The Reliability and In-exercise Reduction of Frontal and Rotational Ultrasound Measurements for Adolescents with Idiopathic Scoliosis Performing Scoliosis-specific Exercises

by

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A Thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science
in
Rehabilitation Science

Faculty of Rehabilitation Medicine,
University of Alberta

ABSTRACT

Adolescent Idiopathic Scoliosis (AIS) is a spine deformity of unknown cause characterized by abnormal lateral curvature (Cobb angle>10°) with vertebral rotation. AIS affects 2-3% of all adolescents whom are likely to progress during their growth spurt preceding skeletal maturity.

The Scoliosis Research Society (SRS) has recognized that physiotherapeutic scoliosis-specific exercises (PSSE) may benefit individuals with AIS. These benefits include slowing curve progression and improved pain management, self-image, strength, and endurance. However, how these PSSEs achieve their effects and which instructions provide the best spinal corrections are still unknown. Skepticism from stakeholders exist about the feasibility of these complex exercises achieving clinically meaningful corrections without compensation.

A novel 3D ultrasound (US) imaging protocol can non-invasively quantify spinal alignment which allows investigation of the immediate effects of PSSE in an ethical manner. This could lead to improved exercise instruction and identifying which exercises offer the best corrections for patients. Recently, it was found that immediate in-brace correction is predictive of treatment success and identifying the immediate amount of correction achieved in PSSE is necessary to study if this may also be true for PSSE treatment outcomes. Lastly, apical vertebral translation (AVT), has long been a neglected measurement in PSSE research even though it is an important surgical decision-making measurement for AIS.

This project used US imaging to quantify the immediate effects of Schroth PSSE on the thoracic and lumbar curve angle, axial vertebral rotation (AVR), and AVT measurements in 16 different positions. The intra- and inter-evaluator reliability of these US measurements were also determined.

In a single session, 16 different positions, comprised of four habitual positions and their passive and active Schroth corrections, were imaged using 3D US imaging. Thirty-six volunteers were recruited after having completed three or more months of Schroth exercise. Selection criteria were: females aged 10 to 18 years old with AIS, with or without a brace, a Cobb angle of 10° to 45° for both a lumbar, and a thoracic, or thoraco-lumbar curve, and no prior surgery.

Custom MATLAB software was used to measure each scan. Images were analyzed using the center of lamina (COL) method. Thoracic and lumbar curve angles were extracted along with the AVR of the levels above, at, and below the apices. Thoracic and lumbar AVR and AVT measurement differences were used to calculate the max AVR twist and interapical distance. Intra-evaluator reliability was determined from 13 participants' scans measured by a blinded evaluator. Inter-evaluator reliability was determined from 35 participants; scans measured by two evaluators. Intraclass correlation coefficients (ICC's) were reported along with standard error of measurement (SEM). Repeated measures ANOVAs were used to compare positions with Sidak pairwise comparison analysis.

Results:

The intra and inter-evaluator reliability of the thoracic and lumbar curve angles, AVR, max AVR twist, AVT, and interapical distance measurements were adequate for research (ICC>0.70). Reliability estimates were lower than previous studies testing in standing or lying, but SEM values were still within accepted thresholds. The novel AVT measurements were among the most reliable measurements across all positions.

The mean age of the participants was 15±3 years old with mean thoracic and lumbar curve angles of 16±8° and 18±9°, respectively. All measurements were largest in habitual standing. The lowest thoracic and lumbar curve angles, AVT, and interapical distance was observed in the sitting active exercise with hip flexion. The lowest max AVR twist was in the prone active exercise with hip flexion. The lumbar curve angle in the final repeated standing was significantly reduced compared to habitual standing indicating residual effects from a single exercise session.

In conclusion, US imaging produces reliable measurements of the thoracic and lumbar curve angles, AVR, max AVR twist, AVT, and interapical distance and can be used to assess the spine in a variety of positions. Comparisons indicated that Schroth exercises produce the greatest corrections for patients, regardless of habitual position. The largest reduction was produced by active correction by the participant without compensatory change elsewhere. Therefore, Schroth exercises create immediate clinically significant corrections to the frontal and rotational profile of AIS. These research findings may help inform clinicians and therapists about the feasibility of achieving corrections from PSSE and influence their instruction. Schroth exercises may provide lasting corrections with unknown duration.

PREFACE

This thesis is an original work by Alex Su. The original research project by Dr. Eric Parent, from which this thesis has been adapted and continued, received research ethics approval from the University of Alberta Health Research Ethics Board, Project Name "Scoliosis autocorrection exercises assessed by US imaging", Study ID No. MS2_Pro00066486, July 6th, 2016. An amendment to include new positions and inclusion of two new measurements for this thesis was approved on February 23rd, 2017. No part of this thesis has been previously published.

The research conducted for this thesis contained collaborative input from Elia Fong, a Barcelona Scoliosis Physical Therapy School (BSPTS) Schroth trained physical therapist at the University of Alberta Hospital; Cindy Marti, a Barcelona Scoliosis Physical Therapy School (BSPTS) Schroth instructor, Society on Scoliosis Orthopaedic and Rehabilitation Treatment (SOSORT) education board member, and owner of Spinal Dynamics of Wisconsin in Milwaukee, Wisconsin, USA; and Dr. Sanja Schreiber, a Schroth trained therapist and regional Schroth instructor, and owner of Curvy Spine in Edmonton, Alberta, Canada.

The literature summary in Chapter 2 and the data analysis in Chapters 3 and 4 are my original works. I was responsible for the data collection, image analysis, extraction, statistical analysis, and the composition of this document.

Dr. Eric Parent, the principal investigator and primary supervisor for this project, was involved through the initial study design, Schroth therapy instruction during data collection, and manuscript edits.

Dr. Edmond Lou, the co-supervisor for this project was involved in the initial study design, the design of the ultrasound image analysis program, the technical support with the ultrasound system, and edits to the manuscript.

Michelle Goonasekera, our undergraduate research assistant, assisted with data collection and completed image analysis for the intra- and inter-evaluator reliability in Chapter 3.

Elia Fong, the study's Schroth therapist, was involved through Schroth therapy instruction throughout the study's data collection.

Jacqueline Eberhardt and Matthew Shaker, practicum student and summer student, respectively, assisted in data extraction.

ACKNOWLEDGEMENTS

Nearly two years has passed since I embarked on this journey and it has been one of the greatest learning periods of my life, both academically and personally. In no particular order, I would like to thank all the individuals involved below who have contributed to my professional and personal growth.

I would first like to thank my supervisor, Dr. Eric Parent, for his tremendous tutelage. His patience, endless dedication, and support in my career and professional goals has meant a great deal to me. Without question, his input has made me a better academic and I am forever grateful for his willingness to hear out my thoughts. Your impact has and will continue to help me grow into a great professional.

I would also like to thank Dr. Edmond Lou, my co-supervisor, for his continued support and input with our project and for the numerous times we needed to troubleshoot. Adding to this I would like to extend this thanks to Dr. Lou's students, Rui (Rachel) Zheng and Mahdieh Khodaei, for their help with troubleshooting the ultrasound system.

I would like to acknowledge the Faculty of Rehabilitation Medicine, The Stollery Children's Hospital Foundation through the Women and Children's Health Research Institute (WCHRI), and the Alberta SPOR Graduate Studentship jointly funded by Alberta Innovates and Canadian Institutes of Health Research (CIHR) for their financial support throughout this project.

Additional thanks to:

> Dr. Marc Moreau, Dr. Sanja Schreiber, and members of the Edmonton Scoliosis Interdisciplinary Research Group for their individual perspectives on my project and passion for scoliosis. My extended gratitude to the clinicians from SOSORT for their input and interest for our project.
>
> Kathleen Shearer, for her kindness and tireless help with patient recruitment.
>
> Elia Fong, for your unwavering optimism and personal support, in addition to your dedication to physical therapy and building personal rapport with your patients.
>
> The Faculty of Rehabilitation Medicine, for their kind support of their graduate students and the research they conduct.

Michelle Goonasekera, for your assistance with data collection and analysis. As well as, Jacqueline Eberhardt and Matthew Shaker, for your tremendous help with data extraction.

My lab mate, Malik, and my fellow grad students for the comradery and learning I received from each of your experiences.

My dearest friends, your collective support has meant more to me than you have known.

Each participant and their families in our study, for their continued support of our clinical research and for their dedicated time and valued input.

Finally, I dedicate this thesis to my mother, whom I would truly not be able to get through this without. My deepest gratitude for providing me with your unwavering support, unconditional love, and for being my greatest role model for perseverance.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

2D: Two-dimensional

3D: Three-dimensional

ADL: Activities of daily living

AIS: Adolescent idiopathic scoliosis

ANOVA: Analysis of variance

AVR: Axial vertebral rotation

AVT: Apical vertebral translation

BSPTS: Barcelona Scoliosis Physical Therapy School

CI95: 95% confidence interval

COL: Center of lamina

CPM: Center of pedicle method

CSVL: Central sacral vertical line

CVL: Central vertical line

CT: Computed tomography

CTLSO: Cervical, thoracic, lumbar orthosis

E: Evaluator

FITS: Functional Individual Therapy of Scoliosis

GPS: Global positioning system

HRQL: Health-related quality of life

IBM: International Business Machines

ICC: Intraclass correlation coefficient

LEV: Lower end vertebra

MIAS: Medical Image Analysis Software

MRI: Magnetic resonance imaging

MT: Main thoracic

PA: Posterior-anterior

PT: Proximal thoracic

PSSE: Physiotherapeutic scoliosis-specific exercise

RAB: Rotational angular breathing

RUS: Radius, ulna, small bones

SEAS: Scientific Exercise Approach to Scoliosis

SEM: Standard error of measurement

SF-36: 36-item Short Form Survey

SOSORT: Society on Scoliosis Orthopaedic and Rehabilitation Treatment

SP: Spinous process

SPSS: Statistical Package for the Social Sciences

SRS: Scoliosis Research Society

TL/L: Thoracolumbar/ Lumbar

TLSO: Thoracic, lumbar, sacral orthosis

TP: Transverse process

SAQ: Spinal Appearance Questionnaire

UEV: Upper end vertebra

US: Ultrasound

USD: United States Dollars

Chapter 1. Introduction

Background

Adolescent idiopathic scoliosis (AIS) is described as a three dimensional (3D) spinal deformity with marked lateral curvature and rotation of the vertebrae[1,2]. This condition, affects 2-3% of all adolescents diagnosed between the ages of 10 to 18 years old with greater risk of curve progression in younger individuals[1,3–7]. The main treatments in North America for AIS are observation, bracing, and surgical intervention[1,2,5,6,8–10].

Recently, physiotherapeutic scoliosis-specific exercises (PSSE), a specialized and individualized form of physical therapy and exercise meant to minimize the three dimensional (3D) spinal deformation, has been recognized to potentially benefit individuals with AIS[2,8,11]. Among numerous benefits, a reduction in curve progression from added PSSE treatment can be observed after 6 months compared to the standard of care[12]. The Schroth method is one of the oldest and most widespread schools of PSSE treatment and is comprised of complex 3D self-correction of the spine, training with activities of daily living, and stabilization of the corrected posture[9,13]. In recent years, several randomized controlled trials on Schroth have shown that PSSE can help reduce curve progression, assist in pain management, and improve self-image, strength and endurance[12,14–16]. In fact, among PSSE approaches, Schroth has cumulated the most evidence to date[9,13].

Even so, PSSE treatments have yet to be adopted into standard treatment plans in North America. This may be due, in part, to hesitation from clinicians related to the lack of evidence on the immediate effects of these complex exercises, and the feasibility for young adolescents to create clinically significant reductions of their physical deformity without compensation in another aspect of their deformity. To date, there has only been one case study on the immediate effects of physiotherapeutic scoliosis-specific exercise on the Cobb angle measurements of a single individual with AIS[17]. Research is needed to help ease patient and care-giver skepticism around the ability to achieve clinically meaningful corrections in their spinal alignment. Clinicians also do not know how different exercise instructions lead to the corrections they see on the surface. Further, examining the immediate effect of different exercise variations will help instructor training other therapists by providing an evidence base to support teaching exercise with maximal immediate effects in hopes that this could later translate into long-term effects. Therefore, there exists a knowledge gap that may benefit multiple stakeholders, once addressed.

Research into these in-exercise effects have likely been restricted to date due to ethical concerns over the repeated exposure to radiation associated with radiographs, even with low-dose EOS imaging, needed to assess the numerous positions[18]. Therefore, there is also need for an imaging technique that can provide non-invasive and non-ionizing measurement of the spine that is reliable before we can investigate the immediate effects of exercise. Ultrasound (US) imaging has quickly become known as a promising validated alternative to non-invasively assess the spine alignment that is radiation free[19–28]. Ultrasound imaging with its non-invasive 3D capabilities provides the unique opportunity to assess the spinal curvature of individuals with AIS in response to performing various exercises.

Traditionally, research on AIS and the effects of PSSE has focused largely on the curve angle, the key clinical measure used in diagnosing and determining progression, and to a lesser extent, the axial vertebral rotation (AVR)[29]. Apical vertebral translation (AVT) is a measure of the displacement of the most laterally deviated vertebra in a scoliotic curve but has often not been quantified because it has been assumed to be captured within the traditional Cobb angle measurement due to good correlation[30]. Yet, apical vertebral translation (AVT) has long been used as an important measurement to assist in the determination of structural double curves and selection of fused vertebral levels when planning surgery[31–33]. Additionally, correction of the frontal plane deviation has been a clinical focus of conservative treatments such as PSSE. However, there is no scientific evidence on the effects of exercise on the AVT measurements of individuals with AIS. Thus, AVT measurements describing the effects of exercise should be included to resolve the inconsistency between surgical literature and evidence on conservative treatment.

Objectives

The main objective of this thesis was to determine the immediate in-exercise effects of Schroth physiotherapeutic scoliosis-specific exercises in standing, prone, side-lying, and sitting on the curve angle, AVR, and AVT measurements of 36 individuals with AIS using 3D US imaging.

To be able to investigate the effects of exercise using US imaging, we first needed to determine the reliability of the curve angle, AVR, and AVT measurements for both the thoracic and lumbar regions in various positions. US imaging has previously shown it can provide reliable curve angle and AVR measurements in standing, prone, and side-bending but not in exercise-related positions[19,21,25,26,34,35].

Once reliability had been established, we could measure the changes in the curve angle, AVR, and AVT measurements in our participants due to PSSE-relevant modifications and positions. We studied 16 total positions consisting of four habitual positions (standing, prone, side-lying, and sitting) and their respective passive and active corrections, reflective of standard Schroth PSSE positions and instructions. Pairwise comparisons between habitual, passive, and active positions will allow us to differentiate what corrections are attributed to changes in positions, what corrections the external forces from passive supports provide, and lastly what amount of correction can be intrinsically produced by the active corrections of participants. Ultimately, this will provide empirical evidence to reveal the feasibility of patients creating clinically meaningful immediate reductions to their curve measurements while performing PSSE.

The following thesis sections will consist of:

Chapter 2, a summary of the general literature on adolescent idiopathic scoliosis and key studies leading to the investigation of this thesis topic.

Chapter 3, a research paper on the intra and inter-evaluator reliability of curve angle, axial vertebral rotation, and apical vertebral translation ultrasound measurements to assess the spine during exercise-related positions.

Chapter 4, the main clinical paper reporting the immediate effects of Schroth exercise on the scoliotic spinal alignment measurements of 36 patients as measured by ultrasound imaging.

Finally, Chapter 5, a final discussion on the entirety of this research work with the future research recommendations and clinical implications.

Chapter 2. Literature Summary and Rationale

Diagnosis definition (pathology), epidemiology, and etiology of idiopathic scolioses

Scoliosis is defined as a 3D structural deformation of the spine with torsional characteristics including a marked lateral curvature with rotation of the vertebrae [1,2]. Scolioses are screened using the Adam's forward bend test with a scoliometer. If a threshold of 5-7° is exceeded, scoliosis may be confirmed by a standing frontal radiograph to measure the Cobb angle[1]. A measured Cobb angle of more than 10° will define a scoliosis and up to 15° when including the possible error of 5° from this technique[1,8]. The Cobb angle is derived from the intersection of lines projected from the upper endplate and lower endplate of the upper and lower end vertebrae, the most tilted vertebrae of a curve, respectively, for the frontal plane curve being measured.[6,8] In normal clinical practice, the Cobb angle measurement is obtained from a standing frontal radiograph of a patient from the back, also known as a posterior-anterior (PA) radiograph, while the sagittal profile of the spine, the thoracic kyphosis and lumbar lordosis, is assessed by a lateral radiograph[6,8].

Scoliosis can be a primary disorder in which it is termed a structural scoliosis but it can also arise from other disorders, thus being termed a secondary scoliosis or functional scoliosis[2]. Scoliosis may arise from congenital changes, mesenchymal conditions, neuromuscular conditions, degenerative spondylosis, or be concluded as idiopathic[3,4]. These scolioses, idiopathic or non-idiopathic, will have different histories of curve progression, different three dimensional deformities, and different patterns of deformity[4]. Congenital scoliosis is caused by a malformation of the vertebrae that has been revealed to have known gene association that can be discovered anytime from birth and onwards although the time of detection may vary[4]. Mesenchymal scolioses are from an insufficiency of passive stabilizers of the spine, such as Marfans's syndrome[4]. Neuromuscular scolioses, however, are from an insufficiency of active neuromuscular stabilizers for the spine that can arise from problems including the likes of muscular dystrophies, cerebral palsy, and spinal cord injuries[4]. Finally, a scoliosis can be found to occur from degeneration with the likes of spondylosis, a degeneration of the vertebral discs[4].

The majority of scolioses become categorized as an idiopathic scoliosis which is the occurrence of scoliosis without a currently known etiology[3,4]. Therefore, when a scoliosis is labelled as idiopathic it is an exclusion diagnosis, ruling out all other possible etiologies, made by the physician[3,4]. Idiopathic scoliosis can occur at any stage of an individual's life but the prevalence is greater in the populations that have not reached skeletal maturity[3,4]. Idiopathic scoliosis is divided into four main age categories: infantile, juvenile, adolescent, and adult[3,4]. Infantile idiopathic scoliosis is diagnosed for any child under the age of 3 years old[3,4]. Juvenile idiopathic scoliosis occurs in children ages 5 through 8 years old and adolescent idiopathic scoliosis (AIS) is diagnosed for a scoliosis that occurs in children aged 10 years old and up[3,4]. These scolioses occurring before age 10 are also termed early onset scolioses. Adolescent idiopathic scolioses occur in children between ages 10 to 18 years old that have not reached maturity[4]. The age ranges given are only considering the age of presentation, as we cannot determine the age of onset, so there is ambiguity at the ages between these ranges[3,4]. In cases of ambiguity, diagnoses discretion is left up to the physician. Idiopathic scoliosis age ranges have also been reported with less ambiguity as infantile (<3 years old), juvenile (3-10 years old), and adolescent (10-18 years old)[4].

Notably, infantile scoliotic curves tend to be left thoracic curves with male predominance whereas juvenile curves are more similar to adolescent curves, right thoracic curves with female predominance[3]. Finally, adult idiopathic scoliosis is a scoliosis that presents itself in an individual over the age of 18, after skeletal maturity typically, and its sudden onset has been called *de novo* scolioses as well[2,3].

Adolescent idiopathic scoliosis (AIS) constitutes 90% of all idiopathic scoliosis and is a condition that is diagnosed in otherwise healthy children[3,4]. AIS affects 2-3% of adolescents globally with equal sex distribution for smaller curves (<15°), but an increasingly skewed female to male ratio, approximately 8:1, is present as the Cobb angle increases (20-45°)[4,36]. The prevalence decreases with increases in curve magnitude, as 0.25% of the population may have a curve greater than 30°, while the majority of those affected by AIS will have minor curves (10-15°)[4,36]. Individuals with curves that fall in the moderate range (>25°) will typically be treated with bracing or be recommended to surgery if their curves are at risk for progression, being greater than 45°, although the prevalence for individuals with large or surgical curves is approximately 0.1%[3,4].

The classifications of scoliotic curves have traditionally been developed with respect to the location of their apical vertebrae on the spine[3,4,8]. The SRS defines curves as the following according to their apices: cervical (C1 to the C6-7 disc), cervicothoracic (C7-T1), thoracic (T2 to the T11-12 disc), thoracolumbar (T12-L1), lumbar (L1-2 disc to L4-5 discs), or lumbrosacral (L5 or lower)[8]. The Lenke classification is a standard classification adopted by the SRS that is used to define curve patterns for scoliotic spines with consideration to their sagittal and coronal profiles as well as the curve flexibility[8,37]. This classification system is an important clinical tool for surgeons, as this system was developed with the intention to improve the reliability of the classification of spinal deformities and to aid in decisions such as the selection of arthrodesis levels and curves to be operated on in surgery[8,37].The Lenke classification has three components comprised of: the curve type (1-6), lumbar spine modifier (A,B,C), and a sagittal thoracic modifier (-,N,+).

The Lenke curve types are the following: 1) main thoracic, 2) double thoracic, 3) double major, 4) triple major, 5) thoracolumbar/lumbar, and 6) thoracolumbar/lumbar-main thoracic[8,37]. These curve types are similar to the SRS definitions as they define the curves by the location of their apices; thoracic (T2 to the T11-12 disc), thoracolumbar (T12-L1), or lumbar (L1-2 disc to L4-5 discs)[8,37]. In addition, the curves are classified by their region as proximal thoracic (PT), main thoracic (MT), or thoracolumbar/lumbar (TL/L), and curves are fit into these descriptions by their magnitudes[8,37]. However, in order to fit these curves into these definitions, curves are determined to be structural or non-structural in nature[8,37]. According to this classification, a curve is structural if the Cobb angle is greater or equal to 25° on a standing radiograph and does not become smaller than 25° on a side-bending radiograph[8,37]. Additionally, the regional kyphosis angle measurement of greater than or equal to +20° is used to determine that a curve is structural even if it is has been deemed non-structural from the coronal criteria[8,37]. For PT curves the kyphosis angle will be measured between T2-T5 levels and T10-L2 will be used for both the MT and TL/L regions[8,37]. Finally, curve magnitude is used to classify major and minor curves, as the largest Cobb angle will correspond to being the major curve[8,37]. With this in mind, it is now possible to describe the Lenke curves types 1-6[8,37]. For curve types 1-4, the main thoracic curve will always be the major curve and will always be structural[8,37]. Thus, a type 1 curve is named main thoracic when there is a single major curve that is structural with the possibility of non-structural curves in the PT and TL/L regions[8,37]. Type 2 curves are given the name double thoracic because there will be one structural curve in the PT region in addition to the major structural curve in the MT area[8,37]. Type 3 is a double major curve type where there is the major structural curve in the MT but there is also a structural curve in the TL/L region[8,37]. For curve type 4, the name triple major is given to this pattern because all regions will have a structural curve with both MT and TL/L having major curves[8,37]. The 5th type is a thoracolumbar/lumbar curve type that consists of a major structural curve in the TL/L region with only non-structural curves in the PT and MT regions[8,37]. Lastly, type 6 is the designation for a thoracolumbar/lumbar-main thoracic where there are structural curves in the MT and TL/L regions but the TL/L curve is the major curve[8,37]. These types of descriptions of curve pattern are meant to be a useful tool for surgeons to determine what curves need to be operated on and which don't[8,37].

The lumbar spine modifiers are used to assess the alignment of the lumbar curve relative to the central sacral vertical line (CSVL) so that a surgeon or physician can consider how much lumbar deformity there is and how it may affect the balance and reaction of other curves in the spine[8,37]. If the CSVL lands on the apical vertebrae medially from the pedicle then it will have an A modifier. If the CSVL lands on the apical vertebrae but outside of the pedicle but within the vertebral border, it is a B modifier[8,37]. Finally, if the CSVL does not land on the apical vertebrae or anywhere on vertebrae immediately above or below, it is designated a C modifier[8,37]. The sagittal thoracic modifier is used to define the thoracic alignment in the sagittal plane[8,37]. There is a tendency to have hypokyphosis associated with AIS and this modifier uses the position of the superior end-plate of the fifth thoracic vertebra and the inferior endplate of the twelfth thoracic vertebra on a lateral radiograph to determine if the curve is normal or not[8,37]. The minus sign (-) indicates hypokyphosis consisting of a kyphosis angle less than >10°, N is normal for a range of +10° to +40°, and the plus sign (+) is for hyperkyphosis of >40°[8,37].

There have been many classification systems, such as the King classification, which formed the basis for scoliosis classification, that are no longer used due to their poor reliability in relation to newer systems[6]. With these classification systems, there needs to be care in determining not only what curves are structural and non-structural but if they are compensatory, as this would be relevant to the surgeons' decision on the location to operate[6,8,37]. One of the issues with the Lenke classification is that it is applicable towards curves with surgical severity predominantly and poorly classifies curves that do not fit its specific criteria as exemplified by their undefined criteria for a "minor" curve[37]. As mentioned previously, smaller magnitude curves are more prevalent for AIS and therefore this classification is not useful in characterizing individuals with curves that are less than 25°. Further classifications have stressed the consideration of rotational torsions in the scoliotic spine in addition to the Lenke classification's consideration in the frontal and sagittal planes[6].

The mechanics of scoliotic curve progression has been proposed by Stokes et al.[13,38]. This animal model study describes a vicious cycle in which progression of the deformity follows the Hueter-Vollkmann law, stating that bone growth is affected by the compression placed upon it[38]. This theory is that compression hinders growth and reduced compression encourages growth[38]. With this in mind, the asymmetric loading in scoliosis would create a vicious cycle that sees a progressive increase of compression on the concave side of the curve and overgrowth on the convex side of the spine, both of which would contribute to further curve progression and promotion of a wedge-like shape in the vertebrae under this asymmetric loading[13,38]. The importance of skeletal immaturity and curve magnitude, being key factors in curve progression, follows the logic of this theory[13,38]. Decreased skeletal maturity with large curve magnitude is a high risk for progression because it can allow even further acceleration of convex side growth and concave side growth inhibition from what would be an increasing amount of load asymmetry[13,38]. Supporting this claim, it was found in another animal study that compression caused damage to the epiphyseal cartilage of the loaded side, creating a wedge shaped growth plate; this cycle may therefore be described as a progression factor and not an inducing factor[38]. More information on factors that influence the risk of curve progression can be found later labelled as "Factors influencing the risk of progression in Scoliosis".

Although there are many theories towards the etiology of AIS, many people have leaned towards the idea that it is in fact a multi-factorial disease with genetic predispositions in play[39]. In twin studies for AIS, monozygotic twins had a 76% concordance rate as opposed to 36% in dizygotic twins[1,39]. The genetic association has also been seen in population studies indicating that approximately 10% of first-degree relatives will be affected as well[39]. Proposed theories of the aetiology have included issues on mechanical, metabolic, neuromuscular, growth related, and genetic foundations[39]. There is a large amount of genetic work being done regarding the etiology of AIS and one theory that is being investigated is that there is a genetic abnormality that is sex-linked and non-dominant on the X chromosome[1]. Epigenetics has also done a large amount of research into this and there is a belief that genetic factors allow the individual predisposition to trigger AIS but environmental factors create this presentation[2,39–41].

Discussion has also focused on melatonin, calmodulin, platelets, and sex and growth hormones, such as estrogen, and their interactions[1,2,39,40]. Animal studies using pinealectomized chickens, to decrease melatonin coming from the pineal gland, demonstrated an associated onset of scoliosis however, it has been shown that lower animal models such as these process melatonin much different than in humans and mammals[41]. Melatonin deficiencies and any known related abnormal melatonin-related diseases have also not been noted in individuals with AIS, therefore suggesting that if melatonin plays a role in AIS presentation it is one that is not direct and may be part of a more complex interaction[1,39,41].

One study has proposed that scoliosis in humans may be initiated by high levels of melatonin and poor quality of light[1,2,40,41]. The authors provide evidence showing an increasingly later onset of puberty in correlation to increasingly higher latitudes, above 25°, where light quality becomes poorer[41]. Accordingly, they are suggesting that the increased levels of melatonin, from increased darkness, causes a larger window for scoliosis to develop[41]. This time frame before puberty would allow a longer period of instability in the spine, therefore being an initiating factor to the onset of scoliosis[41].

In humans, melatonin may have a role in the modulation of calcium-activated calmodulin[1,39,40]. The evidence has shown that there is a raised concentration of calmodulin that can result in altered muscle activity leading to curve progression[1,39,40]. A platelet-skeletal hypothesis by Burwell proposed that the small asymmetric loading on the spine creates damage that stimulates platelet activation triggering calmodulin changes, likely through its pathways[1,40]. This calmodulin change would then create a cascade in its pathways leading to growth factor modulation and asymmetric curve progression[1,40]. This hypothesis is thus similar to Stokes vicious cycle and, in addition to agreement with Stokes theory, Burwell's hypothesis adapts and explains a physiological rationale for the occurrence of this vicious cycle[42]. However, further investigation of this hypothesis and the etiology of idiopathic scoliosis is dependent on the advancement of the biochemistry, genetic, and physiological fields[1,39,40]. Suggestions of an epigenetic and network approach are claiming that creating "diseasomes" will facilitate a multi-hit model to develop preventions and cures to potential abnormal molecular pathways by use of screening, genetics, epigenetics, biochemistry, metabolic phenotypes, and pharmacogenomics[40].

Natural history of untreated AIS

The natural history of AIS is dependent mainly on the curve magnitude, curve type, physiological maturity, and the age of the patient[1,3]. AIS curves progress most during the rapid growth period and large curves (>30-40°) continue to progress into adulthood[1,3]. Small and moderate curves (<30-40°) will grow most until maturation and then generally stabilize[1,3]. Curves that progress to between 40° and 50° before maturity have been shown to progress approximately 1° per year in adulthood[1,3]. The age of presentation for any curve is vital to predict the curve progression[1]. If left untreated, curve progression to large curves magnitudes can create impairments; these will be discussed in the following sections.

The curve type and pattern of an individual with AIS will also affect progression as thoracic curves have the most likelihood to progress in long term follow ups compared to any other single curve types; rotation of more than 20° increases this likelihood[3,43]. Additionally, for double major curves, the lumbar curve typically is more likely to progress than the thoracic curve, and right lumbar apex curves are twice as likely to progress as a lumbar curve with a left apex [3].

The age of diagnosis with AIS is also an important factor when considered in combination with the curve magnitude[1,3]. For an equivalent curve magnitude, a younger individual is always more likely to progress than an older individual due to the greater possibility for growth and thus curve progression[1]. Consequently, an individual who has yet to reach physiological maturity or menarche has an inherently larger risk for progression than someone who is nearing the end of their maturity[1,3]. A physiologically immature individual with a large curve would then be even more at risk for progression than a maturity matched individual with a comparatively smaller curve[1,3].

Short term signs and symptoms

In the short term, individuals with AIS generally do not experience significant impairment or functional restrictions[43]. AIS curves do not contribute to any immediate risk for mortality nor do they bear a significant chance for creating pulmonary dysfunction unless they reach a Cobb angle exceeding 80° with large amounts of vertebral rotation[3]. Shortness of breath and reduced vital capacity has been reported for large curves (>50°) although never reaching a severe level[43]. However, the prevalence of larger curves is only approximately 0.1-0.25%[3,4].

AIS does contribute to worse self-image scores on questionnaires compared to controls although this is not a major issue for small curves[3]. There has been some discrepancy in reports saying that patients experience restrictions or decreases in their ability to engage in activities, self-esteem, and their mental health[43]. However, when we consider the opinion of these individuals and their families in the form of group interviews and focus groups, rather than questionnaires, adolescents with AIS do show poorer body image, psychosocial functioning, appraisal of their deformity, and health related quality of life (HRQL)[3,44]. These reported issues by younger individuals with AIS are not exclusive to this time in their lives and can also progress into adult life[45].

In numerous long-term natural history studies, AIS was shown to increase the prevalence of pain, volumetric pulmonary dysfunction, quality of life deficits, psychosocial dysfunctions, and of significant cosmetic deformity[1,3,43,46–49]. With increased curve magnitude there is an associated increase in the amount of impairment that an individual may experience however, the severity of each of these impairments may be different for each individual[1].

Long term impairments and complications

In a long-term follow up study of 50 years on untreated AIS the 15% mortality rate observed was similar to that of the general population[3,43]. In multiple long term studies, non-disabling chronic back pain occurrence was found to be more prevalent in patients with AIS than the general population but not greater in severity or duration[3,43]. Within individuals with AIS and pain, pain was not related to the curve magnitude but possibly to the curve pattern at a 50 year follow up whereas a separate study had reported that curve magnitude was a significant predictor of back pain at a 60 year follow up[3,50]. The curve patterns most associated with pain were thoracolumbar curves, and the least associated were double curves[3]. A consistent curve progression of 1° per year can be expected for both thoracic and lumbar curves exceeding 50° at maturity[1,50]. Finally, in a 20 year follow-up study of AIS, thoracolumbar and lumbar curves reported an increased prevalence and intensity of low-back pain arising in adulthood and when compared to the general population, which may eventually become progressive[51].

In long term studies of untreated AIS, decreased pulmonary function is the most evident finding[1,3,43,50]. Pulmonary dysfunction, reported by shortness of breath, was greater for individuals with AIS (22%) when compared to the general population (15%)[43,52]. This is said to occur for larger curves (>50°), especially thoracic curves, with increased rotation; limited reports have noted a reduction in vital capacity for curves magnitudes greater than 80°[1,3,50]. Lumbar curves are typically unlikely to cause pulmonary dysfunction but large double curves may be associated with this impairment[3].

Follow-ups of at least 20 years show that 91% of all individuals with AIS are able to live normal functioning lives that were not differing from the general population's quality of life scores[43,51]. A 60 year follow-up of untreated individuals with AIS showed that disability, HRQL, and psychological well-being was comparable to a healthy control group[50]. Individuals with AIS have shown not to experience any abnormal issues in finding employment, marrying, childbearing, birthing, and birthing associated pain, however there are conflicting reports of self-reported disabilities related to participation in recreational activities and performing certain physical functions[1,43]. Self-reported difficulties experienced in the long term are a decreased self-esteem, increased self-consciousness, and problems in finding proper clothing[1,43,52]. With this, marked cosmetic deformity is most prominent with thoracolumbar curves and surgical treatment can be warranted for any curve type if the Cobb angle is expected to reach 50-60°[52].

Treatments for AIS: indications and quality of evidence

Treatments for AIS aim to alter the natural history of an individual's expected outcome with short- and long-term considerations[1,8]. Currently, in North America the treatments used for AIS are observation, bracing, and surgery[8]. For observation, the goal is to determine if any curve progression is occurring to a high enough magnitude that it warrants other treatment[8]. For bracing, the goal is preventative, that is to stop progression from reaching surgical or later-life impairing magnitudes[8]. With surgical intervention the goal is to stop progression, gain correction, and improve cosmetics[8]. Curve progression risk factors in AIS including the age, pre-menstruation, indicators of skeletal maturity and radiographic indications are interpreted when determining treatment[8]. Specifically, risk is greatest for younger individuals that have not reached menarche with a large curve magnitude, and lowest for older individuals who are past their growth spurt, or who've begun menstruating, with a small curve magnitude. The Risser classification of skeletal maturity from pelvic ossification is used as a measure to determine maturation level which correlates with spinal growth[8]. This scale is based on the ossification of the iliac apophysis and graded from 0-5 where 0 indicates skeletal immaturity and rapid growth and a grade of 5 indicates skeletal maturity and potential growth cessation[8]. Risser grades of 0 or 1 present the greatest risk for progression[8]. For further information on curve progression please refer to the section labelled, "Factors influencing progression in Scoliosis".

Observation

Observation is the only necessary treatment option for patients with Cobb angle below 25° but who are still growing, or with curves less than 50° who have stopped growing[8]. This involves regular clinical check-ups at a frequency depending on the patients' risk factors[2,8]. Generally, check-ups are at intervals between 3-12 months with higher frequency given to those with highest risk for progression with a potential need for surgery, and the lowest frequency for individuals who are at low risk for curve progression without a need for other treatments[2].

Bracing

Bracing is given when curves are 25-40° when an individual is still growing. Bracing is a preventative treatment aiming to keep curves under 45°, the surgical threshold[8]. Bracing, or spinal orthoses, are classified by the levels of the spine that they cover. The most common type is the TLSO, but sometimes a CTLSO is used[8]. These names are acronyms where the letters stand for Cervical, Thoracic, Lumbar, Sacral, and Orthosis[53]. An example of the CTLSO is the Milwaukee brace, and for TLSO the Boston or Cheneau brace[53]. CTLSO brace prescription has decreased over the years and is only used in the rare case of high thoracic curves or with abnormal kyphosis.

Braces apply a load to three points of the torso for each curve: one to the apex of a curve on the convex side, another using brace shaping and a pad above the apex on the concave side, and one below the apex also on the concave side, in hopes to balance the loading on the growing spine[54]. These braces are intended to be worn either full time (~23 hrs), part time (~16 hrs), or night-time only (8-10 hrs) until patients reach skeletal maturity which can range from 2-8 years[53]. Brace wear time is also determined based on risk of progression.

The Boston Brace reference manual provides refined bracing indication criteria endorsed by the SRS[54]. Bracing in curves of 20-25°, is warranted if large growth is expected or remains and if progression is documented[54]. A Cobb angle of 25-30° is similar in that it should be progressive and growth remains; 30-40° degree if growth remains. The range of 40-45° is a gray zone because surgery may be a better choice for some[54]. TLSO bracing, which includes the Boston brace, is most effective when the curve is between T6 and L3, and is a single curve[54]. Contraindications of brace wearing are: massive obesity, hypokyphosis that worsens in brace, thoracic lordosis, and psychological reactions[54].

A concern with bracing is the patient compliance and parental cooperation, as patients have shown to only wear their brace 65% of the instructed time[53]. Bracing has shown treatment success in a large multicenter study, defined as prevention of reaching a curve magnitude of 50° or more at maturity, in 72% of participants treated with a TLSO Brace versus 48% in those with only observation[55] However, it has been shown that for individuals prescribed with full-time brace wear, a brace wear time of at least 13 hours was still associated with a treatment success rate of 90%[55].

A 5 year follow-up testing brace treatment effectiveness found that in-brace correction was sustained over time with some minor loss of correction noted, but this loss of correction would not be clinically significant at 0-0.5º per year after discontinuation[56]. The rate of any post treatment progression due to correction loss was the same as the progression rate in natural history and quality of life was said to have not been impacted unless the curve was greater than 45°, in which greater back pain was present[56].

Surgery

Treatment by surgery differs from bracing as it also aims to gain some permanent correction of the deformity, improve cosmetic appearance and balance, and to keep surgery related complications to a minimum[1,8,36]. Surgical intervention is used for curves greater than 45° while growing and greater than 50° if growth is complete[8]. Surgery uses metal instrumentation with rods that will attach to fixations, usually screws or wire, on the vertebrae to permanently immobilize the spine in a corrected state; this generally leads to fusion of the instrumented vertebral segments[1,8,36]. A posterior approach is most commonly used for AIS for all curve types[1,8]. The anterior approach can be used when there is a single curve, either thoracolumbar or lumbar, but this approach comes with more potential complications including a higher rate of implant breakage, impairment of lung function, and large surgical scarring[1,8]. According to the Lenke classification, the decision for selective spinal fusion is heavily determined by the ratio of the major to minor curve Cobb angle, axial vertebral rotation (AVR), and apical vertebral translation (AVT)[31–33]. Then, when the major curve Cobb angle, vertebral rotation, and apical translation are all 1.25 times greater than in the minor curve, spinal fusion of the major curve is suggested[31]. Additionally, the larger the ratio between the major and minor curve measurement values are, the confidence there is in a successful outcome[31]. AVT is the lateral displacement of the furthest vertebra of a curve from midline[30]. AVT is typically measured horizontally from a vertical line drawn from the center of the S1, the sacrum, known as the central sacral vertical line (CSVL)[30]. The CSVL is always drawn parallel in reference to the vertical edge of the radiograph[30].

This decision for surgical approach is a combination of physician suggested options and the individuals' choice. A surgeon will strongly recommend surgery for a large curve magnitude (>45°) which is likely to progress but not for very immature children (Risser grade 0, Tanner Grade 1 or 2) due to the possibility of the crankshaft phenomenon. The crankshaft phenomenon occurs when continued rapid growth in the unfused anterior or posterior face of the spine leads to twisting towards and around the instrumentation[36]. A decision for surgery in adolescence may also be pursued because delayed surgery into adulthood equates a stiffer spine that may require more invasive surgery to achieve the desired outcome[1]. For surgery, the hospital stay is approximately a week and individuals may return to normal daily light functions in 3-4 weeks post-surgery[8]. Depending on the activities of the individual, return to sport participation may be anywhere from 3 to 6 months[8]. However, decisions regarding activities and participation are up to the surgeon[8].

The rehabilitation period needed after surgery can impact children and their families due to missing school attendance and requiring parental leave from work limiting their immediate ability to proceed with their daily lives[44]. After at least 5 years post-surgery, individuals who have sought surgery will have improved quality of life and less severe pain compared to untreated individuals with similar Cobb angles[1].

Curve correction immediately post-surgery is a ~45% reduction in Cobb angle[48]. AIS populations at 20 years after intervention exhibited a minor loss of Cobb Angle correction, 3.5° for surgery, and 7.9° for bracing[48]. Both treated groups had more degenerative disc changes compared to the general population control group but differences were non-significant between the treatment groups[48].

At 30 years post-surgery in adolescence, patients who had AIS averaged significantly higher SRS-22 and SF-36 scores than those operated because of spondylolisthesis in health-related quality of life, general self-image, and function[57]. The results of this study also elucidated that the quality of life for individuals with spinal deformity is more impacted by pain than the spinal deformity itself[57]. However, overall the quality of life impairment that individuals with AIS experience is not severe, as shown by the SRS-24 and SF-36 questionnaire scores; this is consistent with other long-term studies that may be using other assessments[57].

Factors influencing the risk of progression in Scoliosis

With curve progression being the greatest concern for individuals with AIS, identifying the risk factors associated with progression is of great importance. Factors that increase the risk of AIS progression are young age, skeletal immaturity, being in a premenarchal stage for females, and a low Risser grade[7,58]. In addition, more severe curve magnitude and curve location can help predict progression behaviour. Traditionally, skeletal maturity assessed by the Risser sign has been declared the most significant factor compared to all other factors[7,58]. It had been proposed that the sex, rotational prominence, family history, and radiographic measurements may be predictive of progression but no correlation was found for these parameters[7]. Lonstein et al., developed a calculation for a progression factor for individuals with curves between 20-29° based on curve magnitude, Risser grade, and chronological age[7]. This equation is:

$$Progression\ Factor = \frac{Cobb\ angle - 3\ x\ Risser\ sign}{Chronological\ age}$$

In this study, a double curve pattern was progressing more than single curves[7]. An initial curve of 20° or greater led to a three-fold increase in the percentage of patients who had curve progression compared to curves under that magnitude[7].

Assessments of skeletal maturity have been developed to help determine a patient's stage in growth to help predict progression. Pelvis radiographs are used to determine the Risser grade[59]. This scale is based on the ossification of the iliac apophysis and graded from 0-5 where 0 indicates skeletal immaturity and rapid growth and a grade of 5 indicates skeletal maturity and potential growth cessation[8]. Risser grades of 0 or 1 present the greatest risk for progression and a Risser grade of 3 or greater presents a lower risk of progression[8]. Risser 0 grade accounts for the largest percentage of individuals that will experience curve progression[36]. Anatomically, grade 0 shows no iliac apophysis ossification while Grade 1 through 4 signifies incremental quartile ossification of the iliac apophysis from the anterior crest to posterior, and Grade 5 denotes the complete fusion to the crest[59]. One of the issues with this grading system is due to the likeness in the image of a Risser Grade 0 and Grade 5 on a radiographic image, therefore ossification of the triradiate cartilage of the hip joint has been used in combination with typical Risser grades as a way to distinguish grades 0 and 5[59].

The Greulich and Pyle Atlas, made use of radiographs to illustrate stages of skeletal maturity but it was developed without the consideration of the relative timing of the peak height growth or onset of secondary sexual characteristics[60,61]. Additional issues with this assessment are that it marked stages in one-year leaps where in actuality the peak height growth occurs rapidly in between those stages. This atlas had an important reliance focusing on carpal bones and minutia that made it unreasonable for reliable clinical use[60,61].

Another assessment of skeletal maturity is the Tanner-Whitehouse-III RUS (Radius, Ulna, small bones) score on the radiographic appearance of the wrist epiphyses comprised of the distal ulna, distal radius, and small bones of the hand[61]. However, the Tanner-Whitehouse scoring system is poorly applicable to a clinical setting due to the need of an atlas and electronic scoring system[61]. Further, a digital skeletal age maturity scoring system has recently been proposed based on the metacarpal and phalangeal ossification and has shown high correlations to the curve acceleration of female growth[61]. With that being said, a plot of curve progression can be made with an estimated curve acceleration phase deriving from a regression equation using the digital age of an individual[62]. This estimated curve acceleration phase will allow physicians to determine the maturity of an individual during the critical period of rapid progression where the Risser grade would only be sensitive enough to classify maturity in the declination of rapid progression in these children[62]. The maturity plot is a key tool that can integrate the physiological maturity, by the Tanner breast and pubic hair stages and menarche; skeletal maturity, given by the Risser grade and Tanner Whitehouse-III stages; and chronological age to the curve magnitudes and peak growth height velocity[62].

Building on this tool, Sanders et al. has developed the Simplified Skeletal Maturity Scoring System method and has demonstrated it to be highly reliable with a small initial learning curve and has proven that it correlates to growth in idiopathic scoliosis better than the Risser classification or other skeletal age tools[61]. This simplified method has eight stages and uses information from all the digits in a radiograph. These eight stages are: 1) Juvenile, 2) Preadolescent slow, 3) Adolescent rapid-early, 4) Adolescent rapid-late, 5) Adolescent steady-early, 6) Adolescent steady- late, 7) Early mature, 8) Mature. In relation to the Risser classification this simplified method is better able to classify and detect skeletal maturity at an earlier point[61]. To illustrate this, a clear change from Risser Grade 0 to Grade 1 occurs between stage 5 and stage 6 of this method, which is after the onset of rapid growth; thus this system is a more sensitive method that can help track signs of maturity at an earlier stage[61,62]. This simplified method of determining skeletal maturity therefore shows promise clinically to assist in the treatment of idiopathic scoliosis.

The quality & effects of AIS treatments

If left to progress, AIS can bear a heavy cost as physician visits, hospital stays, and surgical fees require time and financial resources, from the health care system and the families affected. For females alone, nearly $600 million USD a year are dedicated to AIS-related hospital stays. Aside from economic considerations, patient quality of life is a priority as significant psychosocial effects stemming from the cosmetic deformity, as well as from treatments, also impact the lives of these adolescents and their families[44].

In the short term, individuals with AIS may exhibit psychosocial difficulties during the treatment process[44]. It is therefore suggested that those providing treatments become aware of and aim to manage the disturbances in body image and psychosocially so that they do not negatively impact the patient's life[44]. Treatment has the potential to create and exacerbate psychological distress in a patient so care should be taken[44,45]. Regarding assessment, Sanders et al., showed that the Spinal Appearance questionnaire (SAQ) is a valid and useful tool to gauge patients' assessment of their physical features pre and post treatment[63]. Other questionnaires used for assessment that include mental health and self-image scales are the SRS-22 and the SF-36.

A study of long term impairment, 20 years later, has also been conducted on lumbar spinal mobility and muscle endurance in people treated with brace or surgically. For spinal fusion, presence of good lumbar mobility and lumbar muscle endurance at 20 years post-op would also correlate with better physical function at the same time point[46]. For those treated with bracing, reduced lumbar spinal mobility at 20 years post-op was correlated with high pain, larger area of low-back pain, and a larger area of pain across the body at that same time[46]. It seems to that both patients treated with bracing and spinal fusion should be interested in improving the lumbar spine mobility as it is associated with better back and physical functioning on the SF-36 and Oswestry Disability Questionnaires[46].

Investigations of the long-term impact of treatment of AIS with bracing and surgery demonstrated no changes to an individual's curves or childbearing ability, however there was a negative impact on their sexual function associated to back stiffness[64]. Treated individuals with AIS reported twice as much limitation in sexual activities when compared to the general population with reasons such as limitation from pain, physical limitations, and self-consciousness[64]. In this same 22 year follow up study, individuals being previously braced showed no notable difference, compared to healthy controls, in daily life and back function between curve types at 22 years after bracing, but would have more chronic back pain with more sensory and affective factors, measured by the McGill Pain Questionnaire[47,65]. A similar study 23 years post treatment with spinal fusion surgery or bracing showed no differing back function, as measured by the SF-36 and Oswestry Disability Index, but those with surgery showed a greater total body area score of back pain than after bracing[65]. Both treated populations presented significantly more lumbar disc degeneration compared to the general population, 15-20% versus 0%[65].

The SRS-22, is a scoliosis specific quality of life questionnaire that has been used to assess the affective, HRQL, and psychosocial aspects of AIS, in short and long term studies[66,67]. A cross sectional study revealed that there are significant ceiling effects using the SRS-22 for many of the age groups [67]. This ceiling effect was especially strong for the younger population under the age of 18 years old [67]. Decreases in the ceiling effect for pain and mental health in older age groups (>25 years old) demonstrate that pain and mental health worsen over time[67]. Increasing ceiling effects in satisfaction found in this study with older age can also demonstrate that there is a greater dissatisfaction in younger adolescents when compared to an older cohort[67]. However, an issue that can be taken from this paper is that the SRS-22 may not be sensitive enough to determine changes in scoring when monitoring the effects of treatments for AIS due to these ceiling effects.

As an additional finding from the summation of these long-term studies, it can be noted that patients with moderate AIS who were untreated due to stabilization remained stabilized and had normal health related quality of life, confirming what is expected from the natural history of these curve sizes.

Critiques on the evidence on the effects of AIS treatments

Richards et al., performed a review of brace effectiveness studies and noted inconsistency in the definitions of success[68]. This team also suggested criteria for standardizing AIS brace study inclusion criteria in order to make valid and reliable comparisons[68]. The standardizing suggestions in whole mean that any conclusions of bracing studies would be to identify if bracing can prevent progression and keep that correction for a population with inherent high risk for progression.

The consideration of the brace wearer and those families immediately affected is rare in the literature. A qualitative study published in 2004, using focus groups and group interviews, gathered patient and family perspectives and opinions to investigate the methods, attitudes, and treatments available[44]. Patients and their families had a general feeling that bracing treatment decision was the only way to proceed and that they were limited in their choice to decide the best treatment possible[44]. Braced patients expressed self-consciousness in brace wearing and bullying from peers[44]. Parents expressed tension and arguments over brace wear and trying to get their child to be compliant with the treatment[44]. Post-surgery, patients mentioned that recovery was a difficult process and some family members even had to take time off to assist them at home[44]. There is a general consensus that brace wearing compliance to the recommended hours was difficult and patients admit to lying to their physician[44]. The study suggested that patients should have more ownership in their treatment in order to improve compliance with their treatment[44]. The age of this population may also explain why there is tension and poor willingness to cooperate because these children are at a stage of life where they are formulating their identities and trying to become independent[44]. Parental monitoring of brace wearing, lack of primary decision making, as well as poor peer support are factors that heavily impact the life of a growing child[44]. The authors also noted from these accounts that the acceptability and compliance of brace wearing was improved when patients had a great understanding and education about the surgery[44].

Alternative treatments

Given the limitations and invasiveness of the standard treatments for AIS, patients and family often look for alternatives. Alternative treatments in North America recognized by the SRS include chiropractic medicine, physiotherapy or physiotherapeutic scoliosis-specific exercise (PSSE), yoga, and other stabilization based exercise therapies[8]. The SRS recognizes that these methods should be considered useful if they show evidence to provide some benefit to the patient[8]. PSSE's have been noted to be increasingly used in combination with bracing treatment[8]. Postural monitoring and prismatic glasses are some experimental treatments that make use of biofeedback to aid the body into corrective postures and awareness but these have only been tested in prospective trials with low sample sizes[53]. In a review of non-traditional treatments, electrical surface stimulation had been used in the 1970's to straighten the spine with muscular contractions, and had originally showed promise in having a progressively improved compliance with treatment use over time[53]. However, studies on electrical surface stimulation showed high variation in success rate due to the large difference in stimulation methods and since then research has shown that electrical surface stimulation is no more effective than observation[53,69]. On summation of the effectiveness of all these different interventions, rigid and semi-rigid braces were deemed the most effective treatment for AIS curves[53]. Exercise has been suggested as a complementary treatment to bracing rather than a standalone treatment and research on PSSE, which the present thesis focuses on, has increased in recent years[53].

Physiotherapeutic Scoliosis-specific Exercise (PSSE)

Physiotherapeutic scoliosis-specific exercise is a specialized method of physical therapy specific to dealing with scoliosis[13]. The reservation of the SRS, and more locally North America, to adopt physical therapy and exercise as a viable treatment is contrasting with the Society on Scoliosis Orthopaedic and Rehabilitation Treatment (SOSORT), and central European countries, where it is widely adopted[70]. Authors investigating PSSE have suggested that perhaps the hesitation and skepticism to adopt physical therapy as a treatment in North America is due to a difference in the definition of treatment success[70]. In central Europe, treatment is considered successful if it can stop progression or decrease the Cobb angle justifying more intensive treatments whereas in the USA, treatment is considered effective if increases in curvature do not exceed 10°[70].

In a review of PSSE, the authors identified the main components of PSSE as focusing on three-dimensional self-correction, training for activities of daily living (ADL's), and stabilization of a corrected posture[13]. PSSE programs are specialized physical therapy exercise regimes that are practiced with a biopsychosocial model approach and include education on scoliosis and psychological support for the patient and family[13]. Additionally, PSSE treatment has also been suggested to have benefits on social acceptability and have reduced psychosocial burden compared to other conservative treatment[2,13,71]. More recently, a randomized controlled trial by Zheng et al. showed that although both exercise and bracing treatment provide improved body and spinal curvature symmetry, exercise provided significantly better function, self-image, mental health, and overall scoring on the SRS-22 assessment at 6 and 12 months of treatment[72]. As such, previous and newer evidence, such as this, can begin to argue the unique benefits of PSSE intervention for treatment of AIS although further improvements to research tools, and the quality and quantity of research should be made to understand the extent of those benefits. The AIS treatment guidelines from SOSORT have stated that PSSE intervention can be used as an additional treatment option that may be used in combination with, rather than as a replacement to, other standard treatments such as bracing or surgery[2,13].

A comprehensive review of PSSE helps understand the differences in PSSE among seven different major schools of PSSE[13]. The seven major schools identified, in order of conception, are the Lyon Approach, Schroth Method, Scientific Exercise Approach to Scoliosis (SEAS), Barcelona Scoliosis Physical Therapy School (BSPTS) approach, Dobomed approach, Side Shift approach, and the Functional Individual Therapy of Scoliosis (FITS) approach, all of which are based out of European countries[13].

The oldest major school of PSSE, the Lyon Approach, dates back to over two hundred years ago and originates from France[13]. The Lyon approach heavily relies on bracing and casting [13]. This approach specifically focuses on mobilizing the ilio-lumbar angle, educating the patient on their body, performing activities of daily living (ADL's), and correction in the sitting position[13]. However, the Lyon approach over the years has largely focused on advancing the quality of the brace[13]. This school of PSSE follows the Lenke classification and focuses on interrupting the aforementioned vicious cycle model that was described by Stokes[13]. Similar to most PSSE approaches, visual cuing and sensory feedback is essential for this method with use of mirrors and video recordings of the patient performing the exercise[13]. Scientific evidence for the PSSE performed in the Lyon approach is bare and limited to minor curves[13].

The second oldest school of PSSE is the Schroth Method started in the early 1900's in Germany by Katharina Schroth. She used physical therapy principles to treat her own moderate scoliosis. This method has been refined since then through treatment of thousands of cases [13]. This method has the widest global network of therapists and focuses on training and educating physical therapists in addition to patient education[13]. The Schroth method describes the scoliosis through the "body block" model where the torso is analysed in four segments separated into the hip-pelvic (H), lumbar (L), thoracic (T), and the shoulder (S) blocks[13,73,74]. The classification used in Schroth is dependent on where the main curve is[13]. Regarding this classification, Schreiber et al. developed a Schroth Scoliosis Curve Classification algorithm[73,74]. A single curve with a balanced pelvic is a 3C curve type, whereas a single thoracic curve with an unbalanced pelvis is a 3CP curve type. A 4C curve type is for double curves with a balanced pelvis and 4CP for a double curve with an unbalanced pelvis[13,73,74]. It is possible that this segmental classification can allow patients to better visualize their own curves in a simplified and structured manner.

Schroth correction first applies a series of pelvic corrections to align the trunk over the central sacral vertical line (CSVL), followed by auto-elongation with detorsion, deflection, derotation, rotational breathing, and finally stabilization[13]. Expansion of the concave sides of the curves is achieved with breathing and using shoulder activation through traction and counter traction forces, and activation of the deep back musculature, such as the iliopsoas, quadratus lumborum, and erector spinae, to mobilize and stabilize the spine[13]. Four common Schroth exercises in order of difficulty are prone active, side-lying muscle cylinder, sitting on the ball, and standing between two poles. The prone exercise incorporates the shoulder traction on the thoracic convex side to offer a counter force to the thoracic side-shift towards midline, and counter-traction from the shoulder on the lumbar convex side to offer a counter force to the lumbar side-shift towards mid-line. The iliopsoas is activated on the lumbar concave side to help pull the lumbar spine to midline. The muscle cylinder exercise is a side-lying exercise that uses gravity to assist in downward correction of the thoracic curve towards the concave side and recruitment of the quadratus lumborum muscle on the lumbar concave side to actively work against gravity and the pull the lumbar curve to midline[13]. Sitting on the ball is where the patient elongates and focuses on derotation of the spine through diminishing the ventral hump and dorsal concavity in the trunk. The standing between 2 poles exercise is aimed at elongating and stretching the thoracic lumbar concavity as well as derotating the spine while holding two poles.

The rotational angular breathing (RAB) technique is used in all Schroth exercises and may also be called orthopaedic breathing, or derotational breathing. Specifically, during inhalation patients focus on maintaining or creating the thoracic kyphosis and expand concave torso area while during exhalation, there is activation of the muscles near the torso convexities resulting from the scoliosis to limit these deformities [75]. The Schroth program is initially intensive hoping to prepare all the patients to use corrections in daily activities so that eventually the highly demanding exercises can be reduced in favour of more leisurely activities of the patient's own choices[13]. However, initially, clinician or therapist-supervised programs show superior results compared to home-based programs without regular therapist visits[13,16]. Given this, Schroth exercises are complex and demanding to perform and skepticism has been expressed by clinicians, patients, and their families about the ability for children to learn these exercises and if they can create meaningful clinical reductions.

Scientific evidence for the Schroth Method is also the most abundant of all the schools of PSSE and in recent years, several randomized control trials have been published that support Schroth's ability to improve Cobb angle measurements, vital capacity, strength, and posture as well as benefits in self-image and quality of life when compared to standard of care[12–16,74]. Schroth PSSE is also the only exercise treatment that has looked at the number needed to treat in order to prevent a progression in a patient's curves[15]. Schreiber et al., found that in a 6 month Schroth intervention one patient could avoid a worsening in their curve for every four patients treated, a number similar to that reported for bracing[15,55]. In a separate study it has also been found that Schroth PSSE added to the standard of care in Canada could prevent clinically significant curve progressions (>5°) for the majority of patients treated[12].

The Barcelona Scoliosis Physical Therapy School (BSPTS) is another school of PSSE that was created from the Schroth Method and consequently can be considered very similar[13]. Key differences lie in the modified classification system it uses because of the incorporation of radiological criteria. The BSPTS school of PSSE incorporates this Schroth classification with the Rigo radiological criteria to guide bracing treatment.

Founded in the 1960's the Scientific Approach to Scoliosis (SEAS) of Italy was adapted from the Lyon approach. This approach is highly individualized. This method practices PSSE by using information on exercises from the scientific literature and therefore is constantly evolving. SEAS focuses on spinal stability and carrying corrections into functional ADL's[13]. The SEAS method uses the principles of neuromotor rehabilitation with different life activities in hopes to adjust the neurosensory and neurophysiological mechanisms controlling the patient's posture[13]. Breathing techniques are not stressed in SEAS unless respiratory function is impaired. The SEAS exercise program, is the least intensive in terms of supervised visits being performed 2-3 times for 45 minutes a week in outpatient care centres[13]. In home programs, it is practiced daily for 20 mins with a 1.5h clinician session every 3 months to assess and modify the program[13]. There are some randomized control trials and positive findings supporting its benefit in reduction of brace and surgery prescription, Cobb angle, curve progression, and even reduction of correction loss after brace weaning[11,13,76–78].

The Dobomed method is the first to come from Poland. The Dobomed approach in comprised of the combination of the Klapps method for kyphotization of the thoracic spine and the Lehnert-Schroth for active breathing. This approach focuses heavily on restoring a normative sagittal profile in the spine and works to correct the primary curve first. The classification is unique to the patient. Unlike the Schroth Method, the Dobomed Method starts with first having the shoulders aligned with the pelvis and assumes that the frontal plane correction will automatically occur when the sagittal and axial planes are corrected[13]. This specialized approach in normalizing the sagittal profile claims to have the most improvement in respiratory function from short-term exercise compared to all other PSSE schools[13].

The Side-Shift Approach was presented in the 1980's in the United Kingdom. This PSSE method proposes that repetitive lateral movement of the trunk to excessively shift away from the curve will help reduce the postural forces, reduce connective tissue stiffness, and realign postural muscles[13]. These repetitive movements also claim to help create somatosensory integration to achieve a more physiological posture[13]. During these side-shifting movements, RAB techniques, similar to Schroth and other PSSE schools, are used. Exercises are held for 10 seconds and patients are asked to do them for 30 times during the day. The Side-Shift approach has its own classification based on spinal flexibility and rigidity of correction to mid-line during shifting[13]. Unfortunately, scientific evidence on the Side-Shift approach is limited.

Lastly, the most recent School of PSSE is the Functional Individual Therapy of Scoliosis (FITS) approach created in Poland in 2004. This approach is created as mixture of other PSSE approaches is meant for curves with severity over 15° in magnitude[13]. Assessment for their patients is also done on an individual basis and training courses last for 1-2 weeks. Evidence for this approach is limited but shows the potential to reduce Cobb angle severity and rotation[13,79]

Therefore, this thesis research focuses on the Schroth exercises because the Schroth and BSPTS approaches are similar, they are the most widely distributed and have shown promising results, in addition to offering widely available training programs. Other PSSE approaches use similar correction instructions and may benefit from the evidence produced in this thesis.

Evidence and criticisms on PSSE and other exercise therapies

While Schroth may have shown some of the most promising evidence, the argument for or against PSSE and other forms of exercise therapy is a long and exhaustive one, but most importantly it is a debate related to the scientific evidence. Literature reviews of PSSE studies from the early 2010's showed a severe lack of Level I and II evidence from randomized controlled trial studies and that the early prospective cohort studies were of poor quality with questionable reporting of results and statistics[2,9,11,76,80,81]. Another finding from these reviews was a lack of long-term follow up studies, creating doubt and a poor evidence base for the sustained effects of PSSE[2,9,11,76,80,81]. Included in these reviews was criticism of a study on the efficacy of the Schroth Method in AIS in Turkey for its lack of proper statistical measures and ambiguity in discussion[16,76,80]. Criticisms of exercise treatment studies continues due to pointing out risk of bias and inability to have long term controls[16,80,81]. Although there is indeed a need for more randomized controlled trials to establish quality evidence in exercise therapy, the ethical considerations and feasibility of having a non-intervention control group is still a complex one[81].

In a 2012 Cochrane review of exercises for AIS the low number of high quality evidence was not enough to support nor refute the effectiveness of exercise as a treatment[76]. The search had only found two studies both of which deemed of low value, but that suggested exercise was more effective than alternative treatments[76].

To address limitations outlined in these reviews, the SRS non-operative committee and SOSORT has created recommendations to help standardize and improve the coherence of research in PSSE studies[2,82]. It is recommended that PSSE aims to prevent curve progression during growth first and foremost, to be used in harmony with bracing treatments and during weaning, and that PSSE practice should be tailored towards the individual patient with a focus on auto-correction in 3-dimensions that can aid daily function[2]. Members from SOSORT had also previously agreed that the goals of conservative treatment should be to stop curve progression, prevent or treat respiratory dysfunction, prevent or treat pain syndromes, and to improve the aesthetics[9]. Currently the newest SOSORT guidelines from 2016 reiterate the same sentiments from previous guidelines regarding standardization of research study designs and have updated the levels of evidence available for different non-operative treatments[9]. Within a period of a few years leading up to the newest 2016 SOSORT guidelines, several randomized controlled trials were published, with more still being conducted, but standardization still limits the generalizability of these studies[9].

PSSE and exercise has been shown to help reduce stress and improve health and fitness, and thus body image[45]. PSSE therapy based studies continue to be published showing encouraging results for HRQL, function, and radiographic parameters but insufficient follow-up duration and issues with control groups are still the predominant criticism needing to be addressed[2,11,76,80]. The aforementioned SOSORT guidelines have and continue to stress the emphasis to create more randomized controlled trials and potentially longer follow-up studies, where possible, in order to promote and validate exercise therapy as a useful approach[2]. Within a small time frame, even since the newest guidelines, there has been warranted optimism for the successful publication of results from controlled trials and an ongoing multi-centre study conducted on Schroth exercises[12,14,15,72,74]. The results show promise for PSSE treatment and provide an improved justification that PSSEs are worthy of investigating[9,12,14,15,74].

As noted in a review from the early 2010's, PSSE based out-patient programs are more widely available showing growth in the appreciation for diverse approaches to treatment[81]. Continued adoption of the standardization guidelines for studies on PSSE will help progress the evidence base to reveal the use of this therapy and help provide further informed choice and autonomy to the individuals and their families[9,82].

Overall, the emergence of exercise's usefulness to the patient is hopeful as studies thus far show the possibility for reducing the Cobb angle, improving back asymmetry, postural stabilization, improving breathing function in specific cases, and improving pain symptoms[2,13]. These scoliosis-specific exercise treatments may also provide greater improvements to the psychosocial functioning and quality of life for patients when compared to other conservative treatments[2,13,71,72]. However, regardless of its benefit, further action must be taken to come to a consensus on research guidelines and practice so clinically relevant high quality research can be conducted to close the knowledge gaps and benefit patients, as well as clinicians[9,82]. As clinicians still hesitate to adopt PSSE into the standard of care in North America research on the immediate effects is needed to provide validity evidence to PSSE treatment practice and so that clinicians can make evidence-based decisions towards the role of PSSE in care[83].

Ultrasound imaging

Spinal curves at all stages of treatment have typically been measured from radiographs. However, due to worries of increased breast cancer from repeated exposure to ionizing radiation from these radiographs, safer alternative methods of assessment have been considered[84]. Assessment tools such as surface topography and magnetic resonance imaging have been suggested but have their own limitations to consider. Surface topography allows collection of 3D information but lacks sufficient correlation to replace Cobb angle measurements on radiographic images[27]. Magnetic resonance imaging allows detailed imaging of the spine but due to its supine positioning, underestimates the curve magnitude, in addition to being costly and lengthy in time[27]. Development of the dual x-ray slot scanning technology such as with the EOS system allows radiographs to be obtained with up to 25 times less radiation but there is still an ethical concern if using for many repeated measurements.

Ultrasound (US) imaging is a non-ionizing imaging method that was first proposed by Suzuki et al. as a novel way to assess the spine[27,85]. The benefits of US imaging are that it allows real-time collection of information, the technology is more cost effective than other methods, and it can be used in a portable system[27]. Over the past decade, much research had been conducted by Dr. Lou's team to investigate the reliability, validity, and feasibility of using US imaging to assess the spine[20–22,25–27]. Early research with spine models identified that in US images seeking to provide adequate information about the structures affected by scoliosis, the spinous process (SP), transverse process (TP), and laminae of spine were the most detectable using US imaging[27,85,86]. *In-vitro* studies with cadaver vertebrae and spine phantom models were used to validate the landmarks that could be used with the US imaging method to estimate the traditional measurements[27,86]. The center of pedicle method (CPM) is radiographic measurement method that lead to the current center of lamina (COL) ultrasound measurement method. The CPM measurements, derived from lines connecting the pairs of pedicles of the vertebrae on a radiograph, were compared to the standard Cobb angle measurements obtained from the endplates on retrospective radiographs[27]. Simultaneously, researchers explored other landmarks that may be found in US images that could lead to measurements comparable to traditional radiographic measurements[27]. The intra and inter-rater reliability using the CPM was comparable to values found in radiographic measurements[19,27,85,86]. Since the use of the pedicles to obtain a

Cobb angle was comparable to using the traditional UEV and LEV landmarks in the Cobb method, the CPM provided verification that other vertebral landmarks could provide similar curve measurements. Since the pedicles and laminae overlap, this verified the theoretical use of the laminae for measuring curves in US images[27]. This led to the development of the center of lamina (COL) method in US image analysis, which is a measurement created by drawing a line connecting the pair of laminae of a vertebral level in the reconstructed US image to obtain the curve angle and vertebra rotation measurements[19,27,86].

Continued *in-vivo* studies with larger sample sizes have shown that US imaging can provide high intra and inter-rater reliability for both coronal curve measurement as well as vertebral rotation measurements using the COL method[20–22,25–27,86]. Measurement comparisons to Cobb angles from radiographs provided validation that the US imaging measurements using the COL method provides curve angle magnitude estimates with a difference that is less than 5° which is equivalent to the clinically accepted error value for Cobb angle measurements[21,22]. Studies by Wang et al and Chen et al. showed that axial vertebral rotation (AVR) measurements taken using the COL method on 3DUS imaging had high intra and inter-rater reliability (ICC>0.90)[25,26]. Additionally, AVR measurements in US imaging had good *in vivo* agreement to AVR measurements using the Aaro-Dahlborn method in magnetic resonance images with 0.2º absolute bias and 95% limits of agreement between -1.4º and 1.8º [25,26]. Using 3D US imaging, lateral deviation measurements have only been studied once prior demonstrating high reliability (ICC>0.90) with a mean absolute difference of <7mm on a PA US image[87].

Studies have also looked at the ability of US imaging to detect curve progression as well as its ability to predict the amount of curve correction that can be achieved from surgical correction of the spine[21,23,24,88]. Young et al. had shown that US imaging may be a useful clinical tool to detect progression using a 5° threshold with 0.91 specificity and 0.83 sensitivity[21]. Ultrasound imaging has also recently shown promise to detect radiologic curve progression with good sensitivity (>0.90) and a small negative likelihood ratio (LR-=0.08) using a 4° progression threshold[24]. This indicates that any curve increase less than 4° on 3DUS can be considered non-progression[24]. Two studies to assess surgical candidates with AIS showed that US imaging can provide high intra and inter-rater reliability in maximal prone bending positions to assess curve flexibility [23,88]. Pre-operative US imaging curve correction angles during side-bending presented higher correlation to the curve correction achieved post-operatively than the predicted curve correction from pre-operative supine bending radiograph[23,88]. However, prone radiographs showed significantly better prediction of vertebral rotation and translation correction that could be achieved surgically compared to lateral side-bending radiographs[89]. Khodaei et al. demonstrated good intra and inter-rater reliability with US curve angle measurements in prone, maximal side-bending, and standing[35]. Khodaei et al. also found that the effect of removing gravity from standing into a prone position, resulted in curve magnitude reductions up to 53% without any additional forces in participants with moderate curve severities (29.4°±8.6°, range of 14°-50°)[35]. Finally, the feasibility of using US imaging to help in brace casting for individuals with AIS has been shown but this application is beyond the scope of this summary[90]. The development of 3DUS imaging described above makes it possible to repetitively assess the posture of patients with AIS in different test positions without worrying about radiation exposure. However, considerations to operator and training costs, time demands, and body interactions in scanning should be made before full adoption to clinical use.

Study rationale

With PSSE becoming recognized by the SRS, more scientific evidence is needed to help improve clinical decisions and inform patients on their treatment options[8]. The Schroth and BSPTS methods of PSSE boast the largest number of trained therapists worldwide, an international network on trainers, while also having the most published research about its outcomes[14,16,81,91]. In addition, these schools of PSSE are among the top providers of certification for PSSE. By considering the existing evidence base and potential impact on clinical practice worldwide, investigating the Schroth and BSPTS methods of PSSE would help progress evidence-based clinical practice the most compared to the other PSSE schools. The Schroth and BSPTS schools of PSSE also have a large number of practitioners in North America so this research may also help provide local and national benefit by helping inform patients seeking PSSE treatment or helping clinicians make informed treatment decisions, in addition to improving the training of these therapists for best practice. The Schroth method of PSSE also has the greatest amount of randomized controlled trials underway and published which is the highest level of experimental evidence for PSSE[14,16].

However, the evidence on PSSE is still deemed to be lacking and skepticism has been expressed by clinicians, patients, and their families about the complexity of the movements needed to achieve curve corrections as well as what is happening to the spine when patients perform their PSSE corrections. Although PSSE therapists can visually track what effect PSSE has on the spinal profiles of their patients over time by reviewing follow-up radiographs, they are still unaware of how each of the PSSE positions influence the spinal measurements of their patients in real time. Therefore, there is a lack of quantitative evidence on the in-exercise changes that can occur and it is imperative to know whether exercise consistently have the desired positive changes to the spinal alignment without negative compensations. So, investigating the immediate effects of physiotherapeutic scoliosis-specific exercises is necessary for progression of the scientific evidence and practice. Researching the immediate-effects of an exercise through separation of the passive and active portions of that exercise can also help reveal the segmental effects of different exercise instructions on the spine. By separating the passive and active portions of exercises we can help clinicians understand what effect their instructions provide to the spine. In addition to this, understanding the in-exercise corrections sequentially will help determine how much correction patients can achieve independent of outside forces. Through understanding the immediate effects of PSSE instructions and the realistic capabilities of patients through empirical evidence, PSSE teaching and instruction may become more easily accepted and increased confidence in clinical evidence-based decision making.

At this point, only a single case study has described the immediate effect of scoliosis-specific corrections by retrospectively looking at radiographic measurements over the course of 30 months[17]. PSSE training occurred at 18 months and radiographs were obtained with and without PSSE corrections at 18 months as well as 30 months[17]. Over the course of the study the patient showed significant improvement in the lumbar curve but also worsening in the thoracic curve at a one year follow-up suggesting compensation may be occurring when one curve is corrected using exercises[17]. Of relevance, just after having learnt her BSPTS PSSE corrections, the results showed a 4° decrease in the lumbar curve and a 2° worsening in the thoracic curve between the relaxed standing radiograph and the corrected radiograph[17]. However, these small changes are within the margin for error for radiographic measurements and further investigation is needed. At 30 months, the magnitude of differences between in thoracic and lumbar curves in the with and without PSSE radiographs was larger; this may mean that the immediate effect of PSSE increases over time with practice[17]. This result is of interest because it shows preliminary evidence that PSSE may have immediate effects on the spine of patients and also that the thoracic and lumbar regions of the spine may be affected differently by PSSE. This study also suggests that PSSE may provide changes to the spine with unknown duration to an unknown degree over time, and the long-term effects can be studied in relation to immediate effects. This study represents low-level of evidence as it is only a case-study. Further, there was no therapist contact outside of the initial one-week intensive training period which could result in the patient incorrectly or suboptimally performing the PSSE corrections over the course of the study[17]. Additionally, this study patient had moderate to large curve magnitudes for which other conservative, or even operative treatment, may be indicated. Further, there is a lack of research on the effect PSSE for different curve magnitudes. This study is also limited to the immediate effect of standing corrections. Therapists would be interested in corrections achieved with PSSE's performed in many positions using different cuing strategies. Finally, since these standing corrections were not guided by the therapist at the time of assessment, results may reflect the patient's understanding and may not be a true reflection for what was instructed in the clinical setting. All in all, this single case study provided evidence that the immediate effect of PSSE can be detected, that compensations may occur but focused only on curve angle measurements for a single case in a single exercise position.

Investigating the immediate effect of PSSE's may also be of interest because the amount of initial in-brace correction has been found to be predictive of long-term treatment outcome and it is unknown if a similar relationship exists for PSSE[92–94]. Clin et al. originally proposed that since there was a correlation between the immediate in-brace correction and the compressive asymmetric loading of the frontal spine, according to the Hueter-Volkmann principle, this could mean that the progression of the curve could be predicted[94]. Future studies on the predictive ability of the initial or immediate correction in PSSE could assist with targeting treatment prescription to those most likely to benefit. However, before such future studies can be conducted, studies are needed to demonstrate the feasibility of assessing real time change and to provide an understanding on how PSSE immediately affects different regions of the spine using a wider array of measurements.

Research on AIS has focused in very large part on curve angles as the key clinical measure most used in diagnosing and determining the progression of AIS, and to a lesser degree on the angle of vertebral rotation (AVR)[6,31,32,95,96]. However, no research on PSSE has delved into assessing the entire frontal profile including the lateral deviation of the apex for AIS. The frontal profile, as measured by AVT, may provide information not fully captured by the curve angle[97–101]. Easwar et al. showed that, in CT scans, the correlation between AVT and Cobb angle, although significant, was less than previously proposed (r=0.66 vs. r=0.76) and is not perfectly linear[99]. AVT also had the lowest correlation to the Cobb angle among vertebral rotation, kyphosis, and lordosis measurements[99]. Additionally, AVT showed the greatest correlation to the rib hump index, more so than Cobb angle, while AVR showed the least correlation with the rib hump index[99]. Importantly to this link, greater SRS-22 satisfaction and self-image scores were correlated with the rip hump improvement post-surgery while higher thoracic AVT is also related to lower probability of good surgical self-image outcomes assessed by the Spinal Appearance Questionnaire[100,101]. In fact, one study found that only the size of the thoracic apical translation changed the general result of the SAQ[101]. These results suggest that AVT may represent a unique and complementary aspect of the deformity. AVT has long been used as an important clinical measure by surgeons treating doubles curves and the thoracic to thoracolumbar/lumbar ratio of the Cobb angle, AVR, and AVT is a large focus for the intended cosmetic changes[31–33]. So, if we are to investigate the immediate in-exercise corrections created by PSSE to the 3D spinal deformity, we should assess an array of spine measurements, including AVT, which are clinically meaningful to all members of health care team. In this way, we can bridge the understanding between surgical treatment measures and the adoption of conservative treatments.

There is warranted clinical and scientific need to investigate the immediate effect of PSSE to advance both knowledge and practice. With the great advancements to technology in ultrasound imaging we can use this mobile and ethical imaging tools to achieve this.

Chapter 3.

The Intra- and Inter-evaluator Reliability of Frontal and Rotational Spinal Profile Measurements for Adolescents with Idiopathic Scoliosis Performing Physiotherapeutic Scoliosis-specific Exercises Measured with Ultrasound Imaging

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Chapter prelude

In Chapter 2, we discussed the potential aetiologies, natural history, and general treatments for AIS. Specifically, towards the focus of this thesis, we introduced the evidence for physiotherapeutic scoliosis-specific exercise (PSSE) treatment, the Schroth method of PSSE, and the relevant literature on curve angles, AVRs, and AVT measurements using ultrasound imaging to assess the scoliotic spine. In doing so, we identified that there was a lack of scientific evidence for the immediate effects of PSSE as well as for AVT measurements in US imaging and PSSE research. To our benefit, we realized that given the recent developments in US imaging technology, we were in a unique position to ethically assess the effects of PSSE on the spine using US imaging compared to repeated exposure of our potential participants by ionizing radiation from traditional radiography. Clinically and anecdotally, there has also been long standing skepticism over the feasibility of achieving clinically meaningful corrections to the spine through PSSE and if compensation could occur elsewhere. Clinicians also sought more information to provide their patients during instruction and wanted to know which exercises provided the most corrections. By linking these clinical concerns to the scientific gap, we provided justification to study the immediate effects of Schroth PSSE. However, before we can study these effects we must determine if our US measurements are reliable for researching PSSE.

Having provided the scientific rationale and clinical context of this thesis, this chapter will establish the intra and inter-evaluator reliability of the thoracic and lumbar curve angles, AVR, max AVR twist, AVT, and interapical distance measurements. After a brief reintroduction of the study rationale, we describe our measurement procedures for the scans of 36 total participants in 16 PSSE-related positions. We report the intra-evaluator reliability, comprised of 13 participant image sets measured twice by a single evaluator, and the inter-evaluator analyses, with 35 total participant image sets measured once each by two evaluators. Discussion from this chapter will address the adequacy of these US measurements for research on PSSE with comparisons to the reliability previously reported in US imaging studies on individuals with AIS. By reporting the reliability of the thoracic and lumbar curve angle, AVR, max AVR twist, AVT, and interapical distance measurements we can determine if studying the immediate effects of PSSE are feasible in a variety of positions. We also determine if AVT measurements are reliable enough to be investigated for further use.

Background

Adolescent idiopathic scoliosis (AIS) is a three dimensional (3D) spinal deformity characterized by abnormal lateral curvature and rotation of the spine[1,5]. AIS is diagnosed between 10 and 18 years old and affects 2-3% of all adolescents[1,3–5,41]. Idiopathic scoliosis is the most common type accounting for roughly 80% of all scolioses and females show increasingly higher prevalence of AIS compared to males as curve magnitudes increase[1,3–6]. In North America, milder curves (15 -25°) are observed without treatment to track progression while moderate curves (25-40°) are treated with bracing[2,8,9]. Finally, curves that exceed 45° may receive spinal surgery[1,2,5,8,9].

More recently, physiotherapeutic scoliosis-specific exercise (PSSE) has become recognized by the Scoliosis Research Society (SRS) to have potential benefits[2,8,11]. Patients also find exercise more socially acceptable compared to other conservative treatments[71]. Schroth PSSE's is the most widespread and researched form of PSSE[9,13]. Scoliosis-specific exercises focus on 3D self-correction of the spine, training with activities of daily living (ADL), and stabilization of the corrected posture[13]. Research quantity and quality has improved in recent years. Several randomized controlled trials have shown that PSSE can help reduce curve progression, assist in pain management, as well as improve self-image, strength and endurance[12,14–16]. However, more research is needed to determine the value of PSSEs because scoliosis-specific exercises are still not adopted as standard practice for scoliosis care in many countries[2,11]. The hesitation from primary care providers to adopt exercises may be, in part, due to a lack of information about the changes to the spinal alignment while performing these complex spine correction exercises.

Unlike bracing, the amount of immediate curve correction that physiotherapeutic scoliosis-specific exercises (PSSE) can achieve is still unknown[92,93]. Only a single case study has described the immediate effect of scoliosis-specific corrections during radiographic measurements. This case showed improvement in the lumbar curve but worsening in the thoracic curve for this patient assessed in standing[17]. This study showed greater immediate changes in thoracic and lumbar curve magnitude after training for one year demonstrating a learning effect[17]. The different changes between the thoracic and lumbar curves with the PSSEs may indicate that the thoracic and lumbar curves may have different responses, positive or negative, to PSSE. In this study, however, no therapist provided support after the initial training, potentially causing this patient with double curve to incorrectly perform the PSSE allowing for compensations in different regions of the spine.

Research into the immediate effects of exercise may also be justified because for bracing, the amount of initial in-brace correction is predictive of treatment outcome[92–94]. It is unknown if a similar relationship exists for PSSE. Xu et al. showed that an initial bracing curve correction of 10% or less predicted 38.5% of those with failed treatment outcome[92]. However, there needs to be a feasible and ethical way to assess how the various PSSE positions immediately affect the spine.

Surgeons and the families of patients also express skepticism on the feasibility of achieving meaningful corrections from PSSE. These concerns may stem from the complexity of the exercise instructions and the perceived difficulty for adolescents to overcome an unknown learning curve. Trained therapists have also shown interest in obtaining evidence about how the PSSE positions and instructions they give help patient achieve the corrections. Hence, there is a need to understand the immediate effects of PSSE.

Research on scoliosis treatments has focused most on the curve angle and, to a lesser extent, on the axial vertebral rotation (AVR)[29]. However, PSSE research has not focused on assessing the frontal profile by measuring the apical vertebral translation (AVT), even though it is an important measurement in surgical decision making and a clinical focus in conservative treatments[31–33]. Apical vertebral translation is measured as the lateral deviation of the middle of the apical vertebral body with respect to the central sacral vertical line (CSVL)[30]. Apical vertebral translation (AVT) has shown a significant negative correlation (rho= -0.29) to the SRS-22 self-image scores[98]. While AVT has often been neglected due to assumptions that it is encompassed in the Cobb angle measurement, AVT has shown the lowest correlation to the Cobb angle among vertebral rotation, kyphosis, and lordosis[99]. AVT also showed the greatest correlation to rib hump index, more so than Cobb angle[99]. Greater SRS-22 satisfaction and self-image scores also correlated with improvement in the rip hump post-surgery while higher thoracic AVT also related to a lower probability of good surgical self-image outcomes assessed by the Spinal Appearance Questionnaire[100,101]. These results suggest AVT may reflect an important complementary aspect of the deformity.

Despite radiography being the standard method to assess the scoliotic spine, this method is unsuitable to assess complex PSSE positioning and, even with the adoption of low dose EOS radiography systems, would be unethical to use due to the need for repeated exposure to radiation[18]. The development of award-winning 3D ultrasound (US) imaging protocols offer a unique opportunity to investigate the immediate effects of exercise that is radiation-free and ethically viable. Recently, 3D US imaging has shown promise to reliably assess AIS curve angles in standing, prone side-bending, and prone with good agreement to traditional Cobb angles on a radiograph[19–24,34,35]. Axial vertebral rotation (AVR) measurements taken using US imaging also had high intra and inter-rater reliability (ICC>0.90) and good *in vivo* agreement to AVR measurements using the Aaro-Dahlborn method in magnetic resonance image with 0.2º absolute bias and 95% limits of agreement between -1.4º and 1.8º [25,26].

Since PSSE positions involves use of isometric exercise movements and positions with high potential for instability, it is possible that these positions may impact the reliability of US measurements. AVT's, described as lateral deviation measurements in the study by Vo, have only been studied once prior in standing, demonstrating high reliability (ICC>0.90) with a mean absolute difference of <7mm on a PA US image[87]. In addition to this, no US imaging study has investigated the use of max AVR twist or interapical distance measurements in any positions.

Objective

The objective of this study was to determine the intra- and inter-evaluator reliability of thoracic and lumbar curve angle, max AVR, max AVR twist, AVT, and interapical distance measurements taken from 3D ultrasound images of adolescents with idiopathic scoliosis in 16 habitual and PSSE positions.

Methods

Study design:

This was a cross-sectional study to determine the intra and inter-evaluator reliability of 3D ultrasound image measurements taken from Schroth exercise-trained volunteers participants in 16 different exercise-related positions.

Clinical participants:

A consecutive sample of 36 volunteer was recruited from participants in the Schroth Exercise Trial for Scoliosis (SETS) at the Stollery Children's Hospital in Edmonton, Canada. Prospective participants received email invitations to volunteer from our research coordinator.

Participant inclusion criteria were: 1) between 10 and 18 years of age at the time of Schroth PSSE training, 2) diagnosis of adolescent idiopathic scoliosis, 3) having completed at least three months of supervised Schroth PSSE exercise training, 4) a major curve with Cobb angle between 10° and 45°, and 5) no corrective spine surgery, torso or lower extremity surgery, or trauma affecting function. Participants with or without a brace, those who have completed brace treatment, and any level of skeletal maturity according to the Risser sign were eligible for this study.

Ethics:

Ethics approval was obtained from the University of Alberta Health Research Ethics Board on July 6th, 2016 (Study ID: MS2_Pro00066486). An amendment to include new positions, (side-lying and a final standing scan), and the inclusion of apical vertebral translation measurements was approved on February 23, 2017. Volunteers over the age of 14 provided written consent prior to participating. Individuals younger than 14 years old provided written assent with parents or guardians providing written consent.

Data acquisition:

In a single 1.5 hr visit, participants were scanned in 16 positions. Upon arrival, participant age, height, and weight were recorded. Participants then changed into a hospital gown to expose the full spine. Spinous processes were palpated to place a sticker at C7 and S1[102]. Warmed US scanning gel was applied liberally to the spine to ensure adequate ultrasound signal. The transducer head was positioned perpendicular to the back surface and moved by the evaluator to follow the contour of each participant's curves. Each scan lasted approximately 10-30 seconds. A research assistant operated the SonixTABLET interface while the evaluator moved the transducer.

Scanning procedure:

All participants were scanned in a total of 16 positions selected to reflect common exercise positions and instructions in Schroth scoliosis-specific exercise programs (Figure 1). Of note, only the final 24 participants were scanned for the side-lying positions and the final standing position after study protocol amendment.

1) ***Habitual standing*** (Figure 1A)

   Participants stood in their habitual upright posture within a frame to provide tactile feedback and minimize body sway.

2) ***Habitual prone*** (Figure 1B)

Lying prone on a therapy table with arms elevated and hands overlapped under the forehead.

3) ***Prone side-bending to the left and 4) right*** (Figure 1C and 1D)

Maximally side-bending to the left (or right) in the prone position without shifting the pelvis.

5) ***Prone with passive correction*** (Figure 1E and 1F)

Positioned prone with passive supports under the torso and select limbs. Bean bags were placed under the shoulder on the convex thoracic side and under the breast on the concave thoracic side. The arm on the convex thoracic side was abducted to 90° with shoulder external rotation and the elbow bent to 90° with the forearm supported on a foam roller. Lastly, a foam roller was placed under the pelvis of the participant with extra bean bags beneath the hip on the concave side of the lumbar curve.

6) ***Prone with active correction*** (Figure 1G)

In the same as position as #5, the participant actively adjusted their spinal alignment. Components of the corrections were: elongation of the spine, shifting their curves to towards midline, derotating the shoulder block, pushing the elbow on the thoracic convex side laterally, derotation of the thoracic and lumbar segments, and rotational angular breathing (RAB)[13].

[RAB includes maintaining or creating a thoracic kyphosis during inhalation and expansion of the concave torso area while during exhalation. Muscles on the convex side of the torso activate to limit prominence deformation.]

7) ***Prone with active correction and hip flexion*** (Figure 1H)

In the same position and with the same corrections as #6, the participant was instructed to push their knee on the concave lumbar side, against the table using hip flexors.

[Hip flexion is used to activate the psoas muscle on the lumbar concave side. Due to its origin on the lumbar transverse processes, this unilateral psoas activation is expected to assist in pulling the lumbar curve to midline and derotating the vertebral bodies.]

8) ***Habitual side-lying*** (Figure 1I)

For the most typical right thoracic with left lumbar curve pattern, participants were lying on their left side (thoracic concave) on the therapy table. Knees were bent to 90°

for stability and two bean bags were placed under the head for neck support. The bottom arm was extended overhead, and the top arm was straightened over the hip.

9) ***Side-lying with passive correction*** (Figure 1J)

In the same position as #8, two bean bags were placed under the left shoulder (thoracic concave side) and under the apex of the lumbar curve. The top arm was abducted to 90° with the shoulder in external rotation and the elbow bent to 90°. The top hand rested on a foam roller for support. The top leg was straightened and rested on foam padding.

10) ***Side-lying with active correction*** (Figure 1K)

In the same position as #9, the participant actively adjusted their spinal alignment. The components of the corrections were: elongation of the spine, shifting their curves to towards midline, derotating the shoulder block, pushing the elbow on the top side laterally, derotation of the thoracic and lumbar segments, and rotational angular breathing (RAB)[13].

11) ***Side-lying with active correction and leg lift*** (Figure 1L)

Adding to instructions in position #10, the participant was asked to abduct their top leg and extend it in the caudal direction, pulling the pelvis in tilting down on the side with the leg elevated.

12) ***Habitual sitting*** (Figure 1M)

Participants sat in their own habitual posture on an exercise ball with their legs spaced at shoulder-width and hips and knees at 90°.

13) ***Sitting with active correction*** (Figure 1N)

From sitting, the participant adjusted their spinal alignment. The components of the corrections were: elongation of the spine, shifting their curves towards midline, derotating the shoulder block, pushing the elbow on the thoracic convex side laterally with the hand holding a pole, pushing the elbow on the lumbar convex side upward and laterally with another pole in hand, derotation of the thoracic and lumbar segments, and rotational angular breathing (RAB)[13].

14) ***Sitting with active correction and hip flexion*** (Figure 1O)

In addition to instructions in position #13, the participant was asked to unilaterally lift their knee on the lumbar concave side, against an anchored yoga strap wrapped around their lower thigh.

[Hip flexion is used to activate the psoas muscle on the lumbar concave side which is expected to assist in pulling the lumbar curve to midline and derotating the vertebrae.]

15) ***Standing with active correction*** (Figure 1P)

In upright standing, the participant adjusted their spinal alignment. The components of the corrections were: elongation of the spine, shifting their curves to towards midline, derotating the shoulder block, pushing the elbow on the thoracic convex side laterally with the hand holding a pole, pushing the elbow on the lumbar convex side upward and laterally with another pole in hand, derotation of the thoracic and lumbar segments, and rotational angular breathing (RAB)[13].

16) Final habitual standing

Identical to position #1, the participant was asked again to stand in their habitual standing posture. This repeated testing allowed determining if there were any carry over effects due to corrections applied in previous positions.

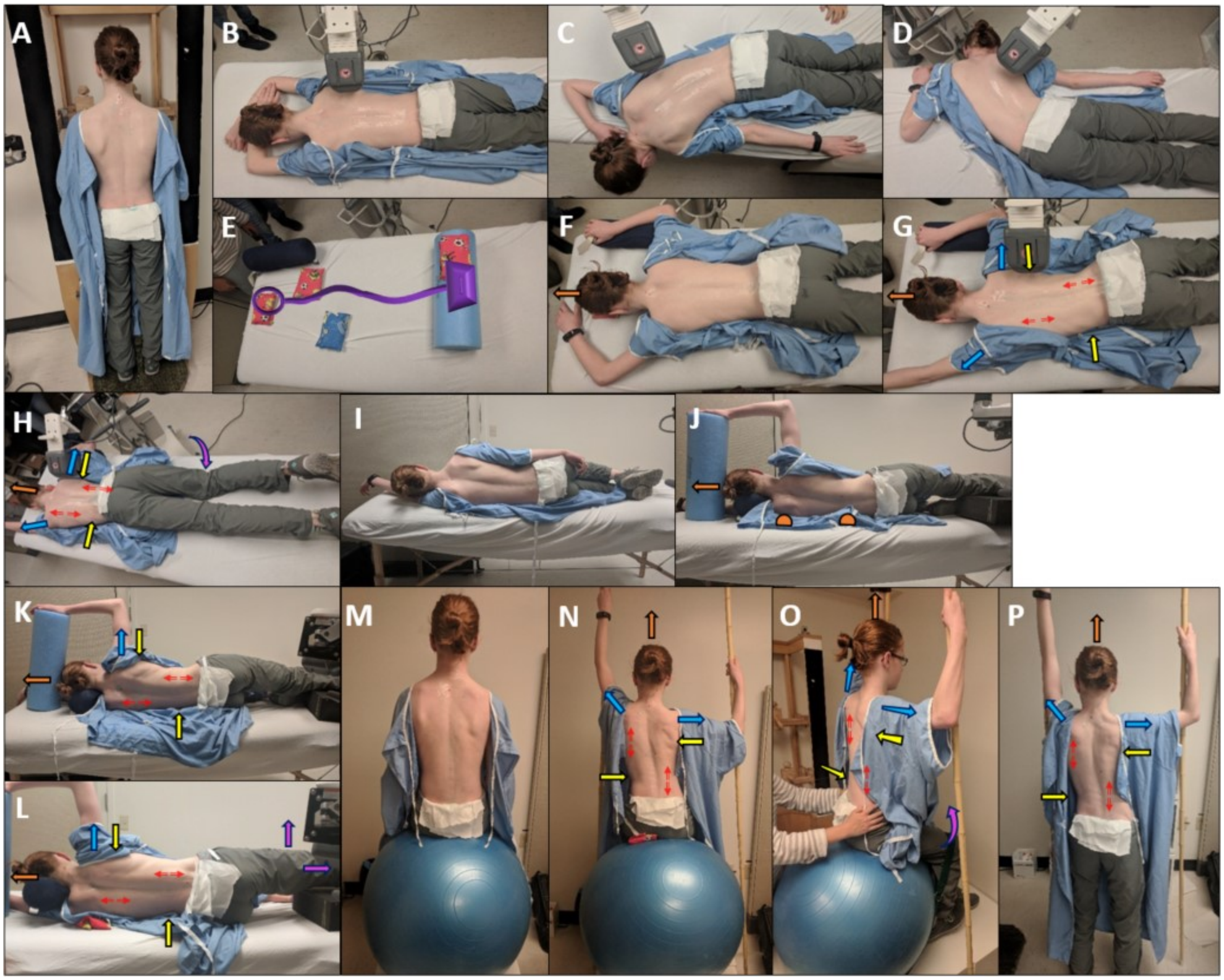

Figure 1. Habitual positions and Schroth exercise positions for a thoracic and lumbar double curve pattern.
Orange arrows illustrate trunk elongation. Blue arrows illustrate the direction of active forces at the upper extremities. Yellow arrows show the direction of torso side-shift corrections towards midline from the curve convexities. Purple arrows represent lower extremity movements with hip flexion and leg abduction with caudal push. Finally, paired red arrows demonstrate the intended expansion of the ribs at the thoracic curve concavity, and filling of the dorsal depression from thoracic and lumbar segment derotation using rotational angular breathing (RAB). A) Habitual standing in a scanning frame, B) Habitual prone, C) Side-bending left, D) Side-bending right, E) Placement of passive supports with overlaid illustration of a scoliotic spine, F) Passive prone, G) Active prone, H) Active prone with hip flexion, I) Habitual side-lying, J) Passive side-lying, K) Active side-lying, L) Active side-lying with leg lift, M) Habitual sitting, N) Active sitting between two poles, O) Active sitting with hip flexion against a strap, P) Active standing between two poles.

Instrumentation:

Images were acquired using a SonixTABLET system with a 60mm curvilinear 128-element C5-2/60 GPS convex transducer and a SonixGPS system (Analogic Ultrasound - BK Medical, Massachusetts, USA)(Figure 2). The SonixTABLET was calibrated for scanning at an imaging depth of 6cm, a frequency of 2.5MHz, a frame rate of 32 Hz, and a 10% gain based on parameters from previous studies[22,23,34]. Scans were performed in the cephalocaudal direction following the spine from the C7 to S1 (Sacrum) for each of the positions. The voxel size of the image was set to 0.5mm width, 0.5mm height, and 1mm depth for exporting from the SonixTABLET to the computer for image analysis. These scans provided a stack of 2D consecutive transverse images which were exported and merged into a 3D image file using a custom program[22].

Figure 2. The ultrasound machine comprised of the SonixTABLET system and SonixGPS system.

Image measurement:

Two evaluators (E1, E2) digitized measurements on each image using custom software MIAS (Medical Image Analysis Software) v10.0.21 Professional Edition. Both evaluators received similar training measuring ultrasounds prior to analysing the study images. Training consisted of practice measurements on a set of 10 images and two phantom spines within a period of 3 weeks after demonstrations by an evaluator with experience measuring over 100 images in standing with high reliability ($ICC_{2,1}$ >0.8) and standard error of measurement (SEM) less than 2.8° for curve angle measurements[34]. The practice set of 10 images was measured twice and any curve measurement differing by more than five degrees were discussed. Evaluator 2

(E2) trained with supervision by E1 but both evaluators did not differ in terms of experience when measuring these images. Both evaluators were blinded to the participant's clinical information, treatment history, and to any previous measurements.

The two evaluators used the center of lamina (COL) method to measure the curve angle, max AVR, and AVT[19–21,25–27,34]. The centers of the laminae from the left and right side of each vertebra were located and a line drawn to connect each pair on the frontal US image (Figure 3)[19,26,27,86]. This line is referred to as the COL line. Each pair of laminae in the frontal US view was viewed on the corresponding transverse US image for the level of interest to aid in landmarking (Figure 4)[19,26,27,86]. The COL method has been validated showing good agreement with the Cobb method on radiographs[20,27]. In previous studies, this measurement technique has also demonstrated high reliability ($ICC_{2,1}$ >0.8) for curve angle measurements in standing, prone, and side-bending US images for scoliosis curves and high intra and inter-rater reliability ($ICC_{2,1}$ >0.8) for AVR measurements in sitting[19–21,23,25–27,34,35]. Using similar software, lateral deviation measurements have shown high reliability (ICC>0.90) with a mean absolute difference of <7mm on a PA US image[87].

Curve angle measurements were extracted from the two most tilted pairs of laminae within each curve in the frontal view, representing the upper and lower end vertebrae of each curve (Figure 3). The same levels as the selected end vertebrae for the thoracic and lumbar curve regions for habitual standing were used throughout the extraction of all other positions to observe the change in the curve segment of interest. Negative curve angle values denoted a leftward convexity whereas a positive value represented a rightward convexity. The AVR was measured by the tilt of the laminae in the transverse US view (Figure 4) and was extracted at the vertebral levels above, at, and below the apex of each curve observed in habitual standing. The levels at and surrounding the apical vertebra chosen in standing were used throughout measurement extraction in the other 15 positions. The largest of the three AVR measurements for each thoracic and lumbar region were used to calculate the difference between the maximal rotation in the thoracic curve and the opposing maximal rotation in the lumbar curve, akin to spinal twisting, as follows for each position / exercise:

$$\boldsymbol{Max\ AVR_{Twist} = Max\ AVR_{Thoracic} - Max\ AVR_{Lumbar}}$$

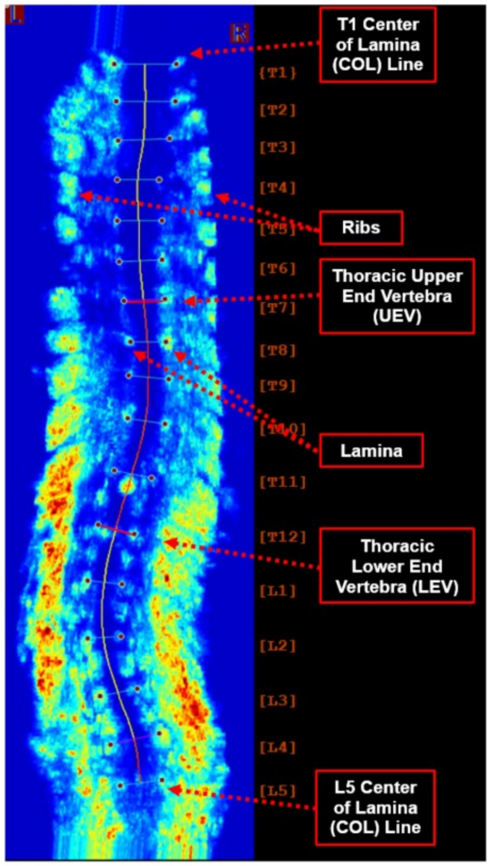

Figure 3. Frontal view of an ultrasound image in standing containing the hyperechoic regions corresponding to the ribs and lamina.
The spinous processes do not generate a reflection of the ultrasound signal perpendicularly to the probe and produce a shadow between the laminae. An automatically generated line follows the curve of the spine and is drawn from the center of the connection between each vertebral level's center of lamina (COL) lines. Also labelled is the COL lines for T1, L5 and the upper (UEV) and lower end vertebrae (LEV) of the thoracic curve.

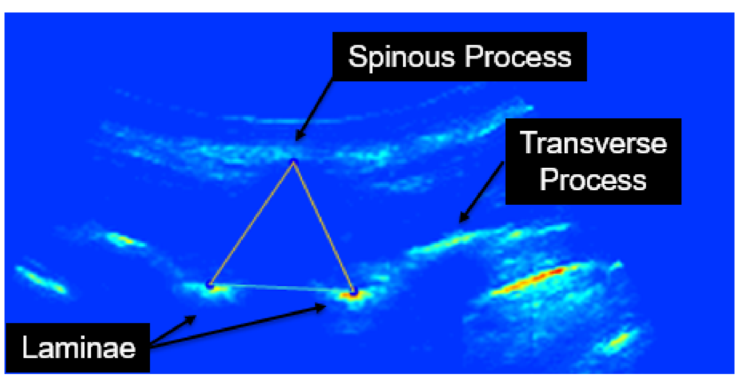

Figure 4. A transverse ultrasound view of the spine illustrating the location of the lamina, transverse process and the shadow corresponding to the location of the spinous process.

For AVT measurements on radiographs, the levels of C7 and S1 are typically used as reference points[30]. For ultrasound image measurements, the levels of T1 and L5 were chosen instead due to their improved signal quality compared to C7 and S1. Consequently, our "central vertical line (CVL)" was determined from the vertical of the frontal US image centered at the midpoint of the COL line for L5. As a result, the AVT measurements were obtained by measuring the lateral deviation of the midpoint of the COL line, produced automatically, for the curve apices compared to the CVL (Figure 5). A positive AVT value signified that the curve apex was to the right of the CVL whereas a negative value would mean that the apex fell left of the CVL. We calculated the interapical distance using the difference between the thoracic and lumbar AVT measurements, as follows[103]:

$$\boldsymbol{Interapical\ Distance\ = AVT_{Thoracic} - AVT_{Lumbar}}$$

Thoracic, lumbar AVT and interapical distance were not measured in prone side-bending left and right due to lack of clinical meaning. All images were analyzed once by both evaluators. Evaluator 2 also repeated measurements on 13 consecutive complete images sets available, with at least one-week separation, to determine the intra-evaluator reliability of the measurements. Of these 13 image sets, three were image sets where the side-lying and final standing positions where not obtained. Separation was needed to reduce the potential for recall effects and memory bias.

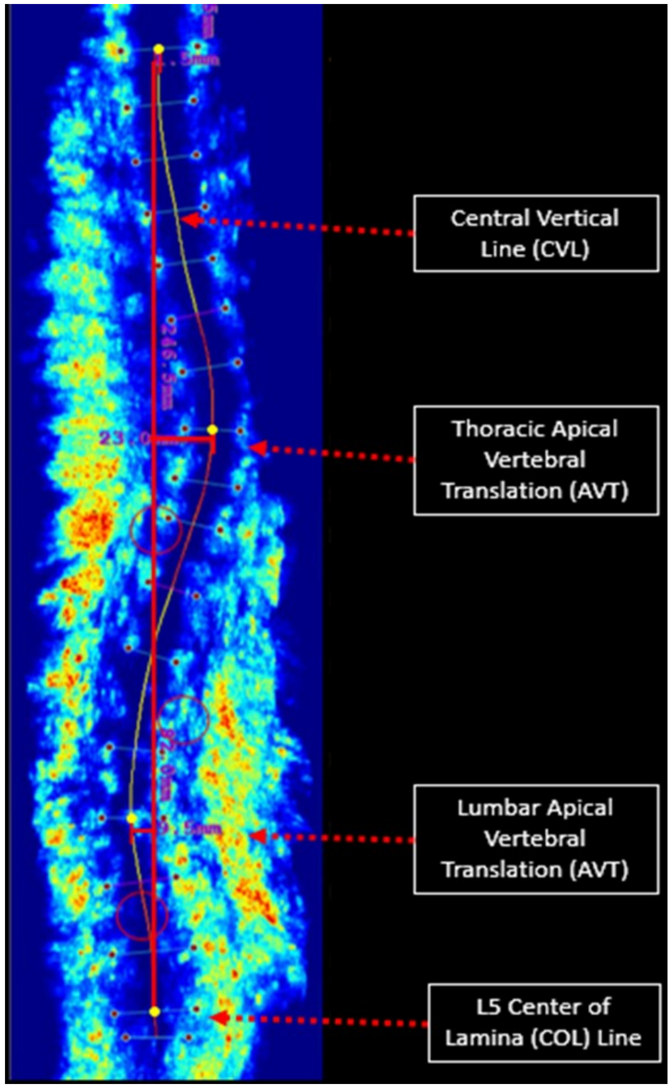

Figure 5. A coronal ultrasound view of the spine illustrating the apical vertebral translation (AVT) measurements.
AVT measurements at T8 and L2 relative to the Central Vertical Line (CVL), extending vertically from the middle of the L5 center of lamina (COL) line.

Data analysis:

Means and standard deviations were reported for continuous sample description characteristics. Frequencies and percentages were reported for categorical descriptive variables. The intra-evaluator reliability of the thoracic and lumbar curve angle, max AVR, max AVR twist, AVT, and interapical distance measurements was assessed using the intra-class correlation coefficient (ICC [3,1], two-way mixed – consistency), using the two repeated measurements from the subsets of 13 participants with repeated measurements from E2 in the each of the 16 positions completed.

The inter-evaluator reliability of the thoracic and lumbar curve angle, max AVR, max AVR twist, AVT, and interapical distance measurements for the 16 positions was obtained using the intraclass correlation coefficient (ICC [2,1], two-way random - absolute agreement) with the measurements of E1 and the first measurement by E2 for all 36 participants.

According to Lohr et al., the accepted minimal levels of ICC reliability are 0.7 for group comparisons in research and 0.9 and above for individual comparisons[104]. Means, standard deviation (SD), and SEM for these measurements were also calculated along with a 95% confidence interval [CI95] of the ICC values[105]. All statistical analyses were completed using IBM SPSS Statistics version 25 (IBM, Armonk, New York, USA).

Results

Usable data

Scans from only 24 participants were available for all side-lying and the final standing positions. Of these 24, all scans from one participant were excluded from the analyses for low image quality. This was due to lack of signal reflection and system artifact due to a recording hardware glitch. Therefore, 13 and 35 participants scans were available for all other positions for intra- and inter-evaluator reliability analyses, respectively. For the side-lying and final standing positions, only 10 and 23 participant sets were available for intra- and inter-evaluator analyses, respectively.

Additionally, for intra-evaluator reliability, two scans, each from a different participant, were removed due to image artifact: one in prone side-bending right and one in sitting active with hip flexion. Further, one measurement was removed from intra-evaluator analysis due to artifact for the thoracic curve angle in sitting active with hip flexion, and one for the lumbar curve angle in the prone active position. In addition, 30 thoracic AVT measurements across 14 positions and 10 lumbar AVT measurements across 7 positions were omitted by the evaluator (34 missing interapical distance measurements out of 181 pairs of measurements).

For inter-evaluator reliability, 24, out of 500 total scans, from 12 of the 35 participants were removed due to image artifact: one in prone side-bending left, two in prone side-bending right, one in side-lying passive, three in habitual sitting, six in active sitting, five in active sitting with hip flexion, and six in active standing. Further, two measurements were removed for the thoracic curve angle in the prone active with hip flexion and two in habitual sitting. Five were removed from the lumbar curve angle analyses in the prone passive, prone active, habitual side-lying, side-lying passive, and sitting active positions. Furthermore, 37 thoracic AVT measurements across 13 positions and 13 lumbar AVT measurements across 10 positions were omitted by the evaluator (44 missing interapical distances out of 469 pairs of measurements).

Participant Characteristics

The 13 female volunteers in the intra-evaluator reliability analysis had a mean age of 15±3 years old and their mean thoracic and lumbar curve angles in standing were 11±8° right convex and 13±7° left convex, respectively. Ten participants had a thoracic and lumbar curve and three had a single lumbar or thoracolumbar curve. The Schroth curve types were 10 4CP's (double curves with pelvis shifted on the lumbar concave side), two 4C's (double curves with balanced pelvis), and two 3CP's (dominant thoracic curve with pelvis on the thoracic concave side).

The 35 females in the inter-evaluator reliability analysis presented a mean age of 15±3 years old and their mean thoracic and lumbar curve angles in standing were 16±8° right convex and 17±9° left convex, respectively. Twenty-eight participants had a thoracic and lumbar curve; three had a single thoracic curve and four had a single lumbar or thoracolumbar curve. The Schroth curve types were 22 4CP's, five 4C's, seven 3CP's, and two 3C's.

Intra-evaluator Reliability

Table 1 shows the Intra and inter-evaluator reliability statistics with the mean thoracic and lumbar curve angles, max axial vertebral rotations (AVR), apical vertebral translations (AVT), max AVR twist and interapical distance for all 16 positions.

For intra-evaluator reliability, most measurements in all 16 positions (113/122) had $ICC_{3,1}$ values greater than 0.70; 68 of which were above 0.90. The $ICC_{3,1}$ did not reach the 0.70 threshold for 10 values from only four of the eight measurements and from seven of the 16 different positions. These measurements were the: thoracic curve angle (in prone side-bending right, side-lying active, and side-lying active with leg-lift), lumbar curve angle (prone active, side-lying active, and final standing), lumbar max AVR (prone side-bending left and habitual sitting), and max AVR twist (habitual sitting).

Excluding positions containing $ICC_{3,1}$ values below 0.7, the SEM range and median were 1.7° to 4.1° (3.0°) for the thoracic curve angle, 2.6° to 4.2° (3.2°) for the lumbar curve angle, 0.9° to 2.1° (1.5°) for the lumbar max AVR, and 1.3° to 3.6° (2.3°) in the max AVR twist. For measurements with all ICC meeting the 0.70 threshold, SEM value range and median were 0.9° to 2.5° (1.6°) in thoracic max AVR, 1.1mm to 4.3mm (2.1mm) for the thoracic AVT, 1.4mm to 6.1mm (2.3mm) for the lumbar AVT, and 0.9mm to 5.8mm (2.3mm) for the interapical distance.(Table 1)

Inter-evaluator Reliability

Similarly, the inter-evaluator reliability for most measurements in the 16 testing positions (113/122) was greater than 0.70 with 42 of those being greater than 0.90. Only nine ICCs from three measurements in five different positions had values less than 0.70. These measurements were the: thoracic curve angle (in prone side-bending left, prone side-bending right, and habitual side-lying), lumbar curve angle (prone side-bending left, prone side-bending right, habitual side-lying, side-lying active, and side-lying active with leg lift), and lumbar max AVR (prone side-bending left).

Excluding positions containing $ICC_{2,1}$ values below 0.7, the SEM range and median were 2.4º to 4.8º (3.1º) for the thoracic curve angle, 2.0º to 6.0º (3.7º) for the lumbar curve angle, and 1.4º to 2.7º (2.0º) for the lumbar max AVR. For measurements with all ICCs meeting the threshold, SEM value range and median were 1.0º to 2.5º (1.7º) in thoracic max AVR, 1.9º to 3.1º (2.6º) in the max AVR twist, 1.7 to 5.5mm (3.0mm) for the thoracic AVT, 1.9 to 6.8mm (3.8mm) for the lumbar AVT, and 1.9mm to 6.5mm (3.6mm) for the interapical distance. (Table 1)

The thoracic and lumbar AVT, interapical distance, and thoracic max AVR were the among the most reliable measurements for intra and inter-evaluator reliability, having no value less than our 0.70 ICC threshold regardless of position. Of all intra- and inter-evaluator measurements, the thoracic AVT measurements yielded the most values reaching ICC values greater than 0.90. All thoracic AVT intra-evaluator $ICC_{3,1}$ values and all inter-evaluator $ICC_{2,1}$ values were above 0.90 with only one exception in habitual sitting ($ICC_{2,1}$=0.89).

Table 1. Means, standard deviations, standard error of measurements, and the intra and inter-evaluator reliability coefficients for the thoracic and lumbar curve angles, max AVR, AVR twist, AVT and interapical difference for all 16 positions measured by 3D ultrasound imaging

	Thoracic Curve Angle					
Position	Intra-evaluator Reliability			Inter-evaluator Reliability		
	Mean ± S.D. (°)	SEM (°)	ICC[3,1]	Mean ± S.D. (°)	SEM (°)	ICC[2,1]
Habitual Standing	10.5 ± 8.3	2.2	0.92	15.6 ± 8.3	3.0	0.86
Habitual Prone	7.9 ± 8.0	2.4	0.91	10.6 ± 6.9	3.0	0.74
Prone Side-bending Left	23.6 ± 9.9	3.2	0.91	21.6 ± 6.9	4.7	**0.62***
Prone Side-bending Right	-14.1 ± 11.0	6.2	**0.56***	-8.5 ± 7.8	5.5	**0.54***
Prone Passive	5.6 ± 7.5	1.7	0.95	9.1 ± 9.5	3.4	0.84
Prone Active	4.9 ± 7.7	3.3	0.80	6.2 ± 5.8	2.9	0.78
Prone Active + Hip Flexion	4.9 ± 4.9	2.6	0.78	6.6 ± 5.7	3.1	0.73
Habitual Side-lying	3.7 ± 6.4	3.0	0.79	7.1 ± 6.1	4.0	**0.58***
Side-lying Passive	4.5 ± 4.6	2.8	0.72	8.3 ± 5.7	2.8	0.72
Side-lying Active	4.2 ± 4.1	3.9	**0.17***	8.0 ± 6.1	3.2	0.70
Side-lying Active + Leg Lift	6.7 ± 3.3	3.8	**0.20***	9.0 ± 5.9	2.4	0.78
Habitual Sitting	11.6 ± 10.3	3.5	0.90	12.3 ± 10.1	4.8	0.80
Sitting Active	4.4 ± 7.5	1.8	0.94	4.8 ± 9.4	2.8	0.92
Sitting Active + Hip Flexion	2.3 ± 7.5	3.4	0.77	4.0 ± 8.4	4.4	0.76
Standing Active	7.8 ± 8.4	3.6	0.81	7.3 ± 10.3	3.9	0.85
Final Standing	7.9 ± 8.3	4.1	0.76	12.5 ± 8.7	3.2	0.89
	Lumbar Curve Angle					
Position	Intra-evaluator Reliability			Inter-evaluator Reliability		
	Mean ± S.D. (°)	SEM (°)	ICC[3,1]	Mean ± S.D. (°)	SEM (°)	ICC[2,1]
Habitual Standing	-12.8 ± 6.6	2.7	0.83	-17.4 ± 8.5	3.7	0.74
Habitual Prone	-9.7 ± 8.0	2.9	0.85	-10.6 ± 6.0	2.8	0.72
Prone Side-bending Left	9.4 ± 13.1	3.2	0.95	16.1 ± 8.1	5.5	**0.51***
Prone Side-bending Right	-27.4 ± 6.3	4.2	**0.68***	-27.9 ± 6.6	5.0	**0.39***
Prone Passive	-5.3 ± 7.6	3.0	0.86	-6.8 ± 7.8	3.0	0.81

Prone Active	-2.2 ± 5.6	4.1	**0.61***	-3.9 ± 8.3	3.9	0.77
Prone Active + Hip Flexion	-2.6 ± 6.3	3.2	0.71	-3.5 ± 8.4	3.8	0.78
Habitual Side-lying	-13.9 ± 8.2	3.6	0.76	-17.5 ± 6.3	3.8	**0.64***
Side-lying Passive	-8.31 ± 5	2.6	0.77	-11.8 ± 4.9	2.0	0.70
Side-lying Active	-4.2 ± 4.7	4.0	**0.44***	-3.6 ± 7.0	4.4	**0.55***
Side-lying Active + Leg Lift	-4.1 ± 5.2	4.1	0.71	-2.2 ± 7.9	5.9	**0.42***
Habitual Sitting	-12.1 ± 7.8	3.2	0.85	-13.8 ± 9.4	3.7	0.83
Sitting Active	0.4 ± 11.0	2.7	0.94	1.3 ± 13.4	6.0	0.80
Sitting Active + Hip Flexion	3.8 ± 13.0	4.2	0.90	3.5 ± 11.3	5.2	0.79
Standing Active	-1.9 ± 7.2	3.2	0.80	-0.1 ± 11.9	5.3	0.77
Final Standing	-9.6 ± 4.6	4.0	**0.53***	-12.5 ± 6.8	3.4	0.76

	Thoracic Max AVR					
Position	Intra-evaluator Reliability			Inter-evaluator Reliability		
	Mean ± S.D. (°)	SEM (°)	ICC[3,1]	Mean ± S.D. (°)	SEM (°)	ICC[2,1]
Habitual Standing	6.2 ± 8.4	1.7	0.95	7.4 ± 6.8	1.8	0.93
Habitual Prone	6.7 ± 4.8	2.1	0.87	7.1 ± 5.6	1.4	0.94
Prone Side-bending Left	7.2 ± 4.7	1.1	0.95	5.8 ± 6.0	1.7	0.93
Prone Side-bending Right	2.7 ± 4.4	2.0	0.81	4.0 ± 4.7	1.2	0.93
Prone Passive	5.3 ± 6.0	0.9	0.97	5.7 ± 6.1	1.2	0.96
Prone Active	5.4 ± 4.4	1.1	0.95	5.4 ± 6.1	1.9	0.89
Prone Active + Hip Flexion	5.7 ± 4.8	1.7	0.89	6.0 ± 5.8	1.7	0.91
Habitual Side-lying	3.9 ± 5.8	1.3	0.95	6.2 ± 6.6	1.5	0.94
Side-lying Passive	4.1 ± 3.7	1.3	0.91	5.8 ± 4.8	1.4	0.92
Side-lying Active	3.0 ± 4.4	1.3	0.92	5.5 ± 6.2	1.0	0.97
Side-lying Active + Leg Lift	7.1 ± 5.5	1.4	0.94	7.4 ± 6.0	2.5	0.81
Habitual Sitting	5.1 ± 4.7	2.5	0.75	8.7 ± 5.4	2.0	0.84
Sitting Active	7.0 ± 3.3	2.1	0.76	8.6 ± 5.7	2.0	0.86
Sitting Active + Hip Flexion	6.0 ± 3.9	1.3	0.88	6.9 ± 4.0	1.7	0.86
Standing Active	7.6 ± 5.1	1.8	0.87	7.8 ± 4.6	1.3	0.93
Final Standing	5.5 ± 4.7	2.5	0.82	9.0 ± 5.5	2.3	0.80

Position	Lumbar Max AVR					
	Intra-evaluator Reliability			Inter-evaluator Reliability		
	Mean ± S.D. (°)	SEM (°)	ICC[3,1]	Mean ± S.D. (°)	SEM (°)	ICC[2,1]
Habitual Standing	-9.5 ± 5.5	1.7	0.92	-7.0 ± 6.7	2.0	0.90
Habitual Prone	-6.6 ± 5.1	1.5	0.93	-4.8 ± 5.6	2.1	0.84
Prone Side-bending Left	-4.8 ± 3.2	2.1	**0.67***	-3.8 ± 5.2	3.0	**0.64***
Prone Side-bending Right	-8.6 ± 7.7	1.6	0.96	-7.4 ± 6.2	2.7	0.82
Prone Passive	-5.3 ± 4.6	1.6	0.90	-4.5 ± 6.0	2.0	0.88
Prone Active	-5.0 ± 5.8	2.1	0.86	-3.6 ± 6.0	2.0	0.88
Prone Active + Hip Flexion	-1.8 ± 6.1	2.0	0.91	-1.4 ± 6.3	2.1	0.88
Habitual Side-lying	-3.7 ± 6.9	1.4	0.96	-4.0 ± 6.1	1.7	0.91
Side-lying Passive	-7.3 ± 3.8	1.0	0.94	-5.7 ± 7.2	1.7	0.95
Side-lying Active	-7.3 ± 4.2	1.1	0.92	-5.0 ± 7.7	1.6	0.85
Side-lying Active + Leg Lift	-3.8 ± 3.7	1.0	0.93	-0.7 ± 6.4	2.0	0.91
Habitual Sitting	-5.8 ± 4.4	3.3	**0.39***	-3.0 ± 5.2	1.9	0.87
Sitting Active	-5.0 ± 5.2	0.9	0.97	-2.0 ± 7.3	2.6	0.87
Sitting Active + Hip Flexion	-5.7 ± 4.7	1.2	0.94	-2.6 ± 6.2	2.0	0.91
Standing Active	-2.6 ± 5.3	1.8	0.90	-2.2 ± -2.0	2.2	0.86
Final Standing	-7.3 ± 6.2	1.4	0.94	-4.9 ± 6.0	1.4	0.95

Position	Max AVR Twist					
	Intra-evaluator Reliability			Inter-evaluator Reliability		
	Mean ± S.D. (°)	SEM (°)	ICC[3,1]	Mean ± S.D. (°)	SEM (°)	ICC[2,1]
Habitual Standing	15.7 ± 8.3	3.0	0.85	14.3 ± 6.7	2.5	0.86
Habitual Prone	13.3 ± 4.7	1.8	0.88	11.9 ± 6.2	2.6	0.80
Prone Side-bending Left	12 ± 4.2	2.2	0.77	9.6 ± 8.3	3.1	0.86
Prone Side-bending Right	11.3 ± 8.1	2.6	0.89	11.4 ± 6.8	2.8	0.83
Prone Passive	10.6 ± 6.6	1.8	0.91	10.3 ± 6.1	2.3	0.85
Prone Active	10.4 ± 6.9	2.5	0.86	9.0 ± 6.3	2.8	0.78
Prone Active + Hip Flexion	7.5 ± 6.0	3.1	0.78	7.5 ± 6.0	2.5	0.80
Habitual Side-lying	7.6 ± 8.9	2.4	0.93	10.2 ± 7.9	1.9	0.92
Side-lying Passive	11.4 ± 6.2	1.3	0.96	11.5 ± 6.9	2.2	0.89

Side-lying Active	10.3 ± 5.8	1.3	0.96	10.6 ± 7.0	2.0	0.91
Side-lying Active + Leg Lift	10.9 ± 6.4	1.3	0.96	8.1 ± 6.5	2.8	0.83
Habitual Sitting	11 ± 5.2	3.8	**0.40***	11.7 ± 6.3	3.1	0.73
Sitting Active	12.0 ± 5.7	2.3	0.83	10.6 ± 5.6	3.0	0.76
Sitting Active + Hip Flexion	11.7 ± 5.2	2.1	0.87	9.5 ± 6.2	2.2	0.87
Standing Active	10.2 ± 5.9	2.8	0.85	10.0 ± 5.5	2.4	0.82
Final Standing	12.8 ± 8.4	3.6	0.85	13.9 ± 6.0	2.9	0.79
	Thoracic AVT					
Position	Intra-evaluator Reliability			Inter-evaluator Reliability		
	Mean ± S.D. (mm)	SEM (mm)	ICC[3,1]	Mean ± S.D. (mm)	SEM (mm)	ICC[2,1]
Habitual Standing	7.7 ± 8.7	1.3	0.98	4.3 ± 11.1	1.7	0.98
Habitual Prone	5.0 ± 12.5	3.0	0.94	4.9 ± 8.9	2.1	0.95
Prone Passive	2.5 ± 16.7	1.8	0.99	4.9 ± 14.0	2.3	0.97
Prone Active	7.4 ± 11.3	2.4	0.96	-1.2 ± 18.3	2.7	0.98
Prone Active + Hip Flexion	11.3 ± 14.8	2.8	0.96	3.3 ± 17.4	3.3	0.96
Habitual Side-lying	-19.1 ± 9.6	1.1	0.99	-19.3 ± 9.8	1.9	0.96
Side-lying Passive	-4.1 ± 8.2	2.3	0.91	-9.9 ± 13.6	3.6	0.93
Side-lying Active	2.2 ± 12.2	1.8	0.98	-3.5 ± 14.9	2.2	0.98
Side-lying Active + Leg Lift	7.7 ± 12.2	1.3	0.99	-0.2 ± 17.1	4.1	0.95
Habitual Sitting	8.6 ± 11.8	2.4	0.96	4.4 ± 13.9	4.7	0.89
Sitting Active	7.6 ± 17.9	1.8	0.99	0.4 ± 19.8	3.8	0.97
Sitting Active + Hip Flexion	5.9 ± 20.0	3.5	0.97	1.1 ± 18.1	5.5	0.90
Standing Active	12.1 ± 16.7	4.3	0.94	7.2 ± 16.0	5.4	0.90
Final Standing	5.3 ± 9.0	1.8	0.97	5.0 ± 9.8	2.5	0.94
	Lumbar AVT					
Position	Intra-evaluator Reliability			Inter-evaluator Reliability		
	Mean ± S.D. (mm)	SEM (mm)	ICC[3,1]	Mean ± S.D. (mm)	SEM (mm)	ICC[2,1]
Habitual Standing	-11.7 ± 9.8	6.1	0.71	-11.8 ± 10.2	2.5	0.93
Habitual Prone	-8.5 ± 7.4	3.4	0.77	-7.3 ± 6.7	1.9	0.91

Prone Passive	-4.7 ± 8.4	3.3	0.86	-4.6 ± 9.9	3.6	0.83
Prone Active	-3.2 ± 10.1	1.9	0.97	-5.4 ± 14.3	4.5	0.87
Prone Active + Hip Flexion	-0.8 ± 8.4	1.7	0.96	-2.6 ± 12.5	3.9	0.89
Habitual Side-lying	-27.5 ± 9.2	2.3	0.93	-28.6 ± 8.2	3.1	0.85
Side-lying Passive	-13 ± 5	2.6	0.77	-16.0 ± 8.6	3.3	0.80
Side-lying Active	-7.9 ± 8.4	1.4	0.98	-6.3 ± 11.5	3.3	0.91
Side-lying Active + Leg Lift	-4.4 ± 9.3	3.4	0.83	-4.6 ± 13.6	6.1	0.76
Habitual Sitting	-13.2 ± 8.4	4.6	0.75	-14.2 ± 10.2	4.0	0.80
Sitting Active	-2 ± 17.6	1.4	0.99	2.1 ± 16.7	4.0	0.94
Sitting Active + Hip Flexion	9.6 ± 25.1	1.7	1.00	1.5 ± 17.0	6.8	0.81
Standing Active	-0.8 ± 12.6	2.2	0.97	-1.1 ± 11.2	4.9	0.80
Final Standing	-9.4 ± 7.0	2.0	0.92	-9.7 ± 6.8	2.4	0.88
	Interapical Distance					
Position	Intra-evaluator Reliability			Inter-evaluator Reliability		
	Mean ± S.D. (mm)	SEM (mm)	ICC[3,1]	Mean ± S.D. (mm)	SEM (mm)	ICC[2,1]
Habitual Standing	19.7 ± 7.5	2.3	0.93	15.8 ± 8.2	2.8	0.91
Habitual Prone	13.1 ± 10.9	5.8	0.77	11.7 ± 8.5	2.3	0.94
Prone Passive	8.3 ± 14.1	3.0	0.94	10.0 ± 9.1	3.7	0.87
Prone Active	8.6 ± 6.1	3.3	0.83	4.4 ± 11.3	3.9	0.89
Prone Active + Hip Flexion	13.8 ± 11.2	2.2	0.96	6.5 ± 12.6	4.3	0.90
Habitual Side-lying	9.6 ± 12.5	1.7	0.98	8.6 ± 8.4	3.2	0.89
Side-lying Passive	7.2 ± 9.6	1.7	0.96	4.8 ± 6.9	3.5	0.84
Side-lying Active	7.5 ± 11.7	2.1	0.97	2.0 ± 9.3	3.1	0.90
Side-lying Active + Leg Lift	12.3 ± 9.4	0.9	0.99	3.7 ± 9.8	5.7	0.78
Habitual Sitting	21.7 ± 11.7	5.2	0.86	17.9 ± 14.6	5.3	0.88
Sitting Active	9.7 ± 8.1	1.6	0.96	-1.1 ± 19.1	3.2	0.97
Sitting Active + Hip Flexion	-3.9 ± 21.1	3.4	0.97	0.0 ± 15.2	6.5	0.79
Standing Active	12.2 ± 15.7	3.5	0.96	7.0 ± 16.8	7.3	0.85
Final Standing	13.3 ± 8.8	1.6	0.97	14.5 ± 8.9	1.9	0.96

Abbreviations: AVR = Axial vertebral rotation, AVT = Apical vertebral translation, S.D. = Standard deviation, SEM = Standard error of measurement, ICC = Intraclass correlation coefficient, mm = millimetres
***** =ICC<0.70

Discussion

Our findings demonstrate that evaluators can produce curve angle, AVR, and AVT measurements from 3D US imaging in different positions with adequate intra and inter-evaluator reliability for research purposes, according to Lohr et al.'s threshold (ICC>0.70)[104]. These findings are consistent with previous US imaging studies that reported intra- and inter-evaluator ICC values for curve angle measurements that were also greater than 0.70 for habitual standing and habitual prone positions[34,35]. Since measurements did not reach the threshold deemed suitable for individual use (ICC>0.90), these results do not support its use in a clinical setting for making decisions about single patients in situation where measurements are not averaged over many individuals[104]. This study established the reliability of curve angle, AVR, and AVT measurements in positions outside of habitual standing, prone, sitting, supine, and side-bending. Additionally, this is also the first study to report adequate measurement reliability of any US imaging measurement in exercise-related positions for continued use in research.

Since modern scoliosis treatment not only aim to improve curve angles but also the frontal deviations, identifying adequate AVT measurements is important. The thoracic AVT, lumbar AVT, and interapical distance measurements were all found to present adequate intra- and inter-evaluator reliability for research purposes in all positions, having ICC values greater than 0.70. The thoracic AVT measurements produced very reliable intra and inter-evaluator ICC values (ICC>0.90) in all but one position. Our reliability values were also in agreement to the previous values established for AVT measurements in standing US images (ICC>0.90)[87]. Therefore, thoracic AVT measurements may be adequate for individual use.

Our results agreed with previous studies as intra-evaluator thoracic curve angle ICC values for habitual standing and habitual prone positions were greater than 0.90, the threshold for individual clinical use[34,35,104]. However, previous reliability estimates for curve angles in these positions did not distinguish between curve regions[34,35]. Interestingly, our intra-evaluator lumbar curve angle ICC's for habitual standing and habitual prone (0.83 and 0.85, respectively) did not meet the threshold for clinical use. This was observed despite the lumbar curve angles having higher ICC values than thoracic angles in 6 of 16 positions in the intra-evaluator analyses and 4 of 16 positions in inter-evaluator analyses.

Compared to thoracic vertebrae, lumbar vertebrae are taller in height and can produce larger areas of signal reflections from their laminae[106,107]. Consequently, these larger areas offer more room for evaluators to vary in digitizing the center of the laminae. Additionally, the orientation of the laminae of the thoracic vertebrae, may also provide a more favourable angle for signal reflection thereby improving the image quality than the lumbar vertebrae, where the laminae are more lateral facing [106,107]. Therefore, our results imply that there may be real differences between the thoracic and lumbar curve angle reliabilities although both measurements are sufficiently reliable for research.

Overall, our ICC and SEM values for the intra and inter-evaluator reliability of curve angle measurements in habitual prone and prone side-bending were slightly lower for thoracic and worse for lumbar than reported in previous studies[34,35]. In habitual prone, Khodaei et al reported an intra and inter-rater ICC of 0.93 and 0.90, respectively, for curve angle measurements without distinguishing between thoracic or lumbar regions[35]. To compare to their ICC values we chose the largest ICC value in either the thoracic or lumbar curve and we achieved intra and inter-evaluator ICC values of 0.91 (thoracic) and 0.74 (thoracic), respectively, in habitual prone. Khodaei's intra and inter-rater reliability SEM values for curve angle measurements in habitual prone were also smaller (0.52º and 0.78º, respectively) compared to our best intra and inter-evaluator results regardless of whether we examine the thoracic or lumbar curve region [2.4º(thoracic) and 2.8º(lumbar), respectively]. In prone side-bending, comparisons resulted in similar observations. The intra and inter-rater ICC from Khodaei et al. were both 0.94 while our highest ICCs were 0.95 for intra-evaluator and 0.62 for inter-evaluator[35]. The intra and inter-evaluator SEM values of curve measurements in prone side-bending in our study were also larger (3.2º and 4.7º, respectively) compared to the previous study (0.55º and 0.52º, respectively)[35].

These differences may be explained by our smaller sample curve magnitude and variability, the measurements used for inter-evaluator reliability, and the difference in experience of our evaluators compared to the previous study. The inter-rater analyses conducted by Khodaei used the first image measurement of the evaluator with four years of experience but compared against the second set of measurements by the novice evaluator[35]. Since there is likely a learning curve to US image measurement, this may have provided some improved measurement values after increased practice with the US images. Our evaluators had minimal training, less than 4 weeks of US image exposure, in relation to the evaluator of the previous studies, having had a range of four months to four years of US experience[21,34,35]. For example, even though our prone-side bending procedure was identical to Khodaei's, our image quality during acquisition may have been poorer due to less operator experience in scanning procedures. Zheng at al. has previously suggested that US image measurement and acquisition may be improved with more experience and "skill"[34]. Evaluator familiarity with spinal anatomy could have impacted their ability. In our study, E1 has had anatomy training whereas E2 had only started learning three weeks prior to image measurement.

Only two previous studies have reported the reliability of AVR measurements with US imaging in supine and habitual sitting[25,26]. Again, we notice that our best thoracic or lumbar results for intra and inter-evaluator ICC for max AVR measurements in habitual sitting (0.75 and 0.87, respectively) were lower than the results reported by Chen et al. (0.95 and 0.91, respectively)[26]. However, the previous study was again comprised of a larger sample size and larger curve severity[26].

The lower intra and inter-evaluator ICC and SEM statistics in our study compared to the studies by Chen et al., Khodaei et al., and Zheng et al. may be due to differences in measurement extraction strategies. Khodaei et al, and Zheng et al., only extracted curve angles for the largest curve angle present with the evaluator selecting the most tilted upper and lower end vertebra in each image, disregarding potential differences in vertebral labelling between repeated measurements. In the present study, both evaluators labelled vertebral levels for each scan and extracted curves across the 16 positions using the same upper and lower end vertebra boundaries for the thoracic and lumbar curve carried from the standing position across all 15 others. This strategy may produce error since evaluators needed to measure the correct curve magnitudes from angulation of the vertebra and to also correctly label and select the upper and lower end vertebrae consistently across all 16 positions. This conclusion is supported by Zheng et al. who suggested that selection of the end vertebrae may be the main source of curve angle error in US imaging[34]. Similarly, although Chen's study on AVR measurement reliability also extracted measurements for the levels above, at, and below the apex, our AVR measurements may have differed due to errors in vertebral labelling in different positions as we also selected levels for all positions based on the standing image[26]. This could have led to AVR measurement extractions at levels other than where maximally rotated values would have been observed if labelling was not consistent across positions. Following this explanation, since the AVT measurements were not influenced by vertebral labelling error, we observed that AVT measurements achieved the largest reliability estimates. In contrast, ICC values suffered for the curve angles and AVR, which are heavily reliant on proper labelling of vertebral levels.

Among the intra-evaluator reliability estimates with an ICC below 0.70, the thoracic curve angles in side-lying active and side-lying active with leg lift both presented the smallest standard deviations of all 16 positions at 4.1º and 3.3º, respectively. The suboptimal lumbar curve angle measurements, the prone active, side-lying active, and final standing positions also had three of the five smallest standard deviations for all lumbar curve measurements at 5.6º, 4.7º, and 4.6º, respectively. The means and standard deviations of these measurements also represent a small portion of the curve angle variation possible in patients treated conservatively. This small curve angle sample variance may lead to paradoxically low ICC values[108]. This is because the ICC is a ratio of the between-person variance over the sum of the between-person variance and the measurement error. Therefore, for a similar amount of measurement error affecting a measurement, the ICC will be lowest in the sample with the lowest between person variance without a true difference in measurement error[104,109]. The reasonably low SEM values observed for the curve angle measurements (<5º) in the situation listed above with low between-subject variance suggest that these ICC values may have been strongly influenced by the small sample variance. Notably, these are also positions where the largest curve corrections were consistently achieved by participants further minimizing the between-subject variances.

Since US imaging provides more noisy images in comparison to other imaging techniques, the distinguishing of reference landmarks and labelling of vertebral levels can be more difficult. Improved US image quality and signal intensity may improve the clarity of vertebral landmarks and consequently, the ability of evaluators to reliably distinguish vertebrae in US imaging. Overlying fascia and tissue can also increase the noise in the measurement areas. Improved image quality might be achieved by adjusting the gain, scanning depth, or frequency of the scans. It may also be possible to have a transducer that can be contoured to the surface of the back to improve overall contact and reflected signals.

Of interest, using a 5^{o} variation in curve angle measurement as the clinically significant error threshold often used in radiographs, our results indicate that 3D US imaging present small enough error to detect clinically meaningful changes in different habitual positions and within Schroth-corrected PSSE positions[34,110]. It is currently unclear how curve angle, AVR, and AVT measurements are related in US imaging and correlation analyses are needed to establish if relationships exist. Such correlations may help determine if measurements provide complementary, redundant or completely independent information about the scoliotic deformity.

A strength of the present study was demonstrating the reliability of the thoracic and lumbar curve angles, AVR, and AVT measurements in quantifying the scoliotic deformity in response to a vast array of 16 habitual and PSSE positions. This meets the recommendation that reliability should be tested in the context in which the measurements will be used[111]. This study introduced the AVT and interapical distance measurements to 3D US imaging positions outside of standing, of which are two clinically relevant frontal balance parameters until now only used on radiographs.

Limitations

The small average curve angle magnitudes of our participants, while reflecting a population of interest, may have resulted in a low variance in some positions that reduced curve angle magnitudes and our ICC values relative to previous studies. The low sample size for the intra-evaluator study may have increased the likelihood that outliers had an influence on the reliability estimates. Our results demonstrated that novice evaluators can achieve reliability levels sufficient to conduct research on scoliosis.

Since the orientation of the L5 vertebra and the vertical in the US image can change in different positions and there is no standardization to a reference orientation, the angle of the CVL may vary. As a result, AVT measurements may not be clinically comparable between repeated images and their meaning within an image would depend on the CVL orientation. In contrast, interapical distance measurements do not depend on the CVL orientation for interpretation and provide clinically meaningful information on the frontal alignment changes.

Conclusion

This study demonstrated that 3D US imaging can produce curve angle, axial vertebral rotation, max AVR twist, apical vertebral translation, and interapical distance measurements with good intra and inter-evaluator reliability adequate for research purposes. Variation in vertebral labelling, selection of end vertebrae, and degree of experience in evaluators are potential sources of error for US measurements.

Chapter 4.

Immediate In-Exercise Reductions in the Frontal and Rotational Deformity of Adolescents with Idiopathic Scoliosis Performing Schroth Physiotherapeutic Scoliosis-specific Exercises

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Chapter prelude

In the previous chapter, we established that the intra and inter-evaluator reliability of thoracic and lumbar curve angle, AVR, max AVR twist, thoracic and lumbar AVT, and interapical distance US measurements were adequate for research purposes (ICC>0.70). We were able to observe that our AVT measurements were among the most reliable of the measurements compared but our curve angles and AVR reliability were less reliable than previous studies had reported (ICC<0.90). We justified these differences by explaining our evaluators limited experience, smaller curve severity in our sample, and differing extraction strategy. Additionally, our sample presented with smaller between-person variance which may have increased the effects of the measurement error on our reliability statistics. By testing the curve angle, AVR, and AVT measurements in a variety of positions, we established that these US measurements can be used in various PSSE-related positions, even if presenting with degrees of instability. In doing so, we were able to proceed with the main objective of this thesis project, determining the effect of Schroth PSSE on these US measurements.

In Chapter 4, we examined the effects of 16 habitual and PSSE-related positions on the thoracic and lumbar curve angles, max AVR twist, and interapical distance measurements of Schroth-trained participants. An introduction frames the clinical relevance and scientific context of the forthcoming study followed by our methodological approach. The effects of the sixteen positions are reported for their effects on the frontal and rotational deformity measurements. Planned comparisons included: each position compared to standing, pairwise comparisons between habitual positions, pairwise comparisons between all variations in prone, pairwise comparisons between all variations in side-lying, pairwise comparisons between all variations in siting, pairwise comparisons between standing positions, and pairwise comparisons between all fully corrected and side-bending positions. This chapter focuses its discussion towards addressing the clinical questions informing this project. That is, can patients achieve meaningful deformity corrections in different areas of their spine, and can it be done without experiencing compensations in other areas? The latter would address skepticism from referring clinicians, patients and parents. By examining the effect of different variations of Schroth exercises, this study also provides guidance for therapists instructing patients, or instructors teaching therapists on how to best perform the exercises.

Background

Adolescent idiopathic scoliosis (AIS) is a three dimensional (3D) spinal deformity that is characterized by abnormal lateral curvature with associated rotation of the spine[1,5]. AIS affects 2-3% of all adolescents[1,3–5]. In North America, milder curves (15 -25°) are observed without treatment to track progression while moderate curves (25-40°) are treated with back braces and other conservative treatments[1,2,5,6,8–10]. Finally, curves that are 45° and greater may receive spinal surgery[1,2,5,6,8,9].

More recently, physiotherapeutic scoliosis-specific exercise (PSSE) has become recognized by the Scoliosis Research Society (SRS) to have potential benefits[2,8,11]. The main components of PSSE are to focus on 3D self-correction of the spine, training with activities of daily living, and stabilization of the corrected posture[13]. As research quantity and quality has improved, several randomized controlled trials have shown that PSSE's can help reduce curve progression, assist pain management, as well as improve self-image, strength, and endurance[12,14–16]. Nevertheless, more research is needed because scoliosis-specific exercises are still not adopted as standard practice for scoliosis care in many countries[2,11]

The Schroth method is the most widespread school of PSSE with the greatest amount of published evidence[9,13]. All Schroth corrections start with pelvic corrections to align the trunk followed by auto-elongation with detorsion, deflection, derotation, rotational breathing, and finally stabilization[13]. Ipsilateral psoas activation on the lumbar concave side is intended to decrease curve magnitude and derotate the lumbar vertebrae[13]. During rotational angular breathing (RAB), the patient focuses on keeping or creating thoracic kyphosis as well as expanding the concave areas of the torso and limit the expansion of the prominent areas on the torso[75]. Among many schools of PSSE, exercises are performed in four positions: standing, sitting, side-lying, and prone[13]. With such variation, we need to understand how spinal alignment changes within these positions, and their PSSE correction instructions, as spinal loading may change.

Unlike bracing, the amount of immediate curve correction that PSSE can achieve is still unknown[92,93]. Only a single case study has described the immediate effect of scoliosis-specific corrections during radiographic measurements and showed improvement in the lumbar curve and worsening in the thoracic curve for the patient assessed in standing[17]. This study showed greater immediate changes in thoracic and lumbar curve magnitude after training for one year demonstrating a learning effect[17]. The different changes between thoracic and lumbar curves with PSSEs may indicate that the thoracic and lumbar curves may have different responses, positive or negative, to PSSE[17]. However, in this study no therapist provided support after the initial training, potentially causing this patient with a double curve to incorrectly perform the PSSE corrections.

Research into the immediate effects of exercise may also be justified because for bracing treatments, the amount of initial in-brace correction is predictive of treatment outcome[92–94]. It is unknown if a similar relationship exists for PSSE. Xu et al. showed that an initial bracing curve correction of 10% or less predicted 38.5% of patients that would fail treatment[92]. Studying the immediate correction in PSSE may allow studying of the prediction of treatment outcome. However, there needs to be a feasible and ethical way to assess how PSSE immediately affects the spine in real time.

Surgeons, patients, and their families have also expressed skepticism on the feasibility of achieving clinically meaningful corrections from PSSE. These concerns may stem from the complexity of these PSSEs and the perceived difficulty for adolescents to understand them. Trained therapists have also shown interest in obtaining evidence about how PSSE positions, and their instructions, help their patients achieve correction. Hence, there is a need to understand the immediate effects of PSSE.

Further, research on AIS has focused most on the curve angle, and to a lesser extent, the axial vertebral rotation (AVR)[29]. However, no PSSE research has focused on assessing the lateral displacement of the apical vertebra even though AIS treatments focus heavily on this area as well. Apical vertebral translation (AVT) is measured as the lateral deviation of the middle of the apical vertebral body with respect to the central sacral vertical line (CSVL), which is the vertical line drawn upwards from the middle of the S1 vertebra on a radiograph[30]. In surgery, AVT is used with the Cobb angle and the AVR to make clinical decisions on spinal fusion, yet, it is neglected in the assessment of conservative interventions[31–33].

AVT has long been assumed to be encompassed in the Cobb angle but, Easwar et al. showed that, in CT scans, the correlation between these measurements although significant, was lower than previously proposed ($r=0.66$ vs. $r=0.76$) and not perfectly linear[99]. AVT also had the lowest correlation to the Cobb angle among vertebral rotation, kyphosis, and lordosis[99]. AVT correlates ($rho= -0.29$) with SRS-22 self-image scores so focusing on AVT may have clinical benefits[98]. Additionally, AVT showed the greatest correlation to rib hump index, more so than Cobb angle[99]. Pertinent to this relationship, greater SRS-22 satisfaction and self-image scores were correlated with the rip hump improvement post-surgery and higher thoracic AVT is also related to lower post-surgical self-image outcomes assessed by the Spinal Appearance Questionnaire[100,101]. The AVT may reflect a complimentary aspect of the deformity worth investigating in studies on the effect of PSSE.

To properly assess the immediate effects of PSSE, an imaging method obtaining valid and reliable measurements in various positions must be chosen. Despite radiography being the standard method to assess the scoliotic spine, this method is unsuitable to assess complex PSSE positioning and, even with the adoption of low dose EOS radiography systems, would be unethical due to the need for repeated exposure to radiation[18]. Recently, 3D ultrasound (US) imaging has shown promise to reliably assess the curve angles of individuals with AIS in standing, sitting, side-lying, bending, and prone with good agreement to traditional Cobb angles on a radiograph[19–24,34,35,112]. Ultrasound imaging has also shown good reliability with for AVR measurements in standing, and good agreement to MRI measurements using the Aaro-Dahlborn method[25,26]. Therefore, the development of award winning 3D ultrasound (US) imaging protocols to non-invasively quantify spinal alignment allows a unique opportunity to investigate the immediate effects of exercise that is ethically viable. Further, the reliability of curve angle, max AVR, max AVR twist, AVT, and interapical distance measurements in various PSSE-related positions has already been established as adequate ($ICC>0.70$)[112].

Schroth exercises involve numerous instructions with both passive (external forces) and active (internally-generated forces) corrections. Accordingly, studying the separate effects of passive and active corrections on spinal measurements can help determine the usefulness of each treatment instruction, currently unknown. We also hypothesize that the curve angles will increase in habitual sitting compared to standing since sagittal loading of the spine is increased in sitting compared to standing[113–115]. In side-lying, we hypothesize that the gravity and interaction of the torso with the surface may reduce the thoracic curve and possibly increase lumbar curve angles. Lastly, we expect that the Schroth-corrected positions will yield the greatest decreases to the thoracic and lumbar curve angles, AVR, and AVT measurements for each position as is the goal of their instructions.

Objective

Accordingly, this study investigated the immediate effects of PSSE on the thoracic and lumbar curve angle, max AVR, max AVR twist, AVT, and interapical distance measurements of adolescents with idiopathic scoliosis in 16 different habitual and PSSE positions measured with 3D ultrasound imaging.

Methods

Study design:

This was a cross-sectional study comparing the immediate effects of 16 different positions or exercises in standing, prone, side-lying, and sitting on spinal 3D US measurements of Schroth-trained volunteers.

Clinical participants:

Volunteers were recruited from participants in the Schroth Exercise Trial for Scoliosis (SETS) at the Stollery Children's Hospital in Edmonton, Canada. Prospective participants received invitations to volunteer from our research coordinator. Participant inclusion criteria were: 1) between 10 and 18 years of age at the time of Schroth PSSE training, 2) diagnosis of adolescent idiopathic scoliosis, 3) having completed at least three months of supervised Schroth PSSE exercise training, 4) a major curve with Cobb angles between 10° and 45°, and 5) no spine, torso or lower extremity surgery, or trauma affecting function. Participants with or without a brace, those who have completed brace treatment, and any level of skeletal maturity according to the Risser sign were eligible for this study.

Ethics:

Ethics approval was obtained from the University of Alberta Health Research Ethics Board on July 6th, 2016 (Study ID: MS2_Pro00066486). An amendment to include new positions (side-lying and a final standing scan), and the apical vertebral rotation and coronal balance measurements was approved on February 23, 2017. Volunteers over the age of 14 provided written consent and those younger than 14 years old provided written assent with parents or guardians providing written consent.

Data acquisition:

In a single 1.5 hr visit, participants were scanned in a total of 16 positions. Upon arrival, participant age, height, and weight were recorded. Participants then changed into a hospital gown to expose the full spine. The spinous processes were palpated to place a sticker at the levels C7 and S1[20,25,26]. Warmed US gel was applied liberally to the outline of the spine to ensure adequate ultrasound signal. The transducer head was positioned perpendicular to the surface of the back and moved by the evaluator to follow the contour of each curve. Each scan lasted approximately 10-30 seconds. A research assistant operated the SonixTABLET interface while the evaluator operated the transducer.

Scanning procedure:

All participants were scanned in a total of 16 positions selected to reflect common exercise positions and instructions in Schroth scoliosis-specific exercise programs (Figure 1). Of note, only the final 24 participants were scanned for the side-lying positions and the final standing position after study protocol amendment.

1) ***Habitual standing*** (Figure 1A)

Participants stood in their habitual upright posture within a frame to provide tactile feedback and minimize body sway.

2) ***Habitual prone*** (Figure 1B)

Lying prone on a therapy table with arms elevated and hands overlapped under the forehead.

3) Prone side-bending to the left and 4) right (Figure 1C and 1D)

Maximally side-bending to the left (or right) in the prone position without shifting the pelvis.

5) Prone with passive correction (Figure 1E and 1F)

Positioned prone with passive supports under the torso and select limbs. Bean bags were placed under the shoulder on the convex thoracic side and under the breast on the concave thoracic side. The arm on the convex thoracic side was abducted to 90° with shoulder external rotation and the elbow bent to 90° with the forearm supported on a foam roller. Lastly, a foam roller was placed under the pelvis of the participant with extra bean bags beneath the hip on the concave side of the lumbar curve.

6) Prone with active correction (Figure 1G)

In the same as position as #5, the participant actively adjusted their spinal alignment. Components of the corrections were: elongation of the spine, shifting their curves to towards midline, derotating the shoulder block, pushing the elbow on the thoracic convex side laterally, derotation of the thoracic and lumbar segments, and rotational angular breathing (RAB)[13].

[RAB includes maintaining or creating a thoracic kyphosis during inhalation and expansion of the concave torso area while during exhalation. Muscles on the convex side of the torso activate to limit prominence deformation.]

7) *Prone with active correction and hip flexion* (Figure 1H)

In the same position and with the same corrections as #6, the participant was instructed to push their knee on the concave lumbar side, against the table using hip flexors.

[Hip flexion is used to activate the psoas muscle on the lumbar concave side. Due to its origin on the lumbar transverse processes, this unilateral psoas activation is expected to assist in pulling the lumbar curve to midline and derotating the vertebral bodies.]

8) Habitual side-lying (Figure 1I)

For the most typical right thoracic with left lumbar curve pattern, participants were lying on their left side (thoracic concave) on the therapy table. Knees were bent to 90° for stability and two bean bags were placed under the head for neck support. The bottom arm was extended overhead, and the top arm was straightened over the hip.

9) *Side-lying with passive correction* (Figure 1J)

In the same position as #8, two bean bags were placed under the left shoulder (thoracic concave side) and under the apex of the lumbar curve. The top arm was abducted to 90° with the shoulder in external rotation and the elbow bent to 90°. The top hand rested on a foam roller for support. The top leg was straightened and rested on foam padding.

10) *Side-lying with active correction* (Figure 1K)

In the same position as #9, the participant actively adjusted their spinal alignment. The components of the corrections were: elongation of the spine, shifting their curves to towards midline, derotating the shoulder block, pushing the elbow on the top side laterally, derotation of the thoracic and lumbar segments, and rotational angular breathing (RAB)[13].

11) Side-lying with active correction and leg lift (Figure 1L)

Adding to instructions in position #10, the participant was asked to abduct their top leg and extend it in the caudal direction, pulling the pelvis in tilting down on the side with the leg elevated.

12) Habitual sitting (Figure 1M)

Participants sat in their own habitual posture on an exercise ball with their legs spaced at shoulder-width and hips and knees at 90°.

13) ***Sitting with active correction*** (Figure 1N)

From sitting, the participant adjusted their spinal alignment. The components of the corrections were: elongation of the spine, shifting their curves towards midline, derotating the shoulder block, pushing the elbow on the thoracic convex side laterally with the hand holding a pole, pushing the elbow on the lumbar convex side upward and laterally with another pole in hand, derotation of the thoracic and lumbar segments, and rotational angular breathing (RAB)[13].

14) ***Sitting with active correction and hip flexion*** (Figure 1O)

In addition to instructions in position #13, the participant was asked to unilaterally lift their knee on the lumbar concave side, against an anchored yoga strap wrapped around their lower thigh.

[Hip flexion is used to activate the psoas muscle on the lumbar concave side which is expected to assist in pulling the lumbar curve to midline and derotating the vertebrae.]

15) ***Standing with active correction*** (Figure 1P)

In upright standing, the participant adjusted their spinal alignment. The components of the corrections were: elongation of the spine, shifting their curves to towards midline, derotating the shoulder block, pushing the elbow on the thoracic convex side laterally with the hand holding a pole, pushing the elbow on the lumbar convex side upward and laterally with another pole in hand, derotation of the thoracic and lumbar segments, and rotational angular breathing (RAB)[13].

16) ***Final habitual standing***

Identical to position #1, the participant was asked again to stand in their habitual standing posture. This repeated testing allowed determining if there were any carry over effects due to corrections applied in previous positions.

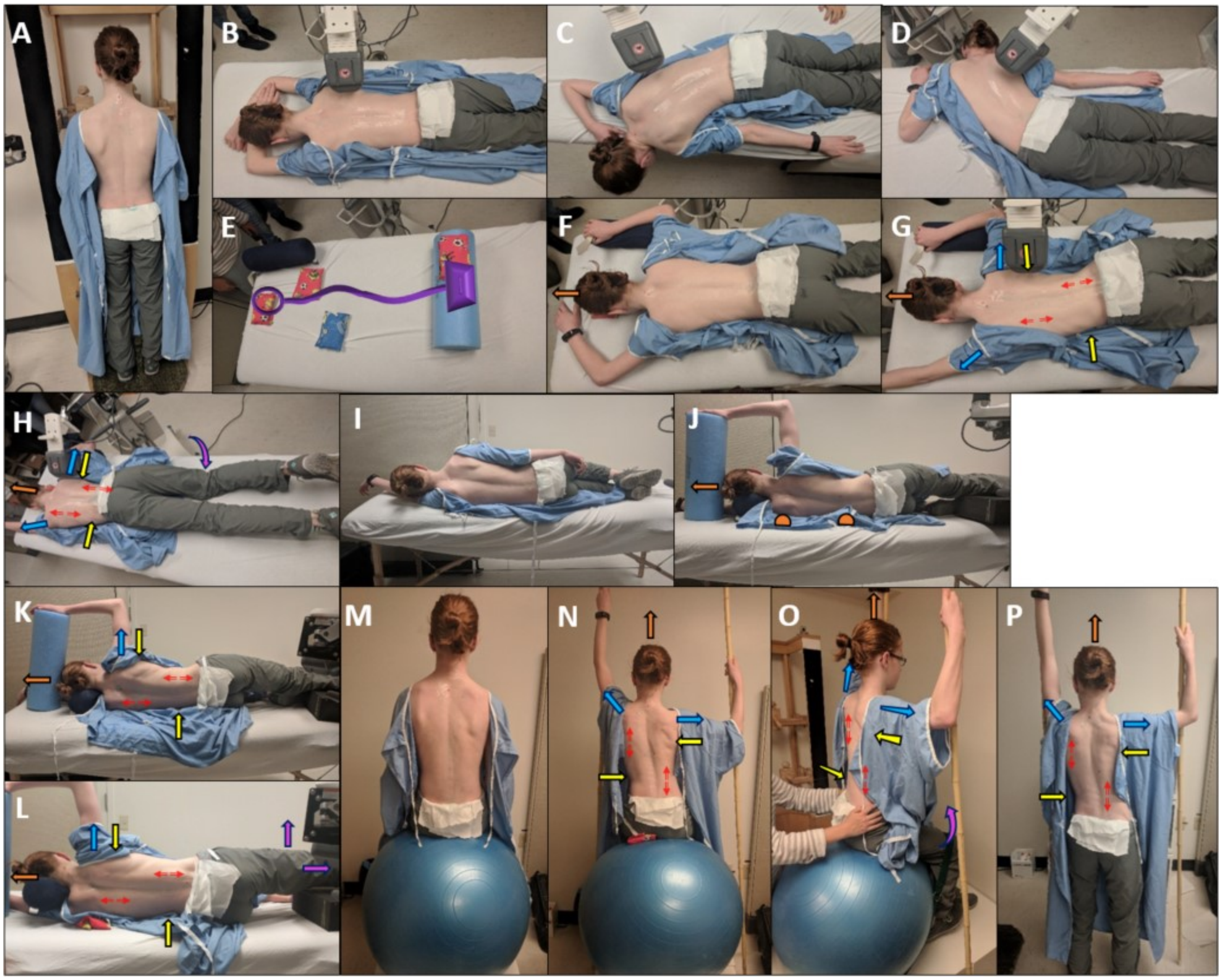

Figure 1. Habitual positions and Schroth exercise positions for a thoracic and lumbar double curve pattern.
Orange arrows illustrate trunk elongation. Blue arrows illustrate the direction of active forces at the upper extremities. Yellow arrows show the direction of torso side-shift corrections towards midline from the curve convexities. Purple arrows represent lower extremity movements with hip flexion and leg abduction with caudal push. Finally, paired red arrows demonstrate the intended expansion of the ribs at the thoracic curve concavity, and filling of the dorsal depression from thoracic and lumbar segment derotation using rotational angular breathing (RAB). A) Habitual standing in a scanning frame, B) Habitual prone, C) Side-bending left, D) Side-bending right, E) Placement of passive supports with overlaid illustration of a scoliotic spine, F) Passive prone, G) Active prone, H) Active prone with hip flexion, I) Habitual side-lying, J) Passive side-lying, K) Active side-lying, L) Active side-lying with leg lift, M) Habitual sitting, N) Active sitting between two poles, O) Active sitting with hip flexion against a strap, P) Active standing between two poles.

Instrumentation:

Images were acquired using a SonixTABLET system with a 60mm curvilinear 128-element C5-2/60 GPS convex transducer and a SonixGPS system (Analogic Ultrasound - BK Medical, Massachusetts, USA)(Figure 2). The SonixTABLET was calibrated for scanning at an imaging depth of 6cm, a frequency of 2.5MHz, a frame rate of 32 Hz, and a 10% gain based on parameters from previous studies[22,23,34]. Scans were performed in the cephalocaudal direction following the spine from the C7 to S1 (Sacrum) for each of the positions. The voxel size of the image was set to 0.5mm width, 0.5mm height, and 1mm depth for exporting from the SonixTABLET to the computer for image analysis. These scans provided a stack of 2D consecutive transverse images which were exported and merged into a 3D image file using a custom program[22].

Figure 2. *The ultrasound machine comprised of the SonixTABLET system and SonixGPS system.*

Image measurement:

A single evaluator used custom program, MIAS (Medical Image Analysis Software) 3D v10.0.21 Professional Edition to complete all the measurements. The evaluator was trained with 10 clinical images and two phantom spines within a period of 3 weeks after demonstrations by an evaluator with experience measuring over 100 images in standing with high reliability ($ICC_{2,1}$ >0.8) and standard error of measurement (SEM) errors less than 2.8° for curve angle measurements[34]. The evaluator has previously demonstrated adequate reliability for research

($ICC_{2,1}>0.70$)[112]. The evaluator was blinded to the participant's clinical information, treatment history, and to any previous measurements.

The center of lamina (COL) method for US image measurement was used to quantify curve angle, axial vertebral rotation, and apical vertebral translation[19–21,23,25–27,34,35]. The centers of the laminae from the left and right side of each vertebra were located and a line drawn to connect each pair on the frontal US image (Figure 3)[19,26,27,86]. Each pair of laminae in the frontal US view was presented on the corresponding transverse US image for the level on interest to aid in landmarking (Figure 4)[19,26,27,86]. This line is referred to as the COL line. The COL method has been validated by showing good agreement to the Cobb method on radiographs[20,27]. In previous studies, this measurement technique has also demonstrated high reliability (ICC>0.8) for curve angle measurements in standing, prone, and side-bending US images for scoliosis curves and high intra and inter-rater reliability for AVR measurements in sitting[19–21,23,25–27,34,35]. Su et al. demonstrated that thoracic and lumbar curve angle, AVR, and max AVR twist measurements have adequate reliability in the exercise-related positions from this study[112]. High intra and inter-evaluator reliability was also observed for AVT and interapical distance measurements on US images in these positions (ICC>0.80)[112].

Curve angle measurements were extracted from the two most tilted pairs of laminae within each curve in the frontal view, representing the upper and lower end vertebrae of each curve (Figure 3). The upper and lower end vertebrae for the thoracic and lumbar curve regions selected in habitual standing were carried throughout the extraction of all other positions to observe the change in the curve segment of interest. Negative curve angle values denoted a leftward convexity whereas a positive value represented a rightward convexity. The AVR measurements were obtained by quantifying the tilt of the laminae in the transverse US view relative to the horizontal (Figure 4) for the vertebral levels above, at, and below the apex for each curve in standing. The selected vertebral levels above, at, and below the apex in habitual standing were used to extract measurements in all other positions. The largest of the three AVR measurements for each thoracic and lumbar region were used to calculate the difference between the maximal rotation in the thoracic curve and the opposing maximal rotation in the lumbar curve, akin to spinal twisting, as follows:

$$\boldsymbol{Max\ AVR_{Twist} = Max\ AVR_{Thoracic} - Max\ AVR_{Lumbar}}$$

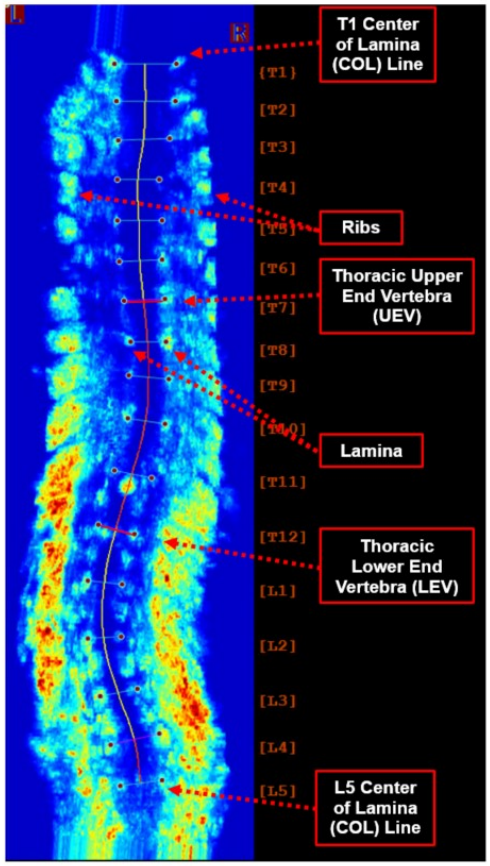

Figure 3. *Frontal view of an ultrasound image in standing containing the hyperechoic regions corresponding to the ribs and lamina. The spinous processes do not generate a reflection of the ultrasound signal perpendicularly to the probe and produce a shadow between the laminae. An automatically generated line follows the curve of the spine and is drawn from the center of the connection between each vertebral level's center of lamina (COL) lines. Also labelled is the COL lines for T1, L5 and the upper (UEV) and lower end vertebrae (LEV) of the thoracic curve.*

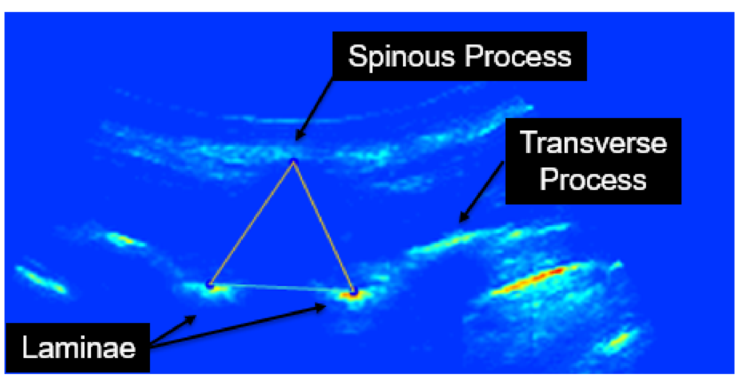

Figure 4. *A transverse ultrasound view of the spine illustrating clearly the location of the lamina, transverse process and the shadow corresponding to the expected location of the spinous process.*

For AVT measurements on radiographs, the levels of C7 and S1 are typically used as reference points[30]. For ultrasound image measurements, the levels of T1 and L5 were chosen instead due to their being visible on all images and their improved signal quality compared to C7 and S1 because of the overlying fascia. Consequently, our "central vertical line" (CVL) was drawn vertically from the midpoint of the COL line of L5, parallel to the edge of the frontal US image. As a result, the AVT measurements were obtained by measuring the lateral deviation of the midpoint of the COL line, produced automatically, for the curve apices to the CVL (Figure 5). A positive AVT value signified that the curve apex was to the right of the CVT whereas a negative value indicated that the apex fell left of the of the CVT. We calculated the interapical distance using the difference between the thoracic and lumbar AVT measurements, as follows[103]:

$$\boldsymbol{Interapical\ Distance} = \boldsymbol{AVT_{Thoracic}} - \boldsymbol{AVT_{Lumbar}}$$

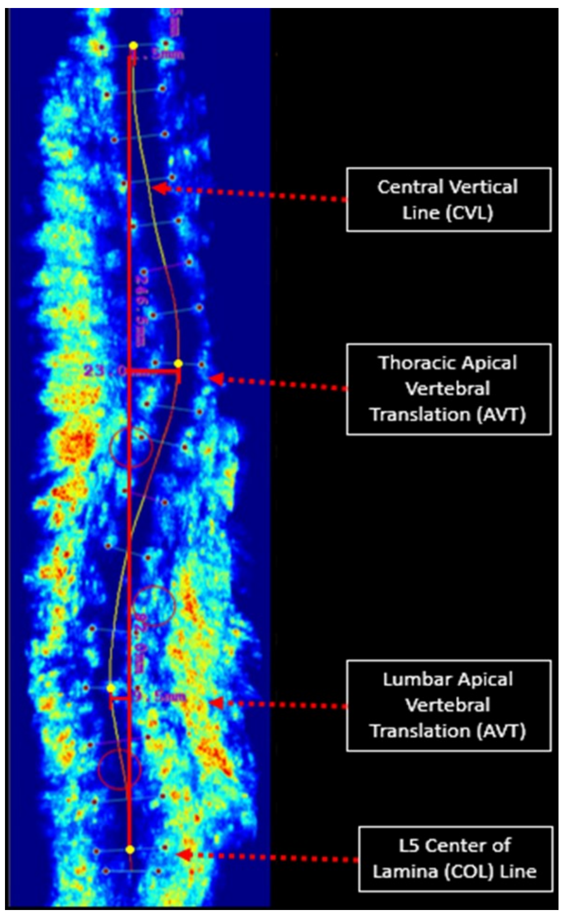

Figure 5. A coronal ultrasound view of the spine illustrating the apical vertebral translation (AVT) measurements.
AVT measurements at T8 and L2 relative to the Central Vertical Line (CVL), extending vertically from the middle of the L5 center of lamina (COL) line.

Sample size calculation:

The primary analysis was the effect of position and exercises on the curve angle. Using a two-tailed paired t-test, assuming a correlation of 0.5 between repeated measurements, a sample size of 35 was sufficient to detect a small effect size of 0.49 with a power of 0.8 and an alpha level of 0.05. Upon correcting alpha for a maximum of 48 possible comparisons planned a priori we still can detect as significant a moderate effect size of 0.75[116]. It was reasonable to anticipate moderate to large effects as participants eligible for the study presented a good ability to produce postural corrections with the exercises and had small to moderate curvatures known to present a good curve flexibility[117,118]. Sample size calculations were performed using G*Power Version 3.0.10.

Data analysis:

Continuous measurements and patient's characteristics were described by the means and standard deviations (age, height, weight, curve angles, Max AVR twist, AVT's, and interapical distance measurements). Scoliosis measurement were also described with 95% confidence intervals [CI95]. Frequencies and percentages were reported for categorical descriptive variables.

Differences between positions:

The thoracic and lumbar curve angles, max AVR, max AVR twist, AVT, and interapical distance in each of the positions were compared to standing each using a separate repeated measure ANOVAs with Sidak post-hoc comparisons[119]. Thoracic and lumbar AVT and interapical distance were not measured in prone side-bending left and right due to lack of clinical meaning. A threshold of a 5º change in curve angle and a 3º change in AVR has been previously established as clinically significant for changes in US imaging[21,22,25,26]. No threshold has yet been established for AVT measurements in US imaging.

In addition to the comparison of all positions to standing, separate repeated measure ANOVAs with Sidak post-hoc comparisons were used to compare measurement differences in the following groups of position of interest: habitual (1,2,8,12), prone (2,5,6,7), side lying (8,9,10,11), sitting (12,13,14), standing (1,15,16), and all maximal side-bending and PSSE-corrected positions (3,4,7,11,14,15). To determine the effects of PSSE that can be attributed to the different instructions, rather than to the adoption of a different habitual position other than standing, we looked at the differences within the same position (E.g. all prone positions).

Post-hoc comparisons where side-lying or final standing positions limited the available sample size were conducted twice. The first post-hoc comparisons were performed including the side-lying or final standing positions with the lower sample size. The analyses was then conducted without the sample limiting position (excluding side-lying and standing) in order to maximize the available sample size for the other pairwise comparisons of interest. Descriptive statistics and p-values were reported for the largest sample size available.

All statistical analyses were completed using IBM SPSS Statistics version 25 (IBM, Armonk, New York, USA).

Results

Thirty-six female volunteers (n=36) were recruited with a mean age, height, and weight of 15±3 years old, 160±11 cm, and 50±12 kg, respectively. Schroth curve types were 22 4CP's (double curves with pelvis shifted on lumbar concave side), 5 4C's (double curves with balanced pelvis), 7 3CP's (dominant thoracic curve with pelvis on thoracic concave side), and 2 3C's (dominant thoracic curves with balanced pelvis). The mean thoracic and lumbar curve angles in standing were 16±8º right convex and -18±9º left convex, respectively. The tables describing all the extracted measurements and the results of statistics comparing positions are presented in Appendix I (Tabulated Statistics for Post-hoc Comparisons Conducted in Chapter 4, Tables 2 to 8).

Usable scans

For all 36 participants, thoracic and lumbar curve data was extracted in all 16 positions for a total of 1152 curves. Fifteen scans from 10 participants were removed due to image artifact: one in prone side-bending right, two in habitual sitting, four in active sitting, five in active sitting with hip flexion, and three in active standing.

Comparisons to standing

Curve Angles

When compared to standing, all prone positions, excluding side-bending left (21±1°), produced significant reductions in the thoracic curve angles ($p<0.05$)(Figure 6A). The side-bending right position resulted in overcorrection to a mean (±SE) thoracic curve angle of -9±1°. Sitting active (4±2°), sitting active with hip flexion (4±2°), and standing active (7±2°) also produced significantly smaller thoracic curve angles. Side-lying positions and the final standing position did not result in significant thoracic curve angle reductions.

Lumbar curve angles in all positions were significantly less than in standing, except for habitual side-lying, side-lying passive, habitual sitting ($p>0.05$) (Figure 6A). Prone side-bending right (-27±1°) was the only position to significantly increase the mean lumbar curve angle compared to standing.

Maximum AVR Twist

The maximum AVR twist between the thoracic and lumbar curves in standing was 15±1°. The AVR twist was significantly reduced in all the other positions except habitual prone, prone side-bending left, prone side-bending right, habitual side-lying, side-lying passive, sitting active, and final standing which were not significantly different (Figure 6B).

Apical Vertebral Translation

The interapical distance in standing was 16±2mm with a thoracic AVT of 2±2mm and a lumbar AVT of -14±2mm. For the thoracic AVT, only habitual side-lying was significantly reduced (-20±2mm) compared to standing (Figure 6C). Meanwhile, the lumbar AVT was significantly reduced in all positions except for prone active, side-lying passive, side-lying active, side-lying active with left lift, habitual sitting, and final standing, which were not significant. The lumbar AVT significantly worsened in habitual side-lying (-27±2mm). The mean interapical distance of all positions was significantly reduced compared to standing except for the following positions: habitual prone, habitual side-lying, habitual sitting, standing active, and final standing (Figure 6D).

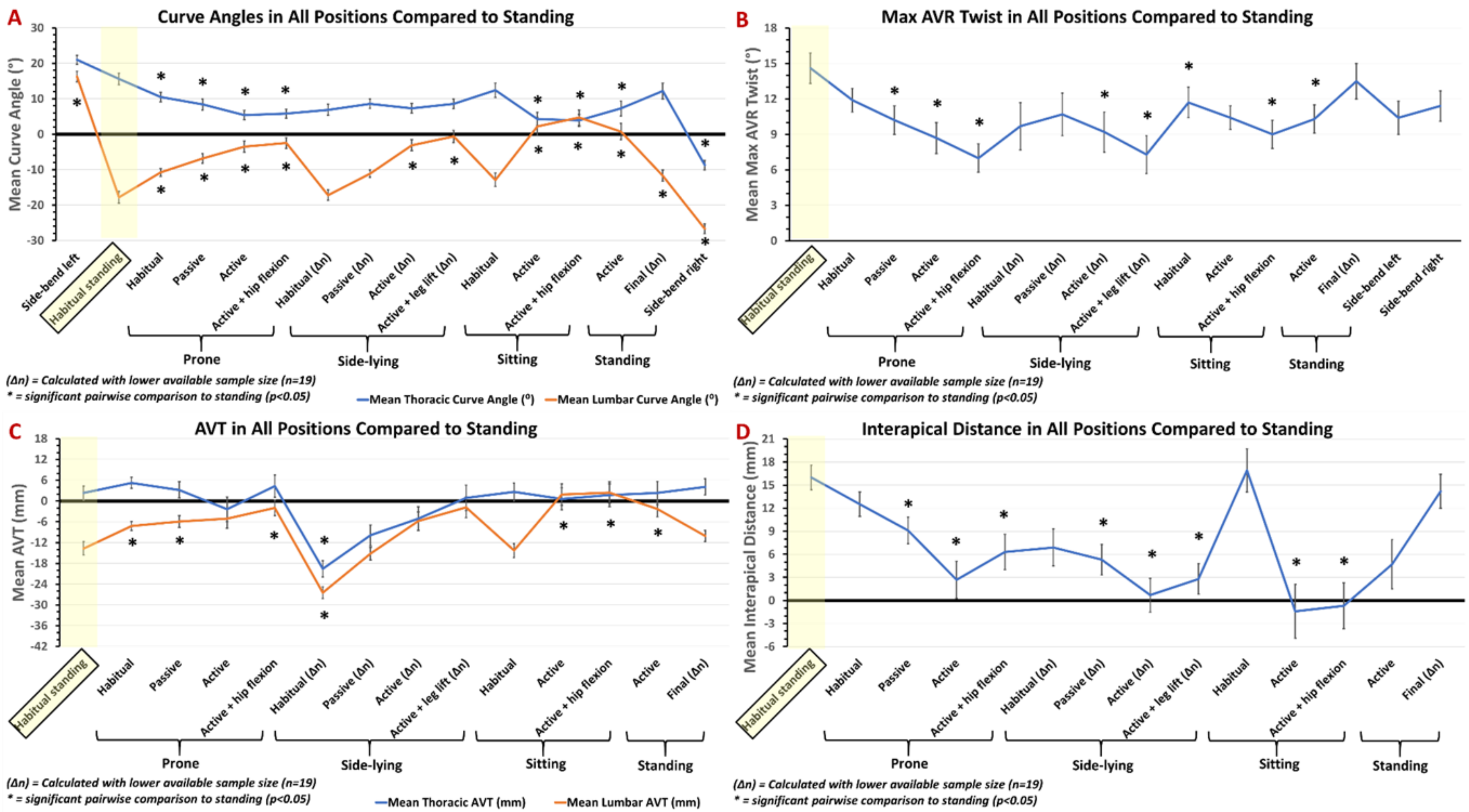

Figure 6. Mean thoracic and lumbar curve angles, max AVR twists, AVTs, and interapical distances for all positions compared to standing.
A) Mean thoracic and lumbar curve angles, B) Mean axial vertebral rotation (AVR) twists, C) Mean thoracic and lumbar apical vertebral translations (AVT), D) Mean interapical distances. All error bars represent the standard error of the mean.

Comparisons among habitual positions

Curve Angles

Habitual prone (10±1°) and side-lying (7±1°), but not sitting, showed smaller thoracic curve angles than standing (p<0.01). Thoracic curves were also significantly smaller in side-lying than sitting or prone (p<0.01)(Figure 7A).

Lumbar curve angles were significantly reduced in habitual prone position (-11±1°) compared to standing and side-lying (p<0.001). Sitting (-13±2°) also presented lower lumbar curve angles than standing (p=0.04)(Figure 7A).

Maximum AVR Twist

There were significant reductions (p<0.05) in max AVR twist in all the habitual positions compared to standing (14±1°)(Figure 7B).

Apical Vertebral Translation

Thoracic AVT was significantly overcorrected in side-lying (-21±2mm) compared to all other habitual positions (p<0.001)(Figure 7C). Lumbar AVT was significantly lower in prone than in all other habitual positions and significantly larger in side-lying (-27±2mm) compared to all other habitual positions (p<0.001). The interapical distance was significantly lower in side-lying (6±2mm) and in prone (12±1mm) than in habitual standing or sitting (p<0.05)(Figure 7D).

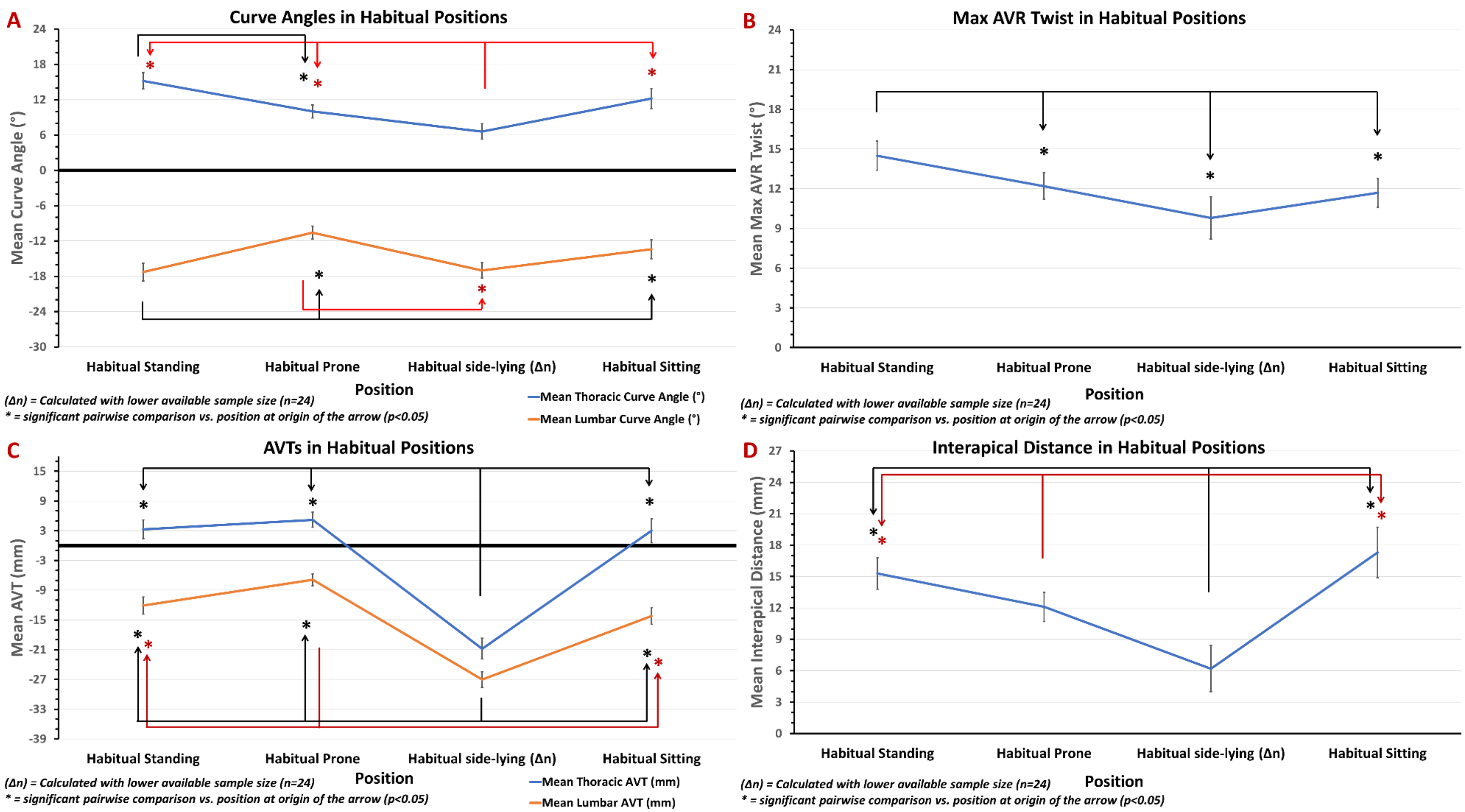

Figure 7. Mean thoracic and lumbar curve angles, max AVR twists, AVTs, and interapical distances for comparisons among habitual positions.
A) Mean thoracic and lumbar curve angles, B) Mean axial vertebral rotation (AVR) twists, C) Mean thoracic and lumbar apical vertebral translations (AVT), D) Mean interapical distances. All error bars represent the standard error of mean

Comparisons among prone positions

Curve Angles

Thoracic curve angles were significantly reduced in prone active (6±1°) and active with hip flexion (6±1°) exercises compared to the habitual prone position (10±1°)($p<0.05$)(Figure 8A).

Lumbar curve angles were significantly reduced in the prone passive (-7±1°), active (-4±1°) and active with hip flexion (-3±1°) exercises compared to the habitual prone position ($p<0.01$) (Figure 8A). The prone active with hip flexion exercise also achieved significant lumbar curve angle reduction compared to prone passive ($p<0.01$).

Maximum AVR Twist

There was a mean max AVR twist of 12±1° in habitual prone which was significantly reduced to 9±1° and 7±1° in prone active and active with hip flexion, respectively (Figure 8B). Active prone with hip flexion also achieved significantly smaller AVR twist when compared to prone passive (10±6°).

Apical Vertebral Translation

The thoracic AVT was significantly lower in the prone active position (-2±3mm) than in prone active with hip flexion (4±3mm). There were no significant differences in lumbar AVT among the prone positions (Figure 8C).

The active prone position (3±2mm) produced a significant lower interapical distance than the habitual prone position (12±1mm) and prone active with hip flexion (7±2mm)(Figure 8D).

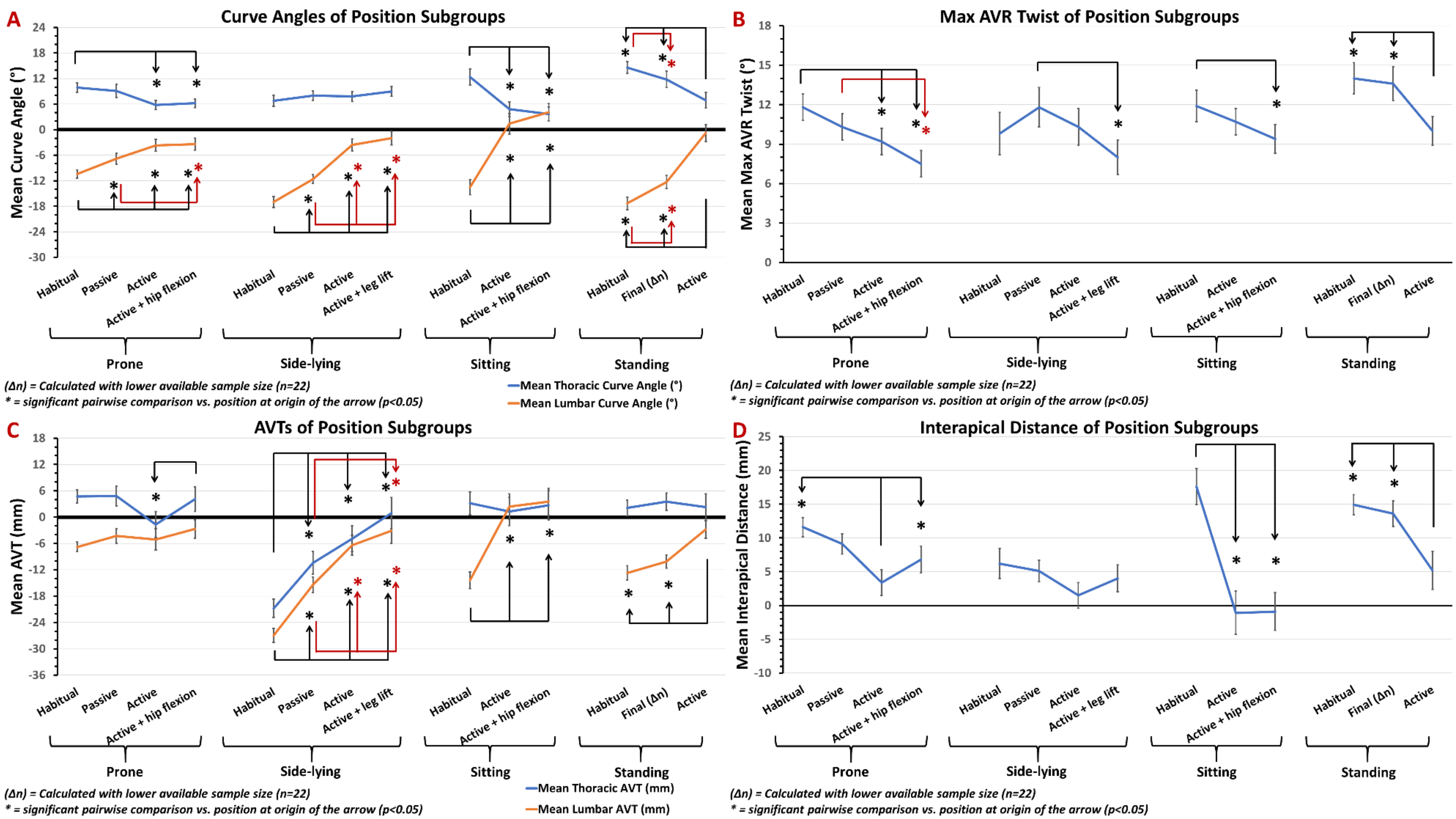

Figure 8. Mean thoracic and lumbar curve angles, max AVR twists, AVTs, and interapical distances for comparisons among each of the prone, side-lying, sitting and standing position subgroups.
A) Mean thoracic and lumbar curve angles, B) Mean axial vertebral rotation (AVR) twists, C) Mean thoracic and lumbar apical vertebral translations (AVT), D) Mean interapical distances. All error bars represent the standard error of mean.

Comparisons among side-lying positions

Curve Angles

No significant differences were observed in the mean thoracic curve angle among the side-lying positions (Figure 8A). All side-lying PSSE positions significantly reduced the lumbar curve angle compared to habitual side-lying (-17±1°)(p<0.001). Active side-lying (-4±1°) and active side-lying with leg lift (-2±2°) also significantly reduced the lumbar curve angle compared to side-lying with passive corrections (p<0.001).

Maximum AVR Twist

The max AVR twist in active side-lying with leg lift (8±1°) was significantly reduced in relation to passively-corrected side-lying (12±1°)(p=0.001)(Figure 8B).

Apical Vertebral Translation

There were significant reductions in thoracic AVT with all the Schroth side-lying exercises compared to habitual side-lying (-21±2mm) (Figure 8C). Further, the thoracic AVT in active side-lying with leg lift (1±4mm) was significantly less than side-lying with passive corrections only (-10±3mm)(p<0.01).
All exercise positions produced significantly smaller lumbar AVT when compared to habitual side-lying (-27±2mm). Further, side-lying active (-6±2mm) and side-lying active with leg lift (-3±3mm) also produced significantly lower lumbar AVT than using only passive corrections in side-lying (-15±2mm)(p<0.01). There were no significant differences in interapical distances among the side-lying positions (p>0.05) (Figure 8D).

Comparisons among sitting positions

Curve Angles

The thoracic and lumbar curve angle were significantly reduced to 5±2° and 1±2° in sitting active, and 4±2° and 4±2° in sitting active with hip flexion compared to habitual sitting (12±2°, -14±2°)(p<0.01) (Figure 8A).

Maximum AVR Twist

Only sitting active with hip flexion (9±1°) achieved a significant reduction in the max AVR twist from habitual sitting (12±1°)($p<0.05$)(Figure 8B).

Apical Vertebral Translation

Only lumbar AVT, and not thoracic, significantly decreased in both sitting active (2±3mm) and sitting active with hip flexion (4±3mm) compared to habitual sitting (-14±2mm)(Figure 8C).

Similarly, the interapical distance was significantly reduced during both active sitting (-1±3mm) and active sitting with hip flexion (-1±3mm) compared to habitual sitting (18±3mm)(Figure 8D).

Comparisons among standing positions

Curve Angles

The thoracic and lumbar curve angles significantly reduced to 7±2° and -1±2°, respectively, for standing active, and to 12±2° and -12±2°, respectively, for final standing in comparison to habitual standing (Figure 8A). Standing active also produced significantly smaller thoracic and lumbar curve angles than final standing.

Maximum AVR Twist

Standing active (10±1°) presented a significantly lower max AVR twist than habitual standing (14±1°) and final standing (14±1°)(Figure 8B).

Apical Vertebral Translation

No difference in thoracic AVT was found among the standing positions. However, the lumbar AVT was significantly smaller during standing active (-3±2mm) than in habitual standing (-13±2mm) and final standing (-10±1mm)(Figure 8C). Similarly, the interapical distance was significantly lessened in standing active (5±3mm) compared to both habitual standing (15±2mm) and final standing (14±2mm)(Figure 8D).

Comparisons among fully corrected positions

Curve Angles

For both the thoracic and lumbar curve angles, all fully Schroth-corrected positions (prone, side-lying, sitting, and standing) were significantly different compared to both the left and right prone side-bending positions (Figure 9A). When compared against prone side-bending right (-8±1°), all other positions achieved less thoracic curve correction. In contrast, when compared to side-bending left (21±1°), all other positions produced significant improvements in the thoracic curve angle.

Likewise, the lumbar curve angle for all positions was significantly less corrected than the overcorrection achieved in side-bending to the left (16±1°)(Figure 9A). In contrast, the lumbar curve angle was less severe in all the positions compared to side-bending to the right (-27±1°). Sitting active with hip flexion (4±2°) achieved some overcorrection of the lumbar curve angle which was significantly better than the correction achieved in prone active with hip flexion (-3±2°).

Maximum AVR Twist

Prone active with hip flexion (7±1°) and side-lying with leg lift (7±1°) achieved significantly better AVR twist values compared to side-bending to the right (12±1°). Prone active with hip flexion also presented significantly reduced AVR twist compared to standing active (10±1°)(Figure 9B).

Apical Vertebral Translation

There were no significant differences in thoracic or lumbar AVT values among any of the Schroth corrected exercises (Figure 9C). In contrast, sitting active with hip flexion (overcorrection to -1±3mm) produced a significantly better interapical distance when compared to prone active with hip flexion (6±2mm)(Figure 9D).

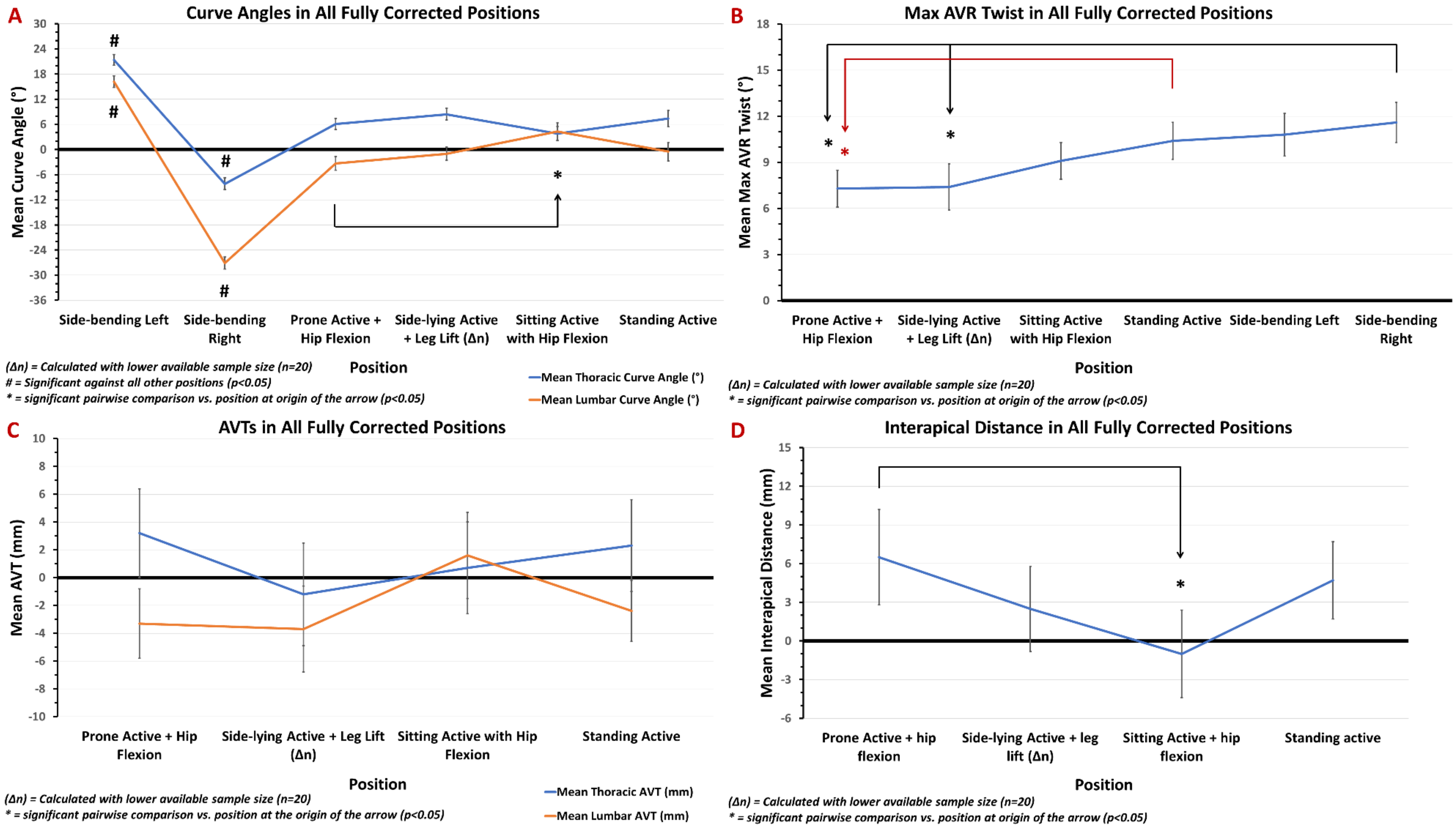

Figure 9. Mean thoracic and lumbar curve angles, max AVR twists, AVT, and interapical distances for comparisons among fully-corrected positions.

A) Mean thoracic and lumbar curve angles, B) Mean axial vertebral rotation (AVR) twist, C) Mean thoracic and lumbar apical vertebral translations (AVT), D) Mean interapical distance. All error bars represent the standard error of mean.

Discussion

Clinical Significance:

This study revealed that the Schroth exercises in each of the positions tested achieved additional clinically important immediate 3D corrections beyond the changes produced by external forces by moving from standing into habitual prone, side-lying or sitting position. Additionally, this study showed the significant effects of PSSE on AVTs and interapical distance. Importantly, individuals trained in Schroth can create 3D autocorrections to their spine in prone, side-lying, sitting, and standing without exhibiting compensations in other spinal regions or on other spine alignment measurements. While Schroth corrections did not approach the maximal curve angle correction limits found in prone side-bending, corrections in each exercise were obtained without the significant compensations in the opposing curve that are seen in side-bending. This evidence can be used to reassure patients, families, and referring clinicians that are skeptical about the patient's ability to achieve meaningful corrections while doing the exercises. Use of the lower limb contractions through hip flexion in prone and sitting and leg lift in side-lying provided changes to the lumbar curve angle and assisted with obtaining derotation. This study provided empirical evidence to the hypothesis that, with hip movements, the unilateral activation of the psoas or quadratus lumborum assist with derotation and lumbar curve correction[13,74]. Finally, Schroth exercises may have a lasting effect within session on the thoracic and lumbar curve angles. It is unknown how long this effect lasts and whether it relates to long-term effects.

Comparisons to standing

Trained individuals were shown to gain corrections with active Schroth PSSE exercises in relation to standing that cannot be attributed solely to adopting a different habitual position. Passive and active Schroth corrections in any positions also always reduced the point estimates of the curve angle, AVR, and interapical distance relative to habitual standing. Each Schroth PSSE variation achieved significance on at least one 3D deformity parameter relative to standing.

The most important deformity was consistently observed in standing if we ignore the side bending positions causing important compensations. Thoracic and lumbar curve angles as well as the max AVR twist were generally found greatest in habitual standing except for the positions noted in the results where differences were not significant. Unlike our hypothesis based on observations by others, habitual sitting did not result in the greatest curve angle magnitudes, max AVR twist, AVT measurements, or interapical distances[113–115,120]. No other habitual position or Schroth exercise produced worse curve angles or AVR twist than standing. Habitual side-lying, and side-lying passive had meaningfully lower max AVR twist compared to standing but did not reach statistical significance possibly because the limited sample size for this comparison resulted in a lack of power.

The curve angles in side-bending demonstrated participants had the flexibility to overcorrect their thoracic and lumbar curves. On the other hand, as expected, all side-lying positions meaningfully reduced the thoracic curve angle from 7-8.7°. However, these reductions did not reach statistical significance possibly due to the limited sample size available for these comparisons. This may also be true for the important but non-significant lumbar curve angle reduction of 11° in side-lying passive and the interapical distance reduction in standing active in comparison to habitual standing.

Interestingly, despite being a more unstable position than prone, sitting active with hip flexion offered the greatest correction in both the thoracic and lumbar curve angles of all positions compared to standing. As expected because it combines stable passive support with strong active corrections, prone active with hip flexion position offered the greatest derotation compared to standing[121]. The greatest reduction in interapical distance compared to standing was seen in the sitting active position.

Habitual positions

While habitual standing presented the greatest spinal deformity measurements, lying prone provided significant reductions in all parameters except thoracic AVT relative to standing. Contrary to our hypothesis, habitual sitting presented similar and not worse deformity than standing. Side-lying on the thoracic concave side offered the best thoracic curve and AVT correction among the habitual positions.

Lying prone resulted in a 34% and 39% decrease in the thoracic and lumbar curve angle, respectively, which was consistent with but slightly less than the 44% scoliotic curve angle reduction reported by Khodaei et al.'s also using US imaging[35]. This is understandable since Khodaei et al's participants presented with nearly double the curve magnitude as our participants. Studies comparing standing Cobb angles to those from CT scans in prone reported reductions of 9°-14° in surgical candidates[122]. We also documented, for the first time, a reduction in the interapical difference in this position, which was mainly comprised of a reduction in the lumbar AVT. Of all the habitual positions, habitual prone resulted in the greatest reduction in lumbar curve angle, the only clinically significant reduction from a habitual position. Habitual prone also yielded a lumbar AVT smaller than all other positions as well as smaller interapical distances than standing and sitting.

Side-lying provided the largest thoracic curve angle reduction (-57%) and decrease in thoracic AVT compared to all other habitual positions. The point estimates of the interapical distance and the max AVR twist in side-lying were also the smallest compared to all other habitual positions. Although the max AVR twist in side-lying was not different from prone or sitting, only side-lying created clinically meaningful derotation in relation to standing. The thoracic curve angle improvement supports our hypothesis that lying on the thoracic concave side with the direction of gravity may decrease this curve magnitude. Contrary to our hypothesis, side-lying did not increase the lumbar curve angle even though the lumbar AVT increased relative to standing. The lack of lumbar curve angle change could be due to the cushioned surface of the table limiting further sinking of the lumbar curve.

Habitual sitting did not worsen any measurement compared to standing and, in fact, achieved significant but not clinically important derotation compared to standing. Of note, sitting was tested immediately upon sitting on an exercise ball without support. Our result is surprising since we hypothesized that sitting may result in a more slouched habitual posture, potentially reducing the lumbar lordosis shown to increase curve magnitude and rotation[115]. It is possible that these trained participants sat in a more erect position (i.e. "like standing") than typically seen on an exercise ball. In the future, it may be relevant to compare the effect of sitting postures on different surfaces, with different support, allowing time for the sitting posture to relax to a habitual position.

Prone positions

As expected, the Schroth exercises including the most active corrections (prone active with or without hip flexion) provided the best corrections in prone. These positions did achieve significant thoracic and lumbar curve angle reductions, but only the lumbar curve reductions were clinically meaningful. Further, prone active with hip improved the lumbar curve angle and max AVR twist compared to the prone passive. Clinically meaningful reductions in the max AVR twist compared to habitual prone were only seen in prone active with hip flexion position. These observations show the value of instructing patients in activating the hip from maximizing corrections. The fascicles of the psoas muscle have little leverage to laterally pull or rotate the lumbar vertebrae in a non-scoliotic spine[123–125]. However, the lumbar rotation and curve present with scoliosis may change the line of pull so that the psoas muscle can now influence the lumbar spine when performing a closed-chain hip flexion contraction against fixed resistance with only the lumbar attachment free to move. Since we cannot conclusively state that the psoas muscle was activated in our participants we can only speculate its potential action. Results also provided evidence that Schroth-trained participants can create 3D spine autocorrection that cannot be attributed to the external force involved in adopting a prone lying position.

Hip flexion in the fully-corrected prone position may however limit the ability to correct the thoracic lateral deformity since the mean thoracic AVT and interapical distance worsened in with hip flexion compared to prone active. Even so, because the hip flexion instruction derotated the spine without loss of the corrections in the thoracic and lumbar curve angles, clinicians may still find benefit in this balance of changes.

Side-lying positions

Side-lying exercises appear most useful to reduce lumbar curve angles with statistically significant reductions found at each level of added Schroth instruction. In side-lying, the lumbar curve can be corrected by a passive external force as the reduction in the side-lying passive position was clinically meaningful. Adding active corrections created further clinically meaningful reductions in the lumbar curve angle. This means that Schroth-instructed participants can also produce autocorrection of lumbar curve angle in side-lying independent of external forces. Adding the leg lift instruction provided the greatest spine derotation which reached clinical significance relative to side-lying with passive corrections. Hip abduction may provide pelvis stabilisation to help autocorrect the lumbar rotation.

On the other hand, side-lying positions did not lead to thoracic curve angle reductions beyond the non-significant reductions relative to standing observed in all side-lying positions. Interapical distance also did not change between side-lying positions.

Sitting positions

The sitting active and sitting active with hip flexion positions both produced clinically significant reductions in the both curve angles. Participants also achieved lumbar curve, AVT and interapical distance overcorrection in the active positions. Sitting active and sitting active with hip flexion did not differ for any measurement but only sitting active with hip flexion created a significant derotation in relation to habitual sitting (however not clinically important). This derotation effect and the slightly better point estimates for sitting with hip flexion provide partial support for using hip flexion in this exercise.

Thus, Schroth-trained individuals can create curve reductions, self-correct their lateral deformity and spine derotation through active Schroth exercises in sitting.

Standing positions

Despite offering little support and passive assistance, active correction in standing between two poles created clinically significant derotation and reductions of both curve angles, lumbar AVT, interapical distance. Trained participants could obtain 3D autocorrection of their spine with clinically meaningful corrections under their own control in standing.

The significant improvements in the final standing position compared to the initial habitual standing position in the thoracic and lumbar curve angle indicate some lasting effect from this short testing session of Schroth exercises. The lumbar curve reduction was also clinically significant. This is notable given that the testing session did not require the participants to complete the normally prescribed set of repetitions and holding times normally used in therapy. More clinically important differences in the different deformity measurements may be observed in more intensive exercise sessions.

Fully corrected positions:

As expected, the fully instructed Schroth corrections did not result in similar amounts of maximal curve angle correction achieved in either side-bending position. This may be because Schroth corrections are performed while carefully avoiding compensatory worsening of the other curve seen in side-bending corrections.

The results did not clearly identify an exercise providing better correction of the 3D deformity. In fact, the fully corrected Schroth positions did not differ in terms of the correction achieved in the thoracic curve angle, or the thoracic or lumbar AVT. Sitting active with hip flexion was the only exercise to achieve overcorrection the lumbar curve and interapical distance with significantly better results than prone active with hip flexion. Therefore, fully corrected sitting may be preferential to prone active with hip flexion if the goal is to minimize these measurements.

A larger sample may allow detecting additional differences between fully corrected positions. However, these exercises are usually taught as a progression from those providing more passive support initially progressing to those offering less[13,74]. Our sample of trained participants experienced with all the exercises showed good corrections in all the exercises. Participants with less training may have shown more differences between exercises. Ultimately, patients are trained to hold as much correction as possible in lifelike positions. Therefore, while standing active did not provide the best corrections looking at point estimate for any of the parameters, it would still be recommended as it mimics much of the activities of daily living.

Of all the fully corrected positions, the most corrected point estimates, regardless of statistically significant comparisons were the following: thoracic curve angle in sitting (3.8°), lumbar curve angle in sitting (4.3°), max AVR twist in prone (7.3°), and interapical distance in sitting (-1mm). Since the majority of the 3D US measurements corrections were not different between fully-corrected positions, the choice of a Schroth exercise to prescribe may be best tailored towards a patient's activities of daily living or their performance ability rather than by trying to select the exercise providing more correction of a specific measurement.

Limitations:

Although analyses were conducted with the largest sample size available in each grouping, the reduction in sample due to image artifact and only 24 participants tested in side-lying/final standing impacted the power available for select groupings. The image artifacts causing exclusion of scans were sometimes due to loss of contact during scanning, probe orientation insufficiently perpendicular to the laminas or to distortion from patient motion with breathing or during unstable exercises. Most removed scans were in the most unstable actively corrected exercises. Participants expressed that this active sitting with hip flexion exercise was the most challenging.

We observed a carry-over effect from the first to the final standing position. Therefore, we may have underestimated the magnitude of the deformity in habitual or exercise positions preceded by other exercises. On the other hand, clinically it is desirable for sequential exercises to add up to greater lasting corrections.

In this study, we only studied exercises that would be used for a double curve pattern (right thoracic/ left lumbar). The 9 participants with only a single curve measuring more than 10 degrees at time of testing may not have had responses to the exercises that maximally addressed their individual deformity. Future studies may wish to recruit participants with completely similar curve types. The relatively older age of the participants could underestimate the correction achieved as curve flexibility decreases with increases in age[118]. The low curve angle magnitudes in our participants may also underestimate the magnitude of correction possible in the different positions due to the limited correction possible relative to the measurement errors. Some individuals that had not performed Schroth exercises for an extended period may have demonstrated reduced amounts of correction due to having reduced proficiency from lack of recent practice.

Finally, the calibration of the 3D ultrasound system and the orientation of the scanning region of interest varies in 3D space from position to position which alters the image vertical from which AVT are measured. Positioning of the transducer during calibration determines the horizontal edge of the image space. Some exercises affect the relative position of the pelvis in relation to T1 independent from the effect on apical vertebra positions. As such, traditional frontal translation measurements other than interapical distance may not be clinically meaningful using ultrasound imaging unless this is addressed.

Research application and future directions

Only a subset of Schroth exercises and specific incremental instructions were tested in the present study. Future studies could compare additional exercises or examine the effect of different correction instructions and difference exercises. Future studies may investigate the relationship between the amount of immediate curve correction and long-term PSSE treatment outcome. As suggested by our results, the correlation between curve angle, vertebral rotation, and AVT may vary through different positionings and different curves regions. Further research is needed to establish these relationships.

Conclusion

Schroth PSSE instructions can produce immediate reductions to the thoracic and lumbar curve angles, rotation, and apical vertebral translation in previously Schroth-trained individuals with AIS. Importantly, when corrections were observed in one spinal region or on a specific deformity measurements, there were no compensations observed in other regions or on other parameters while performing the Schroth exercises. These trained individuals can create 3D autocorrections to their curves beyond the corrections observed moving to different habitual lying positions compared to standing. This simple testing session of Schroth exercises also produced lasting effects on the curves of individuals.

Chapter 5. Conclusion

Summary of thesis

The primary objective of this thesis was to determine the immediate in-exercise effects of Schroth physiotherapeutic scoliosis-specific exercises (PSSE) on the curve angle, axial vertebral rotation (AVR), max AVR twist, apical vertebral translation (AVT) and interapical distance measurements of individuals with AIS. To achieve this objective, we chose US imaging due to its high adaptability, safety, and utility in positions related to Schroth exercises. However, to properly conduct and assess any research findings on these new measurements, we needed to establish the intra and inter-evaluator reliability of our measurements. After recruiting our volunteers (n=36) and scanning participants in 16 positions reflective of Schroth exercise, we showed adequate intra-evaluator and inter-evaluator reliability for research using these US measurements. Finally, once we established reliability, we were able to demonstrate significant in-exercise effects from Schroth PSSE treatment, exceeding corrections achieved by adopting habitual positions other than standing, in a cross-sectional study.

Intra and inter-evaluator reliability

Following intra-evaluator analyses of 13 participant sets of repeated image measurements (n=208 images) by a single evaluator and inter-evaluator analyses of 35 participants sets of image measurements (n=516 images) by two evaluators, our key findings were the following:

- Thoracic and lumbar curve angle, max AVR, AVR twist, thoracic and lumbar AVT, and interapical distance measurements were reliable for research in a large portion of PSSE-related positions (ICC>0.70).
- AVT measurements showed good intra and inter-evaluator reliability (ICC>0.80) in US imaging and can be used to assess the spine.
- Thoracic curve angles generally presented higher intra and inter-evaluator reliability than lumbar curve angle measurements.
- Selection of the end vertebrae, vertebral labelling, low sample variance, poor image quality, and evaluator experience or exposure are potential sources for error for US image measurements.

These findings added to the body of knowledge by demonstrating that key clinical measurements, the curve angle, AVR, and AVT can be measured in a large variety of positions while remaining adequate for conducting research. Not only this, this study established the reliability of AVT, outside of standing, and interapical distance measurements in ultrasound imaging. In agreement with previous evidence, we also found that curve angle (5°) and AVR (<3°) measurements can assess the spine with standard errors of measurement within magnitudes commonly recommended for clinically significant detection[19,34,35].

Regarding clinical use, our findings do not support using US image measurements at an individual level. However, the potential sources of error at play in our study may inform future US image studies to ensure good sample variation, allow additional familiarity to US imaging by evaluators, and further standardize vertebral labelling and selection of end vertebrae. This supports previous statements made be Zheng et al. saying that the largest source of error in US imaging may actually come from the selection of the vertebral levels rather than the precision of the measurement[34]. Further suggestions to future US imaging studies include increasing quality of the collected images through adjusting the scanning depth and the gain for each patient using standardized guidelines to overcome noise caused by overlying fascia on the spine. Improvements to the scanning technology could allow improved surface area of contact with the back to reflect more of the spinal anatomy, thereby increasing the information usable to differentiate landmarks.

AVT measurements are newer to US imaging and there are potential limitations to their interpretation. Like radiographs, AVT measurements in US imaging are subject to the positioning of the pelvis and, consequently, are influenced by the location of L5. However, in radiographs, AVT measurements are made using a CSVL that is parallel to the vertical edge of the image frame, which is standardized and levelled with the horizontal and vertical planes of the real space. In US imaging, the CVL is parallel to the vertical border of the image frame but standardization and levelling to the true horizontal and vertical planes in real space may not always be possible nor meaningful with varying positions (E.g. side-lying). Additionally, since the orientation of the L5 vertebra in the US image can change in different positions with no standardizations to a reference orientation, the angle of the CVL used in AVT measurement may vary and bias the side the pelvis is angled. Further, during scanning, the end positioning of the transducer, in conjunction with the upper and lower calibration points, influence the horizontal and vertical edges of the US scan image. This contributes to more ambiguity in what the CVL is parallel to. As such, individual thoracic and lumbar AVT measurements may not be clinically meaningful as stand-alone measurements. Interapical distance measurements remove directional dependence on the CVL for interpretation and may provide more clinically meaningful information on the global frontal plane changes. Future work may be development of a new strategy to measure the lateral translation without dependence on the pelvis. Since both AVT and interapical distance measurements are dependant on a global vertical axis and influenced by factors other than the specific curve, future research on translation may focus on the regional apical vertebral translation, which uses the upper and lower end vertebra as the reference points[126].

The immediate effects of Schroth physiotherapeutic scoliosis-specific exercises

The thoracic and lumbar curve angles, AVRs, AVTs and the max AVR twist and interapical distance measurements for 36 participants were compared among subgroups of interest from the 16 positions evaluated. The main findings were:

- The thoracic and lumbar curve angle as well as the vertebral rotation were greatest in habitual standing while the thoracic AVT was greatest in habitual prone and the lumbar AVT was greatest in habitual side-lying The interapical distance was greatest in habitual sitting.
- Schroth PSSE created clinically meaningful reductions to all our measurements of interest in relation to standing and beyond corrections achieved by adopting their respective habitual position.
- Of any position, the greatest total reductions were in the fully-corrected positions.
- The greatest incremental amount of reductions were actively generated by the individuals.
- Active Schroth exercises results in incremental improvements to the curve angle, max AVR twist, and interapical distance measurements in relation to passively-corrected positions.
- Participants can correct their spine measurements without compensation or worsening in another part of the spine or on other spine measurements.

- Participants did not lose clinically-significant correction from PSSE with hip movements.
- As hypothesized, the AVT and interapical distance does change throughout different positions and can be improved using Schroth PSSE.
- Participants could create overcorrection of their thoracic AVT in active prone and overcorrection of their lumbar AVT and interapical distance in active sitting and active sitting with hip flexion.
- Although relatively unstable, fully-corrected active sitting provided the lowest thoracic (3,8°) and lumbar (4.3°) curve angle, as well as interapical distance (-1mm).
- Fully-corrected prone had the lowest max AVR twist (7.3°).
- There were carry-over effects within the single testing sessions reducing the lumbar curve angle observed the final standing position.

Through these findings, this research has made contributions by creating validity evidence on the immediate in-exercise effects of numerous Schroth exercises demonstrating that the exercises promote the corrections they are proposed for. Prior to this study, the only evidence on the immediate effects of exercise was the case study by Zapata et al.[17]. With our sample of 36 participants and by imaging multiple positions, in addition to standing, as well as quantifying the rotation and vertebral translation, in addition to curve angles, this has increased the level of evidence available for in-exercise correction by PSSE. AVT measurements also showed the ability to capture the effect of exercises in various positions. However, the minimal clinically meaningful change for this measurement is still unknown.

The clinical significance and implications of this study are numerous. First, the clinically significant reductions in curve angle, AVR, and AVT seen in fully-corrected positions compared to their habitual positions demonstrate that children with AIS can perform these complex exercises and gain meaningful benefits. Secondly, since spinal measurements did not worsen for any Schroth position, this can ease the skepticism from clinicians, patients, and their families about the feasibility of achieving corrections without worsening elsewhere in their spine or negatively affecting other deformity measurements in the same region. Towards clinical practice, our results indicate that the corrections achieved in PSSE cannot be attributed to simply adopting different habitual positions other than standing or external forces from passive supports. The participants activation of their torso musculature created the largest reductions and at times overcorrection. Over-correction of the spine has been theorized to change the loading on the vertebral column and thereby reduce the overload of the concave side of the scoliotic curve which could possibly slow curve progression according to the Hueter-Volkmann Law[38]. In contrast to Stokes vicious cycle, this has been called the "virtuous cycle" of conservative treatment[127].

Further, through the separate imaging of passive, active, and hip activation Schroth instructions we have provided quantitative evidence for the amounts of correction provided by different cues. By providing this evidence, the value of each of the different Schroth PSSE instructions was at least supported and clinicians can now make evidence-based decisions towards recommendations and adjustments to their clinical practice to maximize achieving the immediate desired effects hoping to maximize longer term treatment success. By extension, this should improve the quality of treatment received by patients. Similarly, through knowledge translation, this empirical evidence can be a resource for patients and families to reassure them of the adolescents' ability to obtain the intended immediate benefits of PSSE treatment.

Increased power from a larger sample size may have allowed detection of smaller significant differences by the incremental reductions created from passive PSSE positions compared to habitual as well as between the active and active with leg movement positions. Likewise, we must caution against overreliance on our results for the effects of side-lying PSSE not providing significant correction since they did offer clinically important reductions but lacked statistical significance; increased power may change this. Discretion should also still be used in interpretation of hip flexion's ability to derotate the spine since individual thoracic and lumbar AVR reductions may be minor and we cannot conclusively verify what is producing this change as well as what other factors contribute to derotation. Nevertheless, clinicians and patients should not overlook exercise components that lack significance since PSSE instructions are cumulative and may be used for stabilization of the posture rather than gross correction.

Finally, the carry-over effects observed in our study may implicate that there are potentially lasting effects from a single session of Schroth PSSE. Given that prior evidence shows that Schroth exercises can slow curve progression, there may be a relationship between the immediate in-exercise correction and the long-term treatment success[15].

Limitations

In our reliability study, small between-subject variance in curve angle severity may have limited our results by overemphasizing the effect of the true measurement error on our ICC values. This could have been due to our participants having smaller curve magnitudes from corrections from an extended duration of Schroth PSSE practice. In our in-exercise effects study, these small curve magnitudes may have limited the amount of correction possible or our ability to detect these small changes exceeding measurement error. Similarly, the older age of the participants would have also decreased the curve flexibility and by consequence the amount of correction observed[117,118]. Future studies on the immediate effects of exercises may wish to recruit younger participants with larger curves.

The smaller sample size in side-lying positions and final standing could have caused reduced power and limited our ability to detect the observed changes as statistically significant. Particularly, in some of our positions, such as side-lying, point estimates were nearly identical to positions that achieved statistical significance but reduced sample size in positions due to late inclusion in the study protocol likely led to this discrepancy. Additionally, this small sample size may increase the influence of outliers in our sample for both the intra and inter-evaluator reliability study as well as our in-exercise effects study. This would result in decreased ICC values and the potential to underestimate or, although unlikely, overestimate the effects of PSSE. As such, researchers could conduct larger studies with increased numbers of patients with a greater number of positions. Other Schroth exercise positions with greater stability demands or with continuous motion, such as the Schroth kneeling ‘muscle cylinder’ exercise and active correction in walking, may also have been of interest to clinicians but would have caused too much motion artifact to be usable. Therefore, as technology advances to limit motion artifact limitations and tethering to machine console, research into more dynamic positions may also progress.

Test-retest reliability would have allowed us to determine the consistency of repeated US acquisitions and may be an area worthy of further research. Since Schroth exercises involve many other cues that have not been explored in this project, researchers may wish to further examine the individual instructions in each exercise such as the use of RAB technique, elongation, shoulder traction and counter traction, and the effects of leg-lifts and hip-flexion alone[121].

Lastly, as mentioned previously since we do not know the clinically important difference for AVT measurements and interapical distance we cannot confidently interpret the corrections created by PSSE. Also previously discussed, we must express caution in interpretation of the AVT and interapical distance measurements since they are less standardized compared to translation measurements taken on a radiograph and are influenced by US operator, scanning environment and orientation, and the positioning of the patient being scanned.

Future research directions

By using the end-vertebra selections in habitual standing for the extraction of all other positions throughout our project, we adopted a fixed end-vertebra strategy. This contrasts with the non-fixed end-vertebra selection strategy used in previous US studies and likely contributed to the differences in our reliability statistics. One avenue for future US image measurement research may be to compare the effects of a fixed and non-fixed end-vertebra selection strategy in data extraction to determine reliability of curve angle and AVR measurements. Understanding the effect of the end-vertebra selection on the intra and inter-evaluator reliability of these measurements from a shared set of images could provide the best suggestions for standardized extraction of data in future studies.

As previously mentioned, test-retest reliability of these US measurements in various exercise positions may be explored to determine if these results can be consistently replicated. In particular, future studies may wish to study the fully-corrected exercise positions due to their increased instability and difficulty to the participants. The results of this project demonstrated that PSSE may provide lasting effects beyond the in-exercise reductions on the curve angles of our participants. Assuming good retest reliability, to determine the nature of these lasting effects from exercise, researchers could investigate the time-decay and rate of change of these exercise effects by collecting measurements in short-duration intervals (e.g. one-minute intervals) with varying exercises, repetitions, and length of time held.

Regarding the immediate in-exercise effects, a longitudinal study can also be proposed to determine if a relationship exists between these immediate in-exercise effects and the long-term treatment outcomes described in the literature.

Since our AVT measurements demonstrated good reliability and are sensitive to exercise and changes in positions, validation of AVT measurements could be conducted through comparisons with AVT measurements on a PA radiograph. Additionally, the relationship between the thoracic and lumbar curve angles, max AVR twist, AVTs, and interapical distance in various positions using US imaging is still unknown; a correlation study may reveal this.

Lastly, this research project has demonstrated the effects of exercise on the frontal and rotational deformity in scoliosis, yet, to truly assess the 3D nature of scoliosis, the sagittal profile must also be assessed. Future research projects may establish the validity, reliability, and exercise response of sagittal profile measurements like the kyphosis and lordosis angles. Furthering this, correlation analyses of these sagittal measurements to the frontal and rotational measurements may provide a better understanding of the mechanism and effects of exercise on the global 3D scoliotic deformity.

Conclusion

In completing this research project, this thesis has provided new areas of research to explore for US image measurements and has given validity evidence to clinicians, educators, patients and their caregivers on the in-exercise corrections produced by Schroth physiotherapeutic scoliosis specific exercises (PSSE). This research may provide rationale for longitudinal studies exploring the immediate effects of exercise and its relationship to the long-term treatment outcome. This research project helped show that US image measurements are reliable from a variety of exercise-related and habitual positions and can be used for future exercise studies. We also found that AVT measurements do respond to exercise and may be an important clinical measurement for PSSE assessment.

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Appendices

Appendix I: Tabulated Statistics for Post-hoc Comparisons Conducted in Chapter 4.

Table 2. Pairwise comparisons of the mean curve angle, axial vertebral rotation, and apical vertebral translation measurements in all positions compared to habitual standing.

n=27	*Thoracic Curve Angle*			*Lumbar Curve Angle*			*Max Axial Vertebral Rotation (AVR) Twist*		
Position	Mean Thoracic Curve Angle (^{0})	SE	*P*-value (Habitual standing)	Mean Lumbar Curve Angle (^{0})	SE	*P*-value (Habitual standing)	Mean Max AVR Twist (^{0})	SE	*P*-value (Habitual standing)
Habitual standing	15.6	1.6	-	-17.8	1.7	-	14.6	1.3	-
Habitual prone	10.5	1.3	**0.011***	-10.8	1.1	**0.006***	11.9	1	0.402
Prone side-bending left	21	1.3	0.271	16.3	1.5	**<0.001***	10.4	1.4	0.568
Prone side-bending right	-8.7	1.3	**<0.001***	-26.7	1.4	**0.004***	11.4	1.3	0.224
Prone passive	8.4	1.6	**0.006***	-6.8	1.4	**<0.001***	10.2	1.2	**0.024***
Prone active	5.4	1.3	**<0.001***	-3.5	1.6	**<0.001***	8.7	1.3	**0.003***
Prone active + hip flexion	5.8	1.3	**<0.001***	-2.5	1.5	**<0.001***	7	1.2	**<0.001***
Habitual side-lying[A]	6.9	1.5	0.110	-17.2	1.5	1.000	9.7	2.0	0.900
Side-lying passive[A]	8.6	1.3	0.283	-11.1	1.1	0.556	10.7	1.8	0.240
Side-lying active[A]	7.3	1.4	0.233	-3.1	1.6	**0.005***	9.2	1.7	**0.020***
Side-lying active + leg lift[A]	8.6	1.4	0.348	-0.6	1.7	**0.002***	7.3	1.6	**0.000***
Habitual sitting	12.4	2	0.836	-12.9	1.9	0.27	11.7	1.3	**0.017***

Sitting active	4.3	1.8	**<0.001***	2.2	2.6	**<0.001***	10.4	1	0.065
Sitting active + hip flexion	3.9	1.7	**<0.001***	4.7	2.2	**<0.001***	9	1.2	**0.001***
Standing active	7.3	2.1	**0.038***	0.7	2.3	**<0.001***	10.3	1.2	**0.036***
Final standing[A]	12.2	2.2	0.444	-11.7	1.6	**0.002***	13.5	1.5	1.000
	Apical Vertebral Translation (AVT)								
Position	Mean Thoracic AVT (mm)	SE	*P*-value (Habitual standing)	Mean Lumbar AVT (mm)	SE	*P*-value (Habitual standing)	Mean Interapical Distance (mm)	SE	*P*-value (Habitual standing)
Habitual standing	2.3	2	-	-13.7	1.9	-	16	1.6	-
Habitual prone	5.2	1.6	0.943	-7.2	1.3	**0.001***	12.5	1.6	0.356
Prone side-bending left	-	-	-	-	-	-	-	-	-
Prone side-bending right	-	-	-	-	-	-	-	-	-
Prone passive	3.2	2.4	1	-5.9	1.7	**0.017***	9.1	1.7	**0.003***
Prone active	-2.4	3.6	1	-5.1	2.8	0.443	2.7	2.4	**<0.001***
Prone active + hip flexion	4.3	3.2	1	-2	2.2	**0.025***	6.3	2.3	**0.004***
Habitual side-lying[A]	-19.6	2.4	**<0.001***	-26.5	1.7	**0.025***	6.9	2.4	0.624
Side-lying passive[A]	-9.9	3	0.409	-15.2	1.8	1	5.3	2	**0.024***
Side-lying active[A]	-5.1	3.4	1	-5.8	2.7	0.999	0.7	2.2	**0.000***
Side-lying active + leg lift[A]	0.9	3.7	1	-1.8	3	0.632	2.8	2	**0.002***
Habitual sitting	2.6	2.6	1	-14.3	2	1	16.9	2.8	1

Sitting active	0.6	3.2	1	1.9	3.1	**0.008***	-1.4	3.5	**<0.001***
Sitting active + hip flexion	1.7	3.3	1	2.4	3.1	**0.004***	-0.7	3	**<0.001***
Standing active	2.3	3.4	1	-2.3	2.3	**0.045***	4.7	3.2	0.051
Final standing[A]	4.1	2.3	1	-10.1	1.6	0.935	14.2	2.2	1

[A]Calculated with lower available sample size (n=19)
significant pairwise comparison (p<0.05)
Abbreviations: SE =Standard error of the mean, AVR=Axial vertebral rotation, AVT=Apical vertebral translation

Table 3. Pairwise comparisons of the mean curve angle, max axial vertebral rotation twist, and apical vertebral translation measurements between habitual positions.

n=34	*Thoracic Curve Angle*					*Lumbar Curve Angle*				
Position	Mean Thoracic Curve Angle (º)	SE	*P*-value (Habitual Standing)	*P*-value (Habitual Prone)	*P*-value (Habitual Side-lying) [A]	Mean Lumbar Curve Angle (º)	SE	*P*-value (Habitual Standing)	*P*-value (Habitual Prone)	*P*-value (Habitual Side-lying) [A]
Habitual Standing	15.2	1.4	-	**0.001***	**<0.001***	-17.3	1.5	-	**<0.001***	1
Habitual Prone	10	1.1	**0.001***	-	**0.043***	-10.6	1.1	**<0.001***	-	**<0.001***
Habitual side-lying[A]	6.6	1.3	**<0.001***	**0.043***	-	-17	1.3	1	**<0.001***	-
Habitual Sitting	12.2	1.7	0.062	0.312	**0.005***	-13.4	1.6	**0.04***	0.127	0.352
	Max Axial Vertebral Rotation (AVR) Twist					Apical Vertebral Translation (AVT)				
Position	Mean Max AVR Twist (º)	SE	*P*-value (Habitual Standing)	*P*-value (Habitual Prone)	*P*-value (Habitual Side-lying) [A]	Mean Thoracic AVT (mm)	SE	*P*-value (Habitual Standing)	*P*-value (Habitual Prone)	*P*-value (Habitual Side-lying) [A]
Habitual Standing	14.5	1.1	-	**0.028***	**0.014***	3.3	1.9	-	0.483	**<0.001***
Habitual Prone	12.2	1	**0.028***	-	0.114	5.2	1.5	0.483	-	**<0.001***

Habitual side-lying[A]	9.8	1.6	**0.014***	0.114	-	-20.8	2.1	**<0.001***	**<0.001***	-
Habitual Sitting	11.7	1.1	**<0.001***	0.905	0.772	3	2.4	0.999	0.664	**<0.001***
	Apical Vertebral Translation (AVT)									
	Mean Lumbar AVT (mm)	SE	*P*-value (Habitual Standing)	*P*-value (Habitual Prone)	*P*-value (Habitual Side-lying)[A]	Mean Interapical Distance (mm)	SE	*P*-value (Habitual Standing)	*P*-value (Habitual Prone)	*P*-value (Habitual Side-lying)[A]
Habitual Standing	-12.1	1.7	-	**<0.001***	**<0.001***	15.3	1.5	-	**0.038***	**0.011***
Habitual Prone	-6.9	1.2	**<0.001***	-	**<0.001***	12.1	1.4	**0.038***	-	0.074
Habitual side-lying[A]	-27	1.6	**<0.001***	**<0.001***	-	6.2	2.2	**0.011***	0.074	-
Habitual Sitting	-14.2	1.7	0.46	**<0.001***	**<0.001***	17.3	2.4	0.678	**0.016***	**0.02***

[A]=Calculated with reduced sample size (n=24)
**significant pairwise comparison (p<0.05)*
Abbreviations: SE =Standard error of the mean, AVR=Axial vertebral rotation, AVT=Apical vertebral translation

Table 4. Pairwise comparisons for the mean curve angle, axial vertebral rotation, and apical vertebral translation measurements among all prone positions.

n=35	*Thoracic Curve Angle*					*Lumbar Curve Angle*				
Position	Mean Thoracic Curve Angle (°)	SE	*P*-value (Habitual Prone)	*P*-value (Prone Passive)	*P*-value (Prone Active)	Mean Lumbar Curve Angle (°)	SE	*P*-value (Habitual Prone)	*P*-value (Prone Passive)	*P*-value (Prone Active)
Habitual Prone	9.9	1.1	-	0.996	**0.029***	-10.4	1	-	**0.001***	**<0.001***
Prone Passive	9.1	1.6	0.996	-	0.133	-6.8	1.3	**0.001***	-	0.115
Prone Active	5.8	1.1	**0.029***	0.113	-	-3.7	1.4	**<0.001***	0.115	-
Prone Active + Hip flexion	6.2	1	**0.011***	0.148	0.985	-3.4	1.4	**<0.001***	**0.032***	1
	Max Axial Vertebral Rotation (AVR) Twist					Apical Vertebral Translation (AVT)				
Position	Mean Max AVR Twist (°) (°)	SE	*P*-value (Habitual Prone)	*P*-value (Prone Passive)	*P*-value (Prone Active)	Mean Thoracic AVT (mm)	SE	*P*-value (Habitual Prone)	*P*-value (Prone Passive)	*P*-value (Prone Active)
Habitual Prone	11.8	1	-	0.122	**0.011***	4.7	1.5	-	1	0.32
Prone Passive	10.3	1	0.122	-	0.687	4.8	2.3	1	-	0.214
Prone Active	9.2	1	**0.011***	0.687	-	-1.7	3	0.32	0.214	-

Prone Active + Hip flexion	7.5	1	**<0.001***	**0.002***	0.051	4.1	2.8	1	1	**0.039***
	Apical Vertebral Translation (AVT)									
Position	Mean Lumbar AVT (mm)	SE	*P*-value (Habitual Prone)	*P*-value (Prone Passive)	*P*-value (Prone Active)	Mean Interapical Distance (mm)	SE	*P*-value (Habitual Prone)	*P*-value (Prone Passive)	*P*-value (Prone Active)
Habitual Prone	-6.8	1.1	-	0.203	0.978	11.6	1.4	-	0.349	**0.001***
Prone Passive	-4.3	1.7	0.203	-	0.999	9.1	1.5	0.349	-	0.065
Prone Active	-5.1	2.4	0.978	0.999	-	3.4	1.9	**0.001***	0.065	-
Prone Active + Hip flexion	-2.7	2.1	0.425	0.976	0.437	6.8	2	0.152	0.841	**0.04***

**significant pairwise comparison (p<0.05)*

Abbreviations: SE =Standard error of the mean, AVR=Axial vertebral rotation, AVT=Apical vertebral translation

Table 5. Pairwise comparisons of the mean curve angle, axial vertebral rotation, and apical vertebral translation measurements among the side-lying positions.

n=24	*Thoracic Curve Angle*					*Lumbar Curve Angle*				
Position	Mean Thoracic Curve Angle (º)	SE	*P*-value (Habitual Side-lying)	*P*-value (Side-lying Passive)	*P*-value (Side-lying Active)	Mean Lumbar Curve Angle (º)	SE	*P*-value (Habitual Side-lying)	*P*-value (Side-lying Passive)	*P*-value (Side-lying Active)
Habitual Side-lying	6.8	1.3	-	0.797	0.977	-17	1.3	-	**<0.001***	**<0.001***
Side-lying Passive	8	1.1	0.797	-	1	-11.6	1	**<0.001***	-	**<0.001***
Side-lying Active	7.8	1.2	0.977	1	-	-3.6	1.4	**<0.001***	**<0.001***	-
Side-lying Active + leg lift	9	1.2	0.662	0.955	0.955	-2	1.6	**<0.001***	**<0.001***	0.568
	Max Axial Vertebral Rotation (AVR) Twist					Apical Vertebral Translation (AVT)				
Position	Mean Max AVR Twist (º)	SE	*P*-value (Habitual Side-lying)	*P*-value (Side-lying Passive)	*P*-value (Side-lying Active)	Mean Thoracic AVT (mm)	SE	*P*-value (Habitual Side-lying)	*P*-value (Side-lying Passive)	*P*-value (Side-lying Active)
Habitual Side-lying	9.8	1.6	-	0.643	1	-20.8	2.1	-	**0.005***	**0.002***
Side-lying Passive	11.8	1.5	0.643	-	0.258	-10.4	2.6	**0.005***	-	0.233
Side-lying Active	10.3	1.4	1	0.258	-	-4.9	3	**0.002***	0.233	-

Side-lying Active + Leg lift	8	1.3	0.645	**0.001***	0.093	0.9	3.6	**<0.001***	**0.003***	0.424
	Apical Vertebral Translation (AVT)									
Position	Mean Lumbar AVT (mm)	SE	*P*-value (Habitual Side-lying)	*P*-value (Side-lying Passive)	*P*-value (Side-lying Active)	Mean Interapical Distance (mm)	SE	*P*-value (Habitual Side-lying)	*P*-value (Side-lying Passive)	*P*-value (Side-lying Active)
Habitual Side-lying	-27	1.6	-	**<0.001***	**<0.001***	6.2	2.2	-	0.997	0.532
Side-lying Passive	-15.4	1.8	**<0.001***	-	**0.003***	5.1	1.6	0.997	-	0.272
Side-lying Active	-6.4	2.3	**<0.001***	**0.003***	-	1.5	1.9	0.532	0.272	-
Side-lying Active + Leg lift	-3.1	2.9	**<0.001***	**<0.001***	0.666	4	2	0.988	0.997	0.58

**significant pairwise comparison (p<0.05)*

Abbreviations: SE =Standard error of the mean, AVR=Axial vertebral rotation, AVT=Apical vertebral translation

Table 6. Pairwise comparisons of mean curve angle, axial vertebral rotation, and apical vertebral translation measurements among sitting positions.

n=30	*Thoracic Curve Angle*				*Lumbar Curve Angle*				*Max Axial Vertebral Rotation (AVR) Twist*			
Position	Mean Thoracic Curve Angle (º)	SE	*P*-value (Habitual Sitting)	*P*-value (Sitting Active)	Mean Lumbar Curve Angle (º)	SE	*P*-value (Habitual Sitting)	*P*-value (Sitting Active)	Mean Max AVR Twist (º)	SE	*P*-value (Habitual Sitting)	*P*-value (Sitting Active)
Habitual Sitting	12.4	1.9	-	**0.001***	-13.5	1.8	-	**<0.001***	11.9	1.2	-	0.482
Sitting active	4.8	1.7	**0.001***	-	1.4	2.4	**<0.001***	-	10.7	1	0.482	-
Sitting Active + Hip flexion	3.7	1.6	**<0.001***	0.735	4.1	2	**<0.001***	0.316	9.4	1.1	**0.031***	0.191
	Apical Vertebral Translation (AVT)											
Position	Mean Thoracic AVT (mm)	SE	*P*-value (Habitual Sitting)	*P*-value (Sitting Active)	Mean Lumbar AVT (mm)	SEM	*P*-value (Habitual Sitting)	*P*-value (Sitting Active)	Mean Interapical Distance (mm)	SE	*P*-value (Habitual Sitting)	*P*-value (Sitting Active)
Habitual Sitting	3.2	2.6	-	0.966	-14.4	1.9	-	**<0.001***	17.6	2.7	-	**<0.001***
Sitting active	1.3	3.2	0.966	-	2.4	2.9	**<0.001***	-	-1.1	3.2	**<0.001***	-
Sitting Active + Hip flexion	2.7	3.3	0.999	0.96	3.5	3.1	**<0.001***	0.976	-0.9	2.8	**<0.001***	0.999

**significant pairwise comparison (p<0.05)*

Abbreviations: SE =Standard error of the mean, AVR=Axial vertebral rotation, AVT=Apical vertebral translation

Table 7. Pairwise comparisons of mean curve angle, axial vertebral rotation, and apical vertebral translation measurements among standing positions.

n=33	*Thoracic Curve Angle*				*Lumbar Curve Angle*				*Max Axial Vertebral Rotation (AVR) Twist*			
Position	Mean Thoracic Curve Angle (º)	SE	*P*-value (Habitual Standing)	*P*-value (Standing Active)	Mean Lumbar Curve Angle (º)	SE	*P*-value (Habitual Standing)	*P*-value (Standing Active)	Mean Max AVR Twist (º)	SE	*P*-value (Habitual Standing)	*P*-value (Standing Active)
Habitual Standing	14.6	1.4	-	**<0.001***	-17.3	1.5	-	**<0.001***	14	1.2	-	**<0.001***
Standing active	6.9	1.8	**<0.001***	-	-0.8	2	**<0.001***	-	10	1.1	**<0.001***	-
Final Standing[A]	11.8	1.9	**0.005***	**0.03***	-12.3	1.5	**<0.001***	**<0.001***	13.6	1.3	0.323	**0.006***
	Apical Vertebral Translation (AVT)											
Position	Mean Thoracic AVT (mm)	SE	*P*-value (Habitual Standing)	*P*-value (Standing Active)	Mean Lumbar AVT (mm)	SEM	*P*-value (Habitual Standing)	*P*-value (Standing Active)	Mean Interapical Distance (mm)	SE	*P*-value (Habitual Standing)	*P*-value (Standing Active)
Habitual Standing	2.1	1.8	-	0.96	-12.7	1.6	-	**0.001***	14.9	1.5	-	**0.002***
Standing active	2.3	3	0.96	-	-2.8	2	**0.001***	-	5.2	2.8	**0.002***	-
Final Standing[A]	3.5	2	0.999	0.889	-10.1	1.5	0.236	**0.035***	13.6	1.9	0.212	**0.007***

[A]=Calculated with reduced sample size (n=22)

**significant pairwise comparison (p<0.05)*

Abbreviations: SE =Standard error of the mean, AVR=Axial vertebral rotation, AVT=Apical vertebral translation

Table 8. Pairwise comparisons of mean curve angle, axial vertebral rotation, and apical vertebral translation measurements among all fully-corrected PSSE positions alongside prone side-bending left and right.

n=28	*Thoracic Curve Angle*							*Lumbar Curve Angle*						
Position	Mean Thoracic Curve Angle (°)	SE	*P*-value (Side-bending left)	*P*-value (Side-bending right)	*P*-value (Prone Active + Hip flexion)	*P*-value (Side-lying Active + Leg lift)[A]	*P*-value (Sitting Active + Hip flexion)	Mean Lumbar Curve Angle (°)	SE	*P*-value (Side-bending left)	*P*-value (Side-bending right)	*P*-value (Prone Active + Hip flexion)	*P*-value (Side-lying Active + Leg lift)[A]	*P*-value (Sitting Active + Hip flexion)
Prone Side-bending Left	21.4	1.3	-	**<0.001***	**<0.001***	**<0.001***	**<0.001***	16.2	1.4	-	**<0.001***	**<0.001***	**<0.001***	**<0.001***
Prone side-bending Right	-8.2	1.4	**<0.001***	-	**<0.001***	**<0.001***	**<0.001***	-27.1	1.4	**<0.001***	-	**<0.001***	**<0.001***	**<0.001***
Prone Active + hip flexion	6.1	1.3	**<0.001***	**<0.001***	-	0.48	0.659	-3.3	1.6	**<0.001***	**<0.001***	-	0.965	**0.001***
Side-lying Active + leg lift[A]	8.4	1.4	**<0.001***	**<0.001***	0.48	-	0.068	-1	1.6	**<0.001***	**<0.001***	0.965	-	0.434
Sitting Active with hip flexion	3.8	1.7	**<0.001***	**<0.001***	0.659	0.068	-	4.3	2.1	**<0.001***	**<0.001***	**0.001***	0.434	-
Standing active	7.4	2	**<0.001***	**<0.001***	0.999	0.874	0.342	-0.5	2.2	**<0.001***	**<0.001***	0.757	0.509	0.722
	Max Axial Vertebral Rotation (AVR) Twist							Apical Vertebral Translation (AVT)						
Position	Mean Max AVR Twist (°)	SE	*P*-value (Side-bending left)	*P*-value (Side-bending right)	*P*-value (Prone Active + Hip	*P*-value (Side-lying Active	*P*-value (Sitting Active + Hip flexion)	Mean Thoracic AVT (mm)	SE	*P*-value (Side-bending left)	*P*-value (Side-bending right)	*P*-value (Prone Active + Hip	*P*-value (Side-lying Active	*P*-value (Sitting Active + Hip

					flexion)	+ Leg lift)^A						flexion)	+ Leg lift)^A	flexion)
Prone Side-bending Left	10.8	1.4	-	1	0.183	0.945	0.923	-	-	-	-	-	-	-
Prone side-bending Right	11.6	1.3	1	-	**0.007***	**0.046***	0.259	-	-	-	-	-	-	-
Prone Active + hip flexion	7.3	1.2	0.183	**0.007***	-	1	0.549	3.2	3.2	-	-	-	1	0.899
Side-lying Active + leg lift^A	7.4	1.5	0.945	**0.046***	1	-	0.996	-1.2	3.7	-	-	1	-	0.998
Sitting Active + hip flexion	9.1	1.2	0.923	0.259	0.549	0.996	-	0.7	3.3	-	-	0.899	0.998	-
Standing active	10.4	1.2	1	0.986	**0.014***	0.375	0.668	2.3	3.3	-	-	0.991	1	0.964
	Apical Vertebral Translation (AVT)													
Position	Mean Lumbar AVT (mm)	SE	*P*-value (Side-bending left)	*P*-value (Side-bending right)	*P*-value (Prone Active + Hip flexion)	*P*-value (Side-lying Active + Leg lift)^A	*P*-value (Sitting Active + Hip flexion)	Mean Interapical Distance (mm)	SE	*P*-value (Side-bending left)	*P*-value (Side-bending right)	*P*-value (Prone Active + Hip flexion)	*P*-value (Side-lying Active + Leg lift)^A	*P*-value (Sitting Active + Hip flexion)
Prone Side-bending Left	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Prone side-bending Right	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Prone Active + hip flexion	-3.3	2.5	-	-	-	0.978	0.368	6.5	2.3	-	-	-	0.739	**0.01***

Side-lying Active + leg lift[A]	-3.7	3.1	-	-	0.978	-	0.553	2.5	1.8	-	-	0.739	-	0.566
Sitting Active + hip flexion	1.6	3.1	-	-	0.368	0.553	-	-1	2.9	-	-	**0.01***	0.566	-
Standing active	-2.4	2.2	-	-	0.991	0.915	0.44	4.7	3.1	-	-	0.839	0.964	0.255

[A]=Calculated with reduced sample size (n=20)

**significant pairwise comparison (p<0.05)*

Abbreviations: SE =Standard error of the mean, AVR=Axial vertebral rotation, AVT=Apical vertebral translation