THE EFFECT OF VERTEBRAL BODY TETHERING ON SPINE MOTION IN ADOLESCENT IDIOPATHIC SCOLIOSIS: A PILOT STUDY

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List of Acronyms

3D	Three-dimensional
ANOVA	Analysis of Variance
AIS	Adolescent Idiopathic Scoliosis
AP	Anterior/Posterior
CHEO	Children's Hospital of Eastern Ontario
DDD	Degenerative Disc Disorder
IMU	Inertial Measurement Unit
IV	Intervertebral
LCS	Local Coordinate System
LIV	Lowest Instrumented Vertebrae
ML	Medio-lateral
PSF	Posterior Spinal Fusion
ROM	Range of Motion
SD	Standard Deviation
SI	Superior/Inferior
SPM	Statistical Parametric Mapping
VBT	Vertebral Body Tethering

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Abstract

The current gold standard for the surgical treatment of adolescent idiopathic scoliosis (AIS) is posterior spinal fusion and instrumentation (PSF); however, decreased normal spine function, strain on unfused vertebrae and pain have been suggested as long-term complications with this technique. Vertebral body tethering (VBT) is a novel and minimally invasive approach for scoliosis correction that does not involve fusion and may theoretically preserve spine motion. VBT involves the use of screws and a tether that are inserted thoracoscopically on the convexity of the spine curvature in skeletally immature patients, allowing progressive curve correction as skeletal maturity is achieved. No research to date has explored the effect of VBT on spine motion in AIS. Therefore, the purpose of this thesis was to retrospectively compare global and intersegmental spine range of motion in adolescents (9-18 years of age) without spine deformity, adolescents with untreated AIS, adolescents having undergone PSF, and adolescents having undergone VBT to gain insight on the effect of VBT on spine motion. Twenty participants were recruited into four groups including Control (n = 6), untreated AIS (n = 5), post-operative PSF (n = 4) and post-operative VBT (n = 5). Three-dimensional kinematics of the spine were collected and analyzed using an intersegmental spine model during constrained forward flexion, right-left lateral bending, and right-left axial twist movements. The PSF group displayed significantly lower spine ROM than the two non-operative groups during thoracic and total left axial twist ($p \leq 0.048$), whereas thoracic and total spine range of motion during right-left lateral bending is almost equally lower in the PSF ($p \leq 0.03$) and VBT ($p \leq 0.01$) groups when compared to the Control and AIS groups. These results may suggest some preservation of spine motion in the transverse plane following VBT; however further investigation with a greater sample size and a prospective study design is needed to support and prove the theoretical preservation of spine motion following VBT.

1.0 INTRODUCTION

Adolescent idiopathic scoliosis (AIS) is a three-dimensional structural deformity of the spine, characterized by abnormal curvature and rotation of the vertebrae that develops in children around puberty (Nishida *et al.*, 2017). AIS has an overall worldwide prevalence of 0.47-0.52% and female to male ratios that range from 1.5:1 to 3:1, which increases with age (Konieczny *et al.*, 2013). The largest number of all musculoskeletal deformity healthcare visits are from spine deformities in children and adolescents, where AIS is the most prevalent form of spinal deformity and makes up 80% of all pediatric scoliosis cases (Noshchenko *et al.*, 2015). AIS is patient-specific; thus, a wide variety of characteristics, severities and secondary effects increases the difficulty of determining a true cause of the spine deformity.

The aetiopathogenesis of AIS remains unclear and various demographic factors (i.e. ethnicity, sex, age, genetics and geographic location) influence the progression of the spine deformity (Burwell, 2003; Konieczny, 2013; Lowe *et al.*, 2000). Furthermore, many biological and biomechanical factors (i.e. the central nervous system, bone density, muscles, melatonin, and skeletal framework) are being explored as possible causes for AIS (Burwell, 2003). The multifactorial nature surrounding the cause of AIS limits the development of preventative treatments, leaving patients with only corrective options following a diagnosis.

Current treatment options for AIS are dependent on the severity of the spine deformity. Physiotherapy and bracing are used for curves of lesser magnitude to limit curve progression, whereas corrective surgery is used for curves of greater magnitude. Approximately 29,000 scoliosis-related surgeries are performed on adolescents in the United States every year to correct the deformity (Noshchenko *et al.*, 2015). High costs are associated with the surgical treatment of AIS and were estimated to be $1.1 billion dollars in 2012 in the United States (Vigneswaran *et al.*,

2015). Treatment type is also decided based on the location, shape and pattern of the curve, as well as the patient's future growth potential (*BMUS*, 2014).

Posterior spinal fusion and instrumentation (PSF) is the current gold standard surgical correction for those with AIS. However, potential negative side effects of this invasive surgery include: significant blood loss, post-operative pain, infection, pseudoarthrosis and degenerative disc disease (DDD) (Danielsson *et al.*, 2001; De la Garza Ramos *et al.*, 2016). Further, a large disadvantage of PSF is a reduction in spine range of motion (ROM), observed using motion capture techniques (Engsberg *et al.*, 2002; Wilk *et al.*, 2006). Novel surgical strategies are being developed as a result to lessen and/or eliminate these potential side-effects, such as vertebral body tethering (VBT). VBT is a minimally-invasive and fusionless surgical technique for AIS correction performed in skeletally immature patients (Courvoisier *et al.*, 2015; Samdani *et al.*, 2015). Although the acute and long-term effects of this surgery on spine ROM have yet to be explored, the theoretical advantage of VBT is the preservation of spine ROM due to its fusionless nature.

In order to assess the potential theoretical advantage of fusionless VBT surgery for AIS correction, this pilot work aimed to retrospectively compare spine ROM in the following adolescent populations: 1) those with no spine deformity; 2) those with an untreated diagnosis of AIS; 3) those having undergone PSF; and 4) those having undergone VBT. The primary objective was to compare spine ROM of the thoracic, lumbar, and total spine regions, while the secondary objective was to assess spine ROM at each IV level.

2.0 LITERATURE REVIEW

2.1 Adolescent Idiopathic Scoliosis

Scoliosis is a three-dimensional, laterally and axially rotated curvature of the spine (Weinstein *et al.*, 2008). Many forms of scoliosis exist; however, the diagnosis of idiopathic scoliosis is made when any neuromuscular or congenital causes of the deformity have been eliminated, signifying an unknown cause for the deformity (Konieczny *et al.*, 2013). Adolescent idiopathic scoliosis (AIS) is the most common type of scoliosis that affects 80% of scoliosis patients and develops in otherwise healthy children during puberty (i.e. between the ages of 9-18) (Asher & Burton, 2006).

Ponseti and Friedman (1950) classified AIS as one or two major curves in the cervical, thoracic, and/or lumbar regions; one major curve is the most prevalent making up 70% of all AIS cases. The most common curvature in AIS is a thoracic curvature with an apex towards the right (25% of cases), which is defined as a convex curvature with the apex between the T2 and T11 vertebrae (Machida *et al.*, 2018). A patient with a diagnosis of a main right thoracic AIS curvature can experience many anatomical changes in the trunk region including: chest wall asymmetry leading to rib prominence, elevation of the ipsilateral shoulder, thoracic translocation toward the convexity of the curve, and waistline asymmetry (Sud & Tsirikos, 2013). Many factors influence the onset of scoliosis resulting in a variety of different symptoms and severities, thus creating a patient-specific profile for each diagnosis.

In 2001, Lawrence Lenke developed and presented the Lenke classification system to assist doctors and surgeons to uniformly choose the best treatment option for each patient (Lenke *et al.*, 2001). The commonly used classification system defines curvatures by the curve type (there are six defined curve types), the lumbar modifier (the location of the vertical line going through the lumbar vertebrae) and the thoracic sagittal profile modifier (assesses thoracic kyphosis between

T5 and T12 vertebrae); however, this system fails to address the rotational aspect of the deformity (Ovadia, 2013). More recently, novel technologies such as the EOS imaging system, which provides coronal, sagittal and axial x-ray views of the spine, allow for spine reconstruction strategies to classify and assess the spine deformity in 3D (Illés *et al.*, 2011). Surgeons can now more precisely consult and agree on a surgical technique that would optimize patient treatment and post-operative quality of life.

2.2 Surgical Treatment

A growing understanding of the relationship between the heart, the chest wall, the lungs and the 3D changes of the spine has resulted in the evolution of treatment options for scoliosis (Hardesty *et al.*, 2018). These improved treatment options ensure deformity control, preservation of function, as well as improvements in psychological and quality of life aspects (Hasler, 2018). The careful consideration of all these variables using classification systems and novel technologies allows for patients to receive their optimal individualized care.

2.2.1 Posterior Spinal Fusion and Instrumentation

The current standard of care for the surgical treatment of AIS is posterior spinal fusion and instrumentation (PSF) (Padhye *et al.*, 2018). This surgical technique involves two parts: 1) spinal fusion, and 2) instrumentation. The former involves fusing two or more vertebrae using bone grafts and the latter utilizes various implants (e.g. plates, screws, hooks, rods, etc.) to stabilize, strengthen and maintain alignment of the spine while fusion occurs (Deniz Olgun & Yazici, 2013). PSF may be an effective treatment option to eliminate the spine deformity; however, many side-effects of this surgical technique exist.

PSF has some benefits compared to other corrective surgeries (i.e. preservation of pulmonary functions and allows the use of direct vertebral rotation), but it has been shown that the

execution of PSF may affect the posterior trunk musculature and the risk of infection is higher (Deniz Olgun & Yazici, 2013). PSF may also lead to low back pain and trunk rigidity, negatively impacting the patient's health-related quality of life as they age (Danielsson *et al.*, 2001; Fan *et al.,* 2016*)*. Further potential long-term complications of this technique include impaired spine function, strain on unfused vertebrae, pain and degenerative disc disease (DDD) (Danielsson, Romberg, & Nachemson, 2006). New techniques are being introduced in hopes of minimizing these long-term effects and, consequently, increase patient quality of life.

2.2.2 Vertebral Body Tethering

Vertebral body tethering (VBT) is a novel, fusionless and minimally invasive corrective surgical technique executed thoracoscopically. It was first used in humans in 2010 and involves inserting screws into the vertebrae that make up the concave curvature; this is done when the patient is skeletally immature, so that the growth of the spine results in progressive curve correction until skeletal maturity is achieved (Crawford & Lenke, 2010; Samdani *et al.*, 2015).

The surgery is theoretically based on the Hueter-Volkmann principle, which states that increasing mechanical compression of the growth plates inhibits growth rate, whereas tension (reduced loading) stimulates it (Lalande *et al.*, 2020; Villemure & Stokes, 2009). Vertebrae in humans grow both via longitudinal growth, generated by these growth plates adjacent to the discs, as well as in width by increasing the diameter of the vertebral body (Stokes, Aronsson, Dimock, Cortright, & Beck, 2006; Stokes, Spence, Aronsson, & Kilmer, 1996). During adolescence, the vertebrae are responsible for most of the growth of the spine and because sustained loading of these bones modulates their growth, a combination of disc and vertebral wedging will result in changes of its shape (Stokes & Aronsson, 2001; Stokes & Windisch, 2006). Figure 1 displays a qualitative explanation of the Hueter-Volkmann principle as it relates to scoliosis, where the

reduced compression on the concave of the curve in AIS stimulates growth, while the convex side is inhibited due to increased compression (Stokes, 2007). VBT aims to reverse the asymmetrical distribution of compression in the spine to stimulate longitudinal growth.

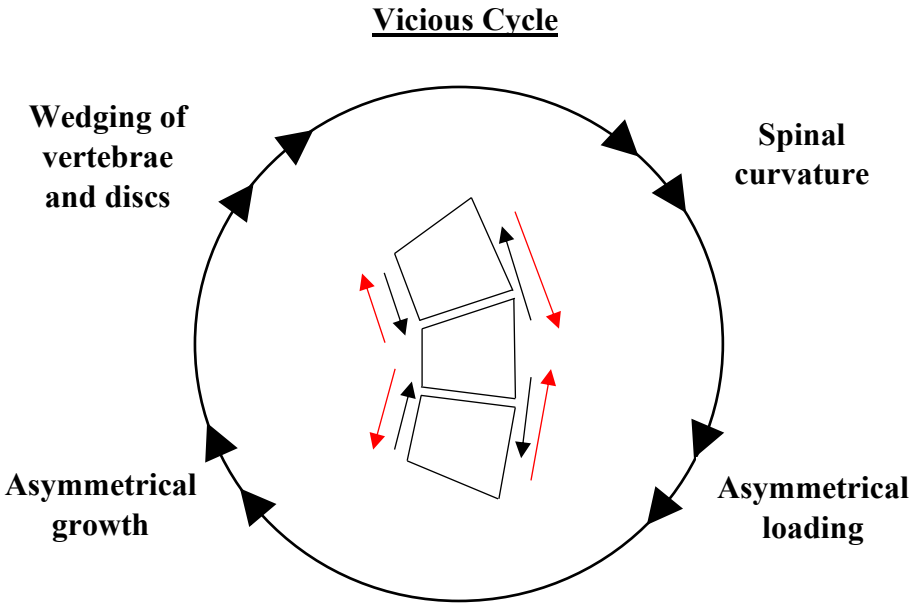

Figure 1. The qualitative explanation of adolescent scoliosis progression via biomechanical growth modulation represented by the black arrows (Hueter-Volkmann principle). Red arrows indicate the effect of VBT on spine growth using this modulation technique (adapted from Stokes, 2007).

Samdani *et al*. (2014) reported two-year results from an initial cohort of eleven patients who had undergone VBT; they found that there was an improvement in their thoracic prominences and the measure of their Cobb angles (a measure used to quantify the magnitude of a curve of the spine), with no infection, neurological or instrumentation-related complications. Current research investigating the effects of VBT on spine range of motion (ROM) is limited to computer simulation and animal models that suggest preservation of disc health and spine motion (Aubin *et al.*, 2018; Cobetto *et al.*, 2018; Newton *et al.*, 2008a).

2.3 Spine Range of Motion

Spine ROM is most commonly assessed by quantifying mobility of an individual during movements in the sagittal, coronal and transverse planes (flexion/extension, lateral bending and axial twist, respectively) (Kozanek *et al.*, 2009). This thesis focused on movements in the thoracic and lumbar regions of the spine and therefore, emphasis will be placed on these regions. The lumbar spine accounts for most of the movement during flexion, the thoracic and lumbar spine combine to account for most of the movement during lateral bending, and the thoracic spine accounts for most of the movement during axial twisting (Nordin & Frankel, 2001). Changes in these movement distribution patterns may arise from spine deformities, pathologies, and post-surgical outcomes; therefore, it is important to assess any potential changes in spine motion during movements in these planes.

ROM measurements are a standard clinical assessment during orthopaedic patient examinations, primarily used for radiographic classification systems and in pre-operative planning for the surgical treatment of scoliosis (Lea & Gerhardt, 1995; Lenke *et al.*, 2001). Radiographs of a patient's spine yield the most accurate vertebral ROM measures during movements of interest; however, concerns over the increased risk of lung cancer and breast cancer as a result of increased radiation exposure prevent the completion of such studies (Bone & Hsieh, 2000; Nash *et al.*, 1979). The concerns arise from the high number of radiographs taken of AIS patients and the increased sensitivity of the pediatric population towards radiation (Donaldson *et al*., 2007). Researchers and medical professionals have resorted to using safer methods to assess spine ROM in clinical populations like patients with AIS by using tools like goniometers, film digitization, optoelectronic motion analysis, as well as newer, low-dosage x-ray systems.

2.3.1 Normative Pediatrics

Assessing spine ROM of the adolescent population with no spine deformity or other existing pathologies is imperative to provide comparative data to accurately assess spine ROM in clinical populations. Pediatric research on normative spine ROM most often looks at the influence of age and sex on the cervical spine (Budelmann, Piekartz, & Hall, 2016; Lynch-Caris *et al.*, 2008; Seacrist *et al.*, 2012), with fewer to no studies concentrating on solely the lumbar and thoracic regions.

Early research investigating lumbar ROM using simpler methods (i.e. spondylometer, Schober bend test) found that lumbar ROM decreased with age, while sex-related differences were variable depending on the movement, where females often displayed greater ROM (Haley *et al.*, 1986; Taylor & Twomey, 1980). Similar results showing decreased lumbar ROM with increasing age were found using a greater variety of additional methods (i.e. inclinometer, kyphometer and BROM II) in children and adolescents (Kondratek *et al.*, 2007; Sullivan, Dicknison, & Troup, 1994; Widhe, 2001). Assessment of total spine ROM and thoracic ROM in asymptomatic children and adolescents is more prevalent in research comparing asymptomatic and clinical populations, which will be further investigated with patients diagnosed with AIS.

2.3.2 Adolescent Idiopathic Scoliosis

The characterization of spine function, specifically spine motion, is essential to fully understand the biomechanical changes caused by spine deformities such as AIS. Studies investigating thoracolumbar and total spine motion (in the sagittal and frontal planes) in patients with AIS compared to those without a spine deformity found either equal (Smidt *et al.*, 1994; Veldhuizen & Scholten, 1990) or decreased spine motion in patients with AIS. Poussa *et al.* (1989) compared thoracic and lumbar spine motion in healthy controls and patients with AIS in all three

planes and found reduced flexion and rotation in the thoracic spine. However, the studies mentioned above used a variety of outdated methods (i.e. tape measure techniques and inclinometers) to evaluate spine motion in participants with heterogeneous curve magnitudes and classifications, resulting in varying values across studies.

Galvis *et al.* (2016) used a magnetic sensor-based system to collect positional data at T1, T3, T6, T10, L1, L3, and S1 vertebrae during sagittal and frontal plane bending tasks in healthy controls and patients with AIS. The increased segmental detail of the model allowed Galvis and colleagues (2016) to observe that patients with AIS showed no significant difference in thoracic spine ROM in comparison to controls; however, increased spine ROM in the AIS group was noted in spine regions directly above and below the apex of the curve.

An optical marker system model used on patients with AIS was developed by Schmid *et al.* (2015) to quantify spine curvature in main thoracic AIS using reflective markers on the spinous processes of the C7, T3, T5, T7, T9, T11 and L1-L5 vertebrae. This marker model was not used to analyze the effect of AIS during spine movements in each of the movement planes. Instead, it was used during gait analysis of AIS and revealed that there was increased lateral deviation in the thoracolumbar/lumbar curvatures in the frontal plane and increased ROM in the sagittal plane, suggesting potential compensation during gait within the spine rather than in spatio-temporal parameters (Schmid *et al.*, 2016). These studies indicate that a comprehensive model assessing spine motion at more levels of the spine would be beneficial. Such a model would help determine the effect of the spine deformity, as well as potential surgical interventions and spine compensatory mechanisms at multiple spine levels during spine movements in patients with AIS.

2.3.3 Posterior Spinal Fusion and Instrumentation

The effect of PSF on spine mobility in AIS has also been explored. Kakar *et al.* (2018) investigated differences in asymptomatic adolescents and patients having undergone PSF during a stop-jump exercise. No significant differences in trunk motion patterns and jump height amplitudes were observed, but the fused trunk region of the PSF group moved in a more synchronous manner with the lower spine and pelvis in the frontal plane during the movement indicating lower ability to solely use the fused region for movement. Further, Holewijn *et al.* (2017) explored the effect of PSF on gait patterns pre- and post-operatively using the plug-in gait (Vicon, UK) model and showed that while thoracic-pelvic ROM was significantly lower at higher walking speeds, there were no other effects on spatio-temporal gait parameters. The plug-in gait model considers the spine to be a rigid segment and does not provide insight into potential changes at each spinal level in detail. This means that potential compensatory movement patterns in the spine at the level of the fused or unfused vertebrae, as observed by Schmid *et al.* (2016), were undetectable. These studies concentrate on post-operative spine movement during full-body dynamic tasks; however, they show the need for a comprehensive model to assess spine ROM during dynamic movements to better understand the effects of surgery on spine motion.

Preserving spine ROM following corrective surgery for AIS has become a great interest to surgeons resulting in recommendations to minimize the number of levels fused to allow for a larger distribution of functional motion across more levels of the unfused spine. Lee *et al.* (2013) found that patients with L3 as the lowest instrumented vertebrae (LIV) following PSF displayed greater loss of total spine ROM in the frontal and transverse planes compared to those with L1-L2 as their LIV, using one marker on C7 and another on the sacrum. It is suggested that there may be an overall decrease in spine motion following surgery and the remaining mobility is occurring in the

remaining segments following the distal end of the fusion (Engsberg *et al.*, 2002; 2003). Similar to the plug-in-gait model, this marker set does not allow for analysis of where along the spine the motion is being distributed. Engsberg *et al.* (2002) prospectively evaluated changes post-operatively at 12 and 24 months in spine ROM in patients with AIS following posterior, anterior, or combined anteroposterior spinal fusion with markers placed on the C7, T4, T7, T10, S2 vertebrae. Post-operative results indicated a reduction in total spine ROM in the sagittal, coronal and transverse planes, as well as in the unfused spine regions above and below the fusion (Engsberg *et al.*, 2002).

In a retrospective investigation using marker triads placed posteriorly at C7/T1 and T12/L1, as well as single markers on pelvic landmarks, Wilk *et al.* (2006) examined spine ROM during forward bending and right-left lateral bending in fused (with varying levels of fusion) and unfused AIS patients and healthy controls. They found no difference between healthy controls and the unfused group, while the fused group displayed an overall 25% loss of spine ROM across motion planes. Patients with a fusion extending into their lumbar spine exhibited less motion in the lumbar region than those with fusions solely in the thoracic region (Wilk *et al.*, 2006). Both Engsberg *et al.* (2002) and Wilk *et al.* (2006) contradicted predictions and found no compensation of motion at the unfused levels of the spine.

Despite previous research showing an evident loss in spine ROM during simple spine movements following PSF, this surgery will remain the standard of care for AIS correction until a safe, novel technique is presented with the proven ability to preserve spine motion, while successfully reducing or eliminating curve magnitude.

2.3.4 Vertebral Body Tethering

The effect of VBT on spine correction has been investigated via radiographic images of patients, as well as computer-simulated models. Currently, the effect of VBT on spine ROM in humans is unknown as no biomechanical studies have investigated this *in vivo*; only initial bovine/porcine models and radiographic images of this novel surgery merely suggest preserved spine motion.

Along with VBT, a few other fusionless techniques for curve correction (i.e. stainless-steel and shape memory alloy staples) have indicated the ability to reduce asymmetrical loading on vertebrae. These studies stress the importance of instrumentation parameters in fusionless surgeries (e.g. implant positioning, initial stress set by the device) for control of curve progression using computer simulated models and finite element modelling (Driscoll *et al.*, 2010, 2011; Lalonde *et al.*, 2008). Thus, Cobetto *et al*. (2018) used a personalized finite element model to assess the effects of cable tensioning and screw positioning on the tridimensional correction of VBT and suggested that adjustment to these parameters improves correction in frontal and sagittal planes, but not as much in the transverse plane. These models provide insight in progressing the design and knowledge surrounding VBT to improve treatment outcomes for patients by maintaining the anatomical integrity of the spine and consequently minimizing the existing disadvantages of PSF.

Newton *et al*. (2008a) first investigated the effect of an anterolateral tether by inducing the deformity in the coronal and sagittal planes (followed by removal of the tether) in the spine of an immature bovine model. Biomechanically, the tethered group showed greater spine stiffness and decreased range of motion compared to both the control group and the group where the tether was removed. Newton *et al.* (2008b) further investigated the same parameters in an immature porcine

model at 6-months and 12-months, where they found decreased ROM in flexion, extension, right lateral bending and particularly in left lateral bending away from the tether. While these studies create the spine deformity rather than correct it, they provide theoretical support that tethering can alter spine structure as a result of spinal growth in patients for scoliosis correction.

One recent study prospectively observed standard of care radiographic images from pre- and post-operative appointments of patients having undergone VBT, where it was observed that right side-bending analysis of post-operative radiographs displayed preservation of most of pre-operative curve flexibility (Wong *et al.*, 2019). This work is the only indication of preserved spine motion in humans having undergone VBT and solely concentrates on unidirectional movement in the frontal plane. More research is required to assess spine ROM in all planes in patients having undergone VBT, with detailed non-invasive methods to confirm its theoretical ability to preserve spine motion.

3.0 PURPOSE

This thesis is a pilot study being done prior to a larger, overarching project. The main goal of the overarching project is to characterize spine motion in pediatric patients with adolescent idiopathic scoliosis pre- and post-operatively to determine the impact of different surgical treatments on vertebral spine movements.

The purpose of this pilot work was to retrospectively compare adolescent spine ROM in i) those without spine deformity (Control), ii) those with untreated adolescent idiopathic scoliosis (AIS), iii) patients having undergone posterior spinal fusion and instrumentation (PSF) and iv) patients having undergone vertebral body tethering (VBT). The primary objective was to compare ROM of global regions of the spine (i.e. total, thoracic, and lumbar regions) during forward bending, right-left lateral bending, and right-left axial twist. The secondary objective was to compare intersegmental spine ROM (from C_7T_1 through to L_5S_1) during the same movements.

It was hypothesized that spine ROM at the total, thoracic, lumbar and intersegmental levels will be the same and/or interchangeable between the Control and AIS groups, who will display the greatest spine ROM at all levels (Galvis *et al.*, 2016; Mattson *et al.*, 1983; Poussa *et al.*, 1989; Veldhuizen & Scholten, 1990). Due to previously observed large decreases in spine ROM in all three planes of motion following PSF, it was hypothesized that the PSF group would display the least amount of spine ROM compared to all groups (Engsberg *et al.*, 2002; *Wilk et al.*, 2006). It was also hypothesized that the VBT group would show decreased spine motion in comparison to the Control and AIS groups; however, greater spine ROM in all regions and movement planes compared to the PSF group due to its fusionless approach. In summary, it was hypothesized that spine ROM will follow the following pattern for all regions and planes of movement: (ROM_{CTRL} = ROM_{AIS}) >* ROM_{VBT} >* ROM_{PSF}, where * indicates a significant difference.

4.0 METHODOLOGY

4.1 Ethics

Research ethics board approval was received from both the University of Ottawa (H-07-19-4773) and the Children's Hospital of Eastern Ontario (19/62X) prior to initiating recruitment.

4.2 Participants

Participants were recruited into four groups for this pilot study: 1) no diagnosis of AIS (Control), 2) patients with untreated AIS (AIS), 3) patients having undergone PSF (PSF) and 4) patients having undergone VBT (VBT). Participants in the Control group were recruited from the pre-adolescent and adolescent population in Ottawa via posters and word of mouth. Participants in the AIS, PSF and VBT groups were recruited from the pre-adolescent and adolescent population via posters and word of mouth from the Children's Hospital of Eastern Ontario (CHEO). General inclusion criteria for all four groups stated that participants must be between the ages of 8-18, were able to consent for participation and were able to follow instructions to perform the spine movements in a safe and controlled manner. Participants in the Control group must not have had a diagnosis of any form of AIS. Participants in the AIS group must have had a diagnosis of AIS with a main right thoracic curve of >40°. Participants in the PSF and VBT groups must have been post-operative selective right thoracic PSF patients or post-operative selective right thoracic VBT patients, respectively, that have been cleared by their surgeon to return to full activity.

Exclusion criteria for all groups included a diagnosis of neuromuscular, congenital, or syndromic scoliosis, major lumbar scoliosis, inability to follow instructions to perform the spine movements in a safe and controlled manner, inability to provide informed assent/consent, lower extremity or lumbosacral pathology that affects spine range of motion or gait, allergy to adhesives and underlying metabolic bone disease.

4.3 Study Design

All participants completed a screening questionnaire (Appendix A) and were only able to participate in the study once deemed eligible. Participants in the AIS, PSF and VBT groups that were deemed eligible had two visits. Visit 1 took place at CHEO for approximately 3 hours and included their routine clinical appointment. It included the collection of various demographic patient data (age, height, weight, etc.), as well as scoliosis characteristics from radiographs (skeletal maturity, curve pattern, flexibility, etc.). Patients were also asked by their operating surgeon to perform basic spine range of motion movements (i.e. forward bending, extension, side bending and rotation) as per routine clinical practice to ensure physiological ROM was possible without causing pain, discomfort, nerve impingement or any other injuries. Visit 2 took place at the University of Ottawa Spine and Movement Biomechanics Laboratory (E020, Lees Hall) for approximately 3 hours to complete the movement protocol. Participants in the Control group had only one visit where they completed the movement protocol at the University of Ottawa Spine and Movement Biomechanics Laboratory. The remainder of the protocol will describe Visit 2 in detail.

4.3.1 Assent and Consent

Before the data collection session began, participants read and signed the participant assent form (Appendix B) and a legal guardian signed the participant consent form (Appendix C), which clearly described the procedure, any possible risks and the purpose of the study. Assent and consent forms for the Control were identical; however, they omit the description of Visit 1 (CHEO appointment).

4.3.2 Questionnaires

All participants completed the 36-Item Short Form Survey (SF-36) and the Scoliosis Research Society Questionnaire (SRS-30) to quantify the participants' quality of life and spine

health, respectively. Further, the Physical Activity Questionnaire for Children (PAQ-C) or Physical Activity Questionnaire for Adolescents (PAQ-A) were completed depending on the participants' age to assess the participant's weekly levels of physical activity. Questionnaire results were not analyzed in this thesis.

4.3.3 Participant Preparation and Equipment

Participants were asked to change into a pair of spandex leggings and a backless shirt. After the participant changed, participant information (i.e. sex, age, height, and weight) was gathered by completing a Participant Demographic Form. Thoracic and thoracolumbar curvatures were also measured using a scoliometer (Baseline, USA) by the same researcher for all participants.

Participants were then outfitted with a lower-limb cluster-based model of reflective markers, with additional individual markers on the left and right acromion and head (Appendix D). An additional 57 reflective kinematic, disc-shaped markers (6.5 mm in diameter) were placed along the participant's spine in a grid-like manner to create the intersegmental spine model; the middle column was placed superficial to each spinous process of the C7-S1 vertebrae in standing, while left and right marker columns were placed 3-5 cm bilaterally of the centre column (Figure 2; Zwambag, Beaudette, Gregory, & Brown, 2018). Only the intersegmental spine model was analyzed in this work.

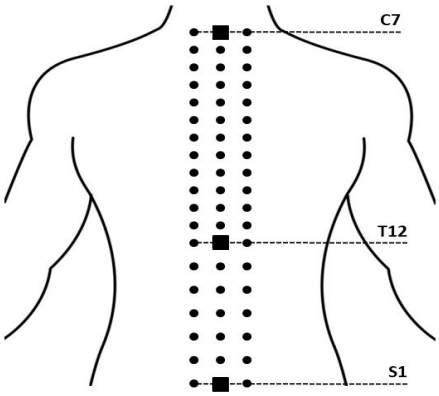

Figure 2. Marker placement for the 57-marker intersegmental spine model from C_7 to S_1 along with three inertial measurement units placed at C_7, T_{12} and S_1.

The three-dimensional (3D) location of each passive reflective marker was tracked using 11 infra-red motion capture cameras (Vicon, Oxford, UK) at a sampling rate of 120 Hz. The participant was standing facing forward with one foot on one of two side-by-side force plates (FP-4060, Bertec, USA), collected at a sampling rate of 1200 Hz. Inertial measurement unit (IMU) data were collected at the C_7, T_{12} and S_1 vertebrae using Mbientlab MetaMotionR IMUs (Figure 2; Mbientlab Inc., San Francisco, USA). IMU and force plate data were not analyzed in this work.

4.3.4 Movement Protocol

Once participants were instrumented with the experimental equipment, they executed a series of spine movement tasks. Participants were instructed to stop if they experienced pain, discomfort, or if they felt the potential for injury. Each movement was completed at a self-selected pace.

All participants practiced each movement prior to performing the testing trials. All participants were strapped into a custom apparatus that was used to constrain the pelvis during the session, similar to previous research aimed at isolating spine movement (Figure 3; Graham, Oikawa, & Ross, 2014; Granata & England, 2006). The apparatus was adjustable such that the height of the rigid segment was adjusted appropriately for each participant. A strap was placed across the front of the pelvis to limit translation of the pelvis in all directions while performing constrained movements. Skalli *et al.*, (2006) found increased post-operative pelvic ROM variation in patients following PSF surgery, thus constrained movements were investigated to minimize potential spine ROM differences caused by compensation at the level of the pelvis between operative and non-operative groups.

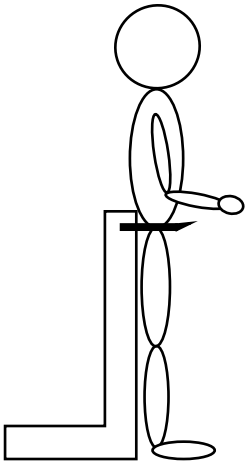

Figure 3. Diagram of the custom pelvis immobilization device used during the movement protocol.

Participants executed 2 sets of 1 repetition of the following movements while constrained at the pelvis: forward flexion, right-left lateral bending, and right-left axial twist. During forward flexion, participants maximally flexed their spine forward from a neutral standing position with their arms following the movement pattern by extending backwards; once they felt they achieved maximal spine flexion, they returned to their neutral standing position. During right-left lateral bending, participants maximally bent their spine towards the right from their neutral standing position with their arms crossed across their chest and returned to their neutral standing position for 3 seconds; the same was then executed on the left side. During right-left axial twist, participants maximally twisted their spine towards the right from their neutral standing position with their arms crossed across their chest and returned to their neutral standing position for 3 seconds; the same was then executed on the left side. More movements were completed during data collections; however, only constrained forward flexion, right-left lateral bending and right-left axial twist were analysed for the purpose of this thesis. The additional movement and their descriptions may be found in Appendix E.

4.4 Data Processing and Analysis

Raw marker trajectories of all movement trials from each participant were processed using a custom Matlab script (MathWorks, Natick, MA, USA) developed by Zwambag *et al.* (2018). The centre markers at C7, T12 and S1 were re-estimated using the spatial mean of the corresponding right and left side markers at each level due to the elevation of inertial measurement units (IMUs) at these levels. Data were filtered with a zero-lag, 4^{th} order, low-pass, Butterworth filter with a cut-off frequency of 6 Hz (Zwambag *et al.* 2018). Each trial was time-normalized to 500 frames to account for different movement speeds between trials and participants. To further investigate spine kinematics, local coordinate systems (LCSs) (aligned with the surface of each participants' back) were created for each spine level from C_7 through S_1 (Zwambag *et al.*, 2018).

Each column was fitted by the anteroposterior, mediolateral, and superior/inferior coordinate positions of each marker column with a 3D piecewise cubic polynomial (five knots and six segments) parameterized as a function of spine level to create splines consisting of 100 evenly spaced points. The minimum 3D Euclidean distance between each 3D raw spinous process marker and the middle spline was taken and was used to index the location of each vertebral segment along all three splines (left, middle and right); these three 3D splines, which consist of 300 3D points in total, were used to create orthonormal LCSs for each vertebral segment (Beaudette *et al.*, 2019; Zwambag *et al.*, 2018). The origin of each LCS was defined by evaluating the middle spline to find the position and orientation of each vertebrae. The superior/inferior (SI) vector of each LCS at each level was taken as the tangent of the middle spline. The anterior/posterior (AP) vectors were taken as the cross product of the SI vectors and an intermediate vector made by taking the difference between the left and right splines at each vertebral level; the AP vectors are thus perpendicular to the SI vectors and connect the left and right splines. The mediolateral (ML)

vectors were taken as the cross product of the SI and AP vectors and are thus perpendicular to the SI and AP vectors. Figure 3 displays the spatial reconstruction of this method. Constructing the LCSs lined up with the surface of the back as per Zwambag *et al*. (2018) has shown to yield similar relative intersegmental flexion ROM values as those from previous studies using radiographic data (Dvorák *et al.*, 1991; Morita *et al.*, 2014).

All 3D rotations (i.e. C_7T_1 through L_5S_1, thoracic and lumbar, and total spine) were computed using flexion-extension, lateral bend, and axial twist Cardan rotation sequences. 3D spine angles of each region were then evaluated: 1) 3D intersegmental angles were obtained by calculating the Cardan angles of C_7 relative to T_1 through to L_5 relative to S_1; 2) 3D thoracic and lumbar spine angles were obtained by calculating the Cardan angles of C_7 relative to T_{12} and T_{12} relative to S_1, respectively; 3) 3D total spine angles were obtained by calculating the Cardan angles of C_7 relative to S_1. This was executed for each trial of each participant.

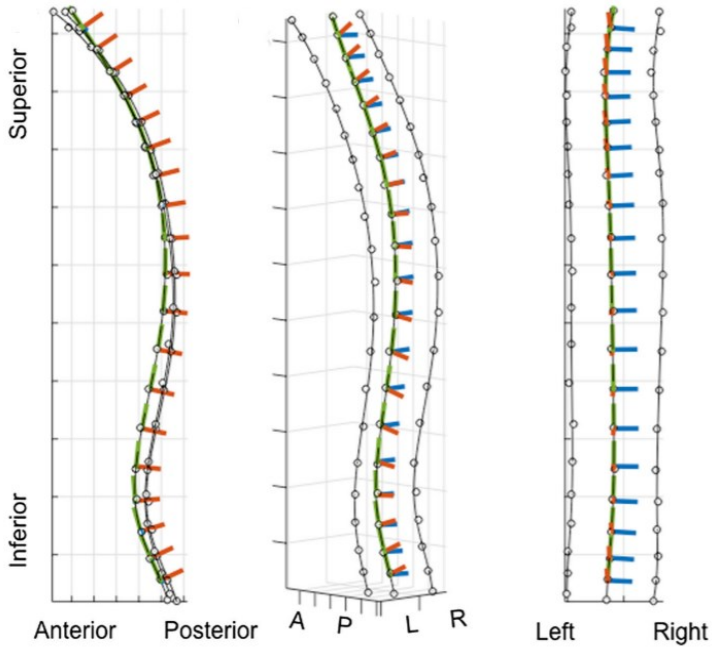

Figure 4. Spatial reconstruction of the intersegmental spine model in the sagittal view (left), posterolateral view (middle) and frontal view (right) during neutral standing (from Zwambag *et al.*, 2018). Green lines represent the superior/inferior vectors, red lines represent the antero-posterior vectors and blue lines represent the mediolateral vectors.

ROM for each movement was calculated by subtracting the maximum relative angle by the minimum relative angle of each group of participants for each intervertebral segment, as well as the thoracic, lumbar, and total spine regions. Right and left movements for axial twist and lateral bending were analyzed separately. Mean ROM of each participant was determined by calculating the mean from both of their trials. Group means were then found by averaging ROM across all participants in that group for each spine region during each movement.

4.5 Statistical Analysis

4.5.1 Global Angles

Fifteen one-way ANOVAs were utilized to determine spine ROM differences between groups of the different levels of the spine (total, thoracic and lumbar) during each movement (forward flexion, right lateral bending, left lateral bending, right axial twist and left axial twist). Dependent variables included global spine regions (thoracic, lumbar and total) during forward flexion, right-left lateral bending and right-left axial twist ROM data and independent variables included the four groups (Control, AIS, PSF and VBT). Prior to statistical analyses, Shapiro-Wilk tests were used to assess residuals for normality. All outlier values, assessed using boxplot analysis, were kept in the dataset. The Kruskal-Wallis H test was used where the assumption of normality violated the Shapiro-Wilk test ($p < 0.05$), and the Welch ANOVA was used where the assumption of homogeneity of variances violated the Levene's test ($p < 0.05$). A Tukey-Kramer *post hoc* was used to identify specific group interactions. Statistical analyses for global angles were performed in SPSS25 (IBM Corporation, USA) and significance level was set at $\alpha = 0.05$.

4.5.2 Intersegmental Angles

Spine ROM at each vertebral level (C_7T_1 through L_5S_1) was analyzed using a statistical parametric mapping (SPM) approach (Friston *et al.*, 2007). SPM accommodates large

spatiotemporal datasets and may be used to assess multiple observed variables across a large spatial or temporal domain. Dependent variables included spine (i.e. C_7T_1 through L_5S_1) forward flexion, right-left lateral bending and right-left axial twist ROM data and independent variables included the four groups (Control, AIS, PSF and VBT). SPM tests assessing parametric model residuals against a normal distribution were used to assess normality prior to analyses. All SPM tests displayed a normal distribution. All significant main effects were assessed using a SPM one-way ANOVA to evaluate specific group interactions between the four groups. Similar to Beaudette, Briar, Mavor, & Graham (2020), a scalar output statistic (i.e. SPM{F}) was calculated for each spine level spanning C_7T_1 through L_5S_1 which quantifies the difference between mean spine ROM values. The null hypothesis cannot be accepted nor rejected solely based on this value, therefore a critical threshold at which 5% of curves would be expected to surpass was calculated (Serrien, Goossens & Baeyens, 2019). A modified threshold was determined using a Bonferroni correction for all SPM post-hoc comparisons for each movement. Following the Bonferroni correction, all post-hoc comparisons were interpreted at an effective $\alpha = 0.0085$. The null hypothesis was rejected for all spine levels where the SPM{F} value surpasses the critical threshold (main effect), and further specific group differences (post hoc comparisons) were determined where curves surpass the modified threshold. All SPM analyses were performed using open-source spm1d code (v.0.0, www.spm1d.org) in Matlab2018b (The Mathworks, Natick MA, USA).

5.0 RESULTS

5.1 Demographics

Twenty adolescent (9 – 18 years of age) participants (1 male, 19 female) were recruited into four groups for this pilot study. Detailed demographics can be found in Table 1. Details on the time since operation and the operated levels can be found in Table 2. Further information (i.e. Cobb angles) of the AIS and operative groups may be found in Appendix F.

Table 1. Participant demographics.

Group	N	Height (cm)	Weight (kg)	Age (years)	Scoliometer (°)	
					Thoracic	Lumbar
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Control	6	167.8 (4.3)	58.3 (12.7)	15 (1.5)	0.6 (1.2)	1.3 (2.1)
AIS	5	148.6 (11.8)	40.2 (8.15)	11 (1.5)	14.2 (2.6)	7.4 (5.0)
PSF	4	163.2 (11.9)	69.6 (21.2)	16 (1.5)	7.5 (2.9)	2.0 (1.8)
VBT	5	164.9 (8.4)	55.4 (8.47)	14 (1.7)	5.3 (4.0)	2.7 (2.3)
Total	20	161.3 (11.5)	55.3 (15.76)	14 (2.4)	6.7 (5.9)	3.4 (3.9)

Note: SD = Standard deviation.

Table 2. Surgical group details.

Operative Group	Time between surgery and ROM testing in years (SD)	Vertebral Start Points	Vertebral End Points
VBT	1.5 (0.6)	T5-T6	T11-L1
PSF	2.7 (0.6)	T4	T12-L2

Note: SD = Standard deviation.

5.2 Global Angles

5.2.1 Forward Flexion

A main effect of group was observed in total spine ROM ($F = 3.489$, $p = 0.040$, $\eta^2 = 0.395$, $\beta = 0.666$; Figure 5) during forward flexion; however, the Tukey-Kramer post-hoc test displayed no significant difference between groups. No main effect of group was observed for the thoracic ($F = 2.952$, $p = 0.064$, $\eta^2 = 0.356$, $\beta = 0.586$) and lumbar ($F = 1.439$, $p = 0.269$, $\eta^2 = 0.212$, $\beta = 0.309$) regions during forward flexion (Figure 5).

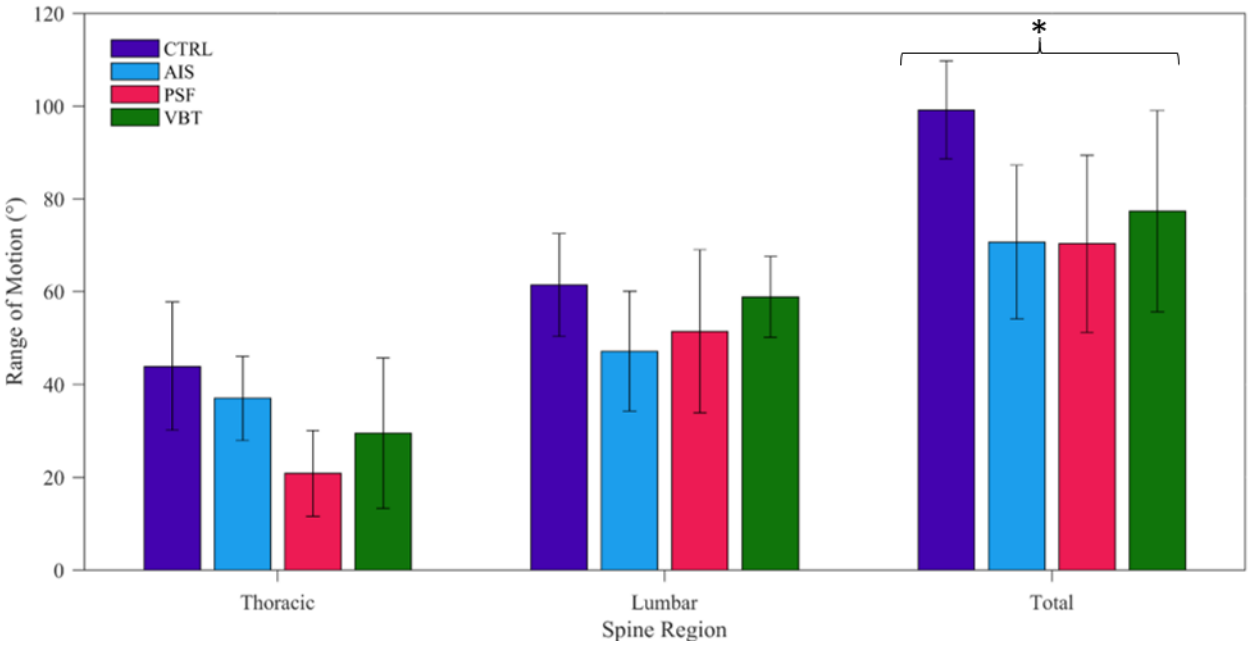

Figure 5. Mean range of motion of the Control (CTRL), Adolescent Idiopathic Scoliosis (AIS), Posterior Spinal Fusion (PSF) and Vertebral Body Tethering (VBT) groups in the thoracic, lumbar, and total spine regions during forward flexion. Asterisks indicate significant main effect in the spine region. Error bars indicate standard deviation.

5.2.2 Lateral Bending

5.2.2.1 Right Lateral Bending

The Welch ANOVA was used for any region that violated the Levene's test. A main effect of group was observed in thoracic ROM (Welch's $F = 16.62$, $p = 0.001$, $\eta^2 = 0.722$, $\beta = 0.999$; Figure 6) and total spine ROM ($F = 4.687$, $p = 0.016$, $\eta^2 = 0.468$, $\beta = 803$; Figure 6) during right lateral bending. More specifically, significant differences were noted between the following groups in the thoracic region: 1. Control (mean = 28.8°, SD = 4.60°) and PSF (mean = 9.86°, SD = 4.08°) where $p = 0.001$, 2. AIS (mean = 34.4°, SD = 9.04°) and PSF (mean = 9.86°, SD = 4.08°) where $p < 0.001$, and 3. AIS (mean = 34.4°, SD = 9.04°) and VBT (mean = 21.25°, SD = 5.01°) where $p = 0.016$. In the total spine region, a significant difference was observed between the AIS (mean = 46.1°, SD = 13.85°) and PSF (mean = 27.3°, SD = 5.63°) groups where $p = 0.030$. Data from the lumbar region violated the Shapiro-Wilk normality test, therefore the Kruskal-Wallis H test was used. No main effect of group was found in the lumbar ($\chi^2 = 6.658$, df = 3, $p = 0.084$, $\beta = 0.638$) region for right lateral bending (Figure 6).

5.2.2.2 Left Lateral Bending

A main effect of group was observed in thoracic spine ROM ($F = 16.59$, $p < 0.001$, $\eta^2 = 0.757$, $\beta = 1.000$; Figure 6) and total spine ROM ($F = 6.935$, $p = 0.003$, $\eta^2 = 0.565$, $\beta = 0.937$; Figure 6) during left lateral bending. More specifically, significant differences were noted between the following groups in the thoracic region: 1. Control (mean = 33.2°, SD = 3.40°) and PSF (mean = 12.51°, SD = 6.25°) where $p < 0.001$, 2. Control (mean = 33.2°, SD = 3.40°) and VBT (mean = 19.01°, SD = 6.36°) where $p = 0.001$, and 3. AIS (mean = 28.0°, SD = 3.98°) and PSF (mean = 12.51°, SD = 6.25°) where $p = 0.001$. In the total spine region, significant differences were observed between the following groups: 1. Control (mean = 48.9°, SD = 6.41°) and PSF (mean =

30.1°, SD = 10.85°) where $p = 0.012$, and 2. Control (mean = 48.9°, SD = 6.41°) and VBT (mean = 30.8°, SD = 7.76°) where $p = 0.010$. No main effect of group was found in the lumbar ($F = 3.179$, $p = 0.053$, $\eta^2 = 0.373$, $\beta = 0.621$; Figure 6) region for left lateral bending.

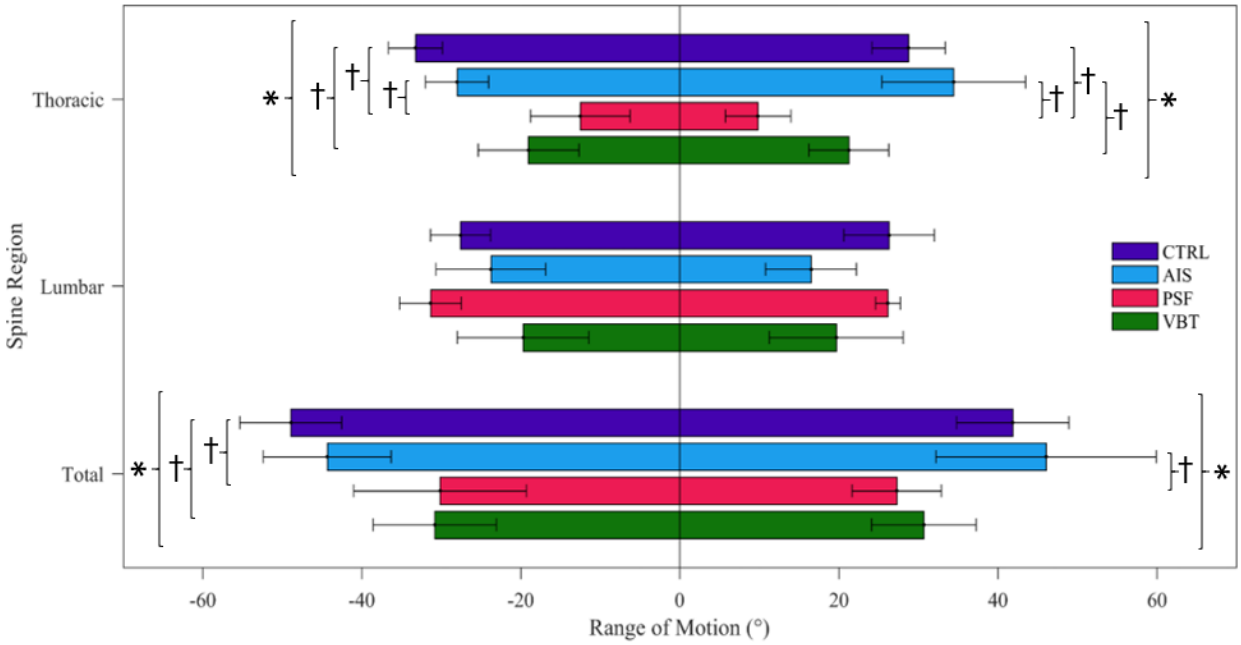

Figure 6. Mean range of motion of the Control (CTRL), Adolescent Idiopathic Scoliosis (AIS), Posterior Spinal Fusion (PSF) and Vertebral Body Tethering (VBT) groups in the thoracic, lumbar, and total spine regions during left (negative values) and right (positive values) lateral bending. Asterisks indicate significant main effect in the spine region. Daggers indicate statistically significant post hoc comparisons ($p < 0.05$). Error bars indicate standard deviation.

5.2.3 Axial Twist

5.2.3.1 Right Axial Twist

No main effect of group was found in the thoracic ($F = 2.091$, $p = 0.142$, $\eta^2 = 0.282$, $\beta = 0.435$; Figure 7), lumbar ($F = 0.592$, $p = 0.629$, $\eta^2 = 0.100$, $\beta = 0.146$; Figure 7) and total ($F = 2.416$, $p = 0.104$, $\eta^2 = 0.312$, $\beta = 0.495$; Figure 7) regions for right axial twist (Figure 7).

5.2.3.2 Left Axial Twist

The Welch ANOVA was used for any section that violated the Levene's test. A main effect of group in thoracic spine ROM (Welch's $F = 9.098$, $p = 0.005$, $\eta^2 = 0.401$, $\beta = 0.653$; Figure 7) and total spine ROM ($F = 3.932$, $p = 0.028$, $\eta^2 = 0.424$, $\beta = 0.723$; Figure 7) was noted during left axial twist. A significant difference was observed in the thoracic region between the AIS (mean = 29.4°, SD = 12.25°) and PSF (mean = 9.95°, SD = 3.01°) groups where $p = 0.023$. Further, significant differences were observed between the following groups in ROM of the total spine: 1. Control (mean = 41.4°, SD = 9.50°) and PSF (mean = 18.45°, SD = 4.00°) where $p = 0.028$ and 2. AIS (mean = 40.29°, SD = 13.79°) and PSF (mean = 18.45°, SD = 4.00°) where $p = 0.048$. No main effect of group was found in the lumbar ($F = 1.579$, $p = 0.233$, $\eta^2 = 0.228$, $\beta = 0.336$; Figure 7) region for left axial twist.

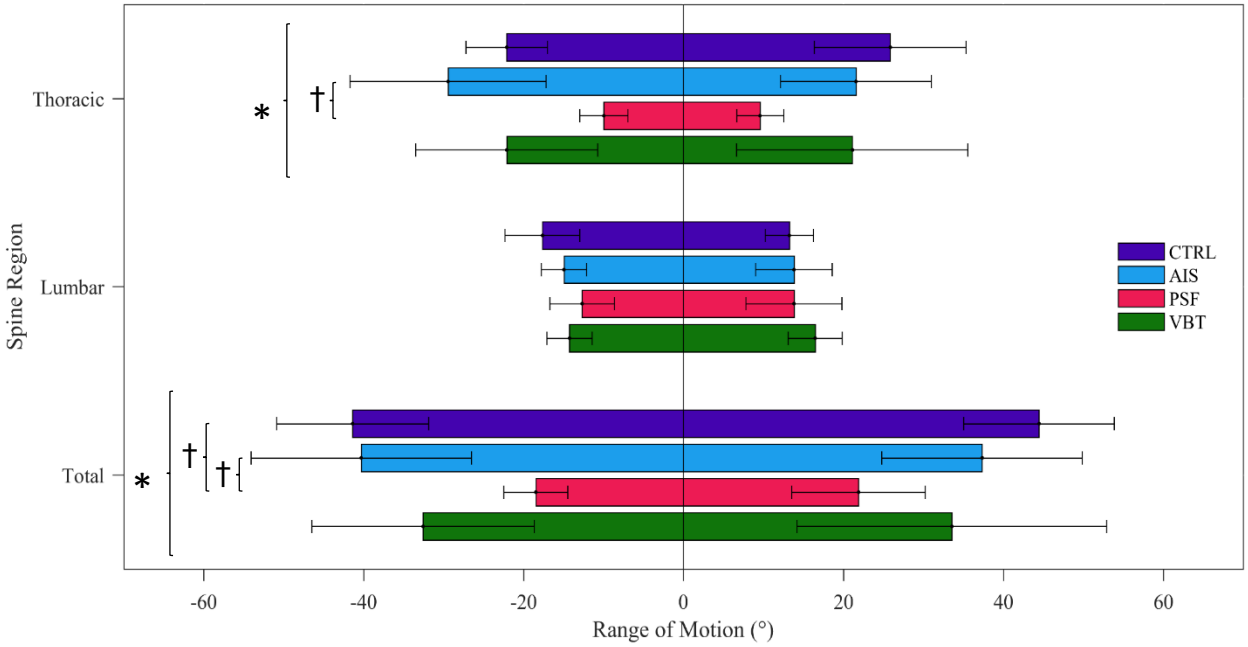

Figure 7. Mean range of motion of the Control (CTRL), Adolescent Idiopathic Scoliosis (AIS), Posterior Spinal Fusion (PSF) and Vertebral Body Tethering (VBT) groups in the thoracic, lumbar, and total spine regions during left (negative values) and right (positive values) axial twist. Asterisks indicate significant main effect in the spine region. Daggers indicate statistically significant post hoc comparisons ($p < 0.05$). Error bars indicate standard deviation.

5.3 Intersegmental Angles

5.3.1 Forward Bending

A significant main effect of group was observed during forward bending (L_1L_2, SPM{F} = 7.209, p = 0.0307) (Figure 8); however, the post-hoc test displayed no significant difference between groups (Figure 9).

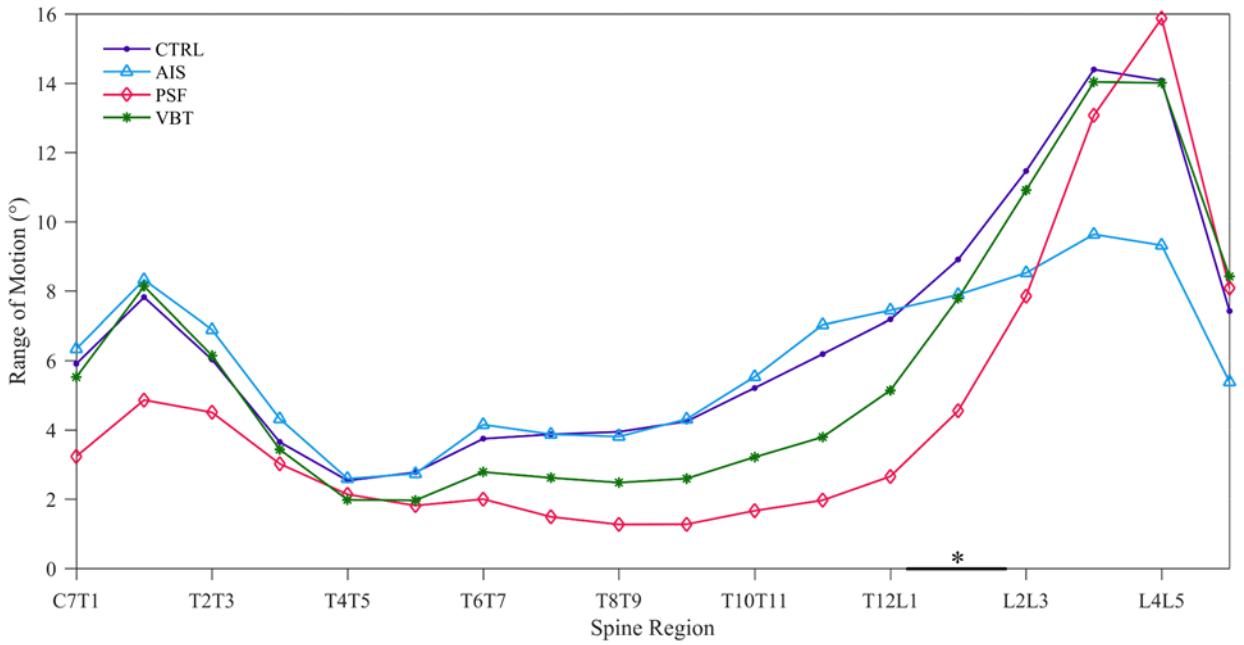

Figure 8. Mean intersegmental spine range of motion of the Control (CTRL), Adolescent Idiopathic Scoliosis (AIS), Posterior Spinal Fusion (PSF) and Vertebral Body Tethering (VBT) groups during forward bending. Bolded bands and asterisks along the x-axis indicate the location of significant main effects.

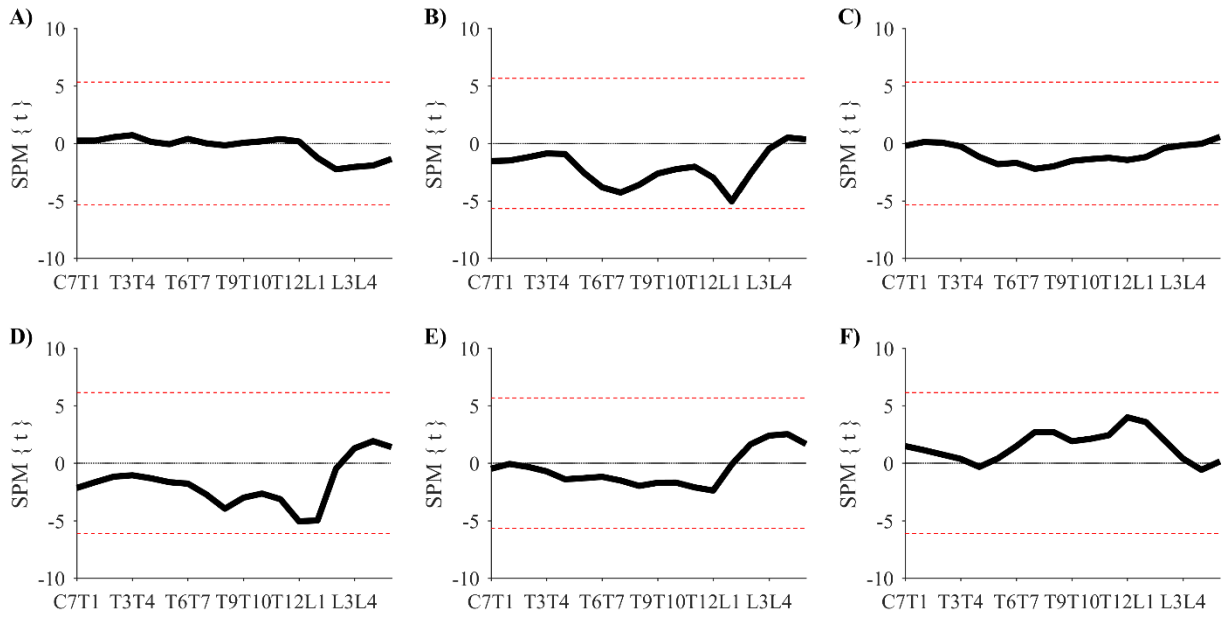

Figure 9. Post-hoc intersegmental spine SPM{t} values during forward bending. Comparisons include A) CTRL vs. AIS, B) CTRL vs. PSF, C) CTRL vs. VBT, D) AIS vs. PSF, E) AIS vs. VBT and F) PSF vs. VBT.

5.3.2 Lateral Bending

5.3.2.1 Right Lateral Bending

A significant main effect of group was observed during right lateral bending (T_5T_6-$T_{10}T_{11}$, SPM{F} = 6.7314, $p < 0.001$) (Figure 10). More specifically, post-hoc comparisons show a significant difference between the Control and PSF groups (T_5T_6-T_9T_{10}, SPM{t} = 5.665, $p < 0.001$) (Figure 11B).

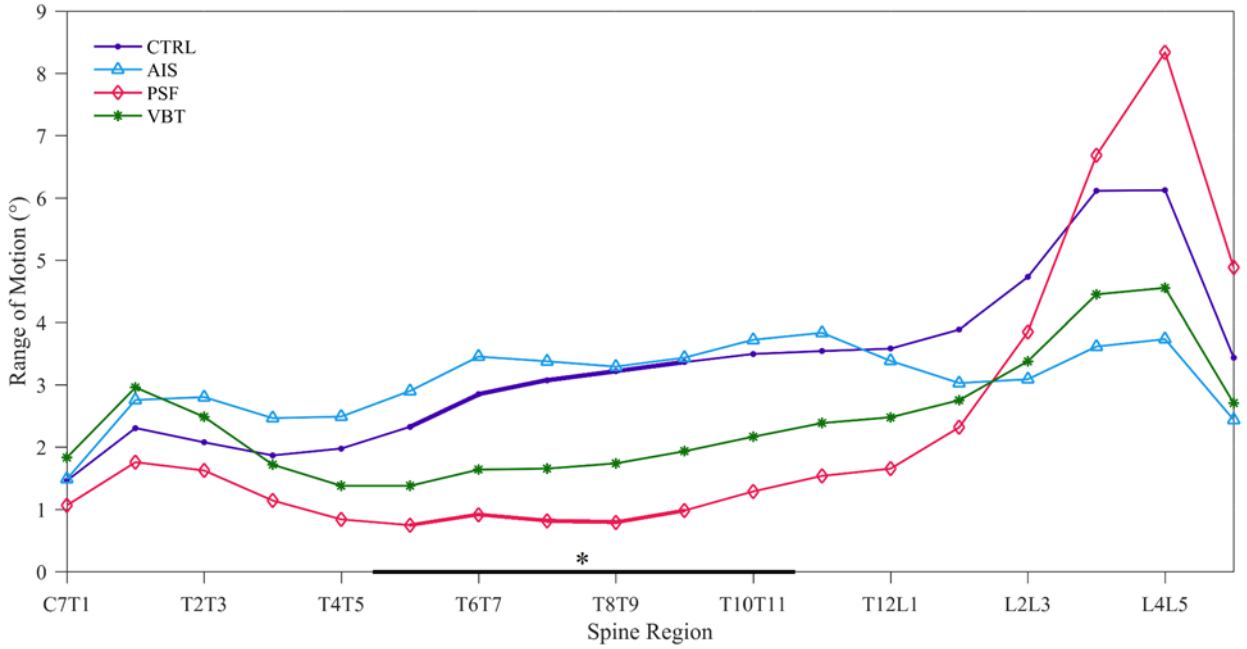

Figure 10. Mean intersegmental spine range of motion of the Control (CTRL), Adolescent Idiopathic Scoliosis (AIS), Posterior Spinal Fusion (PSF) and Vertebral Body Tethering (VBT) groups during right lateral bending. Bolded bands and asterisks along the x-axis indicate the location of significant main effects. Bolded line segments indicate regions and groups with statistically significant post hoc comparisons ($p < 0.0085$).

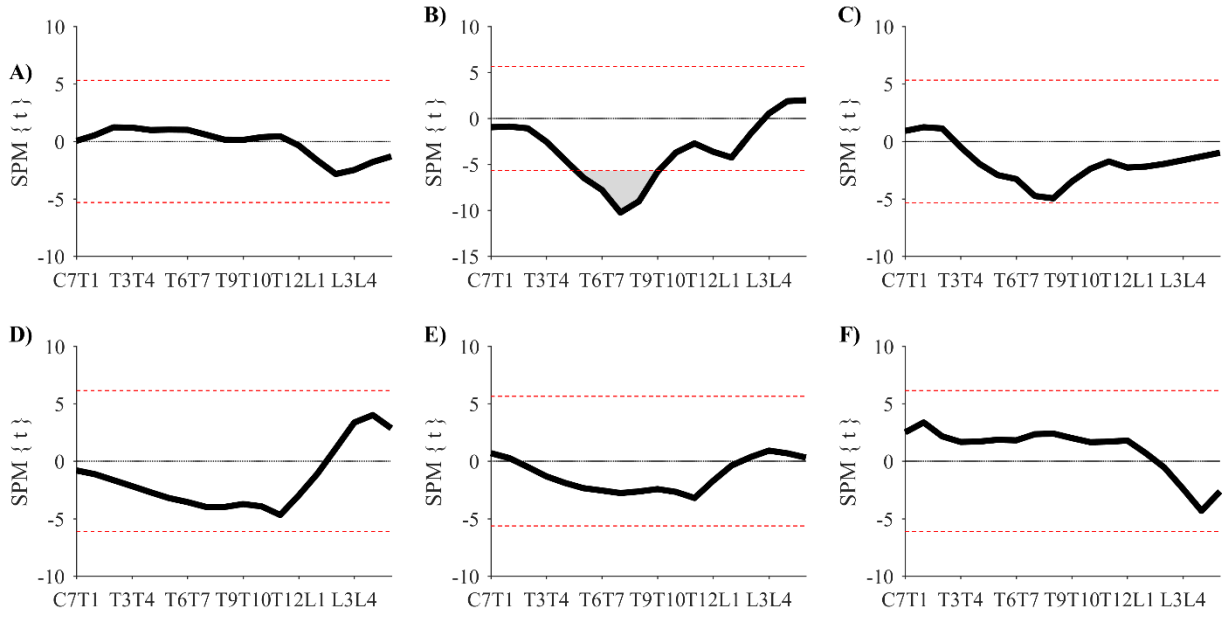

Figure 11. Post-hoc intersegmental spine SPM{t} values during right lateral bending. Comparisons include A) CTRL vs. AIS, B) CTRL vs. PSF, C) CTRL vs. VBT, D) AIS vs. PSF, E) AIS vs. VBT and F) PSF vs. VBT.

5.3.2.2 Left Lateral Bending

A significant main effect of group was observed during left lateral bending (T_4T_5-L_1L_2, SPM{F} = 7.047, $p < 0.001$; L_4L_5, SPM{F} = 7.047, $p = 0.0391$) (Figure 12). More specifically, post-hoc comparisons show a significant difference between the Control and PSF groups (T_5T_6-T_9T_{10}, SPM{t} = 5.665, $p < 0.001$) (Figure 13B) and the Control and VBT groups ($T_{12}L_1$, SPM{t} = 5.333, $p = 0.0052$) (Figure 13C).

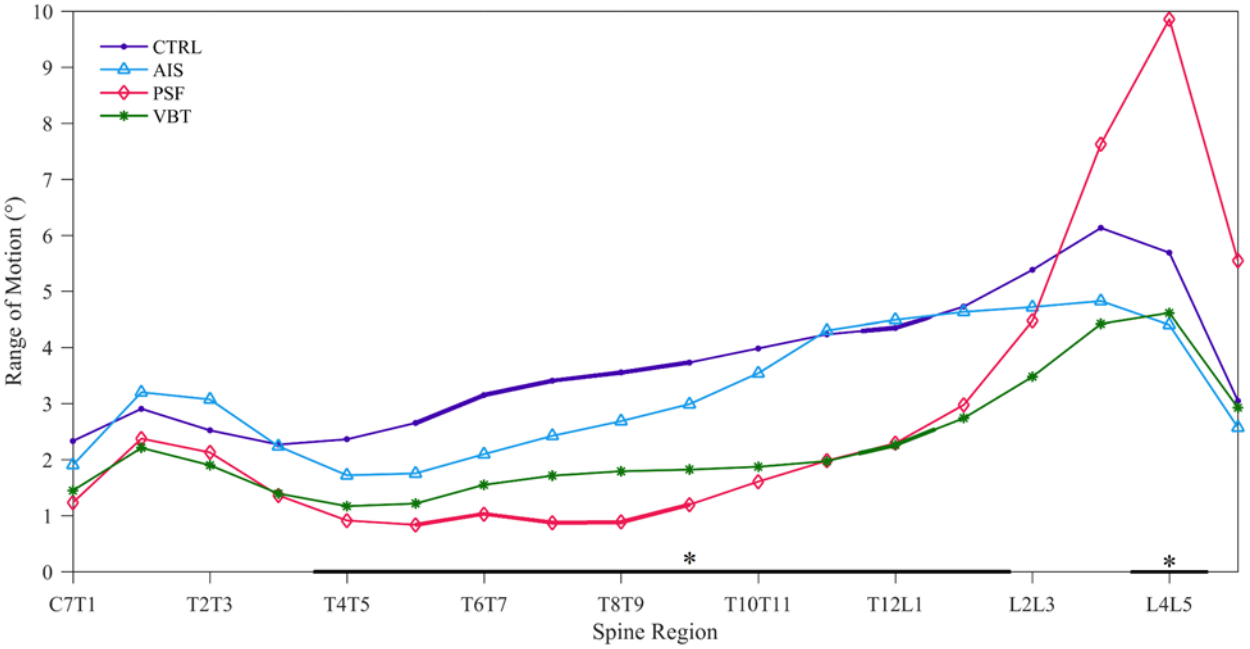

Figure 12. Mean intersegmental spine range of motion of the Control (CTRL), Adolescent Idiopathic Scoliosis (AIS), Posterior Spinal Fusion (PSF) and Vertebral Body Tethering (VBT) groups during left lateral bending. Bolded bands and asterisks along the x-axis indicate the location of significant main effects. Bolded line segments indicate regions and groups with statistically significant post-hoc comparisons ($p < 0.0085$).

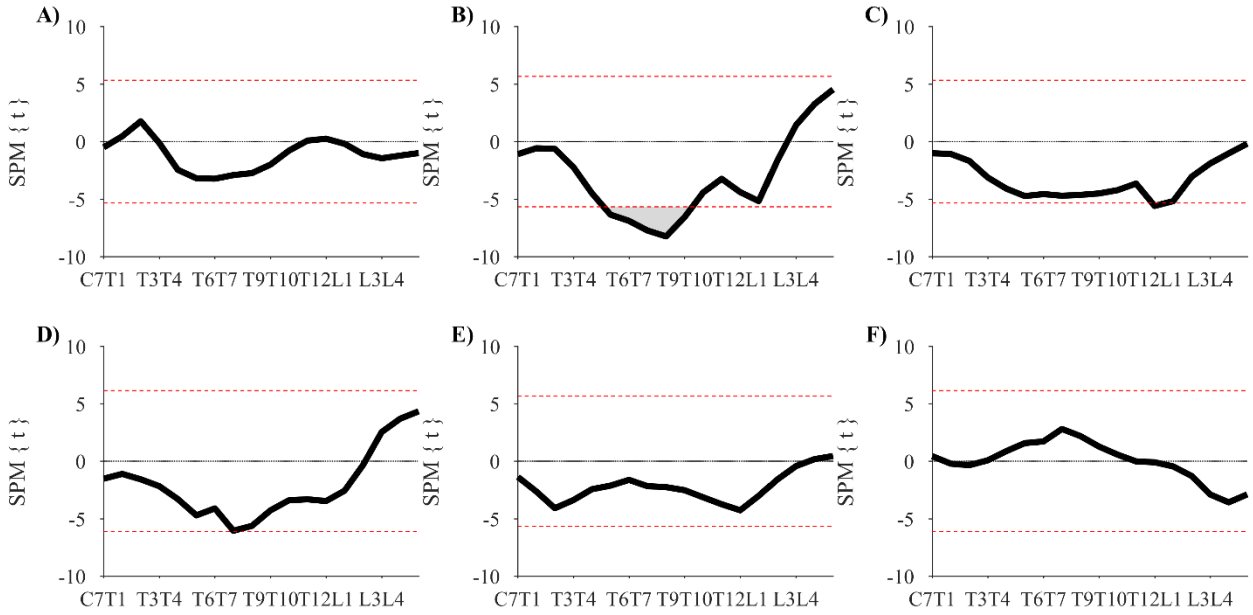

Figure 13. Post-hoc intersegmental spine SPM{t} values during left lateral bending. Comparisons include A) CTRL vs. AIS, B) CTRL vs. PSF, C) CTRL vs. VBT, D) AIS vs. PSF, E) AIS vs. VBT and F) PSF vs. VBT.

5.3.3 Axial Twist

5.3.3.1 Right Axial Twist

No main effect of group was observed at any intersegmental spine level during right axial twist (Figure 14).

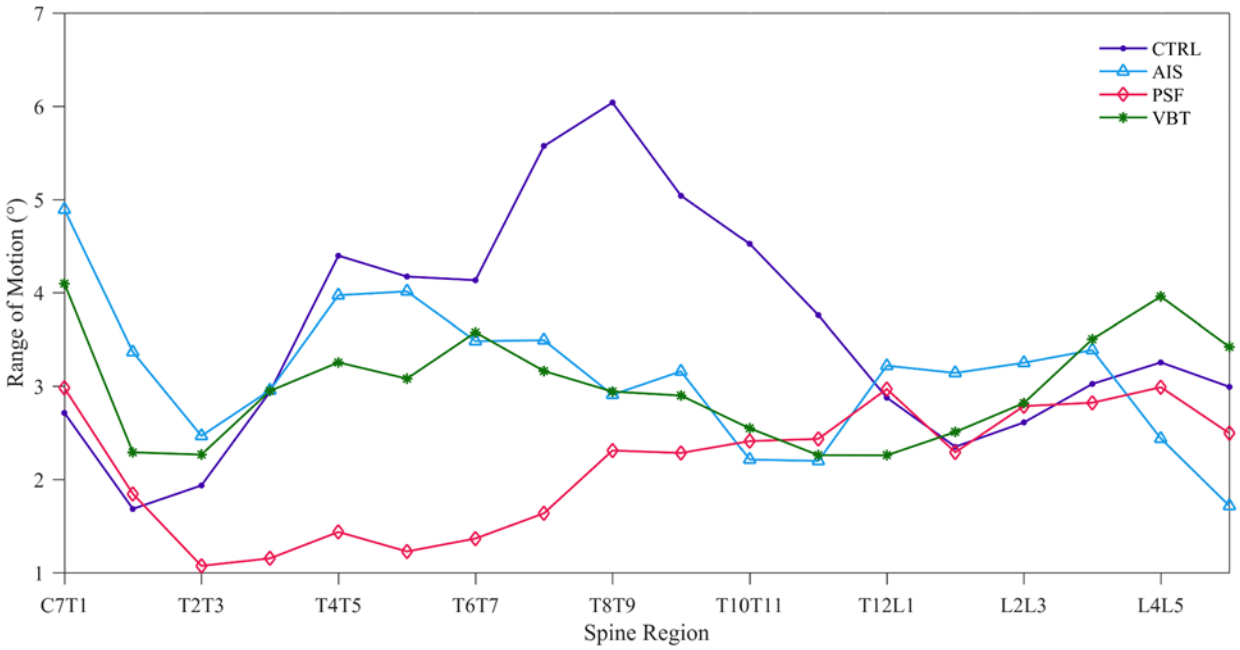

Figure 14. Mean intersegmental spine range of motion of the Control (CTRL), Adolescent Idiopathic Scoliosis (AIS), Posterior Spinal Fusion (PSF) and Vertebral Body Tethering (VBT) groups during right axial twist.

5.3.3.2 Left Axial Twist

A significant main effect of group was observed during left axial twist (T_7T_8, SPM{F} = 7.230, p = 0.0441) (Figure 15); however, the post-hoc test displayed no significant difference between groups (Figure 16).

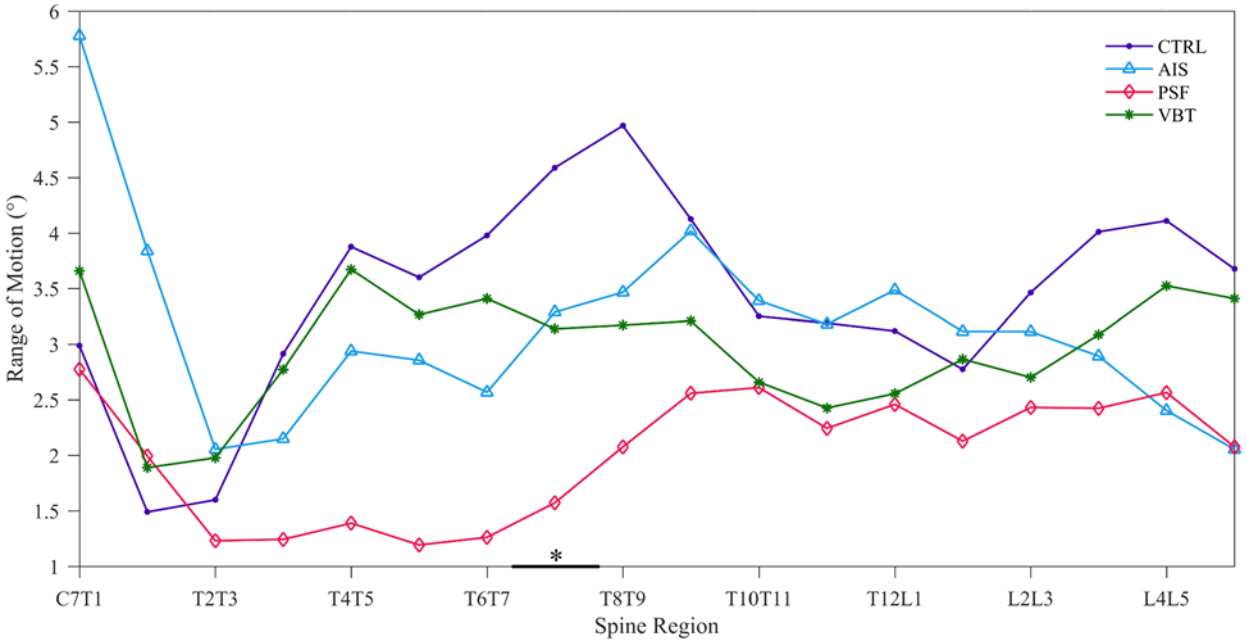

Figure 15. Mean intersegmental spine range of motion of the Control (CTRL), Adolescent Idiopathic Scoliosis (AIS), Posterior Spinal Fusion (PSF) and Vertebral Body Tethering (VBT) groups during left axial twist. Bolded bands and asterisks along the x-axis indicate the location of significant main effects.

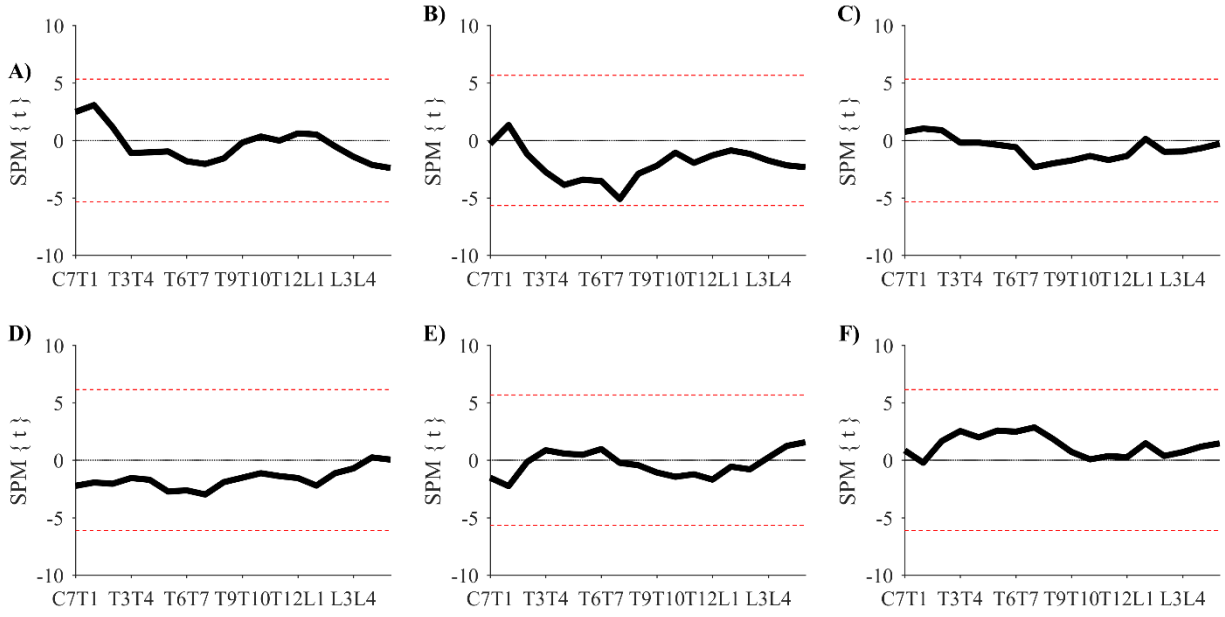

Figure 16. Post-hoc intersegmental spine SPM{t} values during left axial twist. Comparisons include A) CTRL vs. AIS, B) CTRL vs. PSF, C) CTRL vs. VBT, D) AIS vs. PSF, E) AIS vs. VBT and F) PSF vs. VBT.

6.0 DISCUSSION

The purpose of this pilot work was to retrospectively compare global and intersegmental spine ROM in adolescents without spine deformity, those with untreated AIS, patients having undergone PSF and patients having undergone VBT. Determining if differences exist between these groups provides insight on whether VBT, a novel approach to corrective AIS surgery, preserves spine motion compared to the current gold standard surgery: PSF. It was hypothesized that mean spine ROM in all global regions and at all intersegmental spine levels will display the following pattern during all movements: ($ROM_{CONTROL}$ = ROM_{AIS}) >* ROM_{VBT} >* ROM_{PSF}, where * indicates a significant difference.

The Control and AIS groups did not display any differences in spine ROM in any region during all movements. These findings reflect results by Galvis *et al.* (2016) and by Wilk *et al.* (2006) who also found no significant difference in mean spine ROM between the two groups, indicating that the spine curvature did not significantly inhibit spine motion in patients with AIS. As hypothesized, the surgical groups displayed the greatest differences when compared to the Control and AIS groups, indicating that both surgeries may cause a change in spine ROM.

The PSF groups displayed significantly lower spine ROM during right and left lateral bending compared to both the Control and AIS groups (Figure 6), which is indicative of loss of spine motion following this surgical corrective technique for AIS. All participants diagnosed with AIS in this study had a main right thoracic curvature, therefore surgical instrumentation of the VBT and PSF patients was placed primarily in the thoracic region. The thoracic region actively participates during lateral bending, thus any instrumentation in this region may have contributed to the lower movement in the operative groups during this movement. The lower thoracic spine ROM in the PSF group is similar to what has been reported in previous AIS and fusion literature:

significantly less thoracic spine motion in post-operative patients with thoracic fusions when compared to asymptomatic individuals and unfused patients (Wilk *et al.*, 2006; Engsberg *et al.*, 2002). Wilk *et al.* (2006) observed an average 20° thoracic ROM difference between their unfused and fused group during right and left lateral bending, which is what was also found in this work (20.5°). The trunk rigidity caused by removing intersegmental motion between multiple vertebrae via fusion most likely contributes to the repeatedly observed loss of spine motion in post-operative PSF patients (Danielsson, Romberg & Nachemson, 2006).

Similar to the PSF group, the VBT group displayed significantly lower thoracic spine ROM values compared to the AIS group during right lateral bending and less lateral bending compared to the Control group (Figure 6). Unfortunately, the effect of VBT on spine ROM in humans has yet to be explored; however, research by Newton *et al.* (2008a; 2008b) in bovine and porcine models showed increased spine stiffness, as well as decreased ROM during flexion and both right and left lateral bending after using a tether to induce scoliosis. The sudden change in growth patterns of the spine following VBT may cause spine stiffness, resulting from changes in vertebral morphology (as per the Hueter-Volkmann principle) and spine muscle distribution. Further, while the tether is more flexible than the rods and fusion implemented during PSF, the results suggest that VBT instrumentation may still cause some strain during lateral movement. Though not observed in this study, Newton *et al.* (2008a) observed particularly restricted movement during left lateral bending (moving away from the tether) in their tethered group compared to both their control and scoliosis groups. The small sample size and retrospective methodology may have prevented observing similar results while comparing the AIS and VBT groups during left lateral bending in this study. A prospective analysis of a larger group of patients that undergo VBT would have to be analyzed to make conclusive arguments.

Total spine ROM was significantly lower in the PSF group compared to the AIS group during right lateral bending and compared to the Control group during left lateral bending. The lower values of total spine ROM results reflect the findings of thoracic spine ROM during right and left lateral bending, indicating that regional changes as a result of surgical intervention will undoubtedly influence total spine changes in ROM. Engsberg *et al.* (2002) found an approximately 10-15° difference between pre-operative and post-operative PSF groups during lateral bending, whereas Wilk *et al.* (2006) found an approximately 30-40° difference between the controls/unfused groups compared to their fused groups. While ROM magnitudes vary between these studies and this work (which showed an approximate 20° difference between the controls/unfused group and the PSF group), the trend indicating loss of spine motion following PSF is consistent.

The VBT group also showed significantly lower total spine ROM values compared to the Control group during left lateral bending, whereas the AIS group did not indicate this difference. Further, the VBT and PSF groups displayed very similar values for total spine ROM during right and left lateral bending (Figure 6). While surgery seems to affect movement of the total spine most strongly in the frontal plane, other factors may contribute to this difference. It may be a result of inconsistency in a post-operative period and age in the surgical groups in this work, which is particularly important in the VBT group as participants may be at various stages in reaching skeletal maturity. It may also be due to the slightly higher lumbar spine ROM values of the PSF group observed during lateral bending (Figure 5), increasing total spine ROM values in the PSF group. VBT seems to most influence lateral bending based off results in this work; however, this needs to be explored further while minimizing confounding variables to decrease variability within groups.

Contrary to right and left lateral bending, the VBT group displayed greater average total spine ROM during both right and left axial twisting compared to the PSF group. Significant results were as hypothesized, where the Control and AIS groups had a significantly greater total spine ROM than the PSF group and the AIS group had significantly greater thoracic spine ROM than the PSF group during left axial twist (Figure 7). Reduced spine motion in the PSF group was anticipated as Engsberg *et al.* (2002) noted the same trend with 15-20° differences between pre- and post-operative PSF patients during spine rotation. The thoracic region accounts for most of the movement during axial twisting, thus any compensation of the unoperated levels of the lumbar spine would not heavily contribute to total spine ROM. These results suggest that fusion and steel rod instrumentation result in a greater loss of twisting ROM in the spine than does the instrumentation of a tether; this is in line with findings from Newton *et al.* (2008a) who found that tethers did not limit torsional motion in a bovine model after inducing scoliosis. More participants and a prospective study design are needed to make conclusive arguments; however, these results seem to show initial support for the theoretical preservation of spine motion in humans in the transverse plane of motion via VBT when compared to PSF at the total spine level.

Further detail of regional spine ROM changes between groups can be investigated at the intersegmental level of the spine; however, these results should be interpreted with caution due to the model, the small sample size and unequal group sizes substantially increases variability within groups at the vertebral level. The only significant differences noted in the intersegmental data are between the Control and PSF groups between T_5T_6 and T_9T_{10} during both right and left lateral bending (Figure 10 and Figure 12). These vertebral levels are very central to the PSF group's operated levels, indicating that there may be significant reduction in spine motion in the centre of the fused, rigid segment. The loss of movement capability of multiple vertebral segments in the

centre of the spine seems to limit spine motion in the operated region. However, more research is needed on intersegmental spine kinematics in adolescents and clinical adolescent populations to support these claims.

VBT has many known operative advantages compared to PSF including minimal trauma, discreet incisions, and a shorter recovery period (Courvoisier *et al.*, 2015; Samdani *et al.*, 2015). More research is needed to further support the predicted biomechanical advantage of VBT compared to other surgical corrective techniques. If VBT displays significant preservation of spine motion, results from such studies may help advance patient counselling in regarding VBT as a scoliosis surgery option. More research is also needed on determining and understanding any long-term effects of this surgery (i.e. pain, infection, DDD and instrumentation-related complications); if there are less implications in comparison to the known long-term effects of PSF, children should be screened and diagnosed as early as possible to ensure that VBT is a surgery option to optimize patient quality of life in the long-term.

Several limitations are present in this study. Zwambag *et al*. (2018) showed that there is substantial skin movement through re-digitizing the spinous processes in the lumbar and upper thoracic regions during flexion of the spine when creating this model. Therefore, the skin artefact associated with skin-mounted techniques, such as the one used in this thesis, unavoidably influenced the detection of intervertebral kinematics. Unfortunately, due to the nature of the two surgeries observed in this work, participants were not age-matched due to different skeletal maturity requirements for PSF and VBT, potentially introducing age-related differences in spine motion throughout puberty. Many confounding factors, including length of the deformity, number of operated levels in the surgical groups, start and end operated vertebrae and time post-operatively may have caused within group variability. Further, current post-hoc procedures in SPM analysis

are likely too simple; therefore, intersegmental results should be interpreted with caution as validity is not guaranteed (though results error are expected to be small). Finally, the small sample size and unequal group sizes undoubtedly influenced and limited statistical power among the results, particularly in such clinical analyses.

This pilot work should be followed by a longitudinal multi-point prospective study investigating spine range of motion in patients pre-operatively and post-operatively at specific time points across all groups. A larger sample should be used to better represent the population and the observed effect sizes presented in the results can be used in future prospective analyses to determine required sample sizes based on study design. Testing a larger population will minimize within-group variability and will allow for detailed assessment of the influence of surgical type on spine ROM, as well as the influence of potential covariates (i.e., age, skeletal maturity, sex, physical activity, etc.) on spine ROM. This will help in developing a comprehensive long-term understanding of the effect of AIS corrective surgeries on spine motion to increase patient treatment standards and overall patient quality of life.

7.0 CONCLUSION

This pilot work was the first to investigate spine ROM in the frontal, sagittal and transverse planes of patients having undergone VBT for the treatment of AIS. It was also the first to compare spine ROM in patients having undergone PSF, the current standard of care for AIS treatment, to spine motion in patients having had VBT as a treatment for AIS. The results of this work support previous findings presenting lower spine ROM in patients having undergone PSF compared to Controls and patients with untreated AIS during lateral bending and axial twist. The results also suggest that VBT patients display lower spine ROM compared to Controls and patients with untreated AIS during solely lateral bending, implying preservation of spine motion in the transverse plane following VBT. Future prospective investigation is necessary to show that VBT has the potential to improve patient quality of life, preserve spine motion and possibly reduce long-term complications associated with other corrective scoliosis surgeries.

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APPENDIX A

Study ID	

VBT Spinal Motion Study: Screening Case Report Form

Participant ID: _____ Screening Date: _____

INCLUSION CRITERIA

Yes **No** Participant age ranging from 8 and 18 years of age

Yes **No** Ability to consent for participation

Yes **No** Ability to comply with spinal range of motion movements

EXCLUSION CRITERIA

Yes **No** A diagnosis of neuromuscular, syndromic, congenital or syndromic scoliosis

Yes **No** Major lumbar scoliosis

Yes **No** Lower extremity or lumbosacral pathology that affect spinal ROM or gait

Yes **No** Underlying metabolic bone disease

Yes **No** Allergy or discomfort with adhesives on skin

Yes **No** Discomfort with exposing and palpation of the back (spinal region)

SPECIFIC GROUP CRITERIA – Specify which group to which the participant belongs and ensure all additional inclusion criteria are met (YES)

A) Control group

Yes ☐ **No** ☐ Healthy participant with no diagnosis of scoliosis

B) Non-surgical AIS

Yes ☐ **No** ☐ Diagnosis of AIS

Yes ☐ **No** ☐ Main thoracic scoliosis > 40 degrees treated without surgery

C) Posterior spinal instrumentation and fusion AIS

Yes ☐ **No** ☐ Diagnosis of AIS

Yes ☐ **No** ☐ Treated with thoracic posterior instrumentation and fusion

D) VBT AIS

Yes ☐ **No** ☐ Diagnosis of AIS

Yes ☐ **No** ☐ Treated with Vertebral Body Tethering

APPENDIX B

Assent Form

Protocol Title: **Is Spinal Motion Preserved Following Vertebral Body Tethering for Adolescent Idiopathic Scoliosis? A Pilot Study.**

Investigator: Dr. Kevin Smit, MD.

Co-Investigators: Dr. Andrew Tice, MD.; Dr. James Jarvis, MD.; Dr. Ryan Graham, PhD.; Shawn Beaudette, PhD.

Sponsor: Junior Faculty Research Grant, CHEO Department of Surgery Grant, CHEO RI Summer Studentship Grant

Address: CHEO, Department of Orthopedics,
401 Smyth Road, Ottawa, ON K1H 8L1

Telephone Number: (**613) 737-7600 Ext 2998**

Why is this study being done?
We would like to invite you to be part of a research study. Research is a way to test new ideas to see if we can do things better.

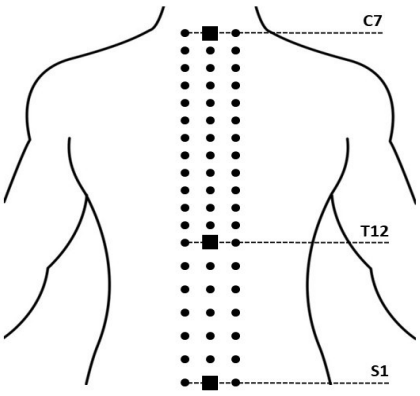
In our study, we want to compare spine movement in patients who have had surgery for scoliosis, who have scoliosis and have not yet had surgery, and patients without scoliosis.

Who will take part?
Children seen at CHEO for scoliosis are being asked to join this study. Also, children who do not have scoliosis will be asked to join this study. We expect to have 24 children, join the study over the next 6 months.
The study will include 4 different groups:

1. Healthy volunteers without scoliosis
2. Patients with Scoliosis who have not yet had surgery
3. Patients with Scoliosis that have had Spinal Fusion Surgery (PSF)
4. Patients with Scoliosis that have has Vertebral Body Tethering (VBT) Surgery

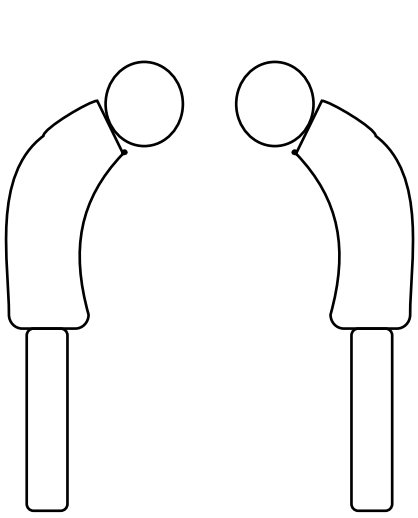
What will happen during the study?
You will have two visits during this study.

During **Visit 1**, you will go to the CHEO Orthopedic Clinic where we will collect information about you (such as how tall you are and how much you weigh). We will also collect information about your scoliosis and have you answer some questions about how you feel. Your doctor will make sure your spine moves in a safe and controlled way.



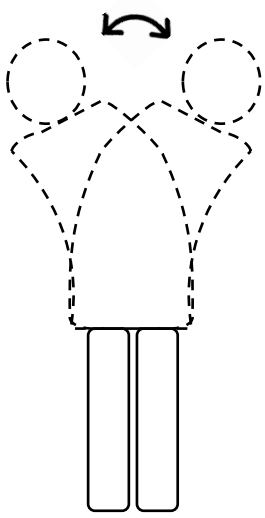
During **Visit 2**, you will visit a lab at the University of Ottawa where we will see how you move your back. This visit will be scheduled within 2-5 weeks of your first study visit. This visit will last about 2 hours. You will first answer a few questions about how active you are. Then, we will put little stickers on your back in the pattern that you see in the picture on the side. These stickers are shiny and can be seen by special cameras that will tell us where these stickers are. We will place more shiny markers on your feet, legs, hips and head. These cameras will not be taking any pictures of you, it will just capture the stickers. We will also put three sensors on your back where you can see the black squares in the picture on the side. These sensors are little machines that help tell us how your back moves as you do different movements.

You will do two sets of each of the movements shown below. In one set, you will be strapped in at the hips and the other you will not be strapped in at the hips. You will be asked to stop if any of the movements hurt or cause discomfort. In one set, we will ask you to do each movement two times.

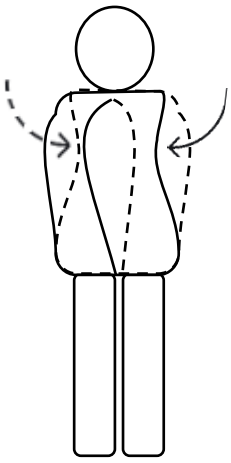


Forward Bending

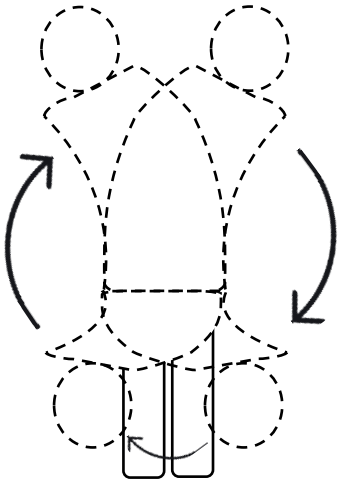
Backward Bending



Side Bending

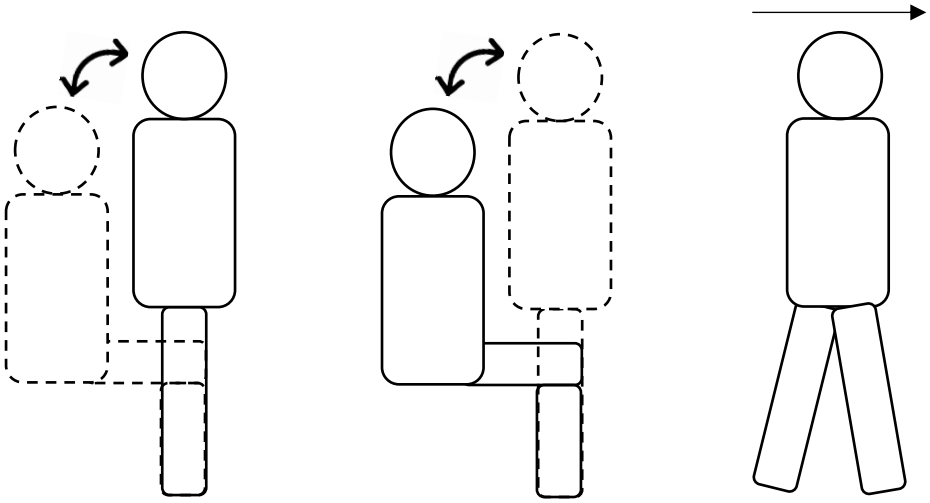


Side Twisting



Circumduction

You will sit down and stand up two times each. You will also walk in a straight line three times.



There is a movement you can choose to do, where you will bend forward and back 35 times without stopping. You do not have to do this part if you don't want to.

Are there good things that can happen from this study?

Sometimes good things can happen to people when they are in a study. These good things are called "benefits." This study will help us better understand children like you, who may have scoliosis. It will help us understand how you move and what the best surgery for correcting your scoliosis is, if you have it, to make sure that you can move and play without feeling uncomfortable. That is a benefit. There are no other benefits that we think will happen to you if you decide to join this study.

Are there bad things that can happen from this study?

There is a very small chance your back might hurt after doing the movements in this study. You will only be allowed to do these movements if your doctor says you can do them. There is also a chance you might get tired during one movement that you do without stopping. This is why you can choose to do this movement. If you do not want to, you do not have to.

Your skin might also get a little red because we will be putting small stickers and some tape on the skin of your back. We will make sure to wipe it after if there is some stickiness left!

What if something bad happens?

If something does go wrong, we will immediately contact your doctor to take care of you.

What if there is new information?
Sometimes during a study, we learn new information. We will talk to your doctors about any new information that might be important to you.

Is this private?
We will keep your information private whether you decide to join this study or not.

Will I be paid to participate?
We will give you volunteer hours towards your middle/high school diploma for your time and effort. If you decide to stop early, you will receive the amount of time (in hours) you have spent participating in the study up to the point of stopping.

Can I say no?
You can choose to be a part of this study or not. You can also decide to stop being in this study at any time once you start. Talk to your parents or your doctor if you want to stop being in the study, and they will tell the researchers. No one will be mad at you if you choose not to take part

What if I have questions?
Please ask us and we will do anything we can to answer your questions.

Assent form Signatures
If you agree to participate in this research study, please sign the form. I understand the information that was explained to me and I can ask any question that I like about the study.

Signature of Participant	Name of Participant	Date

Printed Name of Person Who Conducted Assent Discussion	Signature of Person Who Conducted Assent Discussion	Date

APPENDIX C

Information and consent form

Protocol Title: **Is Spinal Motion Preserved Following Vertebral Body Tethering for Adolescent Idiopathic Scoliosis? A Pilot Study.**

Investigator: Dr. Kevin Smit, MD.

Co-Investigators: Dr. Andrew Tice, MD.; Dr. James Jarvis, MD.; Dr. Ryan Graham, PhD.; Shawn Beaudette PhD.

Sponsor: Junior Faculty Research Grant, CHEO Department of Surgery Grant, CHEO RI Summer Studentship Grant

Address: CHEO, Department of Orthopedics,
401 Smyth Road, Ottawa, ON K1H 8L1

Telephone Number: (**613) 737-7600 Ext 2998**

For more simplicity, the word "you", when used in this form, means "your child".

You are being invited to join in a research study about spine motion following corrective surgery for adolescent idiopathic scoliosis (AIS). You are being invited to join this study because you have or will be having surgery at the Children's Hospital of Eastern Ontario (CHEO) for AIS correction. Before agreeing to take part in this study, it is important that you read and understand this document.

Taking part in this study is voluntary. Your decision to participate, or not participate in this study will not affect the care you receive at CHEO. You are free to withdraw from the study at any time and there will be no penalty to you.

Why is this study being done?
The purpose of this study is to compare spine movement in patients having had vertebral body tethering (VBT) and compare their motion to patient without scoliosis, with pre-operative untreated scoliosis and patients having posterior spinal fusion (PSF). The study will recruit participants into the following groups:

1. Control (no scoliosis) – healthy volunteers
2. Scoliosis (pre-operative) - patients with untreated AIS undergoing PSF or VBT
3. Posterior Spinal Instrument and Fusion (PSF) - having undergone posterior spinal fusion and instrumentation (PSF) for AIS correction
4. Vertebral Body Tethering (VBT) - having undergone vertebral body tethering for AIS correction

This research will help doctors and researchers understand the how different surgical techniques for AIS correction affect spine movement.

How many people will participate?
We expect to have 24 people participate, with 6 patients in each of the four groups recruited from CHEO and the community for the non-scoliosis participants. The study is expected to be recruiting for 6 months.

What will I have to do?
A summarized version (presented in a table) may be found in the appendix.

Visit 1: *Demographic and Medical Data Collection*
This visit will take place at the CHEO Orthopedic Clinic where various demographic data (age, skeletal maturity, etc.) will be collected, as well as scoliosis characteristics (curve pattern, Cobb angle, flexibility, etc.) and other questionnaires. This visit will follow regular standard of care for patients being treated for AIS. The only additional thing being asked of you is to fill-out the questionnaires during your clinic visit. You will be cleared by your doctor to make sure you can safely complete the appropriate spine motion exercises before visit 2.

Visit 2: *Biomechanical Testing*
This visit will take place at the University of Ottawa Spine Biomechanics Laboratory located at E260G – 200 Lees Avenue. This visit will be scheduled within 2-5 weeks of Visit 1 based on your availability. A physical activity questionnaire (PAQ-C or PAQ-A) will be administered prior to the biomechanical testing component (~20 min.).

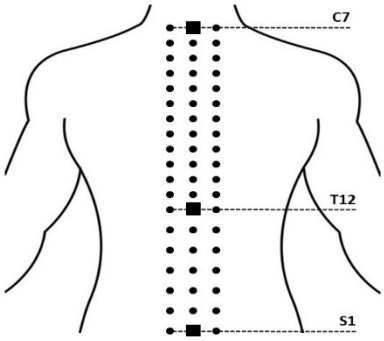
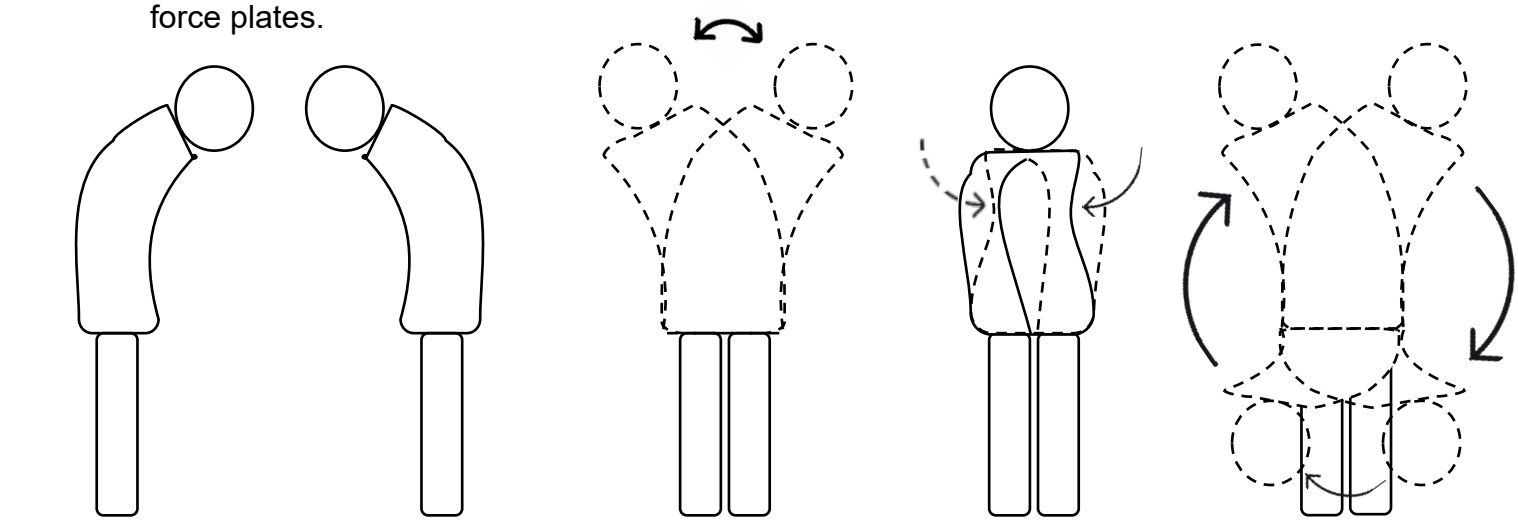


Figure 1. Sensor placement layout. Circles represent the reflective sticker sensors. Squares represent each inertial measurement unit.

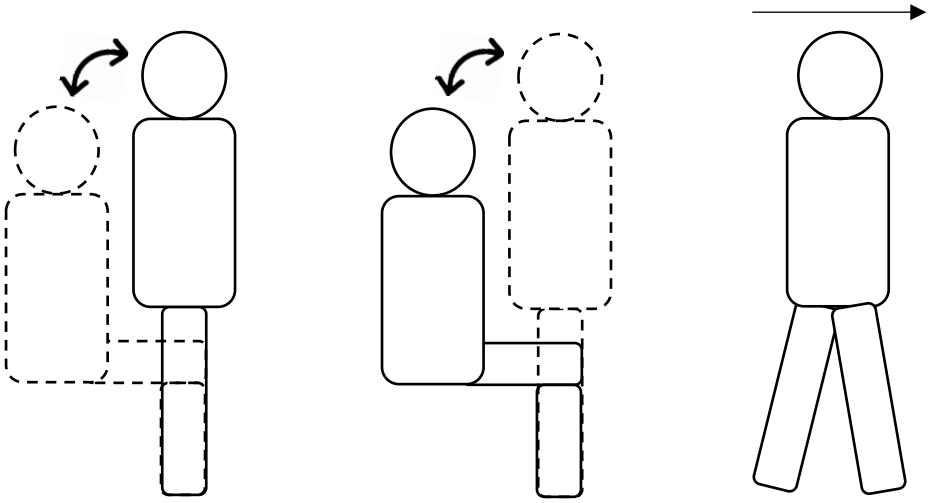
The procedures will include performing various movements involving your back (similar to how you move your back in everyday life). You will be asked to stop these motions if you experience any pain, discomfort or feel like you may get injured. Sticker sensors will be affixed with adhesive along the exposed skin of your back, from the bottom of your neck to the bottom of your waist in a grid-like pattern (Figure 1). Additional reflective markers will be placed on your feet, legs, pelvis and head. Motion capture equipment will be used to track the location of these sensors during movements (this equipment will not be taking any pictures, but simply track where the sensors are in space). Three small sensors capturing back movement, called inertial measurement units, will be placed at three levels of the spine to measure your back position. The setup will take approximately 30 minutes.

The following movements will be completed in sets of two repetitions under a constrained (strapped in at the hips) and unconstrained condition while standing on two force plates.



Forward Bending | Backward Bending | Side Bending | Side Twisting | Circumduction

Two repetitions of stand-to-sit transition and sit-to-stand transition will be completed with each foot on a force plate. Three repetitions of walking in a straight line will be completed.



Stand-to-Sit Transition | Sit-to-Stand Transition | Walking

There is an optional movement that may be completed where you will bend forward continuously 35 times without stopping. This depends on your comfort level with this movement and is therefore up to you if you would like to complete this movement. You do not have to do these motions if you feel tired or are not comfortable proceeding.

Walking

Stand-to-Sit Transition

Sit-to-Stand Transition

Are there any risks to participating?

Physical Risks:

Back movements including your full range of motion may pose a small risk of injury to the spine, so these movements can only be completed once you have been cleared by a medical doctor. Also, you may become tired during the optional repetitive forward bending task, which is why you may choose to not complete this task.

You may be at risk of developing skin irritation or itchiness/redness as a result of skin adhesives for the sensors placed on the back. You will be excluded from this study if you have a history of sensitive skin. You will have your back cleaned using rubbing alcohol to remove leftover adhesives from the skin.

Are there any benefits to participating?
If you decide to participate, you may or may not benefit from participating in this study; however, we hope to take better care of patients in the future with the results from this study.

Will I be paid to participate?
We will provide you with some compensation in the form of volunteer hours towards your middle/high school diploma in recognition of your time and effort. If you withdraw, you will receive the amount of time (in hours) you have spent participating in the study up to the point of withdrawing.

Can I Withdraw?
You can withdraw from the study at any time without any impact to your current or future care at CHEO. Please discuss with your investigator if you would like to withdraw. If you withdraw your consent, the investigator will no longer collect, and disclose your health information for the purpose of this study. Information that was already collected may still be used by the Investigator if provided consent by the participant.

What if I get injured?
In the event that you or your child suffers injury as a direct result of participating in this study, normal legal rules on compensation will apply. Medical care will be provided to you or your child. By signing this consent form you are in no way waiving your legal rights or releasing the investigator from their legal and professional responsibilities.

Will I be told about new information?
We will inform you of any new information that might change your decision to continue to participate in this research project. We will ask you again if you still want to be in the study.

You can receive a copy of the study results at the end of the study. We can also provide a patient summary report if you are interested. Please let the study team know if you would like to receive a copy.

What about confidentiality and privacy?
Your personal information will be kept strictly confidential except as required or permitted by law. Any information that would indicate that a child was being harmed or at risk of such harm, would not be kept confidential and instead be disclosed as appropriate to the appropriate authorities.

For this study we will be collecting these personal identifiers: name, gender, and date of birth, email address for the research purposes described in this consent form. Your personal identifiers will be kept in a document that links this information with a study ID, called a master list. The study ID will be used in all of the research documents instead of your personal identifiers to protect your privacy. The master list will be stored separately from the research data. It will be password protected and stored in a secure location at CHEO with access restricted to the research team.

Representatives from the CHEO research Ethics Board and a quality reviewer from CHEO research institute may look at your records at the site where these records are held, to check that the study is following the proper laws and guidelines.

The research data produced from this study will be stored on a CHEO RedCap database. Only members of the research team and the individuals described above will have access to the data. Following completion of the study the research data and master list will be kept for 7 years after the last publication of this study. They will then be destroyed. You will not be identified in any publication or presentation of this study. This study is taking place at multiple sites which means the research data will be shared outside of the hospital. Representatives from The University of Ottawa Biomechanics Lab will receive research data including your study ID, name, gender and date of birth for data analysis and/or quality assurance. Any other personal information about you that leaves the hospital will be coded with a study ID so that you cannot be identified by name. This is called de-identified data. The de-identified research data will inputed into a secure RedCap database with access to the research team from CHEO and The University of Ottawa Biomechancs lab. A copy of the signed consent form will be provided to you.

Is the research team benefiting from the study?
We have received funding for a medical student, master's student and research coordinator to contribute to running this study. The PI and any other team members are not benefiting from this study personally, financially or any other way.

What if I have questions?
If you have any questions concerning participation in this study, or if at any time feel that you have experienced a study-related injury or reaction to the study medication contact: Dr. Kevin Smit 613- 737-7600 Ext.2998

This study has been reviewed and approved by the CHEO Research Ethics Board. The CHEO Research Ethics Board is a committee of the hospital that includes individuals from different professional backgrounds. The Board reviews all human research that takes place at the hospital. Its goal is to ensure the safety of people taking part in research. The Board's work is not meant to replace a parent or child's decisions and choices that are best for them. You may contact the Research Ethics Board, for information regarding a patient's rights in research studies at (613) 737-7600 (3272), although this person cannot provide any health-related information about the study.

Consent form Signatures

By signing this consent form I agree that:

- I am voluntarily agreeing to participate in this research study;
- I understand the information within this consent form;
- All of the risks and benefits of participation have been explained to me;
- All of my questions have been answered;
- I allow access to my medical records and/or personal information as described in this consent form; and
- I do not give up my legal rights by signing this form.

A copy of the signed Information Sheet and/or Consent Form will be provided to me.

I agree to the secondary use of my data to answer future related research questions:
☐ Yes ☐ No

Signatures

_____	_____	_____
Signature of Participant/ Substitute Decision-Maker	PRINTED NAME	Date

If consent is provided by Substitute Decision Maker: _____ PRINTED NAME of Participant

_____	_____	_____
Printed Name of Person Who Conducted Consent Discussion	Signature of Person Who Conducted Consent Discussion	Date

Use this section if a translator or impartial witness is required.

If the consent discussion has been conducted in a language other than English, and an impartial qualified translator is required.

Table 1. Data collected during Visit 1 and Visit 2 of the study protocol.

	Visit 1 (CHEO)	Visit 2 (University of Ottawa)
Assent/Consent	X	
Relevant Medical History and Physical Exam*	X	
Height and Weight	X	X
Neurological Assessment*	X	
Concomitant Medication Review*	X	
Scoliometer	X	
SRS-30	X	
SF-36	X	
PAQ-C/PAQ-A		X
Standing PA &Lateral X-ray C7-S1*	X	
Supine Lateral Bend* (PA X-ray)	X	
Risser Staging* (on Standing PA X-ray)	X	
Surgical Details (if applicable)	X	
Adverse event review and evaluation	X	
Professional Services/Brace Use* (if applicable)	X	
Biomechanical Testing		X
* The control group will not undergo these assessments, as this is not part of our routine clinical care.		

Printed Name of Translator	Translator Signature	Date

The “Signature of the Witness” line is intended for an impartial witness which is necessary when either the subject or the subject’s legally authorized representative (LAR) speaks and understands English, but cannot read and write or is visually impaired

Printed Witness Name	Signature of Witness	Date

APPENDIX D

Table E1. Calibration and tracking marker placement during movement protocol.

Calibration Marker Placement	
Head	Front right
	Front left
	Back right
	Back left
Trunk	Right Acromion
	Left Acromion
	Left, centre and right C7
	Left, centre and right T1
	Left, centre and right T2
	Left, centre and right T3
	Left, centre and right T4
	Left, centre and right T5
	Left, centre and right T6
	Left, centre and right T7
	Left, centre and right T8
	Left, centre and right T9
	Left, centre and right T10
	Left, centre and right T11
	Left, centre and right T12
	Left, centre and right L1
	Left, centre and right L2
	Left, centre and right L3
	Left, centre and right L4
	Left, centre and right L5
Sacrum	Left, centre and right S1
	Centre S2
Pelvis	Left ASIS
	Right ASIS
	Left Iliac Crest
	Right Iliac Crest
Thigh (Bilateral)	Greater Trochanter
	Lateral Femur Epicondyle
	Medial Femur Epicondyle
	Cluster: Middle; lateral side
Shank (Bilateral)	Cluster: Middle; lateral side
Foot (Bilateral)	Lateral Malleolus
	Medial Malleolus
	1st Metatarsophalangeal Joint
	5th Metatarsophalangeal Joint
	Calcaneus

Tracking Marker Placement	
Head	Front right
	Front left
	Back right
	Back left
Trunk	Right Acromion
	Left Acromion
	Left, centre and right C7
	Left, centre and right T1
	Left, centre and right T2
	Left, centre and right T3
	Left, centre and right T4
	Left, centre and right T5
	Left, centre and right T6
	Left, centre and right T7
	Left, centre and right T8
	Left, centre and right T9
	Left, centre and right T10
	Left, centre and right T11
	Left, centre and right T12
	Left, centre and right L1
	Left, centre and right L2
	Left, centre and right L3
	Left, centre and right L4
	Left, centre and right L5
Sacrum	Left, centre and right S1
	Centre S2
Thigh (Bilateral)	Cluster: Middle; lateral side
Shank (Bilateral)	Cluster: Middle; lateral side
Foot (Bilateral)	Lateral Malleolus
	Medial Malleolus
	1st Metatarsophalangeal Joint
	5th Metatarsophalangeal Joint
	Calcaneus

APPENDIX E

Forward flexion, right-left lateral bending, right-left axial twist and the following two movements were all done in both a constrained and unconstrained (without the pelvis immobilizer) condition. Two sets of one repetition were completed.

Spine Circumduction: Participants will be asked to complete a compound clockwise and counter clockwise circumduction movement of the spine with their arms crossed against their chest. During this movement, participants will trace the path of an imaginary circle with their heads while bending, flexing, and twisting their spine. The movement will be completed at a self-selected pace.

Backward Bending: Participants will be asked to bend their spine backwards as far as they are comfortable with their arms crossed over their chest. The movement will be completed at a self-selected pace and only IMU data will be collected during this movement.

Two sets of one repetition were completed of the following movements:

Sit-to-Stand Transition: Participants will start in their natural neutral sitting posture and will transition to their neutral standing posture. Participants will be instructed to avoid pushing off their legs with the arms during this movement. The movement will be completed at a self-selected pace.

Stand-to-Sit Transition: Participants will start in their natural neutral standing posture and will transition to their neutral sitting posture. Participants will be instructed to avoid bracing their arms against their legs during this movement. The movement will be completed at a self-selected pace.

Three repetitions were completed of the following movement:

Gait: Participants will be asked to walk in a straight line for approximately 8 metres from an indicated starting point in a natural manner to an indicated finishing point. The walk will be completed at a self-selected pace.

As this task is more fatiguing than the other tasks, participants were given the option to complete this additional trial:

Repeated Forward Bending (Optional): During this trial you will be strapped to a rigid support at the waist and will be asked to bend your spine forward and backwards to touch targets placed at shoulder and knee height. A total of 35 spine flexion-extension movements will be repeated as one single continuous trial, paced using an auditory metronome such that each individual flexion-extension cycle is completed over the course of 4 seconds.

APPENDIX F

Table F1. Cobb angle measurements (°) based on radiographic images of patients in the AIS, PSF and VBT groups.

Participant #	Cobb Angle (°)
AIS Group	
1	50.0
2	50.0
3	59.0
4	57.0
5	N/A
Mean (SD)	54.0 (4.69)
PSF Group	
1	24.0
2	14.0
3	20.0
4	12.0
Mean (SD)	17.5 (5.5)
VBT Group	
1	33.0
2	40.0
3	23.0
4	10.0
5	16.0
Mean (SD)	24.4 (12.2)

Note: SD = standard deviation.