange adult and kid group ROM data for writing to excel
zero_row = zeros(1,8);
for parameter = 1:7
    for group = 1:3
    row = (parameter-1)*3+group;
```

```
    if mod(row,3) == 2
        ROM_mean_matrix(row,:) = ROM_all_mean_adults(parameter,:);
        ROM_std_matrix(row,:) = ROM_all_std_adults(parameter,:);
    elseif mod(row,3) == 0
        ROM_mean_matrix(row,:) = ROM_all_mean_kids(parameter,:);
        ROM_std_matrix(row,:) = ROM_all_std_kids(parameter,:);
    elseif mod(row,3) == 1
        ROM_mean_matrix(row,:) = zero_row;
        ROM_std_matrix(row,:) = zero_row;
    end
    end
end

ROM_mean_matrix = flipud(ROM_mean_matrix);
ROM_std_matrix = flipud(ROM_std_matrix);


%Writing ROM to Excel files
header1 =
{'Flexion','Extension','LBending','RBending','LTorsion','RTorsion','L45OP','R
45OP'};
% header2 = flipud({'Torso';'Upper Thoracic';'Mid Thoracic';'Low
Thoracic';'Upper Thoracolumbar';'Lower Thoracolumbar';'Thoracic'});
header22 = flipud({'';'';'Torso';'';'';'Upper Thoracic';'';...
    '';'Mid Thoracic';'';'';'Low Thoracic';'';...
    '';'Upper Thoracolumbar';'';...
    '';'Lower Thoracolumbar';'';'';'Thoracic'});

xlswrite('gen_stats.xlsx',header1,'ROM_AdultsKids','B1:I1');
xlswrite('gen_stats.xlsx',header22,'ROM_AdultsKids','A2:A22');
xlswrite('gen_stats.xlsx',header1,'ROM_AdultsKids','B23:I23');
xlswrite('gen_stats.xlsx',header22,'ROM_AdultsKids','A24:A44');
xlswrite('gen_stats.xlsx',ROM_mean_matrix,'ROM_AdultsKids','B2:I21'); %all
adults and kids ROM mean
xlswrite('gen_stats.xlsx',ROM_std_matrix,'ROM_AdultsKids','B24:I43'); %all
adults and kids ROM std

%Writing Symmetry to Excel files
header3 = {'Bending','Torsion'};
header4 = {'Adults';'Kids'};
xlswrite('gen_stats.xlsx',header3,'Symmetry','B1:C1');
xlswrite('gen_stats.xlsx',header4,'Symmetry','A2:A3');
xlswrite('gen_stats.xlsx',bending_all_mean_adults(1,1),'Symmetry','B2');
%adults bending mean
xlswrite('gen_stats.xlsx',twisting_all_mean_adults(1,1),'Symmetry','C2');
%adults twisting mean
xlswrite('gen_stats.xlsx',bending_all_mean_kids(1,1),'Symmetry','B3'); %kids
bending mean
xlswrite('gen_stats.xlsx',twisting_all_mean_kids(1,1),'Symmetry','C3'); %kids
twisting mean

xlswrite('gen_stats.xlsx',header3,'Symmetry','B6:C6');
xlswrite('gen_stats.xlsx',header4,'Symmetry','A7:A8');
xlswrite('gen_stats.xlsx',bending_all_std_adults(1,1),'Symmetry','B7');
%adults bending mean
```

```
xlswrite('gen_stats.xlsx',twisting_all_std_adults(1,1),'Symmetry','C7');
%adults twisting mean
xlswrite('gen_stats.xlsx',bending_all_std_kids(1,1),'Symmetry','B8'); %kids
bending mean
xlswrite('gen_stats.xlsx',twisting_all_std_kids(1,1),'Symmetry','C8'); %kids
twisting mean


 %%  create excel files with means and stds for all, women, and men
% xlswrite('gen_statsROM.xlsx',ROM_all_mean_adults,'AdultMean','A1:H7');
% xlswrite('gen_statsROM.xlsx',ROM_all_std_adults,'AdultStd','A1:H7');
% xlswrite('gen_statsROM.xlsx',ROM_all_mean_kids,'KidMean','A1:H7');
% xlswrite('gen_statsROM.xlsx',ROM_all_std_kids,'KidStd','A1:H7');
% xlswrite('gen_statsROM.xlsx',ROM_women_mean,'WomenMean','A1:H7');
% xlswrite('gen_statsROM.xlsx',ROM_women_std,'WomenStd','A1:H7');
% xlswrite('gen_statsROM.xlsx',ROM_men_mean,'MenMean','A1:H7');
% xlswrite('gen_statsROM.xlsx',ROM_men_std,'MenStd','A1:H7');
%
% xlswrite('gen_statsBend.xlsx',bending_all_mean_adults,'AdultMean','A1:A7');
% xlswrite('gen_statsBend.xlsx',bending_all_std_adults,'AdultStd','A1:A7');
% xlswrite('gen_statsBend.xlsx',bending_all_mean_kids,'KidMean','A1:A7');
% xlswrite('gen_statsBend.xlsx',bending_all_std_kids,'KidStd','A1:A7');
% xlswrite('gen_statsBend.xlsx',bending_women_mean,'WomenMean','A1:A7');
% xlswrite('gen_statsBend.xlsx',bending_women_std,'WomenStd','A1:A7');
% xlswrite('gen_statsBend.xlsx',bending_men_mean,'MenMean','A1:A7');
% xlswrite('gen_statsBend.xlsx',bending_men_std,'MenStd','A1:A7');
%
%
xlswrite('gen_statsTwist.xlsx',twisting_all_mean_adults,'AdultMean','A1:A7');
% xlswrite('gen_statsTwist.xlsx',twisting_all_std_adults,'AdultStd','A1:A7');
% xlswrite('gen_statsTwist.xlsx',twisting_all_mean_kids,'KidMean','A1:A7');
% xlswrite('gen_statsTwist.xlsx',twisting_all_std_kids,'KidStd','A1:A7');
% xlswrite('gen_statsTwist.xlsx',twisting_women_mean,'WomenMean','A1:A7');
% xlswrite('gen_statsTwist.xlsx',twisting_women_std,'WomenStd','A1:A7');
% xlswrite('gen_statsTwist.xlsx',twisting_men_mean,'MenMean','A1:A7');
% xlswrite('gen_statsTwist.xlsx',twisting_men_std,'MenStd','A1:A7');

%% create plots for data quality check
% age = output(100:117,2);
% ROM_keep(ROM_keep == 0) = NaN;
% for itask = 1:8
%     if itask == 1 || itask == 2 || itask == 7 || itask == 8
%         plane = 1;
%     elseif itask == 3 || itask == 4
%         plane = 2;
%     elseif itask == 5 || itask == 6
%         plane = 3;
%     end
%
%     %torso(:,itask) = control_ROM(:,plane,itask);
%     figure(itask)
%     scatter(age,ROM_keep(100:117,plane,itask));
% end
end
```

B.13 GenStatsNorm

This functions generates statistics for the normalized data. Independent t tests were ran comparing the adolescent and older adult data.

```
function [h7,p7,h8,p8,h9,p9,h10,p10,h11,p11] =
GenStatsNorm(ROM_keep_adults_norm,ROM_keep_kids_norm)

%calculate means and std for 8 trials, 9 parameters in 3 planes
for itask = 1:8
    for parameter = 1:7 %All 7 parameters (torso, ut, mt, lt, utl, ltl, thor)
        %mean and std for all ADULTS for ROM, bending, and twisting
        ROM_all_mean_adults(parameter,itask) =
nanmean(ROM_keep_adults_norm(:,parameter,itask));
        ROM_all_std_adults(parameter,itask) =
nanstd(ROM_keep_adults_norm(:,parameter,itask));

        %mean and std for all KIDS for ROM, bending, and twisting
        ROM_all_mean_kids(parameter,itask) =
nanmean(ROM_keep_kids_norm(:,parameter,itask));
        ROM_all_std_kids(parameter,itask) =
nanstd(ROM_keep_kids_norm(:,parameter,itask));


        %% perform ttests
        alpha1 = 0.05/1;  %divide by 1 because there is one output parameter
(ROM)
        %comparing segments with the same FSUs
        %t-test 7 -> adults UT vs LTL (2 FSUs)
        [h7(parameter,itask),p7(parameter,itask)] =
ttest2(ROM_keep_adults_norm(:,2,itask),ROM_keep_adults_norm(:,6,itask),'alpha
',alpha1);
        %t-test 8 -> adults MT vs UTL (3 FSUs)
        [h8(parameter,itask),p8(parameter,itask)] =
ttest2(ROM_keep_adults_norm(:,3,itask),ROM_keep_adults_norm(:,5,itask),'alpha
',alpha1);
        %t-test 9 -> kids UT vs LTL (2 FSUs)
        [h9(parameter,itask),p9(parameter,itask)] =
ttest2(ROM_keep_kids_norm(:,2,itask),ROM_keep_kids_norm(:,6,itask),'alpha',al
pha1);
        %t-test 10 -> kids MT vs UTL (3 FSUs)
        [h10(parameter,itask),p10(parameter,itask)] =
ttest2(ROM_keep_kids_norm(:,3,itask),ROM_keep_kids_norm(:,5,itask),'alpha',al
pha1);

        %comparing kids and adult segments
        %t-test 11 -> kids vs adults all parameters
        [h11(parameter,itask),p11(parameter,itask)] =
ttest2(ROM_keep_kids_norm(:,parameter,itask),ROM_keep_adults_norm(:,parameter
,itask),'alpha',alpha1);
    end
end
%%
```

```
%Rearrange adult and kid group ROM data for writing to excel
zero_row = zeros(1,8);
for parameter = 1:7
    for group = 1:3
        row = (parameter-1)*3+group;
        if mod(row,3) == 2
            ROM_mean_matrix(row,:) = ROM_all_mean_adults(parameter,:);
            ROM_std_matrix(row,:) = ROM_all_std_adults(parameter,:);
        elseif mod(row,3) == 0
            ROM_mean_matrix(row,:) = ROM_all_mean_kids(parameter,:);
            ROM_std_matrix(row,:) = ROM_all_std_kids(parameter,:);
        elseif mod(row,3) == 1
            ROM_mean_matrix(row,:) = zero_row;
            ROM_std_matrix(row,:) = zero_row;
        end
    end
end

ROM_mean_matrix = flipud(ROM_mean_matrix);
ROM_std_matrix = flipud(ROM_std_matrix);


%Writing ROM to Excel files
header1 =
{'Flexion','Extension','LBending','RBending','LTorsion','RTorsion','L45OP','R
45OP'};
% header2 = flipud({'Torso';'Upper Thoracic';'Mid Thoracic';'Low
Thoracic';'Upper Thoracolumbar';'Lower Thoracolumbar';'Thoracic'});
header22 = flipud({'';'';'Torso';'';'';'Upper Thoracic';'';...
    '';'Mid Thoracic';'';'';'Low Thoracic';'';...
    '';'Upper Thoracolumbar';'';...
    '';'Lower Thoracolumbar';'';'';'Thoracic'});

xlswrite('gen_stats_norm.xlsx',header1,'ROM_AdultsKids','B1:I1');
xlswrite('gen_stats_norm.xlsx',header22,'ROM_AdultsKids','A2:A22');
xlswrite('gen_stats_norm.xlsx',header1,'ROM_AdultsKids','B23:I23');
xlswrite('gen_stats_norm.xlsx',header22,'ROM_AdultsKids','A24:A44');
xlswrite('gen_stats_norm.xlsx',ROM_mean_matrix,'ROM_AdultsKids','B2:I21');
%all adults and kids ROM mean
xlswrite('gen_stats_norm.xlsx',ROM_std_matrix,'ROM_AdultsKids','B24:I43');
%all adults and kids ROM std
end
```

B.14 AnovaNormAdults

This functions generates statistics for the normalized data. ANOVAs were ran comparing the segments in one mode of bending and comparing the bending tasks in one segment.

```
function
[p_F_adults,c_F_adults,p_E_adults,c_E_adults,p_LLB_adults,c_LLB_adults,p_RLB_
adults,c_RLB_adults,...
    p_L45_adults,c_L45_adults,p_R45_adults,c_R45_adults] =
AnovaNormAdults(ROM_keep_adults_norm,TL_adults)
%calculate percent contribution --> normalized segment/(T1->L3)

for itask = 1:8
    for parameter = 1:7
        ROM_adults_norm(:,parameter,itask) =
ROM_keep_adults_norm(:,parameter,itask)./TL_adults(:,1,itask);
    end
end
%     ROM_adults_norm = abs(ROM_adults_norm);

%% anova for segments
%anova comparing all segments in each mode of bending, ADULTS only
F_adults = ROM_adults_norm(:,2:7,1);
E_adults = ROM_adults_norm(:,2:7,2);
LLB_adults = ROM_adults_norm(:,2:7,3);
RLB_adults = ROM_adults_norm(:,2:7,4);
L45_adults = ROM_adults_norm(:,2:7,7);
R45_adults = ROM_adults_norm(:,2:7,8);

[p_F_adults, table_F_adults, stats_F_adults] = anova1(F_adults);
c_F_adults = multcompare(stats_F_adults);

[p_E_adults, table_E_adults, stats_E_adults] = anova1(E_adults);
c_E_adults = multcompare(stats_E_adults);

[p_LLB_adults, table_LLB_adults, stats_LLB_adults] = anova1(LLB_adults);
c_LLB_adults = multcompare(stats_LLB_adults);

[p_RLB_adults, table_RLB_adults, stats_RLB_adults] = anova1(RLB_adults);
c_RLB_adults = multcompare(stats_RLB_adults);

[p_L45_adults, table_L45_adults, stats_L45_adults] = anova1(L45_adults);
c_L45_adults = multcompare(stats_L45_adults);

[p_R45_adults, table_R45_adults, stats_R45_adults] = anova1(R45_adults);
c_R45_adults = multcompare(stats_R45_adults);

close all
```

```
%% anova for modes of bending
ROM_adults_norm_NoAR(:,:,1:4) = ROM_adults_norm(:,:,1:4);
ROM_adults_norm_NoAR(:,:,5:6) = ROM_adults_norm(:,:,7:8);
for itask = 1:6
    UT_adults(:,itask) = [ROM_adults_norm_NoAR(:,2,itask)];
    MT_adults(:,itask) = [ROM_adults_norm_NoAR(:,3,itask)];
    LT_adults(:,itask) = [ROM_adults_norm_NoAR(:,4,itask)];
    UTL_adults(:,itask) = [ROM_adults_norm_NoAR(:,5,itask)];
    LTL_adults(:,itask) = [ROM_adults_norm_NoAR(:,6,itask)];
    thor_adults(:,itask) = [ROM_adults_norm_NoAR(:,7,itask)];
end
%adult anovas
[p_UT_adults, table_UT_adults, stats_UT_adults] = anova1(UT_adults);
c_UT_adults = multcompare(stats_UT_adults);

[p_MT_adults, table_MT_adults, stats_MT_adults] = anova1(MT_adults);
c_MT_adults = multcompare(stats_MT_adults);

[p_LT_adults, table_LT_adults, stats_LT_adults] = anova1(LT_adults);
c_LT_adults = multcompare(stats_LT_adults);

[p_UTL_adults, table_UTL_adults, stats_UTL_adults] = anova1(UTL_adults);
c_UTL_adults = multcompare(stats_UTL_adults);

[p_LTL_adults, table_LTL_adults, stats_LTL_adults] = anova1(LTL_adults);
c_LTL_adults = multcompare(stats_LTL_adults);

[p_thor_adults, table_thor_adults, stats_thor_adults] = anova1(thor_adults);
c_thor_adults = multcompare(stats_thor_adults);

close all

end
```