BIOMECHANICS DISPLAYED DURING THE STOP-JUMP MOVEMENT BY INDIVIDUALS WITH SPINAL FUSION SURGERY FOR ADOLESCENT IDIOPATHIC SCOLIOSIS

by

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(Under the Direction of KATHY J. SIMPSON)

ABSTRACT

Adolescent idiopathic scoliosis individuals after spinal fusion (SF-AIS) often return to intense physical activity, but it is unclear how they adapt their movements to compensate for a rigid spine. The objective was, for the stop-jump task, to compare the spine kinematics and lower biomechanics of SF-AIS and controls (CON). Nine SF-AIS and 9 CON pair-matched individuals performed 5 trials of stop-jump. Vertical ground reaction force (VGRF) signals (1200 Hz) and spatial locations of 39 trunk, pelvis and lower limb markers were recorded (120 Hz). Analysis of covariance (jump height = covariate, $p < .05$) was used to compare the groups' relative (RelAngDisp) and segmental (SegAngDisp) angular displacements of the upper (UT), middle (MT), and lower trunk (LT) and pelvis. Additional 2 x 2 (Group: [SF-AIS, CON] × 2 (Limb: [dominant, non-dominant; repeated factor] mixed-model ANOVAs ($p<.05$) were applied for peak values of angular displacements, VGRF, and joint moments of both lower extremities for the stance phase. 95% confidence intervals of group differences also were assessed.

Performance was similar between groups, as vertical jump height was not different. For kinematic and kinetic group differences, SF-AIS compared to CON displayed 3.2°– 6.2° greater LT-SegAngDisp in the sagittal and frontal planes, 5.1° greater MT-SegAngDisp in the sagittal plane, lower knee extension displacement; 0.06 Nm/kg greater peak internal hip rotator, 0.40 Nm/kg greater peak knee abductor, 0 .39 Nm/kg lower peak knee extensor, and 0.04 Nm/kg greater peak internal rotator ankle moments during the stance phase. For limb differences, the dominant limb demonstrated 0.02 – 0.06 Nm/kg greater peak hip internal rotation moment than the non-dominant limb. Greater peak VGRF of the dominant limb for SF-AIS was partly due to shifting more weight onto the dominant limb. These outcomes indicate that SF-AIS MT appeared to displace with the LT, suggesting LT and pelvis movements were used as a compensatory adaptation to move the trunk. Reliance on the low back and pelvis to extend the trunk may have clinical relevance for back care. Otherwise, physically active SF-AIS display comparable spine and lower limb mechanics to that of CON and can safely perform physical activities like stop-jump.

INDEX WORDS: Adolescent idiopathic scoliosis, spinal fusion, spine kinematics, stop-jump, lower limb mechanics

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TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

CHAPTER 1

Introduction

A. Background and Rationale

Arthrodesis of the vertebral segments commonly known as spinal fusion has been a standard treatment for many medical spinal conditions, such as spinal deformities, trauma, degenerative vertebral disc disease, and spinal fractures[1]. There has been an exponential increase in the number of spinal fusion surgeries being performed in the last two decades primarily due to overall increased life expectancy after the surgery. Researchers report a 137% increase in successful discharges from (174,223 to 413,171) from 1998 to 2008[1].

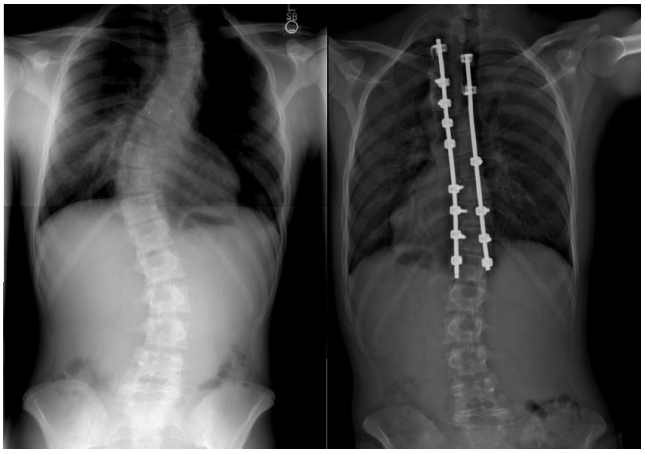

Figure1.1. Antero-posterior radiographs of a representative participant with AIS (pre-surgery = left; postsurgical spinal fusion = right).

Scoliosis is one such spinal deformity where spinal fusion surgery may be the only treatment option if its progression does not abate. A mild case is shown in *Figure* 1.1. Scoliosis is a symptom and not a disease[2]; and is defined as the development of abnormal 3D curvatures of the spine affecting the frontal plane primarily and accompanied by axial vertebral rotation[3].

Approximately 7 million individuals in the United States are affected by scoliosis[4].Adolescent idiopathic scoliosis (AIS) is the most common variant of scoliosis[5]

and the most common spinal deformity witnessed by pediatrician and primary care physicians[6]. AIS is present in 2% to 4% of children between 10 and 16 years of age[7]. In pediatrics, scoliosis is diagnosed as 'idiopathic' in 70% of the structural deformities of the spine[8]. Incidence rates at onset are approximately the same for boys and girls, but higher rates of severe scoliosis develop in girls[9]. The ratio of occurrence of AIS with greater than 30° of spinal curvature is 10:1 for girls as compared to boys[7].

As the name suggests, the scoliotic curvature begins during adolescence due to unknown etiology. The causation has been linked to a number of reasons including genetics, premature osteoarthrosis, repetitive tensile stresses on the spine, compression of the patient's body prenatally, imbalanced growth among soft and hard tissue components of the spine during childhood and adolescence, and generalized osteopenia among other etiological factors[10-12]. Recently, pathogenesis of AIS also has been linked to abnormalities of connective tissues that aid in stabilizing the spine[9]. Dayer et al. also have linked the causation to disarrangement of the elastic fibers of the ligamentum flavum based on immunohistochemical staining in AIS individuals[9].

As more conservative treatments are preferred when suitable, surgeons typically recommend spinal fusion surgery to people with AIS based on the Cobb angle (curvature of the spine calculated using a frontal plane radiograph) greater than 40°, where the curve progression is unlikely to abate and the patient has not yet attained skeletal maturity. Other factors influencing the decision to perform a spinal fusion include, but are not limited to, age and curve location[13]. Otherwise, without surgery, the curvature can continue to progress, producing severe trunk disfigurement and compression of the lungs[14]. This can have significant detrimental effects on physical activity, appearance,

lifestyle and quality of life[15] of an individual. The effects on the patient can be direct, such as the loss in spinal range of motion (ROM), to indirect, but critical physiological sequelae, such as decreased cardio-vascular conditioning[14], reduced bone mineral density[16] and, for untreated cases, increased morbidity due to abnormal lung function[14] and, possibly, substantial reduction in physical activity.

Spinal fusion, compared to conservative management via bracing, has had good success, as fusion individuals have reported better quality of life scores on a Scoliosis Research Society (SRS) questionnaire 10 years post-surgery[17]. Moreover, individuals with spinal fusion for adolescent idiopathic scoliosis (SF-AIS) have been reported to return to competitive sports like golf, gymnastics, aquatic sports and other organized athletics and outdoor physical activities at an equal or higher level[18]. Researchers have also claimed that SF-AIS can and do participate in sports equally as strenuous as those as age-matched controls[18].

However, there is wide variability amongst SF-AIS individuals for participation in physical activities. There are several factors that may affect the type and amount of participation in physical activity and sport. One potential factor may be the patient: some SF-AIS believe that they are not able to be physically active[18]. For a minor number of AIS individuals, the patient's perception of back pain also may discourage activity[18].

A second factor affecting physical activity participation can be the patient's surgeon. Surgeons are concerned that engaging in certain kind of sports may cause spinal trauma[19] during movements involving spinal rotations and bending[20-22]. Thus, without evidence-based recommendations for surgeons to use, there is a very wide variation in prescription of allowable physical activities by surgeons[23]. In a survey by Rubery et al.

60% of the surgeons reported never recommending any collision sports[23]. While few researchers have proposed to promote physical activity after spinal fusion surgery in adolescents[24], only 13% felt contact sports can be allowed 6-12 months after surgery[23]. A major group of surgeons tend to allow patients to go back to low intensity physical education, gym classes 12 months post-operatively.

There is a lack of recommendations or guidelines orthopedic surgeons can use to prescribe safe physical activity due to lack of evidence of the spinal stresses and strains that occur during physical activities. Consequently, In order to ensure the patient's safety, some surgeons and other clinicians may be too conservative when prescribing physical activity, potentially limiting a patient's life needlessly. Ironically, reduced physical activity can cause problems related to problems of a more sedentary lifestyle. Observed within the AIS population, compared to comparable non-spinal individuals, increased risk of heart disease, stroke, and certain cancer types, gradual weakness of muscles, bones and connective tissue; and decline of physical function with ergonomics, certain occupations, daily functioning, and physical activity for health and other purposes[25,26]. Moreover, unnecessary limitations on physical activity, can also affect the patient's quality of life.

For AIS individuals, physical activity may be particularly beneficial for decreasing body fat and improving aerobic capacity and muscle power[27] and is associated with improved proprioception[19] and body image[28]. Conversely, for girls with AIS, insufficient time spent performing weight-bearing physical activity during the peripubertal period has been observed to be a major determinant[29] of low bone mass observed by some researchers[10,29-31] although not others[32].

Therefore, it is apparent that surgeons and related rehabilitation clinicians need better guidelines for prescribing appropriate physical activity for SF-AIS patients. The first step towards this goal is to generate the evidence-based information needed. At present, there is little empirical evidence of the mechanics and movements spinal-fusion patients use to perform high-effort activities. Most of the prior research related to the biomechanics of SF-AIS during physical movements has been focused on deficits of spinal range of motion during semi-static[33-35] or low effort dynamic movements like side stepping[36,37] or walking on a leveled surface[38-42]. Some studies have also aimed at understanding the balance deficits in this population[35,36,42-48].

B. Statement of the Problem/Purpose:

Physical activity is particularly important during adolescence, as the potential for building bone mass is high during this developmental period[10,29-31]. However, likely due to the lack of evidence that shows high-effort physical activities are safe for SF-AIS some clinicians have refrained from allowing adolescents after spinal fusion surgery to engage in such activities.

In addition, perhaps AIS are believed to not be able to move as well as their peers without AIS. Reduced spinal flexibility and balance of AIS with and without spinal fusion have been observed[49-51], and thus, potentially hinder physical performance. However, if the AIS participants were not as physically active as the control participants in these studies, the balance deficits may have, at least in part, been due to lack of balance experience and not neurological, sensorimotor and/or lack of trunk control. Moreover, we believe that, as some SF-AIS are engaging in intense sport activities, these individuals

must be adapting their kinetic and kinematic strategies to compensate for spinal inflexibility.

However, these biomechanical strategies, if they exist, have not been identified, as spinal motions displayed during high-effort movements, such as running and jumping, have never been studied (as best we know) for any spinal patient population. Hence, for the study, a stop-jump task has been selected for the high-effort movement, as it is similar to a several movements in sports that require a movement sequence of a quick stop, jumping upwards, and then landing. Also, simple range of motion movement task will be performed to identify the ranges available at each trunk segments and possibly help explain the difference in the strategies adopted.

Thus, understanding the biomechanics used when participating in sports or physical activities, including the adaptations SF-AIS individuals use to compensate for a rigid spine will be beneficial. Therefore, the purpose of the study was to compare, between groups of physically-active AIS individuals with spinal fusion (SF-AIS) and healthy non-scoliotic individuals (CON), performance (jump height), the spinal kinematics, and lower extremity kinetics and kinematics of the stop-jump task that underlies the performance of the stop-jump.

C. Research Questions

There were two groups: a group with individuals who have had spinal fusion surgery as a treatment for adolescent idiopathic scoliosis (SF-AIS) and a healthy control group with no AIS that were matched for age, height, weight and physical activity.

1. Can physically-active SF-AIS individuals perform a high-effort task (stop-jump) as well as matched CON performers?
    a. Are there significant differences in maximum vertical jump height between SF-AIS and CON groups during a stop-jump?
2. How does the presence of a fused spine affect the kinematics of the three trunk segments (upper, middle and lower) during a stop-jump task?
    a. Do the fused-spinal segments of SF-AIS individuals displace less than those of the CON individuals due to the rigidity of the spinal fusion?
    b. Do SF-AIS performers compensate for the lack of spinal motion of fused segments by displacing the non-fused segments further than CON performers during a stop-jump?
3. How does spinal fusion surgery alter the lower limb kinematics and kinetics during a stop-jump task?
    a. Are there significant differences in kinematics between SF-AIS and CON groups during a stop-jump?
    b. Are there significant differences in kinetics between SF-AIS and CON groups during a stop-jump?

D. Specific Aims:

1. To determine if there is difference in performance outcome between SF-AIS and CON while performing a stop-jump task
2. To determine if there is difference in kinetics and kinematics of hip, knee and ankle joints for SF-AIS and CON during the stance phase (preparation and propulsion) of a stop-jump task.

3. To identify the difference in the movement strategies adopted at the trunk segments adjacent to the fused segments by SF-AIS individuals compared to CON while performing a high effort task (stop-jump).

E. Predictions and Research Hypotheses:

Each research question and sub-questions are listed below followed by the predictions and hypotheses to be used to answer that question.

1. Will there be any effect of the spinal fusion surgery on the performance of individuals during a high-effort task (stop-jump)?
    a. Are there significant differences in maximum jump height between SF-AIS and CON groups during a stop-jump?

    Prediction: There will be no significant differences in performance of the 2 groups during stop-jump.

    Hypothesis: **Mean maximum vertical jump height** attained during the stop-jump task will be similar between the two groups
2. How does spinal fusion surgery affect the kinematics of the three trunk segments (upper, middle and lower) during a stop-jump task?
    a. Are there significant differences in kinematics between SF-AIS and CON groups during a stop-jump?

    Prediction: There will be differences in kinematics of the trunk segments due to the fusion of the vertebral segments.

    Hypotheses:

i. **Displacement of relative angles** of the upper, middle and lower trunk segments will be similar for SF-AIS compared to CON during flight phase.

ii. **Displacement of relative angles** of the upper and lower trunk segments will be higher for SF-AIS compared to CON and that at the middle segment will be lower during stance phase.

iii. **Displacement of relative angles** of the upper, middle and lower trunk segments will be similar for SF-AIS compared to CON during vertical flight phase.

3. How does spinal fusion surgery alter the lower limb kinematics and kinetics during a stop-jump task?

    a. Are there significant differences in kinematics of the trunk segments between SF-AIS and CON groups during a stop-jump?

    Prediction: The kinematics at the hip will be significantly different between SF-AIS and CON due to difference in landing strategies

    Hypotheses:

    i. **Displacement of joint angle** in sagittal plane at the hip, knee and ankle joints will be lower for SF-AIS compared to CON and there will be no difference in transverse and frontal plane joint at the hip, knee and ankle joints displacements during the stance phase.

ii. **Displacement of joint angle** of any plane would not be different between the limbs for SF-AIS, and for CON.

b. Are there significant differences in kinetics between SF-AIS and CON groups during a stop-jump?

Prediction: The compensatory strategy involved will cause a difference in kinetics at the joints of the lower extremity in SF-AIS compared to CON.

Hypotheses:

i. **Peak joint moments of force** for the hip joint will be higher for SF-AIS compared to CON in the sagittal and transverse planes, and there will be no group differences for frontal plane moments during stance phase.

ii. **Peak joint moments of force** at knee will be lower for SF-AIS compared to CON in sagittal plane and will be similar in the transverse and frontal planes for the two groups during stance phase.

iii. **Peak Joint moments of force** at ankle joint will be similar between the two groups in all three planes of motion during stance phase.

iv. **Peak joint moments of force** of any plane would not be different between the limbs for SF-AIS or CON during stance phase.

v. **Peak vertical ground reaction force** would be greater for SF-AIS than CON and for the dominant compared to the non-dominant leg during stance phase.

F. Definitions

Adolescent idiopathic scoliosis: A lateral curvature of the spine greater than 10° accompanied by vertebral rotation in adolescents whose cause is unknown[7].

Cobb angle: The Cobb method of measuring the angle of curvature of the spine in frontal plane consists of selecting the vertebrae with the greatest amount of tilt of the vertebrae at the top and bottom of the curve. Lines are drawn perpendicular to the plates of the end-vertebrae, and the angle formed at the intersection of these lines is the Cobb angle[52].

Stop-jump task: A type of jump performed by taking 1-3 quick steps/run, taking off on one leg into the air, landing with both feet at the same time on the ground, then performing a maximum vertical jump and landing[53].

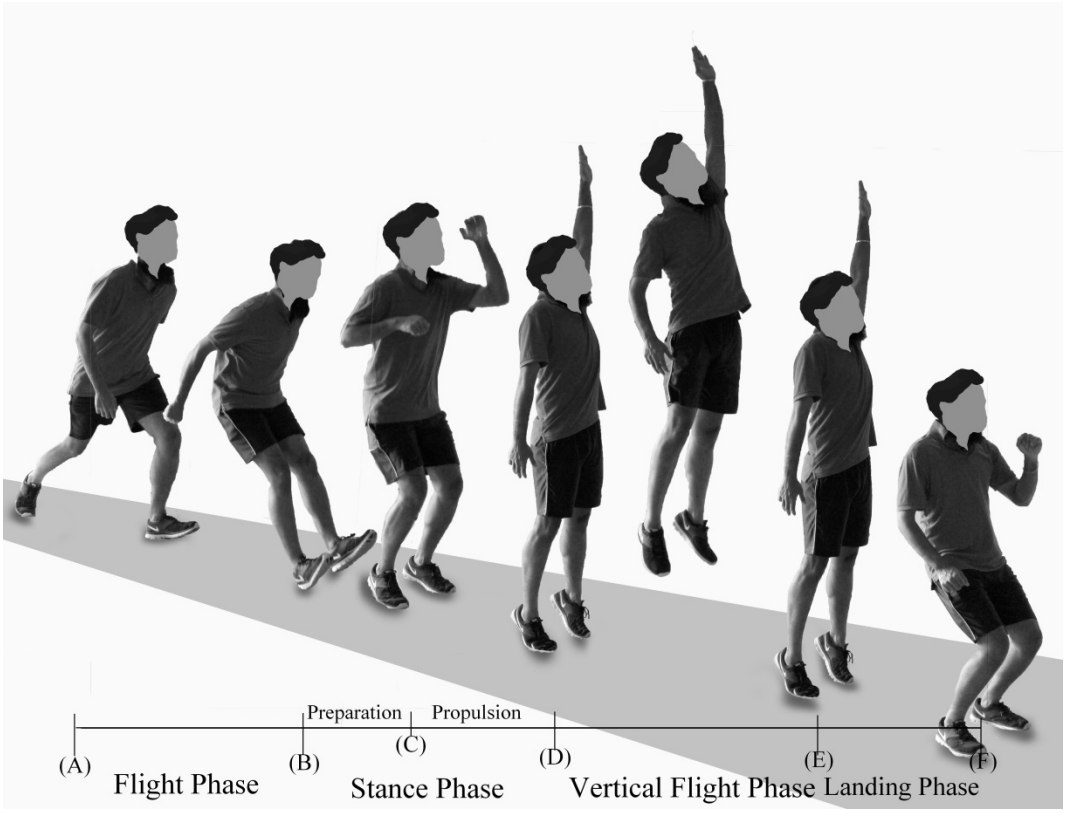

Figure 1.2. The stop-jump task and its phases.

Flight Phase: Phase of the stop-jump task starting from the point of takeoff of the last step of approach run until the point of initial contact of the two feet together on the force plates.

Stance Phase: Phase of the stop-jump task starting from the point of initial contact of the two feet together on the force plates until the feet leave the force plates for the vertical jump.

Preparation sub-phase: Sub-phase of the stance phase of stop-jump task starting from the point of initial contact of the two feet together on the force plates until position of maximum knee flexion of the participant.

Propulsion sub-phase: Sub-phase of the stance phase of stop-jump task starting from the position of maximum knee flexion of the participant until the feet leave the force plates for the vertical jump.

Vertical Flight Phase: Phase of the stop-jump task starting from the point of take-off for vertical jump to the point of initial contact of both feet back on the force plates at the end of vertical jump.

Landing Phase: Phase of the stop-jump task starting from the point of initial contact of both feet back on the force plates at the end of vertical jump, until position of maximum knee flexion of the participant.

Physically Active: A participant were categorized as 'physically active' if they are currently performing physical tasks or sports activities for at least 2.5 hours per week at a moderate intensity level or greater as reported on the International physical activity questionnaire.

G. Assumptions

The following assumptions were made during the study:

1. Participants honestly reported their health status and physical activity history and answer the questionnaires to the best of their knowledge.
2. Participants performed the movements to the best of their ability.
3. The SF-AIS participants very closely represented the population of individuals with AIS after they have had spinal fusion surgery and are involved in physical activities on a regular basis (the inclusion and exclusion criterion were met).

4. There were minimal practice effects or fatigue during testing and participants with SF-AIS will be completely comfortable while performing testing procedures.
5. CON group closely matched SF-AIS group in physical function characteristics, gender, age, height and weight.
6. The effect of using a slightly older (18 yr old) matched control participant for the SF-AIS individuals who were 16-17 years old was assumed to be neglible on any variable.

H. Delimitations

The following delimitations were made during the study.

1. Participants in the SF-AIS and CON groups were males and females, age 16-29 yr and 18-29 yr, respectively.
2. Participants were physically active as inferred by the researcher based on the answers on the Scoliosis Physical Activity and Quality of Life questionnaire and International physical activity questionnaire.
3. Participants in the CON group were matched by gender, age (±2 years), height (±5 cm), mass (±2 kg) and physical activity (±2 hours per week moderate physical activity) to the SF-AIS group.

Chapter 2

Review of Literature

A. Epidemiology

In adolescent and children, scoliosis is diagnosed as idiopathic in 70% of the structural deformities of the spine. Adolescent idiopathic scoliosis (AIS) is the most common variant of scoliosis[5] and the most common spinal deformity witnessed by pediatrician and primary care physicians[6]. AIS is present in 2% to 4% of children between 10 and 16 years of age[7].

Male to female ratio is almost equal for small curves but higher rate of incidence is observed in girls than boys[9]. The ratio of occurrence of AIS with greater than 30° of spinal curve is 10:1 for girls as compared to boys[7]. The prevalence of AIS decreases with increase in curve magnitude. Curve magnitude of greater than 30° is prevalent in only 0.3% of the population[54].

B. Aetiology, and Pathogenesis

Aetiology remains unknown for AIS. Multiple causes have been linked to AIS including neuromuscular, metabolic, genetic and neurobiological factors like: Leg length discrepancy, developmental hip dysplasia, Osteogenesis imperfect; Inherited connective tissue disorders: Marfan syndrome, Homocystinuria; Cerebral palsy, Polio, Friedeich's ataxia, Muscular dystrophy, Spinal tumors, premature osteoarthrosis, repetitive tensile stresses on the spine, compression of the patient's body prenatally, imbalanced growth

among soft and hard tissue components of the spine during childhood and adolescence, and generalized osteopenia among other etiological factors[11,12,55-58].

Recently pathogenesis of AIS has been linked to connective tissues that aid in stability of the spine[9], the neuromuscular or skeletal system[6]. Marked disarrangement of the elastic fibers of the ligamentum flavum on immunohistochemical staining have also been reported as a suitable explanation recently[9].

C. Screening and Diagnosis

Several clinical diagnostic tools have been developed for screening of scoliosis. Clinical evaluations and Adam's forward-bending test are some of the initial tools used. Other tools include humpograms[59], to measure back contour and shape; radiographs; scoliometer[60], Moire topography, a noninvasive method to three dimensional asymmetry of the body[61] and a few others.

Some of the most commonly used methods are described below.

a. Clinical Evaluation by Physical Examination of the back: During a clinical evaluation, the evaluator inspects for

- Shoulder and pelvic asymmetry: Shoulders are different heights – one shoulder blade is more prominent than the other or appearance of a raised, Head is not centered directly above the pelvis and/or a prominent hip, Uneven waist,
- Limb length deformity and leaning of entire body to one side
- Rib and scapular prominence: Rib cages are at different heights,
- café au lait spots and other cutaneous abnormalities and Changes in look or texture of skin overlying the spine (dimples, hairy patches, color changes)

A thorough neurological exam should also be performed including abdominal reflexes for detailed evaluation.

b. Adam's Forward Bend Test: For this test, the patient is asked to lean forward with his or her feet together and bend 90° at the waist. The examiner can then easily view from this angle any asymmetry of the trunk or any abnormal spinal curvatures

c. Scoliometer: measures angle of trunk rotation (ATR)[60]: For this test, the patient bends over with arms dangling and palms pressed together, until a curve can be observed in the *upper* back (thoracic area). The Scoliometer is placed on the back and measures the apex (the highest point) of the upper back curve. The patient continues bending until the curve can be seen in the *lower* back (lumbar area). The apex of this curve is also measured.

d. Radiographic Evaluation: Anteroposterior and Lateral radiographs in the standing position are captured.

Radiographs are used to measure Cobb angles. To measure the Cobb angle: choose the most tilted verterbrae above & below apex of the curve. The angle between intersecting lines drawn perpendicular to the top of the superior vertebrae and bottom of the inferior vertebrae is the Cobb angle. (Figure 2.1).

Figure 2.1. Frontal plane radiograph of the spine showing Cobb angle (α)

Radiographs are used to predict:

a. Curve type: Thoracic/lumbar/thoraco-lumbar

b. Saggital & Coronal Plane Balance

c. Risser Sign[62] & Triradiate Cartilage: Risser sign is defined by the amount of calcification present in the iliac apophysis and measures the progressive ossification from

anterolaterally to posteromedially. A Risser grade of 1 signifies up to 25 percent ossific ation of the iliac apophysis, proceeding to grade 4, which signifies 100 percent ossification (complete growth). Grade 5 is complete maturity

d. Crankshaft phenomenon: Crankshaft phenomenon is a continued growth in the anterior (front) of the spine after a posterior fusion is performed in a young growing patient. This results in further rotation and even curvature of the spine despite a solid posterior fusion. Patients at greatest risk for this problem are under age ten with their growth centers indicating a large amount of remaining growth.

D. Classification of AIS

Scoliosis has been classified mainly based on 2 different criterion namely, time of onset, pathogenesis. Sander JO classified scoliosis into early and late onset scoliosis. Late onset scoliosis is when onset occurs after the age of 18 years. Based on pathogenesis scoliosis can be classified as Idiopathic, congenital, syndromes, compensatory and neuromuscular. Idiopathic scoliosis can be further divided into infantile scoliosis (under age 3), juvenile scoliosis (ages 3 to 9), and adolescent scoliosis (ages 10 to 18). From the surgical and biomechanical perspective, the most common classifications are: Ponte's classification (Ponte, 1950), King's Classification[63] and Lenke's Classification[64]. These are based on the pattern of curvature and are used to select the levels of fusion.

1. Ponte classified curves as single-curve, double-curve, and triple-curve patterns. This included included cervico-thoracic, thoracic, thoraco-lumbar, lumbar and combined double primary.

2. King's classification divides adolescent idiopathic scoliosis curves into 5 types. These are:

Type I: fusion of both curves to lower vertebra, but no lower than fourth lumbar vertebra.

Type II: selective thoracic fusion of lower vertebra that is both neutral and stable. When neutral vertebra and stable vertebra are not the same, stable vertebra is more reliable.

Type III: fusion to include measured thoracic curve, with lower level of fusion ending at the first vertebra that is most closely bisected by the central sacral line.

Type IV: fusion to include measured thoracic curve, with lower level of fusion ending at first vertebra that is bisected by central sacral line

Type V: fusion of both thoracic curves. The lower level should include vertebra that is most closely bisected by the central sacral line.

3. Lenke's and colleagues developed another two-dimensional system of classification for adolescent idiopathic scoliosis based on coronal and sagittal plane radiographs to determine appropriate levels of spinal fusion. The classification consists of 6 curve types (1-6), a lumbar spine modifier (A, B or C) and a thoracic sagittal modifier (-, N or +) (see Figure 2.2)

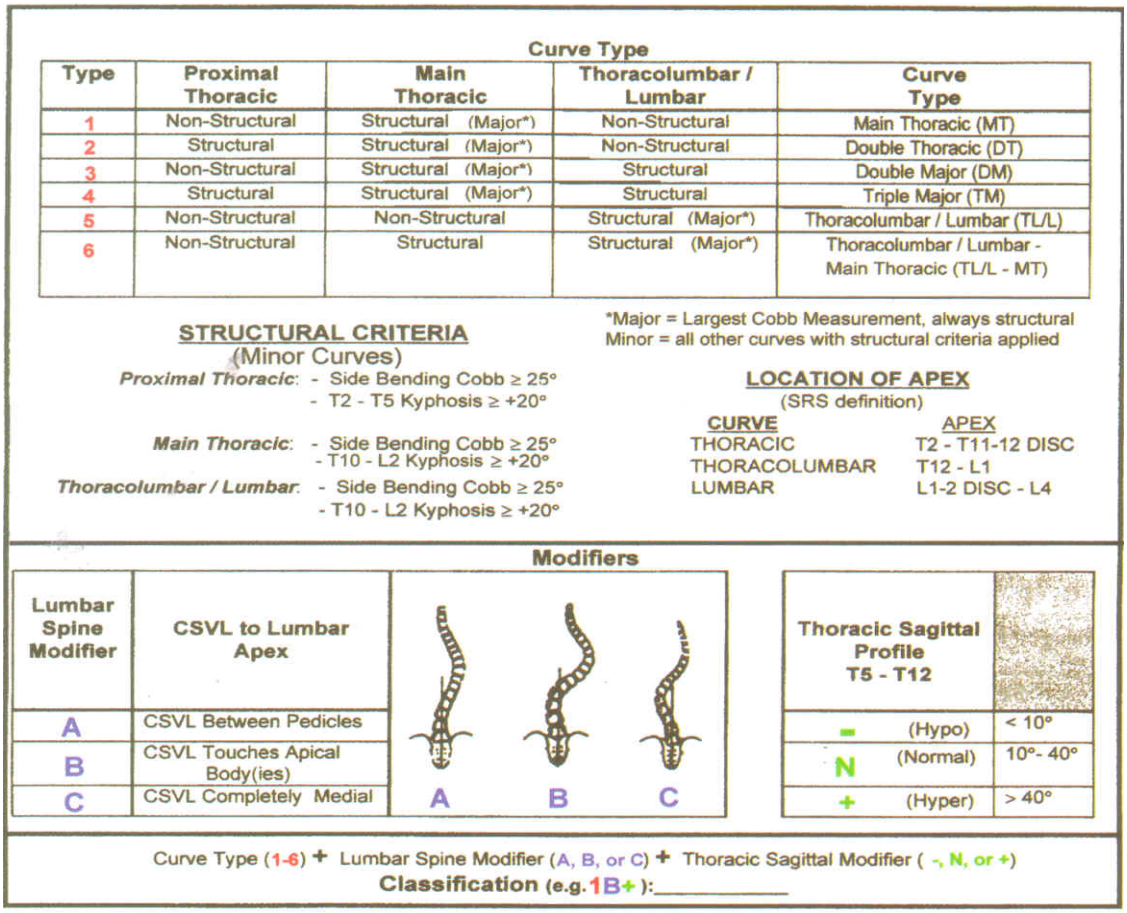

Figure 2.2: The Lenke classification system for adolescent idiopathic scoliosis[64]

E. Treatments

Treatment of AIS can be broadly classified into non-operative/ conservative management and surgical management. The criterion for decision is based on risk of progression as decided by multiple factors like age range, inclusion of both males and females, Risser sign, curve magnitude, and lack of stratification of results regarding curve pattern, curve size, and skeletal maturity[65]

Brace treatment using Milwaukee brace, Boston bracing system, Wilmington orthosis and Charleston bending brace are the most common methods of nonoperative treatment. This is aimed at preventing a smaller curve from progressing and to correct

accompanying cosmetic changes (eg, waistline asymmetry and coronal decompensation)[65]. While several researchers have supported the efficacy of the brace treatment as a method to prevent curve progression[66-73] studies have also shown that brace treatment might not be very effective[74-77].

Richards and colleagues reviewed several studies for their selection criterion for non-surgical management and definitions of successful treatment[78]. It was reported that studies vary in their criterion of inclusion of patients for brace treatment and evaluated the success of treatment differently. The authors then suggested an optimal criterion for brace treatment being as Optimal inclusion criteria for brace studies consist of: age is 10 years or older when the brace is prescribed, Risser 0 - 2, curves 25° - 40°, and no prior treatment. A general acceptable rule for non-operative treatment is:

a. Curves of < 25°: Risser Sign 0 to 4

- Careful monitoring
- Initially every 4-6 months
- Can go yearly with no evidence of progression
- Stop monitoring after skeletal maturity
- MRI with rapid progression or any neurological signs
- Encourage physical activity
- Physical Therapy: Focus on postural alignment, flexibility, and strength

b. Curves 25-40°

- Initiate brace treatment
- Only effective non-surgical treatment
- First visit 25-30°, may watch closely

- Bracing: Milwaukee brace, Boston bracing system (BBS), Charleston bending brace, Wilmington orthosis: 23 hours per day: Length of wearing time correlates with outcome

Only 40% of those wearing braces ultimately required surgery, compared to 68% of those not wearing back braces

Surgical management is aimed at stabilization of a curve and partial correction with reduction of clinical deformity and maintenance or restoration of a balanced spine in the coronal and sagittal planes[65]. Curve magnitudes of greater than 40° and an actively growing adolescent is ideal for surgical fusion. Other factors that help in decision making are Risser grade 0 to 1 in girls and Risser 2 or 3 in boys, Observe skeletally mature patients until curve progression to 50°; Curves that 45° at skeletal maturity are more likely to progress and cause severe cosmetic deformity and disability. Severe curve causes decrease pulmonary function (>90°). Worse if associated with hypokyphosis. These are clear indications of surgery[65]. Multiple options are available for the type of surgical treatment. These are,

a. Anterior fusion (ASF)

- Single rod
- Double rod

b. Posterior fusion (PSF)

- Hooks
- Hooks and pedicle screws
- All pedicle screws.

c. Growing rods

F. Physical Activity

Physical activity or sports participation is generally reduced in AIS individuals, particularly those who have had spinal fusion surgery (SF-AIS). There are several factors that may be responsible for this. These factors could be broadly classified into patient-related and clinician/surgeon-related. Decreased flexibility[40], reduced balance[79] physical deconditioning and loss of desire have been reported to be the few reasons as described by AIS individuals. For a minor number of AIS individuals, back pain also may discourage activity[18].

Lack of physical activity causes problems related but not limited to increased risk of heart disease; stroke; certain cancer types gradual weakness of muscles, bones, and connective tissue; and decline of physical function in activities of daily living[25,26]. Such physical limitations, therefore, also negatively affect the patient's quality of life.

Engaging in regular physical activity is beneficial to children and adolescents and may provide unique benefits to individuals with AIS. According to latest public health guidelines, adolescents should obtain at least 60 or more minutes of physical activity daily[80]. A comprehensive physical activity plan should incorporate three components: aerobic activity, muscle strengthening, and bone strengthening. These components are not mutually exclusive and many physical activities incorporate all three components. The majority of daily physical activity should be aerobic activity. Aerobic activity should be at least moderate-intensity, with vigorous-intensity being incorporated into the routine at least 3 days per week. Aerobic activity encourages movement of the large muscles in a child's body and improves cardiovascular fitness. Examples include running, swimming,

and bicycling. Children and adolescents should participate in muscle strengthening activities, either unstructured or structured, at least 3 days per week. These types of activities promote "overload" as they require the body's muscles to do more work than they are accustomed to doing. Overload strengthens the muscles. These activities should be age and ability appropriate. Examples include gymnastics, calisthenics using body weight (e.g. push-ups), and climbing trees. Finally, children and adolescents should participate in bone strengthening activities at least 3 days per week. Bone strengthening activities are important as these activities encourage bone growth and strength by placing force on bones. Examples of bone strengthening activities include jumping rope, hopscotch, and running. Participating in these activities will help children and adolescents meet physical activity guidelines and promote health and fitness. Additionally, research has demonstrated children and adolescents who are active in their youth are healthier adults[80.]

Prescription of physical activity for AIS-SF has significant public health impacts for scoliosis management. For AIS-SF, physical activity may be particularly beneficial for decreasing body fat and improving aerobic capacity and muscle power[27] and is associated with improved proprioception[19], improved body image perception[28] and resulting in increased self-esteem and decreased associated depression[81]. Conversely, for girls with AIS, insufficient time spent performing weight-bearing physical activity during the peripubertal period has been observed to be a major determinant of low bone mass observed by some researchers[30] but not others[32].

AIS-SF have been reported to return to competitive sports like golf, gymnastics, aquatic sports and other organized athletics and outdoor physical activities at an equal or

higher level than the pre-surgical level. Researchers have also claimed that AIS-SF participated in sports equally as strenuous as age-matched controls[18].

G. Self-report Instrumentation

Scoliosis Research Society (SRS) Short-Form 22-R Health-Related Quality of Life Questionnaire (SRS 22) (see Appendix 2.3)

SRS 22 is a valid and reliable questionnaire developed by Haher et al. to evaluate health related quality of life of individuals pertaining to patient satisfaction and performance and to discriminate among patients with adolescent idiopathic scoliosis[82-85]. SRS 22 is divided into 5 groups of questions (Number of questions per group). These are Function (5), Pain (5), Self-Image (5), Mental Health (5), Satisfaction/Dissatisfaction (2). Each question consists of 5 options on a scale of 1 to 5 with 1 being worst and 5 being best.

International Physical Activity Questionnaire (IPAQ) (see Appendix 2.4)

IPAQ is a valid and reliable questionnaire to measure health related physical activity especially in adults of ages 18-65 yrs[86]. IPAQ has 8 versions each containing different number of questions, with different modes of administration and varied reference lengths. All versions are valid and reliable[87]. In this study the "IPAQ Short last 7 days Self-administered" format was used. It assesses physical activity using 7 questions divided into different intensities of physical activities (vigorous, moderate or walking) performed within the last 7 days. Results are scored categorically into low, moderate and vigorous physical activities, based on the provided guidelines.

Chapter 3

Methods

A. Participants

Twenty (20) participants were recruited, 9 individuals with AIS who have had spinal fusion (SF-AIS) and 9 non-AIS control participants (CON; n=9). The SF-AIS participants were recruited from patient database of Dr. Timothy Oswald, a co-investigator. The CON participants were recruited from the University of Georgia (UGA) and the surrounding community via university classes, department listserves and flyers. A given CON participant was recruited to match a corresponding SF-AIS participant, based on age (±2 yr), height (±5 cm), mass (±2 kg) and physical activity (±2 hr per week similar intensity of physical activity). SF-AIS participants' aged 16-17 yr were matched to CON 18 yr olds.

Inclusionary and Exclusionary Criteria

Inclusionary criteria:

All participants must meet these criteria:

1. Is healthy, with no known current or past illnesses, ailments or injuries or clinically-relevant anatomical misalignments that could affect the participant's ability to perform the tasks without risk of injury or discomfort or that could affect the person's movements or cause abnormal movements.
2. Is post-pubertal based on self-report or parent report.
3. Has the ability to understand and carry out instructions in English.

4. If a minor, must also have written consent of legal guardian.
5. Is classified as physically active as per self-reported involvement in moderate (or higher) level physical activity or sports (≥ 2 hr per week) on the International Physical Activity questionnaire.

SF-AIS participants must also meet these criteria:

1. Between 16 and 29 yr of age.
2. Spinal bone growth is complete, based on assessment by the spinal surgeon who performed the spinal fusion procedure.
3. Scoliosis has been diagnosed as structural AIS via physician or radiograph.
4. Has had only primary spinal surgery via a posterior approach (hence, no revision surgeries).
5. At least 12 mo since spinal fusion surgery.
6. Person has resumed normal daily and physical activities; is not experiencing any unresolved complications or back pain due to surgery.
7. Has obtained medical clearance to participate from the spinal surgeon.

CON participants must also meet these criteria:

1. Between 18 and 25 yr of age.
2. For a given CON participant, must be within age (±2 yr), height (±5 cm), mass (±2 kg) and physical activity (±2 hr per week similar intensity physical activity) of corresponding SF-AIS participant.

Exclusionary criteria:

Criteria relevant to all participants:

1. Does not meet one or more inclusionary criteria listed above.

2. Has a current or past medical condition, e.g., injury, ailment, illness, clinically-relevant anatomical malalignment, or is currently undergoing medical treatment that could affect the participant's ability to perform the tasks without risk of injury or discomfort or that would likely affect the participant's movements.
3. Participant reports nausea, dizziness, balance problems, pain, or other symptoms that may influence performance or compromise participant's safety.
4. Participant cannot be pregnant or unsure of pregnancy status.

Exclusionary criteria relevant to AIS participants:

1. Scoliosis is not AIS or is AIS but not structural type.
2. Spinal growth is not complete as assessed by the spinal surgeon.
3. Fusion surgery occurred less than 12 mo. ago.
4. Is currently experiencing surgery-related complications or back pain.
5. Has had revision surgery.
6. Participant has not resumed normal daily and physical activities since surgery as reported on the Scoliosis Physical Activity and Quality of Life questionnaire and confirmed verbally.

B. Sample Size justification

The sample size is designed to support the exploratory objectives of the study. Ten matched pairs will provide 80% power for a paired t-test at alpha = .05 to detect an effect size of approximately 1, assuming correlation between the matched pairs of .6. Thus, statistically detectable differences between SF-AIS and CON groups will be approximately equal to the size of 1 standard deviation (SD) for any interval

variable. As such, the study will have adequate power to detect the following SF-AIS vs. CON group differences of the lower extremity for high-effort tasks: 3° to 8° for selected joint angles during stop-jump (SD= 3° to 8.5°)[88,89]; and 0.09 Nm/kg for peak knee extensor moment for the stop-jump task (SD = .09)[89].

C. Instrumentation and Experimental Setup

As the AIS participants received their spinal fusion surgery at the Children's Hospital of Atlanta (CHOA), consent, assent and Health Insurance portability and Accountability Act (HIPAA) forms for these participants were written in collaboration with the CHOA-associated investigators and approved by the CHOA Institutional Review board (IRB) first. All other forms and protocols were approved by the UGA IRB first. All forms and protocols have been approved by both IRBs (UGA IRB last approved on 30th April, 2013 and will expire on 11th April, 2014).

- The following forms were used to obtain informed consent and assent (if participant was a minor (and can be found in Appendix A):
    (a) CHOA consent form for SF-AIS participants (18 and older) and legal guardians (ages 16-17) (Appendix A1.1)
    (b) UGA consent form for control participants (Appendix A1.2).
    (c) CHOA assent form for SF-AIS participants under 18: If the participant was less than 18 years old, they provided assent to participate (Appendix A1.3).
    (d) CHOA HIPAA form: The SF-AIS participant/legal guardian gave permission to the researchers to obtain relevant medical information

from the spinal surgeon (Appendix A1.4).

- Pre-Participation and Health Status Questionnaire (Appendix A2.1) was used to assess previous or currently existing medical conditions and health status of all participants.
- Scoliosis Physical Activity and Quality of Life Questionnaire (Appendix A2.2), developed by our laboratory, and completed by participants, was used to determine the types of physical activity (e.g., different sports); and for each physical activity reported, amount of time engaged in, context (e.g., intramural sports or dance class) and intensity.
- Scoliosis Research Society (SRS) Short-Form 22-R Health-Related Quality of Life Questionnaire (Appendix A2.3) is a validated questionnaire[82-84] that is commonly used by clinicians and researchers to evaluate the health-related quality of life of the SF-AIS participants.
- International Physical Activity Questionnaire (IPAQ; Appendix A4) was used to screen a potential SF-AIS participant to ensure that he/she engaged in physical activity at the "moderate" or higher level[86,87,90] and to match a potential corresponding CON participant.

The experimental setup for obtaining signals needed to generate the kinematic and kinetic data for the flexibility and the stop-jump task is shown in figure 3.1. Workstation® 5.1 software (OMG Plc., London, UK) was used to collect all kinematic and kinetic signals. The corresponding instrumentation is described below:

- 7 visible-red light MX40® cameras (240 fps) and motion capture system (Vicon, Oxford, UK) were used to capture, using, the spatial locations of the

reflective markers (mean residual error of ≤ 0.5 mm on the participant's body (described below) when the participant was performing the stop-jump task.

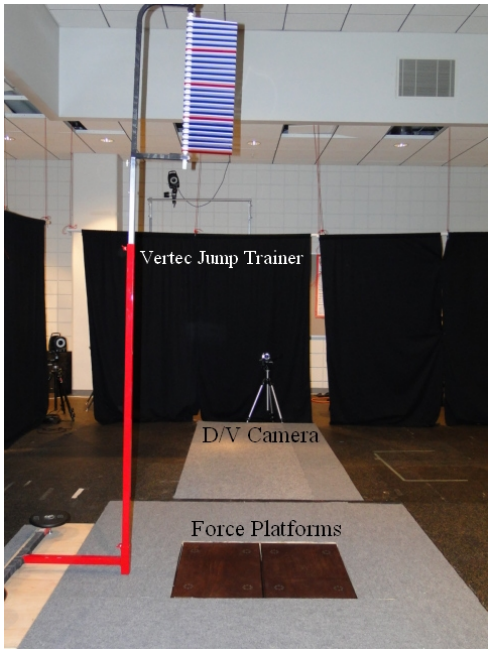

Figure 3.1. Experimental setup for stop-jump task.

- Reflective markers: 39 reflective markers (diameter = 9.5 mm for spinous and transverse processes and 14.0 mm for rest) were placed on different locations of the participant based on the marker model as shown in Figure 1. The location of markers for the lower limb are based on Newington-Helen Hayes gait model used in the Plug-in Gait© (PIG) software[91-92]. Two additional technical markers, one on each iliac crest, were used to reconstruct the pelvis when other pelvic markers may have been obscured during an interval of time. For the trunk segments, markers were placed on selected spinous processes of the following cervical (C), thoracic (T) and lumbar (L) vertebrae: C7, T2, T4, T6, T 8, T10, T12, L2 and L4, right and left transverse

processes for T11 and L3; and the manubrium and xyphoid process. For each upper extremity, one marker was placed on the acromion, olecranon process and middle of wrist (Figure 3.2).

Figure 3.2. Participant with reflective markers located as described in text.

- Two Bertec 4060-NC® force platforms (Bertec Corporation, Columbus, OH; sampling frequency: 1200 Hz; length x width x height: 600mm x 400mm x 100mm; natural frequency Fz = 480 Hz and Fx, Fy = 550 Hz). These are non-conductive fiberglass force platforms that use strain-gage load transducers to measure the forces and moments applied to them by the performer's feet.
- Vertec Jump Trainer© (Vertec; Sports Imports, Columbus, OH): Was used to measure the vertical jump height attained by the participant during the stop-

jump task. The height was measured in increments of 0.5".

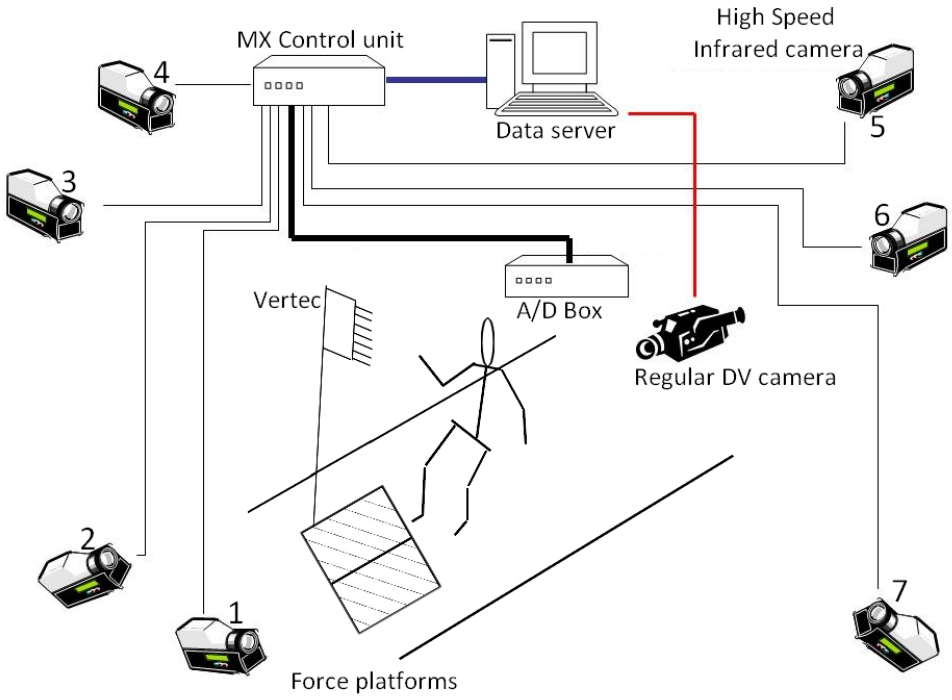

Figure 3.3 Instrumentation Setup for biomechanical analysis of stop-jump[93]

D. Data collection protocol

Screening and Consent

Each potential participant was identified and contacted first by the spinal-fusion surgeon's office to ask if the person was interested and to obtain permission for a UGA investigator to contact the person. If the person agreed, then a UGA investigator called or e-mailed the person (or guardian) to explain the study, arranged for sending out the questionnaires and driving directions, and set up a time for testing at the UGA Biomechanics Laboratory. The surgeon (Dr. Oswald) provided medical clearance once the participant agreed to be a part of the study.

At the UGA Biomechanics Laboratory, participants (and/or guardians) completed

the relevant informed consent, assent, HIPAA forms. The answers to the questionnaires were reviewed after consent was obtained to ensure that the participant meets the eligibility criteria. Individuals who met the eligibility criteria then continued with the testing protocol.

Test Protocol

At the UGA Biomechanics Lab, each participant first underwent pre-test procedures. Anthropometric measures[91] including body mass, height, leg lengths, and knee and ankle widths were obtained to later reconstruct segmental spatial orientations and to calculate segmental inertial characteristics needed in generating inverse dynamics quantities. The leg preferred to manipulate objects (e.g., kick an object) versus supporting body weight was determined by having the participant to kick a soccer ball and then asked if he/she usually kicks a ball with that foot.

Next, the participant underwent a supervised warm-up of jogging for 2 min. at a self-selected pace on a treadmill. The participant then performed stop-jump testing procedures (task is described below). A researcher first demonstrated the task, and the participant then performed 1-2 practice trials. Next, the participant performed five acceptable trials of the stop-jump task. Any trial performed incorrectly was repeated. A rest period of approximately 15 s was administered between each trial.

Stop-jump task: Participant took up to 3 running steps, jumped onto the force platforms with one foot landing simultaneously on each platform, jumped up and touched the highest flap possible on the Vertec©, then landed back on the force platforms with one foot on each platform.

Participants were monitored for comfort, pain, fatigue and discomfort. They were

allowed to rest as necessary and provided with water. If the patient reported discomfort or pain, a 5 min. seated rest-period will ensue. If the discomfort or pain was resolved and/or was gone after 5 min., testing resumed. If discomfort or pain was still reported after 5 min., testing was discontinued.

E. Data Reduction and Analysis

Phases of the stop-jump task analyzed were the flight phase, stance phase including the preparation and propulsion sub-phases and the vertical flight phase. The processed GRF signals from the force platforms were used to determine the motion cycle (timing of the end of flight and start and end of stance and vertical flight phases). Flight phase started from the point of takeoff of the last step of approach run until the first instance of touch down detected by greater than 5N of VGRF on either force platforms. Stance Phase started from first instance of touch down detected by greater than 5N of VGRF on either force platforms until the feet leave the force plates for the vertical jump (instance when VGRF reduces to less than 5 N). Stance phase was divided into 2 sub-phases: preparation sub-phase started from the beginning of the stance phase until position of maximum knee flexion of the participant and the propulsion sub-phase was from the position of maximum knee flexion of the participant until the end of stance phase. Vertical Flight Phase started when VGRF dropped to less than 5N on either force plates at the end of stance phase until the point of initial contact of both feet back on the force plates at the end of vertical jump detected by greater than 5N of VGRF on either force platforms.

Kinematics:

Raw, 2-D marker locations of the cameras were reconstructed into 3-D coordinates using a proprietary algorithm in the Vicon® software (Workstation® v5.2.4). Marker data were filtered using a fourth-order, low-pass Butterworth filter (cutoff frequency = 20Hz). Cut-off frequency was determined based on frequency content analysis performed on the raw data. An unweighted least-squares procedure was applied to reduce skin movement artifacts[94]. The marker coordinates were used to model the body as a combination of multiple rigid segments connected by frictionless joints[95], including each pelvis, thigh, lower leg, foot; and the trunk segments. The trunk was divided into thoracic segment/upper trunk (UT; C7-T8), middle (MT; T9-T12), and lower trunk (LT; L1-L5).

For generating angular data about three clinical axes, the local coordinate system (LCS) of each segment was defined as shown in Appendix B. Two types of angles were generated for the three trunk segments: joint and segment. Joint trunk angles were comprised of the trunk segment relative to the adjacent distal segment (e.g., lower trunk relative to pelvis), and the segment angles were the orientations of the segment to the global coordinate system. Cardan angles were used to generate the joint angles[96] about all three axes for the joints of both lower extremities and the three trunk segment angles for the phases of interest of the stop-jump task[97-99]. The rotation sequence for the trunk segment and joint angles was z-y-x that is internal/external rotation, adduction/abduction and flexion/extension, respectively. For the lower extremity joint angles, the sequence was y-x-z. The dependent variables of interest were the relative and segmental angular displacements of the upper, middle and lower

trunk segments and hip, knee and ankle joint angular displacements for the phases of interest.

Kinetics: For the stop-jump task, GRF signals first were recorded and processed from raw signals via Workstation® v5.2.4 software). The dependent variable calculated from the processed signals was peak vertical ground reaction force (VGRF).

Inverse Newtonian dynamics process was used to calculate lower extremity joint moments for both legs (Workstation® software, Plug In Gait module). Using our Matlab® program, the dependent variables of interest, that is, peak joint moments displayed during the phases of interest were detected and normalized to body mass. Detailed explanations of relevant calculations are provided for each manuscript in Chapters 4 and 5.

MATLAB© (v. R2012b, Mathworks, Inc. US) programs were used for the data output from the Workstation®. Computer programs were written to generate biomechanical quantities, to derive relevant variables for statistical analysis and to complete statistical analyses. IBM SPSS Statistics v21.0 will be used to perform all the statistical analyses in the study.

F. Statistical analyses

Relevant dependent variables listed above for the stop-jump tasks first were explored using summary and graphical methods. If a participant had a value for a variable that was greater than or equal to 3 standard deviations of the rest of the corresponding group's data, then, that value was considered an outlier and none of the

participant's data were included in the results. All variables of spine angular displacements were tested for differences for each hypotheses between SF-AIS and CON ($p < .05$) using one-way analysis of variance (ANOVA) for the sample distributions. A two-way mixed model 2 (Groups: SF-AIS or CON) × 2 (Limbs: dominant or non-dominant) ANOVA ($p < .05$) was performed for peak angular displacements, peak vertical ground reaction forces (VGRF) and peak joint moments at the hip, knee and ankle joints in the 3 planes of motion during the phase of interest. If a peak angular displacement comparison was significant, comparisons for the initial and final angles were then completed in order to understand what created the displacement difference. Not testing all initial and final angles also helped reduce the number of statistical comparisons. As often done in biomechanics studies with small sample sizes, Bonferroni corrections were not used to control for family-wise error unless strongly indicated. Summary statistics, graphs, and values of joint motion variables were examined qualitatively to determine the presence of unique compensatory movement strategies displayed by SF-AIS.

CHAPTER 4

Spine kinematics exhibited during the stop-jump by physically-active individuals with adolescent idiopathic scoliosis and spinal fusion

Kakar RS, Brown CN, Simpson KJ. *The Spine Journal (To be submitted)*

A. Abstract

Introduction: After spinal fusion, adolescent idiopathic scoliosis individuals (SF-AIS) often return to exercise and sport. However, the movements SF-AIS use to compensate for the loss of spinal flexibility during high-effort tasks are not known. The objective of the study was to compare, between SF-AIS and healthy controls (CON) groups, the spinal kinematics of the trunk segments displayed during the stop-jump, a maximal effort task.

Methods: Nine SF-AIS (physically active; posterior-approach spinal fusion: 11.2 ± 1.9 fused segments; post-op time: 2 ± .6 yrs; and 9 CON individuals, pair matched for gender, age (17.4 ± 1.3yr, 20.6 ± 1.5yr, respectively), mass (63.50 ± 12.2kg, 66. 40 ± 10.9kg), height (1.69 ± 0.09m, 1.72 ± 0.08m) and level of physical activity participated. SF-AIS and CON performed 5 acceptable trials of the stop-jump task. Spatial locations of 21 retro-reflective trunk and pelvis markers were recorded via high-speed motion capture methodology. Mean differences and analysis of covariance (jump height = covariate, $p <$ .05) were used to compare the groups' relative (RelAngDisp) and segmental (SegAngDisp) angular displacements of the 3 trunk segments (trunk segments = upper trunk [UT: C7 to T8], middle trunk [MT: T9 to T12], lower trunk [LT: L1 to L5]) for each rotation plane in the 3 phases of interest (flight, stance and the vertical flight phases).

Results: No significant group differences for jump height and RelAngDisp were detected in the 3 phases of stop-jump. SF-AIS displayed 3.2° greater transverse plane RelAngDisp of LT compared to CON (p =.059) in the stance phase. Group differences for RelAngDisp ranged from 0° to 15.3°. For SegAngDisp in stance phase, LT demonstrated

greater SegAngDisp in the sagittal and frontal plane (mean difference: 3.2°– 6.2°) while SegAngDisp for MT was 5.1° greater in sagittal plane and had a tendency of 2° greater displacement in frontal plane ($p = .070$). In the vertical flight phase greater LT displacement in frontal plane was observed for SF-AIS than CON. In the flight phase, LT had a tendency for greater SegAngDisp for SF-AIS than CON in transverse plane ($p = .089$).

Discussion: Fewer differences for relative angular displacements of the spine were observed than anticipated, between physically active SF-AIS and CON during stop-jump task. This finding and the greater segmental angular displacements of SF-AIS for many variables suggests that the superior spinal segment was moving with the adjacent inferior segment. Thus, the fused MT appeared to be moving synchronously with the LT, thereby suggesting a compensatory adaptation of SF-AIS to achieve sufficient spinal movements during this high-effort movement. Overall, SF-AIS individuals who participate in physical activity on a regular basis are able to achieve the same jump height as healthy peers using the low back to extend, rotate and bend the spine.

B. Introduction

Among surgeons, there is very wide variation in prescription of physical therapy and the physical activities allowed post-operatively for individuals with spinal fusion for adolescent idiopathic scoliosis (SF-AIS)[23,100]. The spectrum of physical activity/therapy allowed as reported by Lehman and colleagues, vary from none to highly-demanding. At the low end of physical activity prescription, for example, physical therapy is still not favored post-operatively by approximately 78% of surgeons[23,100]. Fortunately, however, the percentage of surgeons recommending physical activity has increased over the past decade. Hence, at the high-end of prescribed physical activity, SF-AIS have been reported to return to competitive sports, such as golf, gymnastics, aquatic sports and other organized athletics and outdoor physical activities, at an intensity equal to or higher than that of pre-surgery[18].

One reason that recommendations for physical activity and/or therapy suggested by surgeons to their patients post-surgery varies so broadly is the concern for patient safety. At present, the spinal motions of a partially-fused spine after surgery are not known for high-intensity movements. Prior research related to spinal motions of SF-AIS has reported that SF-AIS display deficits of spinal range of motion, implying that SF-AIS cannot move their spines sufficiently[34]. Additionally, these findings have come from studies involving low intensity, semi-static activities[33-35]; or low-effort dynamic movements like side stepping[36,37] or walking[38-42]. Hence, surgeons may fear that during higher-effort, fast movements, spinal injury could occur.

There is little empirical evidence of the movements spinal-fusion patients perform during high effort activities/sports involving jump-related movements, such as basketball,

soccer, volleyball, and jump-based exercises. Therefore, it is not known whether SF-AIS adapt a compensatory strategy for the loss of spinal ranges of motion among the fused segments to achieve the performance goals of high-effort activities.

Therefore, the purpose of this study was to compare the spinal kinematics displayed during the performance of the stop-jump task of physically-active SF-AIS to those of comparable, healthy, non-scoliotic individuals (CON). The stop-jump was chosen as the test task because the elements are similar to those in jump movements performed during many common sports. The stop-jump is comprised of the following phases: flight, stance, vertical flight and landing phases (see *Figure 4.1*). The phases of interest for this study are flight, stance and vertical flight phases.

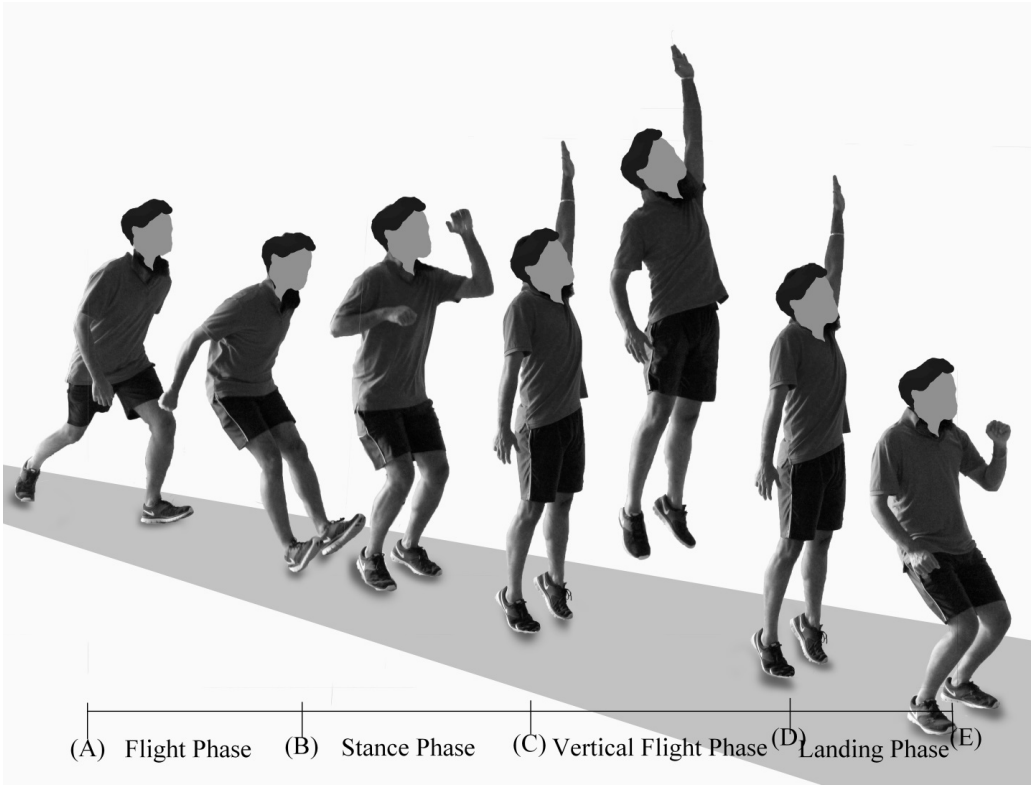

Figure 4.1: The stop-jump task and the phases of the jump. ((A): takeoff of the last step of approach run; (B): initial contact of the two feet; (C): takeoff for vertical flight; (D): touch-down after vertical flight; (E): maximum knee flexion position)

There were three main predictions. First, it was predicted that there would be no significant between-group difference for mean maximum vertical jump height or the jump performance. SF-AIS individuals recruited were physically active and were pair matched to a similar physical activity levels CON, hence the prediction. Second, that for phases and movement planes during which the amount of spinal motions were expected to be relatively low or moderate, physically-active SF-AIS would demonstrate spinal movements within 5° of CON group's values. Third, it was predicted that, compared to CON, for SF-AIS, vertebral segments proximal and distal to the surgically-fused

segments would demonstrate greater angular displacements, while the fused segments would demonstrate lesser angular displacements during the stance phase. This was surmised because non-fused segments were expected to compensate for the lack of flexibility at the fused segments to be able to achieve the desired trunk movement.

C. Materials and Methods

Participants

Sample size estimation

Ten participants for each of the two spine groups (CON and SF-AIS) were calculated to be adequate to detect a group difference with an effect size of approximately 1. An a priori power analysis was performed using G*Power™ (Kiel University, Germany) to determine the appropriate sample size to support the exploratory objectives of the study with a $\alpha = .05$, $1-\beta = .80$. Results of selected lower extremity joint angles and the peak knee extensor joint moment magnitude reported by Ferber and colleagues for running and Wei-Ling and colleagues on stop-jump for healthy and physically active individuals were used for the power analysis[88,89]

Recruited were 24 healthy, moderately physically-active participants; 14 SF-AIS and 10 matched controls (CON). Each SF-AIS participant was required to be 16-19 yrs old; had completed spinal growth, based on radiological assessment by the spinal surgeon; had scoliosis that was classified as structural AIS and a primary spinal fusion surgery to correct the AIS that was performed using a posterior approach (hence, no revision surgeries) at least 12 mo prior to testing; had resumed normal daily and physical activities (based on International Physical Activity Questionnaire; IPAQ) since the

surgery; was not experiencing any unresolved complications or back pain due to surgery; and had obtained medical clearance to participate from the spinal surgeon. Each CON participant was pair-matched to a corresponding SF-AIS participant, based on age (±2 yr), height (±5 cm), mass (±2 kg) and physical activity (±2 hr per week at similar intensity of physical activity). SF-AIS participants aged 16-17 yr were matched to 18 yr old CON.

Data were analyzed for 18 participants (9 SF-AIS, 9 CON) (Table 4.1). Four potential SF-AIS did not participate, as they did not meet the eligibility criteria. Data for another SF-AIS participant were not used, as many of the participant's outcomes were found later to be outliers (i.e., had values ≥ 3 standard deviations). Therefore, the corresponding data of the matched CON participant were also not included.

Demographic and anthropometric data are reported in Table 4.1 for the 9 SF-AIS (pre-surgery curvature: 5 right thoracic curve and 4 right thoracic and left lumbar curves; pre-surgery Cobb angle: range = 45–71°) and 9 non-AIS control participants (CON). The spinal vertebrae fused for each participant and the frequency distribution among the SF-AIS group of the lowest instrumented vertebra (LIV) are presented in Figure 4.2.

Table 4.1: Participant characteristics and anthropometric data (means ± standard deviations) for the individuals with spinal fusion for adolescent idiopathic scoliosis (SF-AIS) and the matched healthy controls (CON).

Group	Gender (n)		Post-surgical Cobb angle (degrees)	Post-surgical time (yr)	Age (yr)	Height (m)	Leg Length (m)	
	Females	Males					Left	Right
SF-AIS	6	3	59.3±12.2	2.00±.66	17.4± .3	1.70±0.87	0.92±0.06	0.93±0.06
CON	6	3	NA	NA	20.6±1.5	1.71±0.82	0.90±0.06	0.90±0.07

	Vertebrae by Trunk Segments																
	Upper Trunk									Middle Trunk				Lower Trunk			
Participant ID	C7	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	L1	L2	L3	L4	L5
1																		
2*																		
3																		
4																		
5																		
6																		
7																		
8																		
9																		
LIV (% of total SF-AIS participants)													11.1	11.1	11.1	55.6	11.1	0

Figure 4.2: The fused vertebrae (solid region) of each scoliosis participant by trunk segment. LIV: This row shows the percentage of SF-AIS individuals whose lowest instrumented (fused) vertebra (LIV) was a given vertebra. Qualitatively, L3 was the LIV for the greatest percentage of SF-AIS individuals.

Instrumentation and Experimental Setup

For motion capture, 39 reflective markers (diameter = 9.5 mm for spinous and transverse processes and 14.0 mm for rest of body) were placed on the participant's skin or clothing on the anatomical and technical locations by the same experienced physical therapist for all participants (*Figure 4.3*). The Newington-Helen Hayes gait model as implemented in the Plug-In-Gait module of the data collection software[91] was used for the reflective marker locations. Two additional technical markers, one on each iliac crest, were used later to reconstruct the pelvis when other pelvic markers were obscured during data capture. A subset of 21 reflective markers placed on the spine and pelvis was used in this study. For the spine, the trunk was divided into 3 segments, upper trunk ('*UT*'; vertebrae included: C7-T8), middle ('*MT'*; T9-T12), and lower trunk ('*LT*'; L1-L5). A novel spinal marker model was developed for the three trunk segment to later reconstruct the trunk segment orientations, as per the ISB recommendations outlined for the thoracic trunk segment and extended to define our trunk segments [97-99]. Markers were placed on spinous processes of the following cervical (C), thoracic (T) and lumbar (L) vertebrae: C7, T2, T4, T6, T 8, T10, T12, L2 and L4; right and left transverse processes for T11 and L3; and the manubrium and xyphoid process (*Figure 4.3*).

Figure 4.3. Participant with reflective markers located as described in text. The markers on the extremities were placed in accordance with the plug-in gait model; the trunk and spinal markers for our laboratory-developed spinal motion model.

Seven visible-red light MX40® cameras (240 fps; Vicon, Oxford, UK) and motion capture system (Vicon) were used to capture the spatial locations of the reflective markers on the body during the stop-jump task. Workstation® v5.2.4 software (OMG Plc., London, UK) was used to process the reflective marker data with a mean residual error of ≤ 0.5 mm. GRF signals from two Bertec 4060-NC force platforms® (Bertec Corporation, Columbus, OH) were recorded (sampling frequency = 1200Hz) to identify later the start and end of different phases of the stop-jump. The Vertec Jump Trainer© (Vertec; Sports Imports, Columbus, OH) was used to measure the vertical jump height attained by the participant (to the nearest 0.5") during the stop-jump task.

Test task

For the stop-jump test task, the participant took 1 - 3 running steps, landed simultaneously with both feet together, jumped up as high as possible, touching the highest flap possible on the Vertec© jump trainer followed by landing with both feet together (*Figure 4.1*).

Protocol

Written consent or assent (if less than 18 yr old) was obtained from the participant as approved by the institutional review board of the participating institutions. Both SF-AIS and CON participants completed the following set of questionnaires: IPAQ[86,87,90] and a Pre-Participation and Health Status Questionnaire (PHSQ). These were used, in part, to finalize the eligibility based on any previous or currently existing medical condition/ health status, the level of physical activity of the participant by subjectively assess their involvement in different sports and the intensity level for each of them and to identify the kinds of physical activities and the approximate time they spent on each activity respectively. Scoliosis Physical Activity and Quality of Life (SPAQOL) Questionnaire and Scoliosis Research Society (SRS) Short-Form 22-R Health-Related Quality of Life (SRS-SF-22) Questionnaire[82-84], was also completed by only SF-AIS group in addition to IPAQ and PSAQ to evaluate the health-related quality of life post-surgery. The answers to the questionnaires were reviewed after consent was obtained to ensure that the participant met the eligibility criteria. Individuals who remained eligible then continued with the testing protocol.

Anthropometric measures were recorded which included mass, height, leg lengths, and knee and ankle widthsf[91]. The participant kicked a soccer ball and also

confirmed that this was the leg used to kick objects. The kicking leg was considered to be the dominant leg. The reflective markers were then placed on the participant. Next, the participant performed a supervised warm-up of jogging for 2 min. at a self-selected pace on a calibrated treadmill.

A standing reach height was measure for the participant before performing the test task. Next, the participant performed one or two practice trials, followed by five acceptable trials of the stop-jump task. Maximum vertical jump height was recorded for each trial by subtracting the vertical jump distance from the participant's standing reach height. A rest period of approximately 15s was administered between each trial to prevent fatigue of the participant.

Data Reduction and Analysis

The phases of interest were the flight, the stance and the vertical flight phases of the jump. GRF signals were used to decide the start/stop of each phase. Marker locations were reconstructed into 3-D coordinates using a proprietary algorithm in the Vicon® software (Workstation® v5.2.4). Marker data were filtered using a fourth-order, low-pass Butterworth filter whose cutoff frequency (20 Hz) was based on a frequency content analysis of the data. The body, including the three trunk segments, was modeled as a combination of multiple rigid segments connected by frictionless joints[95]. The boundaries and orientations relative to the global reference frame of the three trunk segments were defined based on the ISB recommendations outlined for the thoracic trunk segment and extended to define our trunk segments[97-99]. The pelvis segmental orientation was defined by reflective markers on the 2 anterior and posterior superior iliac spines.

Two types of angles were calculated for the trunk segments, relative (RelAng) and segmental angles (SegAng)[92,97-99]. To understand the spinal motions between trunk segments, the RelAng was used and expressed as the proximal segment's orientation relative to the adjacent distal segment. As the orientation of two adjacent segments comprised a trunk RelAng, the SegAng, the orientation of each segment in the global reference frame, of the three trunk segments were used to understand their individual contributions to a given RelAng. MATLAB© (v.R2012b, Mathworks, Inc. US) programs were developed for generating all angular quantities.

The angular displacement (the amount of angular motion, defined as the difference between the maximum and minimum angle) for the three planes of motion (sagittal, transverse and frontal) and each phase of interest were calculated for the RelAng of UT, MT and LT (UT-RelAngDisp, MT-RelAngDisp and LT-RelAngDisp, respectively) and SegAng of UT, MT, LT and pelvis (UT-SegAngDisp, MT-SegAngDisp, LT-SegAngDisp and Pel-SegAngDisp, respectively) (see *Figure 4.4-4.5*). Results of the 5 acceptable trials were averaged for each variable of a participant.

Statistical Analysis

All statistical analyses were performed using SPSS® software (IBM Version 21.0, IBM, Inc., Armonk, NY), with statistical significance set at $p < .05$ and a tendency of a potentially- meaningful difference at a range of $p = .05 - .10$. To confirm that the matched the spine groups were equivalent on participant characteristics and to test if the groups had different test task performance, age, height, body mass, leg lengths and maximum vertical jump height were compared between SF-AIS and CON ($p < .05$) using one way-analysis of variance (ANOVA). Pearson's correlations were performed to test for

correlation between jump height and the angular displacements of different segments in the planes of motion. As a moderate correlation was obtained for most comparisons ($r > .250$), jump height was used as a covariate for between group comparisons for angular displacements. The groups were tested for assumptions of the univariate statistical tests. Angular displacements for relative and segmental angles in the three planes of motion for the three phases were tested for differences between groups using analysis of covariance (ANCOVA; $p < .05$) with vertical jump height as a covariate. Significance values (*p value*) for the comparison with $r < .250$ were very similar when analysis of variance was performed with or without the covariate. Hence, ANCOVA was adopted and reported for all the comparisons. Confidence intervals for the mean difference between the two groups were also calculated. Partial η^2 was calculated for effect size. As Bonferroni corrections are more appropriate for use with larger sample sizes, they were not used to control for family-wise error.

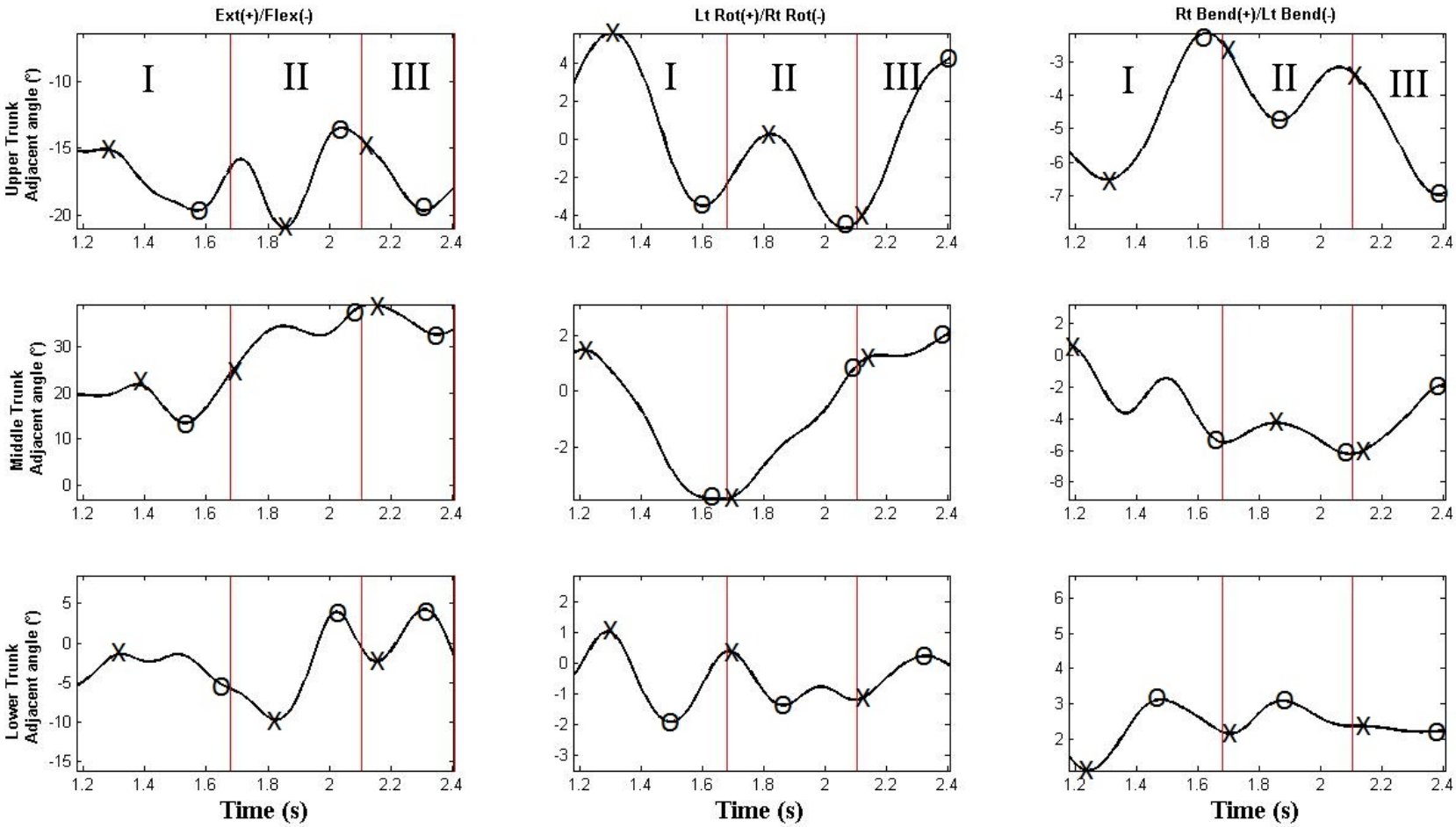

Figure 4.4: Relative angle-time curves of one trial to demonstrate the peak angles used to calculate relative angular displacements of each phase (I: Flight phase, II: Stance subphase and III: Vertical Flight subphase). An angular displacement of a phase was calculated as the difference between the "X" and the "O" within a given phase/ subphase.

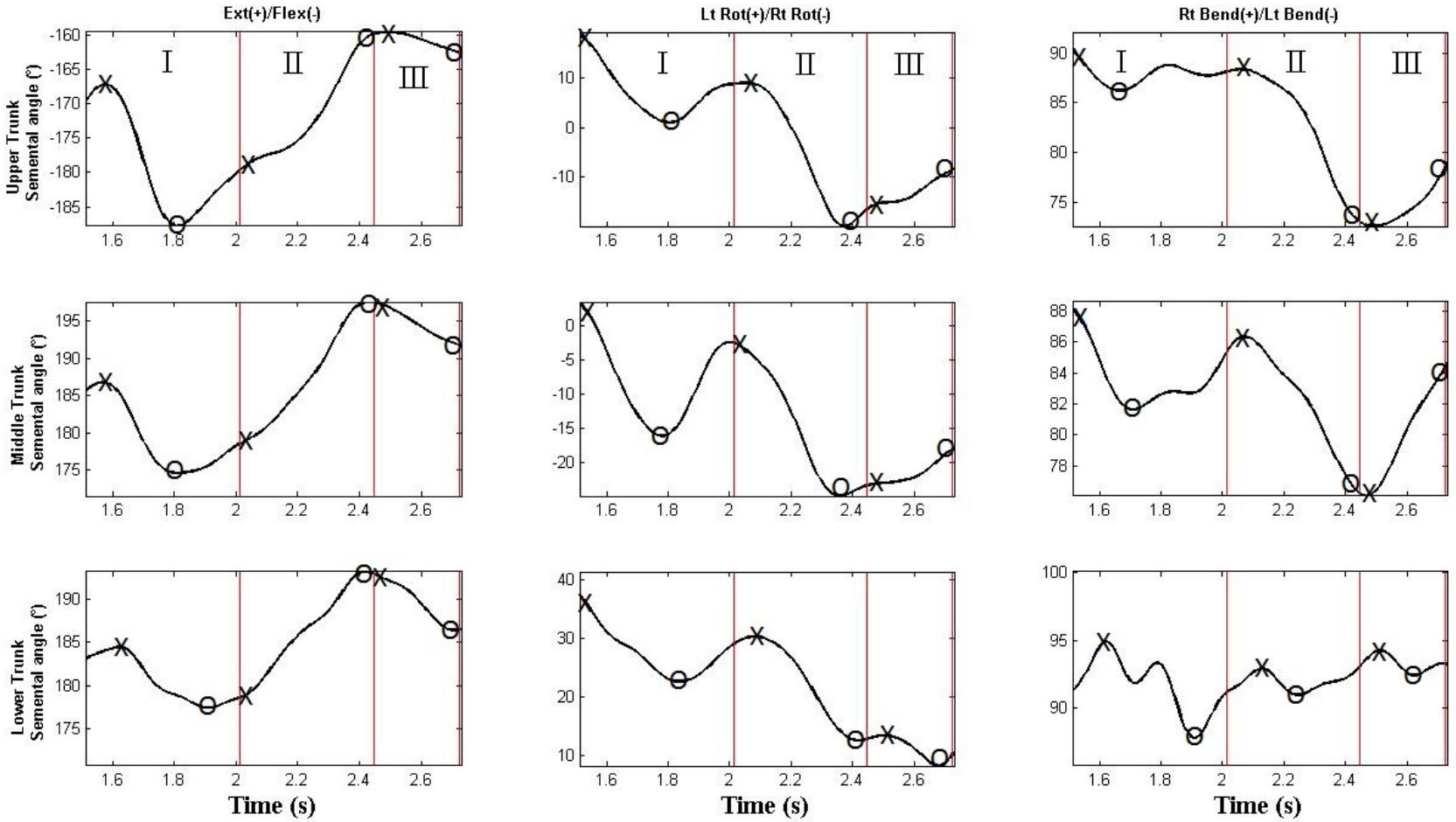

Figure 4.5: Segmental angle-time curves of one trial to demonstrate the peak angles used to calculate segmental angular displacements of each phase (I: Flight phase, II: Stance subphase and III: Vertical Flight subphase). An angular displacement of a phase was calculated as the difference between the "X" and the "O" within a given phase/ subphase.

D. Results

Distributional and parametric statistics for each of the dependent variables are presented for each group in tables 4.1. Participant characteristics are presented first. The SF-AIS group was significantly younger than their matched CON ($p < .001$). The two groups were not significantly different for any other characteristic (p =.147 – .632). For comparing the groups' performance, jump height was not significantly different between the two groups. Moreover, the means varied by less than 0.013m (p = .872; CI (-.1m to -.1m)). Next, the angular outcomes are reported for each phase.

Flight Phase:

For RelAng displacements of the three spine segments, no significant group differences were detected for any of the spine segments or planes. The mean differences between the spine groups were less than 5° and ranged from 0.3° to 2.8° (*Figure* 4.6). Among the SegAng, SF-AIS had a tendency for greater LT displacement in the frontal plane compared to CON (p = .089; CI (0° to 4.3°)) (see *Figure* 4.7).

Stance Phase:

SF-AIS demonstrated a tendency (p = .059) for significantly greater RelAng displacement of the LT in the transverse plane compared to CON, with a mean difference of 3.2°. No other RelAng displayed significant displacements (*Figure* 4.6).

For SegAng, SF-AIS demonstrated significantly greater spinal flexion displacements of the MT and LT in the sagittal plane and LT in the frontal plane compared to CON (Figures 4.5-4.6). SF-AIS also demonstrated a tendency for greater MT SegAngDisp compared to CON in the frontal plane for both left and right lateral

flexion (p = .070). No significant differences were observed for the LT SegAngDisp or Pel SegAngDisp in the transverse plane. (*Figure* 4.7)

Vertical Flight Phase

No significant group differences were detected for the vertical flight phase for RelAng displacements (Figures 4.5-4.6). Mean differences for angular displacements for the groups ranged between 0° and 8.2°. Moreover, the mean difference between the spine groups was less than 5° for most of the angular displacements, except for LT displacement in the sagittal plane, where the mean difference between groups was 8.2°. Moreover, the CI of the mean difference contained the null value for all variables (*Figure* 4.6).

Amongst the SegAng displacements, SF-AIS demonstrated 2° significantly greater LT displacement in the frontal plane compared to CON. No other statistically significant group differences were observed. Mean differences for angular displacements for the groups ranged between 0° and 3.9°(*Figure* 4.7).

Table 4.2: Group Differences of Displacements of Relative Joint Angles (°)

Relative Angle	Plane	Mean difference (degrees)	95% CI of the mean difference (degrees) Upper limit	Lower limit	*p* value	Partial η^2	Power
Flight Phase:							
Upper	Sagittal	1.8	-0.6	4.3	0.208	0.103	0.234
trunk	Transverse	1.3	-1.3	3.8	0.375	0.053	0.137
	Frontal	0.7	-1.5	6.6	0.276	0.078	0.185
Middle	Sagittal	-1.1	-4.7	2.4	0.593	0.019	0.080
trunk	Transverse	1.2	-2.8	5.1	0.543	0.025	0.090
	Frontal	0.3	-1.9	2.5	0.778	0.005	0.058
Lower	Sagittal	0.4	-3.3	4.1	0.818	0.004	0.056
trunk	Transverse	1.2	-0.8	3.1	0.291	0.074	0.176
	Frontal	1.4	-0.5	3.4	0.225	0.096	0.220
Stance Phase							
Upper	Sagittal	4.1	-2.1	10.3	0.269	0.081	0.190
trunk	Transverse	2.5	-0.2	5.0	0.113	0.159	0.350
	Frontal	15.3	-8.4	39.0	0.199	0.124	0.241
Middle	Sagittal	-0.2	-4.6	4.4	0.983	0.000	0.050
trunk	Transverse	3.6	-0.8	8.0	0.177	0.118	0.264
	Frontal	1.9	-1.5	5.4	0.255	0.085	0.198
Lower	Sagittal	0.7	-5.4	6.8	0.777	0.006	0.058
trunk	Transverse	3.2	0.5	5.9	0.059[Ŧ]	0.218	0.482
	Frontal	1.4	-1.5	4.2	0.362	0.056	0.142
Vertical Flight Phase							
Upper	Sagittal	2.4	-3.5	8.3	0.477	0.034	0.105
trunk	Transverse	-0.4	-3.8	3.0	0.878	0.002	0.052
	Frontal	0	-11.7	11.8	0.982	0.000	0.050
Middle	Sagittal	4.4	-8.4	17.2	0.569	0.022	0.085
trunk	Transverse	0	-5.6	5.6	0.967	0.000	0.050
	Frontal	-0.6	-6.6	5.3	0.864	0.002	0.053
Lower	Sagittal	8.2	-3.9	20.3	0.273	0.079	0.187
trunk	Transverse	0.2	-2.7	3.1	0.843	0.003	0.054
	Frontal	0.4	-2.7	3.6	0.766	0.006	0.059

Note. A positive mean difference signifies that the angular displacement was greater for SF-AIS than CON and a negative difference represents the opposite.
[Ŧ] Tendency for difference between groups (p =.05 – 0.10).

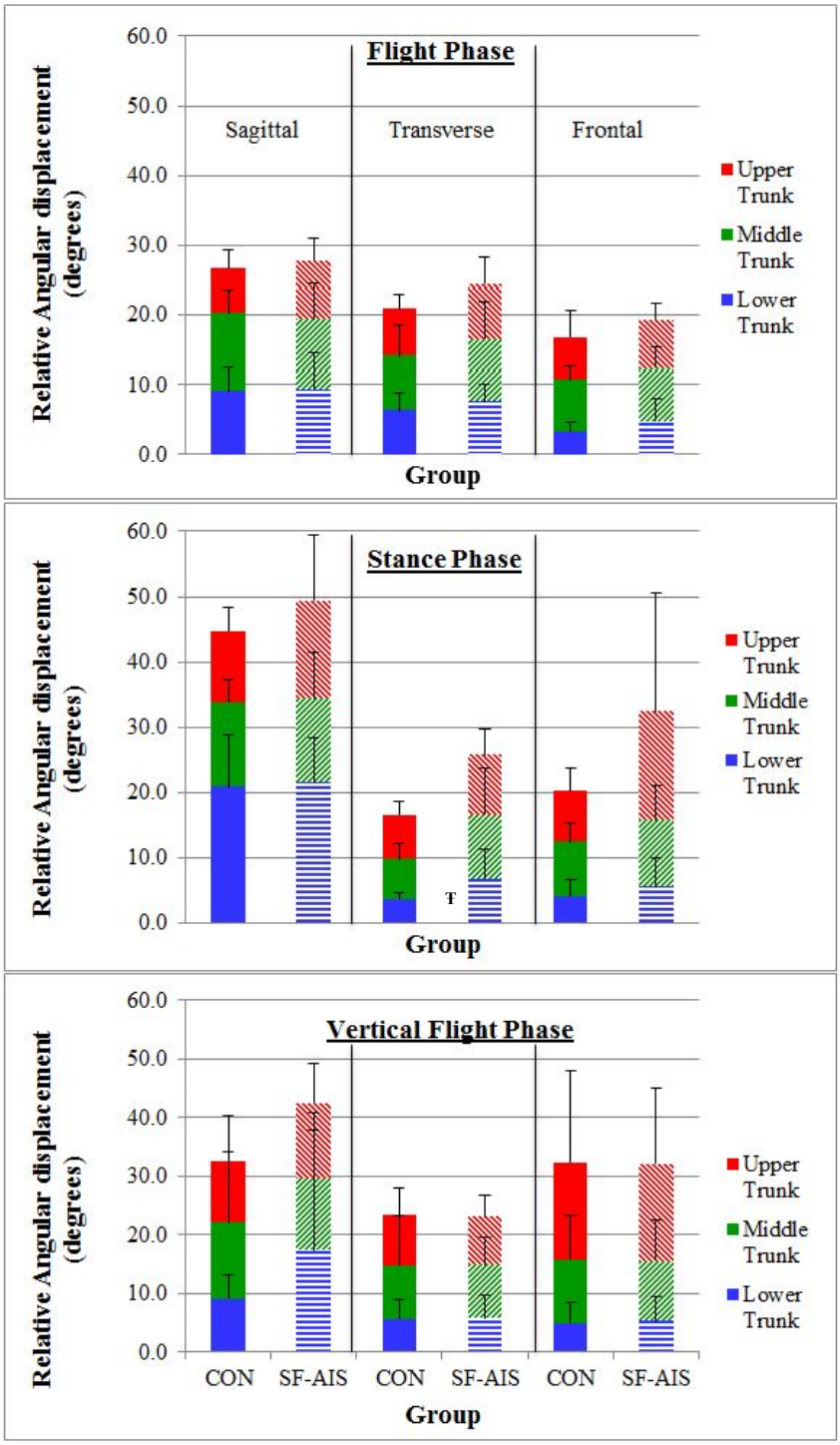

Figure 4.6: Means (SD) of displacements for relative angles for scoliosis (SF-AIS) and control (CON) individuals. ^{T} indicates tendency of a trunk segment displacement to be statistically different between groups (p = .05 – 0.10)

Table 4.3: Group Differences of Displacements of Segmental Joint Angles (°)

Segmental Angle	Planes	Mean difference (degrees)	95% CI of the mean differences (°) Upper limit	Lower limit	*p* value	Partial η^2	Power
Flight phase							
Upper trunk	Sagittal	0.7	-5.4	6.7	0.825	0.003	0.055
	Transverse	-2.2	-7.1	2.7	0.473	0.035	0.106
	Frontal	12.3	-3.5	28.1	0.206	0.105	0.236
Middle trunk	Sagittal	4.7	-1.9	11.2	0.196	0.109	0.245
	Transverse	0.5	-5.9	7.0	0.858	0.002	0.053
	Frontal	2.4	-1.4	6.2	0.195	0.109	0.246
Lower trunk	Sagittal	5.7	-0.2	11.4	0.104	0.166	0.366
	Transverse	1.2	-4.5	6.8	0.691	0.011	0.067
	Frontal	2.1	0.0	4.3	0.089 ₸	0.181	0.399
Pelvis	Sagittal	2.0	-4.0	7.9	0.544	0.025	0.090
	Transverse	-0.4	-4.0	3.1	0.861	0.002	0.053
	Frontal	0.9	-0.6	2.3	0.319	0.066	0.162
Stance phase							
Upper trunk	Sagittal	2.8	-0.7	6.3	0.187	0.113	0.254
	Transverse	-6.3	-14.3	1.6	0.194	0.11	0.247
	Frontal	8.2	-3.3	19.7	0.236	0.092	0.211
Middle trunk	Sagittal	5.1	1.8	8.3	0.009*	0.376	0.802
	Transverse	-3.1	-10.3	4.0	0.483	0.033	0.104
	Frontal	2.9	-0.3	6.1	0.070 ₸	0.203	0.448
Lower trunk	Sagittal	6.2	2.4	9.9	0.012*	0.355	0.765
	Transverse	0.8	-5.9	7.6	0.821	0.004	0.055
	Frontal	3.2	0.8	5.8	0.039*	0.255	0.564
Pelvis	Sagittal	1.4	-1.4	4.2	0.349	0.059	0.148
	Transverse	0	-3.4	3.4	0.979	0	0.050
	Frontal	0.9	-0.7	2.5	0.336	0.062	0.154
Vertical Flight Phase							
Upper trunk	Sagittal	-2.6	-5.8	0.7	0.124	0.15	0.332
	Transverse	1.2	-4.8	7.2	0.688	0.011	0.067
	Frontal	3.9	-8.8	16.6	0.568	0.022	0.085
Middle trunk	Sagittal	1.8	-3.3	6.7	0.487	0.033	0.102
	Transverse	0	-7.1	7.1	0.926	0.001	0.051
	Frontal	0.8	-2.0	3.7	0.511	0.029	0.097
Lower	Sagittal	2.2	-2.0	6.4	0.376	0.053	0.137

trunk	Transverse	2.7	-1.7	7.2	0.291	0.074	0.176
	Frontal	2.0	0.3	3.7	0.044*	0.244	0.538
Pelvis	Sagittal	-2.0	-5.1	1.1	0.294	0.073	0.175
	Transverse	-0.3	-3.5	3.0	0.921	0.001	0.051
	Frontal	0.2	-1.4	1.8	0.798	0.004	0.057

Note. A positive mean difference signifies that the angular displacement was greater for SF-AIS than CON and a negative difference represents the opposite.

* Statistically significant difference between groups ($p < .05$)

^{T} Tendency of difference between groups ($p = .05 – 0.10$)

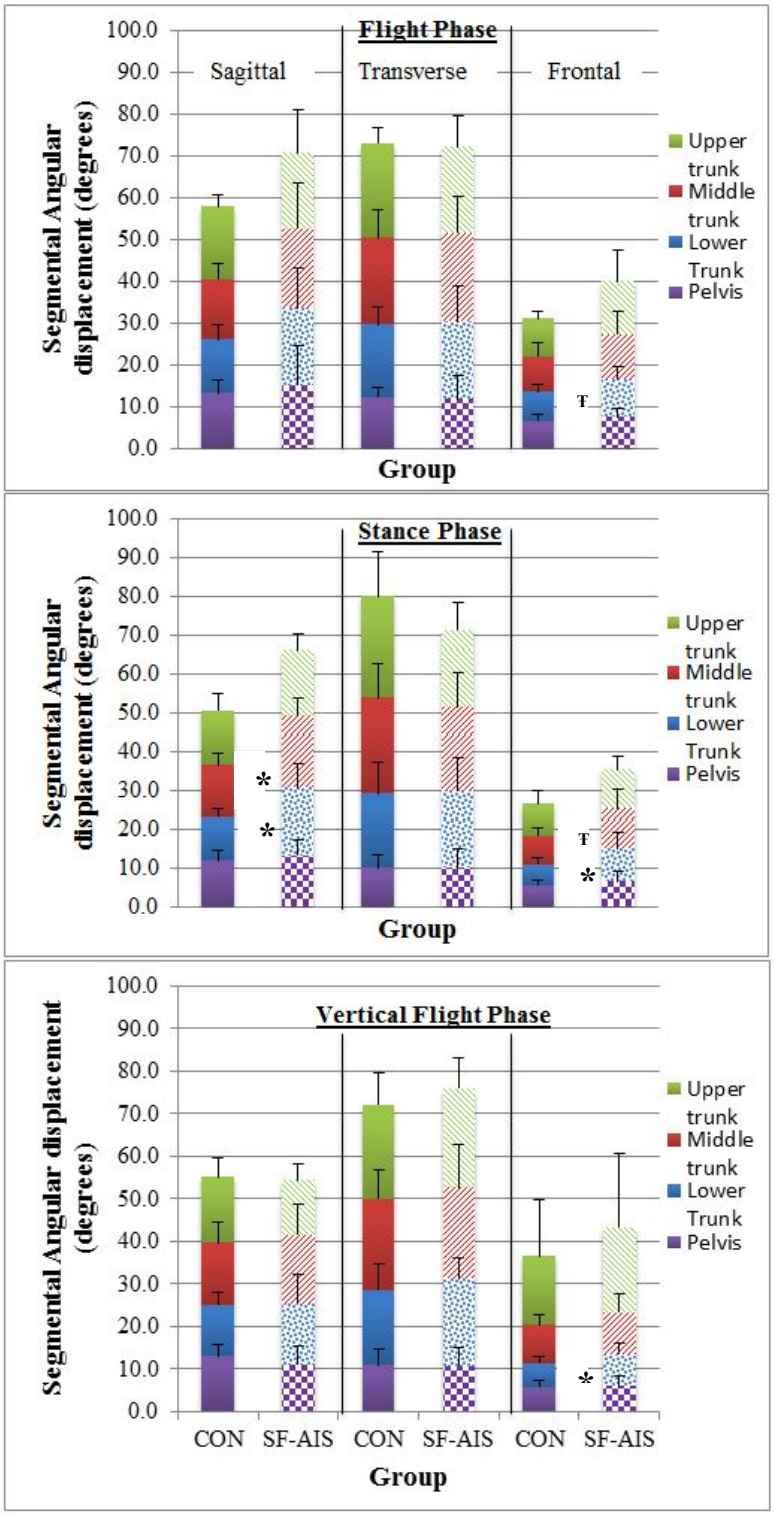

Figure 4.7: Means (SD) of displacements for segmental angles of the 3 trunk segments and pelvis for scoliosis (SF-AIS) and control (CON) individuals. * is statistically significant difference between groups ($p < .05$). ^{T} indicates tendency of a trunk segment displacement to be statistically different between groups ($p = .05 – 0.10$)

E. Discussion

The study was aimed at comparing the jump performance and angular kinematics of the spinal segments of moderately physically-active individuals with adolescent idiopathic scoliosis who have had spinal fusion surgery to comparable control individuals. We had surmised that SF-AIS individuals would demonstrate similar jump performances compared to CON and would display few differences for relative angular displacements of the spinal segments during the stop-jump. Group differences were anticipated to be less than 5° for spinal displacements during the 2 flight phases (flight and vertical flight). SF-AIS were also predicted to demonstrate greater segmental UT and LT displacements that would, consequently, contribute to correspondingly greater relative trunk angles and angular displacements of the UT and LT during the stance phase. Our predictions for jump performance were supported, but those for angular kinematics were only partially supported.

Our prediction that SF-AIS individuals who are physically active are capable of jumping as high as their non-scoliotic peers was supported. Our evidence is that the mean jump heights of the two groups differed by less than 0.013m, which is the limit of the size of detectable differences for the jump height apparatus. Also, the CI range was very small and included the null value (CI (-.1m to -.1m)). In addition, there was a small tendency for shorter jumps when the individual participant jump height ranges are compared each CON participant reached a maximum jump height (0.21 - .46m) roughly similar to the matched SF-AIS (.31- .47m).

For the angular kinematics in the flight phase, the hypothesis that the displacements of the relative and segmental angles for SF-AIS would be similar to the

CON group was supported. The mean difference between the groups for RelAngDisp was less than 2.6°, which was within the prediction of between-group differences being no greater than 5°. Additionally, the between-group differences displayed CI ranges that were relatively low and all included the null value.

Displacement differences of less than 5° between the groups for segmental and relative angles were anticipated because it was expected that the spinal motions of either group would be low for the flight phase. Indeed, the observed magnitudes of flexion/extension displacement for the 2 groups ranged between 6.5-11.2° among all of the spinal segments. Low sagittal plane displacements were expected because the mechanical purpose of this phase was to move the legs into position for touchdown and maintain the trunk in an appropriate body position for starting the next phase. Thus, these goals could be achieved predominantly with pelvic movement in the sagittal plane. The posterior rotation of pelvis, femoral flexion and the associated forward flexion of the trunk at the pelvis are surmised to be sufficient to rotate the legs forward to reach for the floor to make ground contact.

The participants demonstrated low trunk flexion displacements as shown by the relatively low (0.4°) RelAng displacement of LT in sagittal plane, which suggests that LT and pelvis moved as a unit. This is also supported by the finding that the SegAng displacements of the LT in sagittal plane are nearly the same as pelvic angular displacement. Also, there were no behaviorally meaningful differences for pelvic segmental motions as observed by the small between-group differences that ranged from 0.4° to 2° among the three rotation planes. Additionally, the difference 95% CI for the pelvis SegAng displacement was narrow (-.6° to 2.3°) and included the null value,

suggesting that the true differences between these populations for pelvis movements were likely very low.

For the stance subphase of the jump, it was hypothesized that angular displacements of the RelAng of the UT and LT would be higher, and MT would be lower. The results were not supported for this prediction, as no statistical differences were found between groups. Narrow confidence intervals for most of the comparisons provide evidence that the angular displacements of the two groups likely were not different with one exception. SF-AIS did demonstrate a tendency ($p = .059$; difference CI (.5° to 5.9°)) toward a greater LT angular displacement in the transverse plane.

Expectations of greater UT and LT RelAng displacements were based on the premise that these segments, containing some non-fused vertebral joints, could and would move further to compensate for the lack of spinal motion in the MT, the segment that was fused entirely. These results, therefore, did not support this notion. One explanation for the lack of significant group differences for UT and LT RelAng displacements was that although the stop-jump task is predominantly in sagittal plane, SF-AIS may differ in their approach to the task causing the higher displacement in the transverse plane.

Compensatory UT and LT displacements also were the basis of the prediction that SegAng of the UT and LT trunk segments would be higher and SegAng of the MT lower for SF-AIS compared to CON. The results supporting these predictions was mixed. SF-AIS did demonstrate significantly greater LT motion in the sagittal and frontal planes compared to CON. However, not expected were the greater MT SegAng displacements of SF-AIS in these planes. The moderate effect sizes for the LT and MT SegAng

displacements (.203 - .376) provide evidence that these group differences may be clinically meaningful.

These significant difference between SF-AIS and CON observed for the MT and LT SegAng displacements but not the MT RelAng displacements indicates that the MT may be moving as a synchronous unit with the LT, while the LT moves over the pelvis to move the spine. Two pieces of evidence together support that the SF-AIS MT may be moving more as a unit with the LT. First, the mean of the SegAng displacement in the sagittal plane of the MT (17.9° ± 1.6°) was similar to that of the LT (16.8° ± 2.1°) for SF-AIS, which suggests that the MT is extending due to LT extension. SegAng displacement observed in CON in the sagittal plane was qualitatively more for MT (14.1° ± 0.7°) than LT (12.1° ± 0.8°). Second, the MT RelAng displacement of SF-AIS in the same plane was relatively low (13.4° ± 3.7°) when compared to individual segment displacements for SF-AIS. As the MT RelAng displacement represents the amount of motion between the MT and the LT for SF-AIS in this plane, which suggests that MT and LT are moving together in the same direction. The use of LT extension to also extend the MT is one of the few compensatory adaptations used by SF-AIS during this movement. This adaptation likely helps achieve greater ranges of extension for the fused segments and, thus, in the trunk as a whole.

The displacement (posterior tilt) of the pelvis did not appear to be part of the SF-AIS compensatory adaptation that was used to produce trunk extension. As predicted, no differences between groups for pelvic SegAng displacements occurred.

Being able to move the trunk through the greatest extension displacement feasible during the stance phase before takeoff is important for jumping as high as possible. That

is because trunk extension helps achieve the mechanical purposes of the stance sub-phase which are to raise the body mass and to gain maximum vertical momentum for the jump. Therefore, in the sagittal plane, the trunk segments of both groups were qualitatively observed to move through a greater range of extension during this phase as compared to the any other phase of the movement.

To extend the trunk to achieve a successful jump performance, our findings, therefore, suggest that these moderately-active SF-AIS individuals accomplish this largely through low back extension. Therefore, for improving performance and to prevent injury to the low back, we suggest that formal rehabilitation of the core muscles, particularly the lower spinal extensor group, may be beneficial to SF-AIS individuals planning a return to physical activities.

For the vertical flight phase, it was predicted that there would be no meaningful RelAng differences between the groups, as the mean difference between the groups would be less than 5° for displacements in all three planes. This was supported with one exception (LT extension displacement); none of the other group differences exceeded 5°. Additionally, the limits of the CIs for the group differences were narrow and included the null value. The exception to the predictions was the RelAng displacement of the LT in the sagittal plane, where SF-AIS showed 8.2° greater extension than CON (p = .273) and the difference CI displayed a broad limits range.

These outcomes mostly support our rationale for expecting few meaningful RelAng group differences for this phase. Our premise was that the spinal motion demands were low relative to what SF-AIS could achieve. The mechanical purpose of this phase was to contact the highest flag possible. Thus, some frontal plane movement of

the trunk to position the arm and scapula was expected to occur. However, the lateral bending needed was expected to be well within what SF-AIS could achieve, and the needed scapular movement as not expected to be restricted by spinal fusion. Thus, the lateral trunk movements were expected to be similar between the two groups. For the other planes, as little movement in the other planes were likely needed during this phase, SF-AIS was anticipated to achieve the same amounts of spinal movements.

The expectation that the amount of spinal motion for any plane during the vertical phase was achievable by SF-AIS also led to our hypotheses for the SegAng displacements of the vertical flight phase. However, the prediction that SegAng displacements of the two groups would be within 5° of one another were only partially supported. SegAng for UT in all the three planes and for MT and LT in sagittal and transverse were observed to be similar between groups. The CIs support the prediction of similarities between the groups. However, compared to CON, SF-AIS demonstrated greater LT-SegAngDisp in the frontal plane. Moreover, more surprising was that MT SegAngDisp also was greater for SF-AIS.

Greater MT and LT SegAng displacements of the SF-AIS group in the frontal plane again suggests that LT movements are important for SF-AIS to move the spine. Extension of the SF-AIS spine is mostly achieved via the extension of the pelvis and LT. For SF-AIS, the MT SegAng lateral bending displacements were similar to that of LT, possibly because the MT was passively rotating with the LT. Also, the difference confidence intervals of all variables (except LT SegAngDisp in frontal plane) included the null value (3.2 – 25.4).

The potential clinical relevance of these outcomes is that using pelvis and LT movements to not only extend, but laterally bend the trunk could be demanding on particular trunk muscles. Future evidence is required to confirm this deduction and to develop appropriate rehabilitation and training protocols.

There may be several possible reasons for not observing predicted differences in different phases and planes. First, high inter-participant variability of the movement technique used for reaching for the flag within each group was observed visually. The use of different movement techniques among the participants may have affected the spinal motions of the trunk more than having a fused spine. As example, we qualitatively observed from the reconstructed spinal animations that there were different movement strategies used to laterally bend the trunk. Some individuals reached high with maximal scapular elevation while some coupled scapular elevation with lateral flexion to the non-dominant side to reach for the flag.

Overall, our results are contrary to what has been previously reported in most studies that compared the kinematics of SF-AIS to CON individuals for gait[38,40,41], side stepping[36,101], and flexibility[33-35,40]. It was reported in these studies that SF-AIS display lesser spinal motion than CON. Our findings indicate that, for a jumping task using maximal effort, SF-AIS display RelAng spinal motions that are, for the most part, within the range of motions displayed by healthy individuals.

There likely are multiple reasons for differences between the results of this and prior studies. First, one of the two most important reasons likely is that this study required participants to perform a very different movement than has been previously used. To our knowledge, this study is among the first to investigate spinal motions of SF-

AIS for a maximal effort movement. In addition, the stop-jump task required landing, jumping and reaching to a target while in the air. Hence, the spinal motions required for these movements likely are different than typical gait. In comparison, walking on a level surface at a self-selected speed, while is comprised of three-dimensional motions throughout the body, may not require as much spinal rotation in the sagittal or frontal planes as the stop-jump. Conversely, for the stop-jump (depending on the phase), some planes of motion may require less spinal motions than gait, and thus, SF-AIS can achieve spinal motions comparable to healthy spines. For example, during the stance phase of the stop-jump, transverse plane motion is expected to be less while greater displacement is expected in the sagittal plane. However, what is encouraging is that our SF-AIS can achieve displacements comparable to CON for most relative spinal angle displacements, (Figure 4.6).

Second, even though the stop-jump task requires higher effort and spinal movement than gait, perhaps the spinal displacements needed to perform the task are not maximal, and thus, achievable by SF-AIS. Therefore, our SF-AIS participants would not exhibit lower displacements compared to CON as revealed within the flexibility literature[33-35,40]. With spinal fusion, total range of motion available for trunk flexibility movements is reduced compared to healthy controls). The SF-AIS group means for minimal and maximal relative angle displacements displayed among any spinal RelAng plane or segment in our study were 4.8° to 21.6° In contrast, range of motion values of 15° – 26° have been reported previously for SF-AIS[40]. In our study, therefore, SF-AIS were likely able to meet the complex demand of each phase, and thus the jump by

utilizing sufficient ranges in each plane to be able to perform at par with the healthy controls.

Another potential reason for findings of this study being different from other studies is methodology. The three most influential and interrelated methodological differences among AIS spinal motion studies might be how the spine was divided into segments; the types of spine angles and mathematical methods used to create the angles; and the method used to capture spinal motions.

Previous researchers also have mathematically calculated the spine angles differently than ours. Engsberg and colleagues used a linear vector created from two bony landmarks on the spine about a fixed linear vector such as that made between the pelvis and/ acromioclavicular joint[34,40,102]. Other spinal motion methods have calculated the amount of spinal motion as the sum of the intervertebral movements generated within each spinal link segment.

The difference in results between the current study and those reported previously could also be due to the number of vertebrae included per segment. While most of these previously-used methodologies may provide a fair estimate of the total displacement of the trunk, results may differ from that observed in the present study. Some studies have investigated trunk range of motion by dividing it into upper and lower segments and calculated spinal motion as the relative angle between them[103]. For our study, the trunk was divided into three, rather than two major segments, and the motion of each segment relative to its distal segment was calculated along with individual segmental motion relative to the global frame of reference.

The other major methodological difference among studies was the spine segment definitions. The segment definition, that is, the mathematical representation of the external shape of each trunk segment (2D or 3D) used to calculate the variables RelAng displacement and SegAng displacement was different from that used in the current study although the calculations of some of the previous studies also were also based on ISB recommendations[103].

Moreover, most prior studies have only calculated the relative angles between spinal segments. Therefore, there are no equivalent data to compare for segmental angular displacements. We used the segmental angles to understand which of the two segments that comprise a given relative angle are moving in a given plane. For example, for the displacement of the RelAng of the MT that is formed between the MT and LT segments, we were able to distinguish that the LT, not the MT, was primarily responsible for the relative motion between the two segments.

Another reason for our study demonstrating differences from prior investigations were factors related to the participant sample. First, the level of spinal fusion of the individuals recruited for various studies may differ among and within each study, leading to different spinal motions observed. Theoretically, the greater the number of intervertebral joints involved in the spinal fusion, the lower the total range of motion (ROM) of the trunk, although no direct relation has been reported in the literature. Thus, the lowest involved vertebra fused (LIV) during the spinal fusion procedure may be inversely related to total ROM. In our study, approximately 89% (8 out of 9) of the participants had L3 or higher level (T12-L3) as their LIV and only 11% (1 participant) had L4 or lower LIV. The group variability of LIV for participants in the gait and/or

flexibility studies compared to this study tended to be higher, although the range of LIV (T12-L4)[40,102] was similar to the current study (our participants' LIV range: T11-L4).

A patient's LIV may also be one factor used by a surgeon when deciding to allow return to particular physical activities or sports, such as collision sports[100]. Therefore, it would be reasonable to expect that our participants, who were moderately physically active, have LIV values that would allow them to produce greater trunk displacement than the general SF-AIS population.

For post-operative time and physical activity, the participants included in this study tended to be further out in their post-operative time (2.00 ± 0.66 yr) compared to prior gait (range: 1 - 2 yr)[40,102,104] and flexibility (1 - 4 yr) studies[34,40,51]. Moreover, although not reported, our participants, as a group, likely were more physically active than those in these studies. This deduction is based on the finding that AIS individuals tend to be less active than the corresponding general population, and we deliberately recruited moderately physically active SF-AIS individuals.

Therefore, our SF-AIS participants may have benefited from four potential consequences of regular movement and physical activity (and slightly longer post-op time) a) muscle strength, endurance and/or power of the trunk and rest of the body; b) restoration of pre-surgical flexibility; c) practice developing/learning/refining movement strategies to regain performance effectiveness to compensate for lack of a mobile spine; and d) having learned to modify their postural control strategies to adapt to a more rigid trunk that also has been realigned to a more neutral alignment during surgery. However, as we did not measure these potential benefits, nor compare such outcomes between active and sedentary SF-AIS participants, this remains conjecture.

Another participant-related factor that may have differed between studies is participant motivation, although this cannot be determined, as motivation was not measured in this or prior relevant studies. We assume that when participants are motivated and physically able to demonstrate their best performance, they will move their spines as far as necessary to achieve that performance. We believe our participants likely performed at their best effort for several reasons. One, both of our groups had similar jump heights. Two, our SF-AIS participants likely were prepared psychologically to give maximum effort. They were physically active and comfortable performing activities that are physically demanding, and likely knew their physical limits, particularly for their spine. Third, motivation can also be affected by the research tasks. For gait studies, the movement goal is not necessarily viewed as a 'challenge' or novelty; rather the goal is simply to walk naturally and consistently at a designated pace. For our study, participants of both groups appeared keen to use the jump-height measuring device and find out their vertical jump height. We also challenged them to try and beat their maximum height on each subsequent jump.

The authors acknowledge several limitations. One limitation of this initial, exploratory study was a lack of statistical power for some variables that could be improved with a larger sample size. Conversely, the large number of pairwise comparisons performed in the study may have potentially inflated the probability of Type I error. Hence, we only cautiously suggested that for a non-significant group difference, the SF-AIS value may be comparable to the CON group only when our group difference confidence intervals had relatively low bandwidths and included zero, and the mean difference between groups was less than 5°.

Another limitation associated with our sample is that various factors may have affected the spinal motions of our SF-AIS, such as LIV. Both groups were samples of convenience, thus, for SF-AIS, the level of spinal fusion and LIV was not controlled. The results also may not be generalizable to the SF-AIS population. The surgical procedure and surgeon were the same for nearly all of our SF-AIS individuals, and our age range includes only young adults. Last, as with any motion capture study that uses superficial markers to track spinal motions versus capturing bone movement directly, skin movement artifacts, marker placement and the validity of the mathematical assumptions used when estimating spinal motions may affect the accuracy of the outcomes. However, we minimized marker placement error that could have affected one group more than the other by having the same researcher, who is professionally experienced in spinal anatomy and palpation, place the spinal markers on all participants. Reducing the influence of skin movement artifact and other noise was achieved by applying an unweighted least-squares method to the relative spatial location of the position vectors of the segments.

Moreover, the spine was divided into only 3 segments, and relative motions of the segments were accepted as representative of the major movements within the trunk. However, it is recognized that each intervertebral segment has some contribution to trunk motion, and our 3-segment model may underrepresent the amount of spinal motion that occurs, particularly for the control group. Care was taken to divide the trunk segments into the three major anatomical segments of the spine to capture these major trunk motions.

F. Conclusion

These SF-AIS individuals who participate in physical activity and/or sports on a regular basis are able to jump as high as healthy peers during the stop-jump task, a maximal effort movement that requires landing safely, propelling one's self vertically at maximal takeoff speed and reaching the highest target possible. The only spinal motion adaptation observed was that, compared to CON, the fused middle trunk of SF-AIS moved more as a synchronous unit with the lower spine and pelvis, particularly during trunk extension and lateral bending.

Clinicians may need to consider the implications of rotating the LT and pelvis as a primary method to move the trunk. The integrity of the tissues of the lower trunk and pelvis needed to move and stabilize these segments should be considered. Formal post-surgical rehabilitation of the core muscle groups may be beneficial.

Otherwise, to move the trunk as needed for each phase of this task, SF-AIS exhibited amounts of spinal motions that are, for the most part, as high as healthy individuals. Therefore, these outcomes suggest that SF-AIS can be encouraged to perform similar high-effort movements during sport and/or physical activities.

CHAPTER 5

Lower limb kinematics and kinetics exhibited during stop-jump by physically-active individuals with adolescent idiopathic scoliosis and spinal fusion

Kakar RS, Brown CN, Simpson KJ. *The Spine Journal (To be submitted)*

A. Abstract

Introduction: Spinal fusion for individuals with adolescent idiopathic scoliosis (SF-AIS) is aimed at correcting the 3D deformity of the spine. However, whether improvement of the associated atypical lower limb mechanics also occurs and does lower limb mechanics of SF-AIS differ compared to healthy peers during physical activities, is not known. Therefore, the objective of the study was to compare the lower extremity kinematics and kinetics displayed during the stop-jump between SF-AIS and healthy matched controls (CON).

Methods: The stop-jump task was performed by 9 SF-AIS (physically active; posterior-approach spinal fusion: 11.2 ± 1.9 fused segments; post-op time: 2 ± .6 yrs; and 9 CON individuals, pair matched for gender, age (17.4 ± 1.3yr, 20.6 ± 1.5yr, respectively), mass (63.50 ± 12.2kg, 66. 40 ± 10.9kg), height (1.69 ± 0.09m, 1.72 ± 0.08m) and level of physical activity participation (International Physical Activity Questionnaire). SF-AIS and CON performed 5 trials of the stop-jump. The locations of the 16 reflective markers placed on the pelvis and lower extremities were recorded via 7-camera motion capture system. A two-way mixed model 2 (Group: SF-AIS or CON) × 2 (Limb: dominant or non-dominant) ANOVA ($p < .05$) was performed for peak values displayed in the preparation and propulsion sub-phases of the stance phase of angular displacements, vertical ground reaction forces (VGRF) and joint moments of the lower extremity of both limbs and the 3 planes of motion.

Results: For the preparation phase, a tendency for Limb main effect was observed, with dominant limb knee ab/adduction displacement greater than the non-dominant (5.5° – 5.7°; $p = .061$). For the propulsion sub-phase, the only significant outcome was a Group

main effect. SF-AIS demonstrated lower knee extension angular displacement than CON (p = .02). Tendencies of lower hip extension and ankle plantarflexion displacement (p = .055 – .084) for SF-AIS also were exhibited. A tendency for Limb main effect demonstrated that transverse hip joint displacement was greater for the dominant than the non-dominant limb (8.1° and 5.9°, respectively; p = .089). SF-AIS generated a 0.06 Nm/kg greater peak hip internal rotation moment than CON, and the dominant limb displayed a 0.02 – 0.06 Nm/kg greater peak internal rotation moment than the non-dominant limb. At the knee, a 0.39 Nm/kg lower peak extensor and .40 Nm/kg greater abduction moment were displayed by SF-AIS than CON. At the ankle, SF-AIS produced a 0.03 Nm/kg greater peak internal rotation moment and tendency (p = .065) for greater peak plantarflexion moment (.04 – .18 Nm/kg).

Discussion: Lower magnitudes of lower extremity angular displacements and kinetics for SF-AIS compared to CON could be the result of the associated effects of spinal fusion surgery on pelvis dynamics. Inter-limb differences observed maybe more related to the asymmetrical nature of the jump and not due to associated effects of having had a spinal fusion. The clinical implications of these deficits are not yet known, especially as the magnitudes of the group differences were relatively low. Clinically, physically active SF-AIS possess comparable lower limb mechanics to that of CON and can safely perform physical activities including activities like stop-jump.

B. Introduction

The spine has been proposed as "the engine of locomotion" that transmits energy to the pelvis while the lower limbs follow the pelvic movement[105]. As mechanical energy likely is transmitted among the lower extremities, trunk and pelvis in more complex pathways than this, it is remarkable that spinal fusion surgery for individuals with adolescent idiopathic scoliosis (SF-AIS) can result in improvement of the associated atypical lower limb mechanics displayed during gait. Even with a more rigid spine, the lower extremity gait kinematics and kinetics have been observed to be similar to their healthy peers[104,106,107]. More typical gait after spinal fusion may occur, in part, because the pelvis acts as an anatomical link to the spine and lower extremities. Any abnormal pelvic alignments due to the AIS deformity that, consequently, might also cause atypical lower extremity mechanics, which may be corrected with spinal fusion surgery.

However, typical gait is not very physically demanding, and therefore, may not represent the spectrum of movements and the load experienced by lower limbs common occur in high-effort physical activities and sports. If SF-AIS individuals can achieve similar performance objectives and exhibit lower-extremity kinematics and kinetics comparable to healthy individuals for high-effort movements such as a stop-jump, the results will provide scientific evidence to help prescribe appropriate physical activity involvement. At present, surgeons and physicians are willing to allow return to various sports for SF-AIS, but there is great variability in prescription of physical activity, as decisions are not based on evidence, as little exists.

It is also important from the rehabilitation point of view to understand if SF-AIS use one lower limb more than their healthy peers, while performing an asymmetrical

movement such as that being investigated. This may be the result of the shape of the spinal deformity pre-surgery and/or because of a residual, post-surgical curve. If so, post-surgical rehabilitation should also include training of the proper lower limb mechanics to avoid any overuse injuries.

To the best of our knowledge no study has investigated the lower limb kinematics and kinetics of SF-AIS displayed during a maximal-effort task such as the stop-jump. Therefore, the purpose of this study was to compare the lower extremity kinematics and kinetics displayed during the stop-jump between individuals who have had surgical fusion of spine for adolescent idiopathic scoliosis (SF-AIS) and non-scoliotic healthy individuals (CON). A secondary objective was to compare the mechanics of the dominant and the non-dominant lower limbs within a group while performing a stop-jump task.

The stop-jump movement was chosen, as it is a high-intensity physical activity similar to jump movements performed in most common sports such as basketball, volleyball, soccer, and tennis. The stop-jump task being used in this study is comprised of the following phases: flight, stance (2 sub-phase: preparation and propulsion) and vertical flight and landing phases (*Figure 5.1*). This phase of interest for this study was the stance phase.

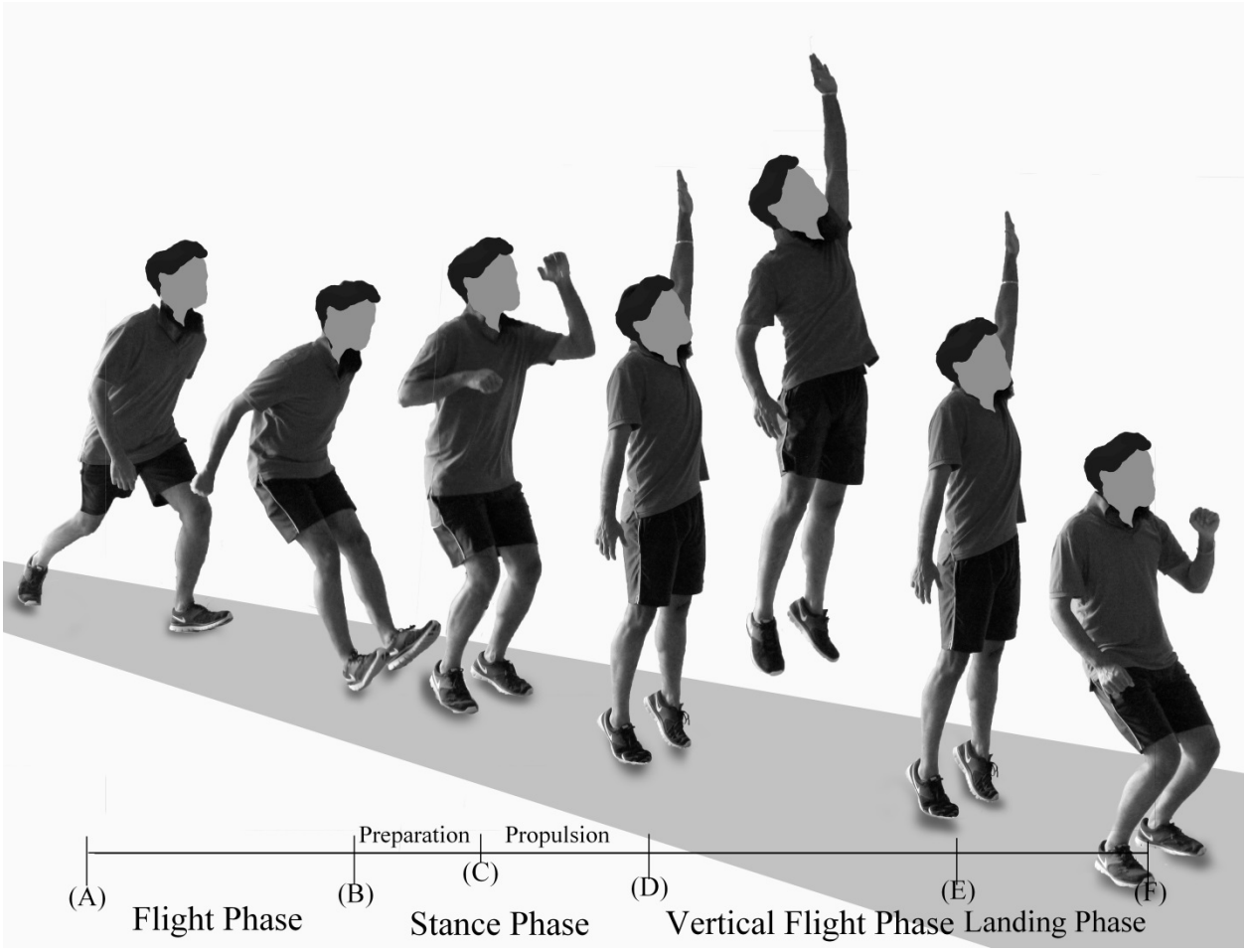

Figure 5.1: The stop-jump task and the phases of the jump. Critical events separating phases: (A): toeoff of the last step of approach run; (B): initial contact of the two feet; (C): Maximum knee flexion; (D): instant of takeoff for vertical flight; (E): instant of touchdown after vertical flight; (F): maximum knee flexion position.

The joint angular displacements at the hip, knee and ankle joints were predicted to be lower for SF-AIS compared to CON in the sagittal plane. SF-AIS may land more stiffly, resulting in less angular displacements as compared to CON.

Lower extremity joint displacements of the frontal and transverse planes, however, were anticipated to be similar between the two groups, that is, between-group differences were expected to be less than 3°. This was based on the rationale that the

spinal fusion would correct the spinal deformity that, in turn, would eliminate pelvic misalignment that could create atypical mechanics of lower limb.

If spinal fusion does allow more typical mechanics as explicated above, then SF-AIS should not display inter-limb asymmetries greater than that of healthy individuals. However, it is not known whether SF-AIS individuals regain more symmetrical limb function. For untreated AIS, muscle imbalances have been thought to be associated with inter-limb gait differences[108]. However, we hypothesized that for physically-active SF-AIS, the bilateral nature of the movement, coupled with spinal correction would constrain the joint displacements of both limbs to be similar to one another[108,109]. Hence, no inter-limb kinematic differences of SF-AIS were expected, as we anticipated that healthy performers would not display angular displacement differences greater than 3° between their dominant and non-dominant limbs, either.

For the kinetic outcomes, our predictions were based on the plane of motion. Joint moments were predicted to be higher at the hip joint for the sagittal and transverse planes for SF-AIS compared to CON. Lower knee joint moment in the sagittal plane was predicted for SF-AIS than CON. Ankle joint moments in the three planes were expected to be similar between the two groups as it is the most distal joint in the kinetic chain relative to the spine and may not be affected by any compensations at the pelvis/ hip joints for existing deformities or fused spinal segments. However, as we surmised that physically active SF-AIS individuals could regain muscle moment symmetry for the lower extremity musculature, we anticipated that the peak moments of any plane would not be different between the limbs for SF-AIS or CON.

For vertical ground reaction forces (VGRF), we anticipated that there would be an interaction between the spine group and limb for VGRF magnitudes. Greater peak VGRF were anticipated for SF-AIS than CON and for the dominant compared to the non-dominant leg. However, the interlimb differences were expected to be greater for the SF-AIS than the CON, group as extensor moments of the lower limb joints drive the VGRF.

C. Materials and Methods

Participants

Sample size estimation

Ten participants per group (SF-AIS and CON) were calculated via an apriori power analysis (G*Power™; Kiel University, Germany) to provide 80% power with an effect size of approximately 1 at $\alpha = .05$ to detect a group difference. The data used for the estimates were the results of selected lower extremity joint angles and the peak knee extensor joint moment reported in a study done by Wei-Ling and colleagues on stop-jump biomechanics of healthy and physically active individuals[88,89].

Participants

Twenty-four (24) healthy physically active participants were recruited to participate in the study, 14 SF-AIS and 10 matched controls (CON). Four potential SF-AIS were declared ineligible after screening at data collection, thus, no matched controls for these individuals were recruited. Data for one SF-AIS participant were not used, as some of the participant's data were judged later to be outliers (≥ 3 SD) during data processing. Therefore, the corresponding data of the matched CON participant also were not included.

Eligibility criteria for an SF-AIS participant included being 16-19 yrs of age; having structural AIS; having spinal growth completed, based on radiological assessment by the spinal surgeon; having had a primary spinal fusion surgery performed using a posterior approach (hence, no revision surgeries) at least 12 mo prior to testing; had resumed normal daily and physical activities since the surgery; had no surgical complications or back pain; and had obtained medical clearance to participate from the spinal surgeon. CON participants were recruited to pair-match corresponding SF-AIS participants, based on age (± 2 yr), height (± 5 cm), mass (± 2 kg) and physical activity (± 2 hr per week at similar intensity of physical activity).

Data were analyzed for 18 participants; 9 SF-AIS (pre-surgery curvature: 5 right thoracic curve and 4 right thoracic and left lumbar curves; pre-surgery Cobb angle: range = 45–71°; post-op time = 2.00 ± .66 yrs) and 9 non-AIS healthy control participants (CON). Fused vertebrae of the SF-AIS ranged from T3 to L4 vertebra (8-13 segments; mean = 11.2 vertebrae).

Instrumentation and Experimental Setup

For motion capture, 39 reflective markers (diameter = 9.5 mm for spinous and transverse processes; 14.0 mm for rest of body) were placed on the participant's skin or clothing on the anatomical locations (*Figure 5.2*). The Newington-Helen Hayes gait model as implemented in the Plug-In-Gait™ module of the data collection software[91] was adopted for the subset of 16 reflective marker locations of the pelvis and lower extremities for this study. Markers were placed on anterior superior iliac spines, posterior superior iliac spines, lateral aspect of the thighs, lateral knees, lateral aspects of the shanks, lateral malleoli, heels and toes[91].

Figure 5.2: Participant with reflective markers located as described in text. The markers on the extremities were placed in accordance with the Newington-Helen Hayes model

Seven visible-red light Vicon MX40® cameras (240 fps) and motion capture system (Vicon, Oxford, UK) were used to capture the spatial locations of the reflective markers during the participant's performance of the stop-jump task via Workstation® v5.2.4 software (OMG Plc., London, UK) with a mean residual error of ≤ 0.5 mm. Ground reaction force (GRF) signals were recorded (sampling frequency = 1200 Hz) using two Bertec 4060-NC®force platforms (Bertec Corporation, Columbus, OH)). Jump height attained by the participant during the stop-jump task was measured (to the nearest 1.27 cm [0.5"]) using the Vertec Jump Trainer© (Vertec; Sports Imports, Columbus, OH).

Test task

For the stop-jump test task, the participant took up to 3 running steps; landed simultaneously with both feet together, with one foot on each force platform; jumped up as high as possible, touching the highest flap possible on the Vertec© jump trainer; then

landed, contacting the ground with both feet simultaneously, with one foot on each force platform (*Figure 5.1*).

Protocol

Each participant provided written consent or assent (if less than 18 yr old) as approved by the institutional review board of the participating institutions. The following questionnaires were completed by both SF-AIS and CON participants to ascertain eliebility to participate: IPAQ[86,87,90] and our laboratory Pre-participation and Health Status Questionnaire (PHSQ). PHSQ was designed by the authors and used to screen for previous or currently existing medical conditions and current health issues that could have adversely affected the participant's performance, safety or health. Medical clearance from the orthopedic surgeon also was required to ensure the participant's safety. SF-AIS also completed the Scoliosis Physical Activity and Quality of Life Questionnaire and the Scoliosis Research Society (SRS) Short-Form 22-R Health-Related Quality of Life Questionnaire[82-84] to provide information about physical activity and evaluate the health-related quality of life post-surgery, respectively. The answers to the screening questionnaires were reviewed to confirm the eligibility of the participant. Testing protocol was then continued for a given eligible participant.

Anthropometric measures were recorded using Davis and colleagues procedures[110]. Next, to determine leg dominance, the participant kicked a soccer ball and also confirmed that this was the preferred side to reach for the highest flag in the vertical jump. The reflective markers were then placed on the participant before the participant performed a supervised warm-up of jogging for 2 min. at a self-selected pace on a calibrated treadmill.

For the testing, first, standing reach height was measured, followed by one or two practice trials performed by the participant. Five acceptable trials of the stop-jump task were then performed. Maximum vertical jump height was recorded for each trial by subtracting the vertical jump distance from the participant's standing reach height. To prevent fatigue of the participant a rest period of approximately 15 s was administered between each trial.

Data Reduction and Analysis

The phase of interest was the stance phase of the jump that began from first instance of touch down detected by greater than 5N of VGRF on either force platforms until the feet left the force plates for the vertical jump (instance when VGRF reduces to less than 5 N). The stance phase of the jump was further divided into 2 subphases; Preparation: started from the beginning of the stance phase until position of maximum knee flexion of the participant and, the Propulsion: from the position of maximum knee flexion of the participant until the end of stance phase.

For each trial, the marker locations were reconstructed into 3-D coordinates using a proprietary algorithm in the Vicon® software (Workstation® v5.2.4). Marker data were filtered using a fourth-order, low-pass Butterworth filter (cutoff frequency = 20 Hz). A frequency content analysis was performed to calculate the optimum cutoff frequency. The lower extremities were assumed to be rigid, linked segments connected by frictionless, tri-dimensional pin joints[95]. A regression formula based on that used by Davis et al. was used to calculate hip joint center[110]. The hip joint center, along with the positions of the thigh and knee markers and published offset values for the thigh and knee markers were

used to calculate the knee joint center via a modified chord function[91]. Similarly, the ankle joint center was calculated via the knee joint center, shank marker, ankle marker, ankle offset and shank rotation using a modified chord function. Origin coordinates of the segment were calculated. Joint angles of the hip, knee and ankle joints were calculated using the kinematic models with a rotation sequence of y-x-z (Workstation® software, v5.2.4; Vicon)[92,98,110].

Joint angular displacements of both lower limbs were generated for the preparation and propulsion phases. For each phase or sub-phase of interest, lower extremity joint and joint axis, the joint angular displacement was calculated as the first peak joint displayed angle subtracted from the second peak joint angle displayed. A 'peak' angle could be either a local minimum or maximum value.

Joint moments for the the joints of the lower extremity for all planes of both limbs were calculated for the stance phase using inverse dynamics and Euler's equations of motion using joint centers, segmental mass, ground reaction forces and kinematics of the joint [111]. Joint moments were normalized to body mass.

MATLAB© (v.R2012b, Mathworks, Inc. US) programs were developed for generating all dependent variables. Dependent variables of interest were the joint angular displacements, peak joint moments, and peak VGRF scaled to body weight (BW) for both lower limbs (dominant and non-dominant). The dominant limb also corresponded to the limb ipsilateral to the arm that contacted the highest flag on the jump measurement apparatus. For each of the dependent variable, the values of the five trials were averaged.

Statistical Analysis

All statistical analyses were performed using SPSS® software (IBM Version 21.0, IBM, Inc., Armonk, NY), with statistical significance set at $p < .05$ and potentially-meaningful tendencies at $p = .05 - .10$. To determine how closely matched the spine groups were on participant characteristics and test task performance, age, height, body mass, leg lengths and maximum vertical jump height were compared between SF-AIS and CON using one way-analysis of variance (ANOVA). Pearson's correlations were performed between jump height and the dependent variables to determine whether jump height was a potential covariate for subsequent statistical comparisons. As the correlations were low for most comparisons ($r < .250$), jump height was not used as a covariate. Dependent variables were tested for main and interaction effects of groups and limb dominance using a two-way 2 (Group: SF-AIS or CON) × 2 (Limb: dominant or non-dominant) mixed analysis of variance (ANOVA) (Limb = within subject factor; $p < .05$). As the assumptions of the ANOVA were not violated, no adjustments were necessary. Partial η^2 was used as the effect size estimate. Bonferroni corrections were not used to control for family-wise error, as this correction is more appropriate for use with larger sample sizes.

D. Results

SF-AIS was significantly younger than CON ($p < .001$). The two groups were not significantly different for other participant characteristics ($p = .147 - .632$). Jump height also was not significantly different between the two groups. The means varied by 0.013 m, which is less than the least detectable difference of the test device ($p = .872$).

Angular kinematics

For the preparation sub-phase (Table 5.1), no statistical differences for limb or group were observed for angular displacement about any joint or plane. A tendency for a significant limb difference was observed for the frontal plane angular displacement of the knee joint (p = .061, partial η^2 = .161, power = .471). The dominant leg limb tended to produce a 5.5° – 5.7° greater abducted knee joint displacements compared to the non-dominant lower limb

For the propulsion sub-phase, no significant differences were evident for the hip joint angular displacements. However, two tendencies for group main effects were observed. First, SF-AIS tended to display 3.8° lower hip extension displacement than CON (p = .055, partial η^2 = .011, power = .489). Second, the dominant limb of SF-AIS and CON tended to have, respectively, 8.1° and 5.9° greater internal rotation displacement than the non-dominant limb (p = .089, partial η^2 = .088, power = .398).

A significant main effect for group was observed for knee joint displacement occurring during propulsion sub-phase, with SF-AIS demonstrating lower knee extension angular displacement than CON (p = .02, partial η^2 = .159, power = .663). No other significant main effects or interactions were observed.

No significant main effects or interactions were detected for the ankle joint displacements of either phase. However, a tendency for SF-AIS to produce 5.0° lower plantarflexion displacement than CON) was observed (p = .084, partial η^2 = .09, power = .408).

Kinetics

For peak VGRF, there was no statistically significant interaction or main effects. Qualitatively, participants demonstrated a slight tendency (p = .107, partial η^2 = .079, power = .363) toward greater VGRF for the dominant (1.65 ± .26 BW) compared to the non-dominant lower limb (1.52 ± .19 BW).

For joint moments displayed during the support phase, at the hip joint (see Table 5.2), SF-AIS demonstrated a significantly greater peak internal rotation moment than CON (mean difference = .06 Nm/kg; p = .015, partial η^2 = .173). Also, there was a tendency for a significant main effect of limb dominance (p = .096, partial η^2 =.084, power = .384). A greater peak internal rotation moment was displayed by the dominant compared to the non-dominant leg (mean difference = .02 – .06 Nm/kg).

At the knee joint, SF-AIS demonstrated a significantly lower peak extensor moment compared to CON (mean difference= .39 Nm/kg; p = .011, partial η^2 = .186). Similarly, the peak knee abduction moment of SF-AIS was .40 Nm/kg lower than that of CON (p = .032, partial η^2 = .136). No other significant differences were detected.

SF-AIS moments at the ankle joint demonstrated a .04 Nm/kg significantly greater peak internal rotation moment compared to CON (p = .033, partial η^2 =.134). Also, there was a tendency for a significantly greater peak plantarflexion moment for SF-AIS compared to CON (mean difference= .18 Nm/kg; p = .065, partial η^2 = .102, power = .457). No significant interactions or other main effects were

Table 5.1: Mean ± standard deviations for joint angular displacements (degrees) for control (CON) and individuals with adolescent idiopathic scoliosis post spinal fusion (SF-AIS) groups and within the spine groups for dominant (Dom) and non-dominant (NDom) lower limb.

			Stance Phase					
			Preparation sub-phase			Propulsion sub-phase		
			Planes					
			Sagittal	Frontal	Transverse	Sagittal	Frontal	Transverse
Hip	CON	Dom	15.56 ± 7.07	5.71 ± 3.43	14.68 ± 6.66	50.64 ± 6.22	5.59 ± 2.56	**19.47 ± 11.72^{T}**
		NDom	14.36 ± 7.21	4.82 ± 1.91	12.99 ± 7.62	50.73 ± 4.71	7.34 ± 2.43	**14.48 ± 10.77^{T}**
		Total	14.96 ± 6.95	5.27 ± 2.73	13.83 ± 7.00	**50.69 ±5.35 ^{T}**	6.47 ± 2.58	16.97 ± 11.22
	SF-AIS	Dom	13.81 ± 6.57	5.42 ± 2.74	11.66 ± 9.24	46.34 ± 4.71	9.11 ± 4.42	**23.37 ± 12.24^{T}**
		NDom	13.08 ± 4.29	4.02 ± 1.86	10.73 ± 7.31	47.52 ± 6.69	6.91 ± 4.49	**15.31 ± 9.74^{T}**
		Total	13.44 ± 5.39	4.72 ± 2.38	11.19 ± 8.10	**46.93 ± 5.65 ^{T}**	8.01 ± 4.47	19.34 ± 11.50
	Total	Dom	14.68 ± 6.68	5.57 ± 3.02	13.17 ± 7.97	48.49 ± 5.79	7.35 ± 3.95	21.42 ± 11.80
		NDom	13.72 ± 5.79	4.42 ± 1.87	11.86 ± 7.34	49.13 ± 5.85	7.13 ± 3.51	14.89 ± 9.97
Knee	CON	Dom	49.70 ± 5.71	**17.83 ± 8.71^{T}**	23.88 ± 10.84	79.99 ± 6.62	27.33 ± 17.55	34.97 ± 10.18
		NDom	50.03 ± 9.22	**12.13 ± 3.91^{T}**	20.76 ± 7.39	83.20 ± 9.96	19.33 ± 10.49	35.06 ± 7.48
		Total	49.87 ± 7.44	14.98 ± 7.18	22.32 ± 9.14	**81.59 ± 8.37***	23.33 ± 14.62	35.01 ± 8.67
	SF-AIS	Dom	46.73 ± 11.68	**17.51 ± 12.06^{T}**	24.59 ± 9.47	68.91 ± 14.58	27.11 ± 16.16	34.34 ± 15.68
		NDom	50.40 ± 9.31	**12.02 ± 7.83^{T}**	24.88 ± 12.65	76.30 ± 11.25	20.21 ± 15.78	36.73 ± 13.90
		Total	48.57 ± 10.42	14.77 ± 10.26	24.73 ± 10.84	**72.61 ± 13.19***	23.66 ± 15.90	35.54 ± 14.42
	Total	Dom	48.22 ± 9.05	17.67 ± 10.21	24.23 ± 9.88	74.45 ± 12.37	27.22 ± 16.36	34.66 ± 12.83
		NDom	50.22 ± 8.99	12.08 ± 6.00	22.82 ± 10.27	79.75 ± 10.90	19.77 ± 13.01	35.89 ± 10.86
Ankle	CON	Dom	26.74 ± 7.09	5.96 ± 1.29	21.60 ± 7.49	62.69 ± 6.00	13.97 ± 3.48	28.94 ± 11.47
		NDom	33.04 ± 12.80	9.19 ± 5.52	21.53 ± 10.23	67.09 ± 9.26	15.36 ± 6.05	28.96 ± 13.44
		Total	29.89 ± 10.55	7.57 ± 4.23	21.57 ± 8.70	**64.89 ± 7.90 ^{T}**	14.66 ± 4.84	28.95 ± 12.12
	SF-AIS	Dom	31.09 ± 10.95	9.41 ± 5.05	19.02 ± 6.90	58.88 ± 8.26	14.16 ± 4.80	28.91 ± 9.97
		NDom	28.53 ± 14.58	7.88 ± 5.84	17.01 ± 8.32	60.93 ± 9.58	13.29 ± 6.73	27.98 ± 10.07
		Total	29.81 ± 12.58	8.64 ± 5.36	18.02 ± 7.49	**59.91 ± 8.75 ^{T}**	13.72 ± 5.69	28.44 ± 9.73
	Total	Dom	28.92 ± 9.22	7.68 ± 3.99	20.31 ± 7.11	60.78 ± 7.27	14.06 ± 4.07	28.93 ± 10.42
		NDom	30.79 ± 13.51	8.53 ± 5.56	19.27 ± 9.34	64.01 ± 9.67	14.32 ± 6.30	28.47 ± 11.53

* represents statistically significant difference ($p \leq .05$) and ^{T} represent tendency for statistically significance ($p = .05 - .10$). Bold indicates statistical significance or tendency of significance within group for limb dominance

Table 5.2:Mean ± standard deviation for peak joint moments (Nm/kg) for control (CON) and individuals with adolescent idiopathic scoliosis post spinal fusion (SF-AIS) groups and within the groups for dominant (Dom) and non-dominant (NDom) lower limb

			Extension	Flexion	Abduction	Adduction	External Rotation	Internal Rotation
Hip	CON	Dom	2.04 ± 0.59	0.69 ± 0.26	0.45 ± 0.26	0.97 ± 0.54	0.26 ± 0.14	**0.11 ± 0.06** ^{T}
		NDom	1.86 ± 0.41	0.93 ± 0.23	0.62 ± 0.36	0.87 ± 0.58	0.29 ± 0.11	**0.09 ± 0.05** ^{T}
		Total	1.95 ± 0.50	0.81 ± 0.27	0.53 ± 0.32	0.92 ± 0.55	0.28 ± 0.13	**0.10 ± 0.05***
	SF-AIS	Dom	2.12 ± 0.78	0.92 ± 0.61	0.68 ± 0.18	1.08 ± 0.64	0.21 ± 0.18	**0.19 ± 0.06** ^{T}
		NDom	1.71 ± 0.75	0.98 ± 0.71	0.57 ± 0.19	0.91 ± 0.59	0.28 ± 0.13	**0.13 ± 0.11** ^{T}
		Total	1.92 ± 0.77	0.95 ± 0.64	0.62 ± 0.19	1.00 ± 0.61	0.24 ± 0.16	**0.16 ± 0.09***
	Total	Dom	2.08 ± 0.67	0.80 ± 0.47	0.56 ± 0.25	1.03 ± 0.58	0.23 ± 0.16	0.15 ± 0.07
		NDom	1.79 ± 0.59	0.96 ± 0.51	0.60 ± 0.28	0.89 ± 0.57	0.29 ± 0.12	0.11 ± 0.08
Knee	CON	Dom	1.82 ± 0.53	0.62 ± 0.26	0.95 ± 0.54	0.32 ± 0.30	0.19 ± 0.09	0.05 ± 0.06
		NDom	1.84 ± 0.37	0.61 ± 0.21	0.96 ± 0.46	0.30 ± 0.24	0.19 ± 0.10	0.05 ± 0.04
		Total	**1.83 ± 0.44***	0.61 ± 0.23	**0.95 ± 0.49***	0.31 ± 0.27	0.19 ± 0.09	0.05 ± 0.05
	SF-AIS	Dom	1.41 ± 0.39	0.66 ± 0.19	1.48 ± 0.56	0.37 ± 0.26	0.26 ± 0.10	0.05 ± 0.03
		NDom	1.48 ± 0.41	0.48 ± 0.17	1.23 ± 0.59	0.26 ± 0.19	0.19 ± 0.08	0.04 ± 0.03
		Total	**1.45 ± 0.39***	0.57 ± 0.20	**1.36 ± 0.57***	0.31 ± 0.23	0.22 ± 0.10	0.04 ± 0.03
	Total	Dom	1.61 ± 0.50	0.64 ± 0.22	1.21 ± 0.60	0.35 ± 0.27	0.23 ± 0.10	0.05 ± 0.04
		NDom	1.66 ± 0.42	0.55 ± 0.20	1.09 ± 0.53	0.28 ± 0.21	0.19 ± 0.09	0.04 ± 0.03
Ankle	CON	Dom	1.67 ± 0.24	0.21 ± 0.24	0.19 ± 0.09	0.05 ± 0.04	0.39 ± 0.21	0.07 ± 0.05
		NDom	1.60 ± 0.27	0.21 ± 0.31	0.22 ± 0.13	0.02 ± 0.03	0.41 ± 0.24	0.10 ± 0.13
		Total	**1.63 ± 0.25** ^{T}	0.21 ± 0.27	0.20 ± 0.11	**0.04 ± 0.03***	0.40 ± 0.22	0.08 ± 0.10
	SF-AIS	Dom	1.85 ± 0.32	0.09 ± 0.13	0.22 ± 0.16	0.09 ± 0.07	0.58 ± 0.28	0.15 ± 0.10
		NDom	1.78 ± 0.30	0.12 ± 0.15	0.14 ± 0.13	0.06 ± 0.05	0.54 ± 0.40	0.11 ± 0.10
		Total	**1.81 ± 0.30** ^{T}	0.10 ± 0.14	0.18 ± 0.15	**0.07 ± 0.06***	0.56 ± 0.34	0.13 ± 0.10
	Total	Dom	1.76 ± 0.29	0.15 ± 0.20	0.20 ± 0.13	0.07 ± 0.06	0.48 ± 0.26	0.11 ± 0.09
		NDom	1.69 ± 0.29	0.16 ± 0.24	0.18 ± 0.13	0.04 ± 0.05	0.47 ± 0.33	0.11 ± 0.11

* represents statistically significant difference ($p \leq .05$) and ^{T} represent tendency for statistical significance ($p = .05 - .10$). Bold type indicates statistical significance or tendency of significance for limb within a given spine group

E. Discussion

The study was aimed at determining whether lower limb mechanics of individuals with spinal fusion for adolescent idiopathic scoliosis are similar to those of healthy controls for the stop-jump task. No previous study, to our knowledge, has investigated SF-AIS lower limb kinetics for maximal effort jumping or other high-effort movements beyond walking or sidestepping.

It was predicted that this physically active SF-AIS group compared to the CON group would demonstrate differences for angular displacements only for the sagittal plane of all lower extremity joints of both limbs. SF-AIS were expected to demonstrate lower peak angular sagittal plane displacements compared to CON. Inter-limb kinematic differences for any plane were not anticipated for either group. For joint moments, it was predicted that there would be no interaction effect but main effects for group were expected: greater peak extensor and internal rotator moment at the hip joint and lower knee extensor moment was predicted for SF-AIS compared to CON. For VGRF, both group and limb main effects were anticipated. SF-AIS was expected to experience greater peak VGRF than CON; and the dominant limb would demonstrate a greater value than the non-dominant limb. Therefore, our predictions for group and limb comparisons were partially supported by the results for most kinematic and kinetic variables. Neither group nor limb main effect predictions were supported for peak VGRF.

For angular kinematics of the preparation sub-phase, the predictions were partially supported. Supported were the group differences for the transverse and frontal planes that were not significantly different. Moreover, the group differences for these two planes only ranged between 0.2° to 3.6°. However, the lack of group differences for

sagittal plane displacements was not anticipated. The group differences only varied from 0.1° to 1.5° for the three joints.

For the propulsion sub-phase, the predictions that difference in the mean angular displacements between the groups for the transverse and frontal planes would be less than 3° and non-significant held true. This is evident as the difference between the group means ranged from 0.3° to 2.4° among all joints of these two planes. The prediction of significantly lower sagittal plane displacements was mostly supported. Knee joint extension displacement and tendencies for lower hip joint extension and ankle joint dorsiflexion displacements for SF-AIS compared to CON occurred. These group differences, ranging from 3.9° to 9.0°, likely were clinically meaningful.

It was also predicted that there would be no main effect for limb for angular displacements of both lower limbs. However, limb as a main effect did display tendencies ($p < .089$) for significant differences for knee ab/adduction and internal/external hip rotation displacements during the preparation and propulsion sub-phases. The dominant limb showed 5.0° to 8.5° greater angular displacements for these motions than the non-dominant limb.

For sagittal plane displacements, the group differences and tendency of differences of less displacement by SF-AIS than CON may appear to contradict the notion that SF-AIS produce similar lower extremity angular kinematics. However, our initial rationale that SF-AIS would land in a stiff manner with less angular displacement at the joints holds true. The hip, knee and ankle demonstrated lower or showed tendency for lower angular displacements. This may predispose SF-AIS for greater lower extremity injuries. However, the lack of interlimb differences for sagittal plane displacements

supports the idea that spinal fusion can potentially reduce inter-limb imbalance and help achieve typical lower limb kinematics.

There are a few potential interpretations for the low number of group differences and no interlimb differences for the angular displacements of the transverse and frontal planes. First, the lack of group differences may be true, that is, displacements by SF-AIS may indeed by similar to healthy individuals, at least for the motions of these two planes. Explanations that would support this interpretation include our original premise. We surmised that spinal fusion would correct correcting associate pelvis misalignments, which would lead to symmetrical kinematics of lower limb. This was evident since most comparisons did not show difference between limbs. Also, the stop-jump is primarily a sagittal plane task, with little frontal or transverse plane motion. Thus, may not be sufficient to test difference in motion in these two planes.

A possible explanation for the interpretation is that SF-AIS frontal and transverse plane displacements may be similar to healthy individuals for this task. The initial alignment of the pelvis can be one of the major factors for greater transverse plane motion of the pelvis and femur. There may also be an effect of the initial pelvic alignment on the joints distal to pelvis in the kinematic chain.

Previous research of sagittal plane angular kinematics displayed during gait is partially in consensus with our results[106]. Mahaudens, et al. also reported significantly reduced knee joint motion in sagittal plane, similar to that observed in our results, for untreated AIS individuals compared to healthy controls during level walking. No differences for angular displacements in sagittal plane were observed for the hip and ankle joint by Mahaudens, et al.[106]. The results for knee and ankle joints are similar to

those obtained in our study. These results are clinically very meaningful as the decrease motion in lower limb joints could be the result of spinal fusion surgery and its associated effect on the pelvic dynamics[112].

One major cause for difference in results observed here and those reported previously can be the fact that participants include in our study have undergone spinal fusion surgery while those recruited by Pasha et al. had untreated right thoracic and right thoracic-left lumbar curve, with the pelvis rotated toward the side of the major curve. Once the spinal fusion is performed, the initial pelvic alignment is expected to be corrected which would lead to improvement of lower limb mechanics to that closer to typical individuals or controls.

Mahaudens and colleagues have reported prolonged contractions of gluteus medius and semitendinosus as a probable explanation for different hip transverse plane motion while walking between AIS and controls[106].Mahaudens surmised that, for nonsurgically-treated AIS individuals, that this occurred to control for excessive pelvis, hip and knee movements in the frontal and transverse planes when the position of center of mass changes from preparation to propulsion sub-phases. A similar mechanism can likely explain the inter-limb differences of angular displacements observed in this study.

Another potential interpretation for the low number of group differences and no inter-limb differences for the transverse and frontal plane displacements is the lack of statistical power observed in the comparisons. Also, the effect sizes for the comparisons were low.

The hypotheses for the group differences of the joint moments were partially supported. At the hip joint, as was predicted, a greater hip internal rotation moment for

SF-AIS compared to CON (group difference = 0.06 ± 0.04 Nm/kg) was found. However, there was no main effect of group for hip extensor moment as predicted.

At the knee joint, the hypothesis of lower knee extensor moment for SF-AIS compared to CON (mean difference = 0.39 ± 0.05 Nm/kg) was supported. Not anticipated was SF-AIS generating greater knee abduction moments (mean difference = 0.40 ± 0.08 Nm/kg). It is not known why these knee moment results occurred. One potential consequence for SF-AIS may include ACL loading, although this cannot be proven with these data. Lower knee extensor moments but greater knee abductor moments for SF-AIS compared to CON during the preparation sub-phase of the stance could potentially increase strains on the anterior cruciate ligament.

Our finding of greater knee abduction moment of SF-AIS, therefore, suggests that post-surgical evaluation of the muscle strength of the lower extremities and formal physical therapy for the lower body of SF- AIS may be considered to prevent varus-related injury before returning to sports. However, this recommendation will need to be confirmed.

Also not expected were group findings for the ankle joint, including greater ankle internal rotation moments (mean difference = 0.04 ± 0.03 Nm/kg) for SF-AIS compared to CON, and a tendency for greater ankle plantar flexor moments (mean difference = 0.18 ± 0.05 Nm/kg). Extensor moments are essential to create greater VGRF and hence propel the body higher in the vertical jump. It was expected that extensor moments required for the jump would be generated predominantly at the hip joint but the results were contrary to that. A possible explanation of greater ankle plantar flexion moment could be the compensation for the low extensor moments at the knee and hip.

Main effects for limb were not expected for joint moments at hip, knee and ankle joints. The hypothesis was partially supported as main effect was observed only for hip internal rotation moment, with the dominant limb generating greater hip internal rotation moment within groups (.02 - .06 Nm/kg). However, the effect sizes for the differences were low to moderate (0.10 – 0.19). Greater hip internal rotation moment coupled with greater knee abduction moment could lead to a potentially negative effect on the knee health and may need to be addressed when assessing physical activity participation.

The lack of statistical inter-limb differences for the sagittal plane and frontal plane joint moments suggests that there might be minimal effect if any, of the spinal fusion surgery on inter-limb symmetry for joint moments. Another explanation for the lack of inter-limb differences for the joint moments may be participant variability. The moment magnitudes may have been influenced more by the movement technique employed by the participant than anything else. Movement techniques in performing the stop-jump of individuals may differ based on familiarity with the test task or participation in specific sports that involve vertical jumps such as volleyball, basketball or soccer compared to those involved in strength training, swimming or running.

For peak VGRF, the predictions that there would be group and limb main effects did not hold true. No significant interactions or main effects were observed. Although no statistical evidence for a significant group x limb interaction was found and the effect size was low, observationally, there appeared to be a tendency for such. Qualitatively, the difference between limbs for SF-AIS (1.9 ± .7 BW) was more than double the difference for CON (.7 ± .7 BW). This maybe a clinically-meaningful finding to be confirmed in the future, as it suggests that SF-AIS individuals do not distribute body weight equally

between the limbs compared to matched controls. This could partially be attributed to the asymmetrical nature of the task as the individuals may be positioning themselves to prepare for the asymmetrical trunk and arm motion to hit the flag during the subsequent vertical flight phase.

Another potential reason for asymmetrical VGRF generation is the effects of the interactions of right limb dominance and the particular thoracic curvature of this group. The SF-AIS group was comprised of individuals with residual right thoracic curve or right thoracic and left lumbar curves, and the dominant side of the body (that is, the right arm hit the flag) and the right leg was the dominant leg for the majority of the group was the right side. This would explain then how that leads to increased VGRF on the dominant side. Another possible reason for the potential inter-limb VGRF difference is post-surgical pelvic malalignment that may lead to unequal VGRF between limbs. Post-surgical radiographs should be analyzed to rule out any residual pelvic deformity. Muscular imbalance of the extensor groups at the pelvis and lower limbs caused by the major curve could potentially lead to imbalance in the force generation between the two lower limbs and hence causing a difference in VGRF. However, muscle imbalance involving the extensors of the lower extremity joints is not likely to be an explanation, as the extensor moments that create propulsive force were not different between limbs for the SF-AIS group.

Inter-limb differences in individuals with idiopathic scoliosis for peak magnitudes of VGRF have also been reported in gait but were unrelated with the direction or magnitude of the scoliosis curve[113]. Clinically, it would be essential for a physician or a rehabilitation specialist to evaluate if any such cause pertaining to the structural

imbalance exists. If this finding is confirmed with future evidence, a post-surgical rehabilitation protocol may help alleviate this and reduce any overuse stress or trauma on the dominant side. Correction will thus help promote safer participation in physical activity of SF-AIS.

The authors acknowledge several limitations. Due to the exploratory goal of this study one limitation was a lack of statistical power for some variables that could be improved with a larger sample size. Other limitations include a lack of generalizability to the SF-AIS population and/or other populations with spinal fusions for correction of structural deformities. Our population age range includes only young adults and the surgical procedure and surgeon for nearly all of our SF-AIS individuals were the same. Future research including subsets of different age groups with different spinal deformities is warranted. Lastly, due to the inherent nature of studies involving motion capture and superficial markers, skin movement artifacts and marker placement may affect the accuracy of the outcomes. Single researcher placed markers on the participants to avoid inter-tester errors. Skin movement artifact and other noise components were reduced by applying an unweighted least-squares method to the position vectors of the segments.

F. Conclusion

SF-AIS display mostly comparable lower limb kinematics to that of CON to prepare and propel their body vertically to a similar jump height and land back safely without losing control. For joint moments outcomes, it is not known yet why SF-AIS individuals generate greater knee abductor moments and lower extensor moments. Clinicians, therefore, may need to be aware that this can occur. Otherwise, low magnitudes of angular kinematic and kinetic differences between groups and between

limbs were observed. Clinically, these results suggest that physically-active AIS individuals who have had spinal fusion surgery, can successfully produce typical lower limb mechanics similar to healthy controls during high-effort tasks such as the stop-jump.

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Appendix A

Forms and Questionnaire

1.1 CHOA consent form

Children's Healthcare of Atlanta
Consent to be in a Research Study

Title: What are the Biomechanical and Physical Function Characteristics of Post-Spinal Fusion Surgery for Individuals with Adolescent Idiopathic Scoliosis?

Co-Investigators: Timothy Oswald, MD and Kathy Simpson, PhD

Funding Source: Scoliosis Research Society

If this form is being read by the parent or legal guardian, the term "you" refers to "your child."

You are being asked to volunteer for participation in a research study. In order to decide whether or not you want to be a part of this study, it is important that you read and understand this form. It is also important that you ask any questions that you may have and that you understand all the information in this form. This process is called "informed consent."

Why is this study being done?
This study has two groups of participants. Some of the participants have a condition called adolescent idiopathic scoliosis (AIS), or side-to-side curvature of the spine, that has been treated with a spinal fusion surgery to correct the curve. Some of the participants do not have scoliosis. The purpose of this study is to find out how people's bodies with AIS bend and move doing different tasks. You have been asked to participate in this study because you fit into one of the two groups.

By collecting this information we hope to learn more about how AISpeople with spinal fusion surgery to correct scoliosis perform movements often used in sport, such as running and jumping. 10 AIS participants who have had spinal surgery and 10 participants who do not have AIS are expected to participate in this study, with a total of 20 participants in this study at Children's Healthcare of Atlanta and the University of Georgia.

What will happen to you in this study?
You will be asked to fill out three questionnaires. These questionnaires will ask you about your health, how many physical activities, like sports, you are involved in, and how you feel about your body and your health. Some of the questions in the questionnaire may make you feel uncomfortable. You do not have to answer those questions. If you are due for an X-ray of your spine, you will receive one. This X-ray is part of your routine clinical care for scoliosis. You also will get an appointment to come to the University of Georgia Biomechanics Lab.

The researchers at the Biomechanics Lab will measure your weight, height, and they will measure how long your arms and legs are. Next, you will perform several simple tasks, e.g., kicking a ball, so the researchers can see which legs you use to do these tasks.

As this study is trying to learn more about your body movements and spinal flexibility, you will also be asked to perform several different physical tasks. You will do each task approximately 3 times. You will be given some time to warm-up before performing the tasks. You will also be given short breaks in between each task to rest. These tasks will include:

- Bending forward, backward, and side-to-side
- Twisting your torso from side-to-side
- Balance testing
- Running on a treadmill at a speed somewhat faster than your natural jogging pace
- Stop-land-jump: A vertical jump test where you take a step or two, stop, jump as high as possible, then land.

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Children's IRB Approval Date: 10/23/2012
Children's IRB Expiration Date: 10/22/2013

University of Georgia
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These tasks will be recorded using special video equipment that is connected to a computer. The researchers will attach small silver balls to your arms, legs, torso, and back. The computer will record your movements and show the researchers how much you can bend and move.

It will take about 2½ hours to complete all of the tasks at the lab. Once you are done, you can choose to look at simple animations of some of your movements if you wish. You will be able to go home. You will not be asked to do anything else for the study.

How long will you be in this study?
You will be in this study for about one month. If you agree to be in the study, you will perform some of the tasks like filling out the questionnaires and, if needed, getting an X-ray. After going to the UGA Biomechanics Lab in Athens, GA, and performing those tasks, you will be done being in the study.

What are the possible risks to being in this study?
The risks of being in this study are minimal. There is always a risk when performing certain physical activities, but the tasks you will perform pose less risk than that encountered when running and jumping during physical activity or sports.
Why? Plenty of rest is provided to prevent muscle tiredness. The total amount of movement is much less than what you would do in an hour of physical activity. You will not be asked to bend or stretch farther than what you feel is comfortable to your body. You may feel some minor muscle soreness in 24 to 48 hours if you are in poor physical shape. If you have X-rays for this study, they are part of your routine clinical care for scoliosis. There is no additional risk to you for having an X-ray taken for this study.

Some of the questions in the questionnaire may make you feel uncomfortable. You do not have to answer those questions.

Due to the investigational nature of this study there may be risks, discomforts, or side effects that are not yet known.

Your safety and health will be monitored at all times by one researcher. It is YOUR responsibility to ***tell any researcher right away if you start to feel any signs of something being wrong; for example, feelings of discomfort, pain, nausea, light-headedness, dizziness.*** If you or any researcher thinks that something is wrong, testing will stop. The researchers and you will decide whether to reschedule the rest of the testing.

What are the possible benefits of being in this study?
Taking part in this study will not benefit you personally but you will have the chance to learn the process of movie animation as it is applied to your own movements, and you will also learn some of the results of how well you perform the test tasks. This study may, however, help surgeons improve surgical and other treatment methods for future spinal-fusion patients, and develop guidelines for prescribing physical activity that is safe for these patients

What are the alternatives to being in this study?
The alternative is to not participate, as this study does not involve treatment.

What is the cost of being in this study?
There is no cost to you for being in the study. If you complete the study, you will receive $50 plus money for traveling, depending on the distance traveled. If you withdraw from the study before you complete all of the tasks, then you will receive a minimum of $10 and ½ of the travel money.

What if you are injured while in this study?
The researchers will exercise all reasonable care to protect you from harm as a result of your participation. However, in the event of an injury as an immediate and direct result of your participation in this study, the researchers' sole responsibility is to arrange transportation for you to go to an appropriate medical facility, if needed.

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University of Georgia
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No further compensation by Children's Healthcare of Atlanta, Inc. is planned other than what your insurance carrier may provide although you are not precluded from seeking to collect compensation for injury related to malpractice, fault, or blame on the part of those involved in the research. For more information about risks or if you believe you have been injured by this research, you should contact Dr. Timothy Oswald at 404-321-9900.

What if there is new information about this study?
We may learn new things during the study that you may need to know. We may also learn about things that might make you want to stop participating in the study. We will tell you about any new information.

What if you have any questions or problems while in this study?
If you have any questions, concerns or complaints about this study, call Dr. Timothy Oswald at 404-321-9900 or Nikki McCain at 770-815-1349. If you have any questions, concerns or complaints about your rights as a participant in this study, or would like to obtain information, or offer input, you can call the Children's Healthcare of Atlanta Institutional Review Board (IRB) at (404) 785-7477. The IRB is a committee of people that approves all research in this hospital and follows all the rules and regulations made by government agencies about how research is done.

Who will be able to see your records of study participation?
Your records of participation in this study are not accessible to the general public and every effort will be made to maintain confidentiality. However, all records may be subject to subpoena by a court of law. Information that may be gained from this study will be used only for research and educational purposes. Information may be published in medical journals with permission of the Co-investigators, Dr. Timothy Oswald or Dr. Kathy Simpson, but your identity will not be revealed or written in a way that you can be recognized. Additionally, identifying information will be available to people from the Children's Healthcare of Atlanta IRB and the University of Georgia IRB.

Only the researchers of this study will know your identity; your individually-identifiable information will not be shared with others *except if: a) necessary to protect your rights or well-being (for example, if you are injured and need emergency care); b) required by law; or c)* members of the Institutional Review Boards that approve and oversee research at Children's Healthcare of Atlanta or the University of Georgia request access to these records.

All of your information, forms, data, file names, etc. will be identified with a code name and not your real name. Electronic files will be password-protected; hard copy records will be kept in a secure-access area. All individually-identifying information will be destroyed no later than 10 years after the last participant has completed the study. Video files will be destroyed as soon as motion data are accurately tracked by the researchers but no later than 10 years after the testing date. Data may be published in professional journals but your name or identity will not be revealed.

What are your rights as a study participant?
Taking part in this study is completely voluntary. You may choose not to take part in this study. If you take part in this study, you may stop being in the study at any time. Your decision to not take part in the study or to stop being in the study will not in any way affect your current or future medical care at this hospital.

The study doctor or researcher may stop you from taking part in this study for any of the following reasons: (1) it would be dangerous for you to continue, or (2) you do not follow study procedures.
If you decide to stop or withdraw from the study, or if the investigator decides to terminate your participation without regard to your consent, the information/data collected from or about you up to the point of your withdrawal may be kept as part of the study and may continue to be analyzed.
Your signature below indicates that you have read this informed consent form and understand its meaning, you have been given the chance to ask questions and have had those questions answered to your satisfaction, and you voluntarily agree to participate in this study and sign this informed consent form. You will be given a copy of the signed informed consent form.

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Printed Name of Research Subject | Age | Date of Birth

Signature of Research Subject | Date | Time
(Required unless research subject is under the age of 18 years and assent was not obtained for reason provided below

Signature of Research Subject's Parent/Legal Guardian | Date | Time
(Required for research subjects under the age of 18 years)

Signature of Person Obtaining Assent/Consent/Permission | Date | Time

Signature of Interpreter | Date | Time

☐ The child is 5 years of age or younger and assent is not required for participation in this research study.
☐ The child is between the ages of 6-10 years old and has been orally assented to participate in this research study.
☐ In my opinion, the child is not able to assent to participate in this research study for the following reason:

Signature of Person Obtaining Assent/Consent/Permission | Date | Time

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1.2 UGA consent form

The University of Georgia (UGA) and Children's Health Care of Atlanta (CHOA)

Informed Consent to be in a Research Study

Study Title: "What are the Biomechanical and Physical Function Characteristics of Post-Spinal Fusion Surgery for Individuals with Adolescent Idiopathic Scoliosis?"

Primary Investigators:
- Kathy Simpson, PhD: *Dept. of Kinesiology, UGA (kjsimpsonuga@gmail.com; 706/542-4385 or 706/542-4132)*
- Dr. Timothy Oswald, *CHOA (404-785-6753)*

[Note. If my child is the research participant, and I am the parent or legal guardian, the words, "I, me, or my" refers to "my child"; "consent" refers to "permission."]

What is the reason for this form?

I am being asked to volunteer to (or agree for my child to) participate in this research study. To make this decision, I must be 'informed' about the study, my rights, and what I am being asked to do. Therefore, I will read the contents, have the researcher show and explain the tasks to me, and ask any questions. When I understand everything in this form, if I want to take part in the study, I will give my consent by signing this form.

What are my rights as a study participant?

Taking part in this study is completely voluntary. It is my choice to be in the study or not. I also can take back my consent and stop participating at any time without giving any reason, and without penalty or loss of any benefits to which I am otherwise entitled.
The researchers may stop me from taking part in this study for any of the following reasons: (1) I do not meet the requirements to participate, (2) I am ill, injured, have a medical condition that would affect my movements or safety; (3) it could be unsafe for me to continue; or (3) I do not follow study procedures. *If I decide to stop or withdraw from the study, or if the investigator decides to terminate my participation without regard to my consent, the information/data collected from or about me up to the point of my withdrawal may be kept as part of the study and may continue to be analyzed.*

What do the researchers want to learn?

In the study will be 2 groups of people with about 20 people in each group. One group will be people who have adolescent idiopathic scoliosis (AIS). This is a back problem that starts in the pre-teen or teen years in which the spine curves sideways. The AIS group will have had part of their spine fused during surgery to fix this problem. If I take part, I will be a member of the second group, that is, people with a healthy back and no AIS.

The researchers want to know whether an AIS fusion affects spinal flexibility, spine and body movements during running, jumping and balance of AIS surgery patients compared to people without scoliosis. This will help surgeons understand the effects of this type of surgery on spinal movements during daily life.

What will I do in this study?

I will fill out two forms with questions that ask about my past medical history, current health, and what physical activities I do. I may choose not to answer a given question for personal reasons. If the researchers then determine I am eligible to participate, I will continue.

The researchers will ask me to complete several questionnaires. Next, they will measure my weight, height and lengths of my arms and legs. I will perform several simple tasks, e.g., kicking a ball, so the researchers can see which legs I use to do these tasks.

As animation techniques like those used for video games or movies will be used to understand how I move, the researchers will put small, reflective balls (markers) on various parts of my body. When I perform the following movement tasks, the special animation video cameras will record the movements of the reflective markers. The researchers then will be able to later reconstruct my movements. An ordinary digital video camera also will be used to video my movements. These video clips will only be viewed by the researchers if needed to resolve a technical problem with the animation-camera data.

I will then perform a simple warm-up for several minutes. For the *trunk flexibility tasks*, I will perform a series of several different movement tasks. I will do each task 3 times while standing and 3 times while sitting. After I finish a task, I will have a short rest break. Before starting a new task, I also will warm up my back and practice the task. The trunk flexibility tasks will be: a) Bending the trunk forwards and backwards; b) bending sideward; c) twisting the trunk left and right.

Running: I will warm up walking on a treadmill, then the speed will be increased so that I am jogging, then running at a natural pace. After a brief rest, I will then run on the treadmill at a somewhat faster speed than my natural pace for approximately 30 steps.

Maximum vertical jump task: I will practice, then perform 3 vertical jumps, during which I will try and jump as high as possible. During this task, I will take off and land onto force plates (metal plates flush with the floor) that will be used by the investigators to measure the amounts of force I generate.

Balance tasks: I will be standing on force plates within a special balance machine. For each of several different test conditions, I will be asked to remain in balance as best that I can. I may be asked to have my eyes open or closed; the force plates may remain in place or tilt up or down slightly. I will practice each balance test, then perform each balance test condition 3 times in a random order.

After the reflective markers have been removed, I can choose to look at simple animations of some of my movements. Once I am done, I can leave; I will not be asked to do anything else for the study.

How long will I be in this study? Participation in this study will take about 2½ hours to complete the tasks described above during one (1) session.

What are the possible risks to being in this study? The risks of being in this study are minimal. There is always a risk when performing certain physical activities, but the tasks I will perform do not pose any more risk than is expected.

Why? The tasks require little effort, with little/no change in my breathing and heart rate. Plenty of rest is provided to prevent muscle tiredness. The total amount of movement is less than what I would do in an hour of physical activity. I will not be asked to bend or stretch farther than what I feel is comfortable to my body. I may feel some minor muscle soreness in 24 to 48 hours if I am in poor physical shape.

Some of the questions in the questionnaire may make me feel uncomfortable. I do not have to answer those questions.

My safety and health will be monitored at all times by one researcher. It is MY responsibility to ***tell any researcher right away if I start to feel any signs of something being wrong; for example, feelings of discomfort, pain, nausea, light-headedness, dizziness.*** If I or any researcher thinks that something is wrong, testing will stop. The researchers and I will decide whether to reschedule the rest of the testing.

What are the possible benefits of being in this study? Taking part in this study will not benefit me personally but I will have the chance to learn the process of movie animation as it is applied to my own movements, and I will also learn some of the results of how well I perform the test tasks. This study

may, however, help surgeons improve surgical and other treatment methods for future spinal-fusion patients, and develop guidelines for prescribing physical activity that is safe for these patients.

Will I receive a stipend for being in the study? Yes. I will receive $50 for completing the study and a travel stipend, based on my travel distance. If I choose not to complete the study, then I will receive $10 and one-half of the travel stipend.

What if am injured due to taking part in this study? The researchers will exercise all reasonable care to protect me from harm as a result of my participation. However, in the event of an injury as an immediate and direct result of my participation in this study, the researchers' sole responsibility is to arrange transportation for me to go to an appropriate medical facility, if needed.

In the event that I suffer a research-related injury, my medical expenses will be my responsibility or that of my third-party payer, although I am not precluded from seeking to collect compensation for injury related to malpractice, fault, or blame on the part of those involved in the research.

Who will be able to see my records or know my identity as a study participant? Only the researchers of this study will know my identity; my individually-identifiable information will not be shared with others except if: a) necessary to protect my rights or well-being (for example, if I am injured and need emergency care); b) required by law; or c) members of the Institutional Review Boards that approve and oversee research at Children's Healthcare of Atlanta or the University of Georgia request access to these records.

All of my information, forms, data, file names, etc. will be identified with a code name and not my real name. My electronic files will be password-protected; hard copy records will be kept in a secure-access area. All of my individually-identifying information will be destroyed no later than 10 years after the last participant has completed the study. Video files will be destroyed as soon as my motion data are accurately tracked by the researchers but no later than 10 years after the testing date. Data may be published in professional journals but my name or identity will not be revealed.

What if I have any questions, concerns, comments at any time until the study is completed? I can contact Dr. Simpson at any time during or after I take part in the study (kjsimpsonuga@gmail.com 706-542-4385).

Additional questions or problems regarding my rights as a research participant should be addressed to: The Chairperson, Institutional Review Board, University of Georgia, 629 Boyd Graduate Studies Research Center, Athens, Georgia 30602-7411; Telephone (706) 542-3199; E-Mail Address IRB@uga.edu. (This board is a committee that approves research with human participants at this university and makes sure that researchers and the university follow all government rules and regulations.)

My signature below indicates that I have read and understand the contents of this informed consent form, have had my questions answered to my satisfaction, and I agree to participate in this study. I will be given one copy for my records.

Please complete and sign two copies.

Printed Name of Research Participant	Signature	Date

University of Georgia
Institutional Review Board
Approved: 4-30-13
Expires 4-11-14

Printed Name of Research Participant's Parent/Legal Guardian (required if participant is less than 18 years old)	Signature	Date
Printed Name of Researcher	**Signature**	**Date**

1.3 CHOA assent form

SRS Funded

Appendix A

Children's Healthcare of Atlanta
Assent to be in a Research Study[1]

Title: What are the Biomechanical and Physical Function Characteristics of Post-Spinal Fusion Surgery for Individuals with Adolescent Idiopathic Scoliosis?

Principal Investigator: Dr. Timothy Oswald and Dr. Kathy Simpson (UGA)

Subject age:_____years.

Should the assenting child decline participation in this study, they the parent(s), legal guardian(s) cannot force the child to participate.

1._____ (ages 16-17) WRITTEN ASSENT See attached Written Assent document.
Once the study and treatment have been explained to the child, he or she should be asked to sign the written assent document. If the process of signing is too intimidating, the consenter may document (here and in the medical record) that the assent as been obtained verbally. It is suggested that the written assent document be read to the child as part of this age-appropriate discussion.

2._____ (any age) UNABLE TO PROVIDE ASSENT
If the child is too immature or otherwise unable to give informed assent, it is the investigator's prerogative to state the following:

In my opinion, this child cannot give informed assent. Reason(s):_____

Person Soliciting Assent _____ Date _____ Time _____

3. ALL SUBJECTS: Is subject postpubertal? Yes ☐ No ☐ Don't Know ☐

Initial here to indicate you discussed any reproductive risks with the subject _____, or initial here if there are no reproductive risks whatsoever for this study:_____

[1] For use with prospective subjects ages 5 to 17

CHOA IRB#: 09-132
Children's IRB Approval Date: 10/23/2012
Children's IRB Expiration Date: 10/22/2013
Version Date: 8-6-2012

University of Georgia
Institutional Review Board
Approved 4-30-13
Expires 4-11-14

SRS Funded

Written Assent Document

We are asking you to volunteer to be in a medical research study. This study is about learning more about how people who have had spinal surgery to correct adolescent idiopathic scoliosis move around and do physical activity tasks after surgery. We are inviting you to be in the study because we think that this study is important to learn what types of sports movements and other activities are good for patients to perform after this surgery.

What will you be doing? You will fill out 3 questionnaires about your health and physical activity. Your answers are confidential, and you do not have to answer questions that make you uncomfortable. If you are due for an X-ray of your spine, you will receive one. At the University of Georgia's Biomechanics Laboratory in Athens (UGA), you will perform trunk flexibility, running, vertical jumping and balance tasks while video/movie animation cameras capture your movements. There is little risk of injury, as you must be physically active to participate, and these are movements typically performed if you engage in sport and/or physical activity. If wearing shorts and a sports bra is uncomfortable or embarrassing for you, please tell your surgeon, the UGA researcher or staff or your parents. Testing at UGA will take about 2½ hours.

You can refuse (say no) to be in this study. Your doctors or your parents cannot make you be in the study if you don't want to be in it. Your surgeon will talk to you, and the UGA researchers will also explain the study. Make sure you understand what you will be doing and ask if you have questions. You can ask your surgeon and/or UGA researcher any questions about the study at any time, before, during or after being in the study. To contact: ***Dr. Oswald: 404-321-9900***; ***Dr. Simpson*** (UGA researcher) at ***706/542-4385*** or kjsimpsonuga@gmail.com. You can also talk to your parents about being in the study.

Writing your name on this page means that you agree to be in the study, and you know what will happen to you. You can change your mind and stop being part of this study at any time. Even if you write your name on this paper, you can say no later. All you have to do is tell a parent, the doctor or a UGA researcher.

_____	_____	_____
Participant	Date	Time
_____	_____	_____
Signature of Person Obtaining Assent	Date	Time

CHOA IRB#: 09-132
Children's IRB Approval Date: 10/23/2012
Children's IRB Expiration Date: 10/22/2013
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University of Georgia
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1.4 CHOA HIPAA form

Children's Healthcare of Atlanta

Authorization to Release Protected Health Information for Research Purposes

Title: What are the Biomechanical and Physical Function Characteristics of Post-Spinal Fusion Surgery for Individuals with Adolescent Idiopathic Scoliosis?
Principal Investigator: Timothy Oswald, MD and Kathy Simpson, PhD

The Health Insurance Portability and Accountability Act (HIPAA) is a federal law passed to protect the privacy of your child's Protected Health Information (PHI). PHI is any information about your child that could tell someone else who your child is. "Researchers" are what we call the people who are conducting the study. Government agencies may also need to look at your child's health information; these agencies make rules and policies about how research is done. The Institutional Review Board (IRB) can also look at your child's health information. The IRB is a committee that reviews research to make sure your child's rights and welfare are protected while being in the study. Sponsors who pay for the research also have the right to review your child's health information. Your child's health information may be disclosed if a court of law should order it. We will not use or share your child's health information in any way other than what we explain in this form. We will keep your child's health information private to the extent allowed by law. We will use a study number or other code rather than your child's name on study records when we can. Your child's name or any other fact that might point to your child will not appear if we publish the study results or make a presentation about the study.

Signing this document means you allow the researchers conducting the research to use your child's health information for this research study. Below is a list of things that HIPAA defines as PHI, the boxes that have an 'X' in them is the PHI that we will collect.

What PHI will be collected for this study:

☐ Name	☐ Email or IP address
☐ Address	☒ Dates of admission, discharge, treatment or death
☐ Telephone #	☐ Health Plan #'s
☒ Date of Birth	☒ Full face photogenic images or comparable images
☐ Social Security #	☐ Certificate/License #'s
☐ Fax #	☐ Vehicle identifiers, vehicle serial #'s or license plate #'s
☐ Medical Record #	☐ Device identifiers and serials #'s
☐ Account #	☐ Biometric identifiers, including finger and voice prints

What other information will be collected for this study: Questionnaire answers, height, weight, arm and leg lengths, and motion analysis data (computer generated 3D images similar to movie animation).

Who will collect the information:
The research staff conducting this study will collect and copy the PHI described above. If any of the PHI is to be shared with other people, as described later in this section, then the research staff will be responsible for sharing the information.

Who else will see the information at this hospital or office:
☒ Children's Healthcare of Atlanta Institutional Review Board (IRB), the committee that oversees research studying people.
☐ Other people that work for Children's Healthcare of Atlanta who need the information to perform their job duties (for example, to provide treatment, to ensure the integrity of the research, or for accounting and billing matters).
☐ People that work at where your child will be seen for office visits.
☐ Other people that work at who need the information to perform their job duties.
☐ Office for Human Research Protections (OHRP), a government agency that makes rules and policies about how research is done.

☐ The Food and Drug Administration (FDA), another government agency that makes rules and policies

CHOA IRB#: 09-132
APPROVED CHOA IRB: 10/23/2012

about how research is done.
☒ IRB's at other places where this study is being conducted.

Other people outside of this hospital or office that may see the information:
In conducting this research, we may share your child's health information with people outside of this hospital or office. If your child's study record is looked at by any of these groups, they may also need to see your child's entire medical record. The health information that is shared with these groups may no longer be covered by the HIPAA regulations. These groups include:

- University of Georgia Biomechanics Lab study staff

It is your choice to let the researchers use and share your child's health information. You can, at any time, change your mind about the researchers using your child's health information. If you no longer want your child's health information used or shared you must make the request in writing by signing a "Request for Withdrawal of Authorization". The researcher will give you a copy of this form to sign. This is called "withdrawing your authorization". If you withdraw your authorization it will not effect your child's current or future health care at this hospital or office and there will be no penalty or loss of any benefits you may be otherwise entitled to. If you withdraw your authorization we will not be able to collect any new health information and your child will be withdrawn from the study. However, we can continue to use the health information we have already collected as needed to protect the integrity of the research. You have the right to look at the information we collect. However, the information from the results of the study will not be available during the study; it will be available after the study is finished.

This authorization expires: no expiration designated

You will receive a copy of this form.

_____
Print Patient Name

_____
Printed Name of Parent, Legal Guardian or Patient
Check one of the following:
☐ I am the parent
☐ I am the Legal Guardian (state relationship to patient): _____
☐ I am the patient (must be 18 years of age or older)

_____ _____
Signature of Parent, Legal Guardian or Patient Date

_____
Printed Name of Person Obtaining Authorization

_____ _____
Signature of Person Obtaining Authorization Date

CHOA IRB#: 09-132
APPROVED CHOA IRB: 10/23/2012

University of Georgia
Institutional Review Board
Approved: 4-30-13
Expires: 4-11-14

2.1 Pre-Participation and Health Status Questionnaire

For researcher use only
Participant ID: _____
Date: _____
Researcher: _____
Reviewed by: _____

Questionnaire A

Pre-Participation and Health Status Questionnaire

When is your birthday? Month: _____ Day ____ Year _____

HEALTH AND MEDICAL CONDITIONS

If you now have or have had one of the conditions listed, put an X in the box provided. If you are unsure, put a question mark next to box.

- ☐ Heart problem
- ☐ Lung problem
- ☐ Trouble breathing or asthma
- ☐ Broken bones
- ☐ Sprains, or hurt an ankle, shoulder, hip, or knee
- ☐ Injury requiring major medical attention
- ☐ Inner ear problem
- ☐ Pain lasting more than 2 weeks
- ☐ Balance problem
- ☐ Blurred or bad eyesight or other eye problem not corrected
- ☐ Surgery
- ☐ Other medical condition(s)

CURRENT HEALTH STATUS

Have you had during the past 2 weeks or have today, any of the following: (check all that apply)

- ☐ Discomfort or pain to any part of body
- ☐ Chest pain or tightness, tingling in arm
- ☐ Trouble breathing
- ☐ Injury
- ☐ Illness
- ☐ Any other health problems
- ☐ Feeling sick to your stomach
- ☐ Trouble with balance
- ☐ Trouble seeing
- ☐ Had any medical or dental procedures
- ☐ Feeling dizzy or light-headed
- ☐ Soreness

1. How do you feel? In the space provided, write "N" for no and "Y" for yes for the following:

___ fine ___tired ___energetic ___happy ___sad ___ grumpy

2. How long has it been since your last menstrual period? _____ days

3. __Yes __No Are you taking or using any medications? If yes, list each, including those you can buy without a nonprescription:

_____

4. Is there any chance that you are pregnant? __Yes __No ___Don't know

   If you have scoliosis, you will get a radiograph (x-ray) of your spine during this study. Currently, the effects of radiation on an unborn baby's health and development are not known. Therefore, you may not participate in this study if there is any chance that you may be pregnant and you have scoliosis.

5. Is there anything else that we should know concerning your health?

___ No ___ Yes ___ Maybe

2.2 Scoliosis Physical Activity and Quality of Life Questionnaire

Questionnaire B
Scoliosis Physical Activity and Quality of Life Questionnaire

For researcher use only
Participant ID: _____
Date: _____
Researcher: _____
Reviewed by: _____

General Instructions:

- Ask us at any time if you have any questions.
- For some questions, to help you, you may want to look at the handout that we will show you.

For the first two questions, here is what to do for every question:

- Circle "Y" for "yes" and "N" for "no." If you are not sure, ask us.
- There may be more tasks to do depending on your answer to the question.

1. **Y N** Within the past year, have you competed in a sport or other physical activity (for example, cheerleading, stepping)? If yes, for each sport/activity you compete in, fill in the following:

Name of sport/activity	Are you practicing/competing currently?	Intensity level	For researcher

2. **Y N** Within the past year, have you attended classes or workouts led by an exercise leader/teacher in a physical activity, sport, dance, exercise (for example, yoga class, or a volleyball camp) etc.? For each activity you have participated in, fill in the following:

Name of activity	Are you currently attending this class/workout? (y/n)	Intensity level	For researcher

3. Physical activity done on your own: For this question, you will be filling in the boxes below about the activities you do that you do on your own, for example, shooting hoops with your friends, walking/riding a bike to school/work, chores, etc.
   - For the following areas, list the activity/activities, estimate the amount of time you spend in the activity, and estimate your exercise intensity level (look at the figure, "Exercise Level").

Name of activity	List activity(s)	How often (per month) and for how long each time (in hours)?	Intensity Level
Walking/hiking/running			
Dancing or pilates, stepping, clogging, etc.			
Exercises: workouts of exercises, lifting weights, Wii Fitness®, Wii Sports®, etc.			
Martial arts (ex.: judo, karate)			
Cycling, rowing, swimming, rollerblading, skateboarding			
Sport-type activities: basketball, volleyball, racquetball, tennis, boxing, golf, etc.			
Housework, yard-work			
Job requiring physical labor			

Please continue filling in boxes as above.

Name of activity	List activity(s)	How often (per month) and for how long each time (in hours)?	Intensity Level
Outdoor activities such as Frisbee golf, mountain/rock climbing, orienteering, etc.			
Other activities not fitting any categories above			

For the questions below, circle the ONE BEST answer to EACH question. Answer these by yourself. If a question does not apply to you, skip it.

I. What below best describes the amount of back pain you have felt during the past 6 months:
1. None ☐
2. Mild ☐
3. Moderate ☐
4. Moderate to severe ☐
5. Severe ☐

II. What below best describes the amount of back pain you have felt during the last month:
1. None ☐
2. Mild ☐
3. Moderate ☐
4. Moderate to severe ☐
5. Severe ☐

III. How often does your back limit the physical activities you can do or want to do?
1. Never ☐
2. Rarely ☐
3. Sometimes ☐
4. Often ☐
5. Very often ☐

IV. In the last 3 months, have you stayed home from work/school due to pain pain? Yes/No
If yes, how many days?
1. 0 ☐
2. 1 ☐
3. 2 ☐
4. 3 ☐
5. 4 or more ☐

2.3 Scoliosis Research Society (SRS) Short-Form 22-R Health-Related Quality of Life Questionnaire

Questionnaire C
Scoliosis Research Society (SRS) Short-Form 22-R
Health-Related Quality of Life Questionnaire

For researcher use only
Participant ID: _____
Date: _____
Researcher: _____
Reviewed by: _____

INSTRUCTIONS: We are carefully assessing the condition of your back and it is IMPORT THAT YOU ANSWER EACH OF THESE QUESTIONS YOURSELF.

Please CIRCLE THE ONE BEST ANSWER TO EACH QUESTION.

1. Which one of the following best describes the amount of pain you have experienced during the past 6 months.

   None ☐
   Mild ☐
   Moderate ☐
   Moderate to severe ☐
   Severe ☐

2. Which one of the following best describes the amount of pain you have experienced over the last month.

   None ☐
   Mile ☐
   Moderate ☐
   Moderate to severe ☐
   Severe ☐

3. During the past 6 months have you been a very nervous person?

   None of the time ☐
   A little of the time ☐
   Some of the time ☐
   Most of the time ☐
   All of the time ☐

4. If you had to spend the rest of your life with your back shape as it is right now, how would you feel about it?

   Very happy ☐
   Somewhat happy ☐
   Neither happy nor unhappy ☐
   Somewhat unhappy ☐
   Very unhappy ☐

5. What is your current level of activity?

   Bedridden ☐
   Primarily no activity ☐
   Light labor, and light sports ☐
   Moderate labor and moderate sports ☐
   Full activities without restriction ☐

6. How do you look in clothes?

- Very good ☐
- Good ☐
- Fair ☐
- Bad ☐
- Very Bad ☐

7. In the past 6 months have you felt so down in the dumps that nothing could cheer you up?

- Very often ☐
- Often ☐
- Sometimes ☐
- Rarely ☐
- Never ☐

8. Do you experience back pain when at rest?

- Very often ☐
- Often ☐
- Sometimes ☐
- Rarely ☐
- Never ☐

9. What is your current level of work/school activity?

- 100% normal ☐
- 75% normal ☐
- 50% normal ☐
- 25% normal ☐
- 0% normal ☐

10. Which of the following best describes the appearance of your trunk; defined as the human body except for the neck and head and your arms :

- Very good ☐
- Good ☐
- Fair ☐
- Poor ☐
- Very Poor ☐

11. Which one of the following best describes your medication usage for your back?

- None ☐
- Non-narcotics weekly or less (e.g., aspirin, Tylenol, Ibuprofen) ☐
- Non-narcotics daily ☐
- Narcotics weekly or less (e.g., Tylenol III, Lorocet, Percocet) ☐
- Narcotics daily ☐
- Other: _____ (Medication), _____ (Usage (weekly or less or daily))

12. Does your back limit your ability to do things around the house?

- Never ☐
- Rarely ☐
- Sometimes ☐
- Often ☐
- Very Often ☐

13. Have you felt calm and peaceful during the past 6 months?

- All of the time ☐
- Most of the time ☐
- Some of the time ☐
- A little of the time ☐
- None of the time ☐

14. Do you feel that your back condition affects your personal relationships?

- None ☐
- Slightly ☐
- Mildly ☐
- Moderately ☐
- Severely ☐

15. In the past 6 months have you felt downhearted and blue?

- Never ☐
- Rarely ☐
- Sometimes ☐
- Often ☐
- Very often ☐

16. In the last 3 months have you taken any sick days from work/school due to back pain and if so how many?

- 0 ☐
- 1 ☐
- 2 ☐
- 3 ☐
- 4 or more ☐

17. Do you go out more or less than your friends?

- Much more ☐
- More ☐
- Same ☐
- Less ☐
- Much less ☐

18. Do you feel attractive with your current back condition?

- Yes, very ☐
- Yes, somewhat ☐
- Neither attractive nor unattractive ☐
- No, not very much ☐
- No, not at all ☐

19. Have you been a happy person during the past 6 months?

- None of the time ☐
- A little of the time ☐
- Some of the time ☐
- Most of the time ☐
- All of the time ☐

20. Are you satisfied with the results of your back management?

- Very satisfied ☐
- Satisfied ☐
- Neither satisfied nor unsatisfied ☐
- Unsatisfied ☐
- Very unsatisfied ☐

21. Would you have the same [back] management again if you had the same condition?

- Definitely yes ☐
- Probably yes ☐
- Not sure ☐
- Probably not ☐
- Definitely not ☐

2.4 International Physical Activity Questionnaire

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE

We are interested in finding out about the kinds of physical activities that people do as part of their everyday lives. The questions will ask you about the time you spent being physically active in the **last 7 days**. Please answer each question even if you do not consider yourself to be an active person. Please think about the activities you do at work, as part of your house and yard work, to get from place to place, and in your spare time for recreation, exercise or sport.

Think about all the **vigorous** activities that you did in the **last 7 days**. **Vigorous** physical activities refer to activities that take hard physical effort and make you breathe much harder than normal. Think *only* about those physical activities that you did for at least 10 minutes at a time.

1. During the **last 7 days**, on how many days did you do **vigorous** physical activities like heavy lifting, digging, aerobics, or fast bicycling?

   _____ **days per week**

   ☐ No vigorous physical activities → ***Skip to question 3***

2. How much time did you usually spend doing **vigorous** physical activities on one of those days?

   _____ **hours per day**

   _____ **minutes per day**

   ☐ Don't know/Not sure

Think about all the **moderate** activities that you did in the **last 7 days**. **Moderate** activities refer to activities that take moderate physical effort and make you breathe somewhat harder than normal. Think only about those physical activities that you did for at least 10 minutes at a time.

3. During the **last 7 days**, on how many days did you do **moderate** physical activities like carrying light loads, bicycling at a regular pace, or doubles tennis? Do not include walking.

   _____ **days per week**

   ☐ No moderate physical activities → ***Skip to question 5***

SHORT LAST 7 DAYS SELF-ADMINISTERED version of the IPAQ. Revised August 2002.

4. How much time did you usually spend doing **moderate** physical activities on one of those days?

_____ **hours per day**

_____ **minutes per day**

☐ Don't know/Not sure

Think about the time you spent **walking** in the **last 7 days**. This includes at work and at home, walking to travel from place to place, and any other walking that you have done solely for recreation, sport, exercise, or leisure.

5. During the **last 7 days**, on how many days did you **walk** for at least 10 minutes at a time?

_____ **days per week**

☐ No walking → ***Skip to question 7***

6. How much time did you usually spend **walking** on one of those days?

_____ **hours per day**

_____ **minutes per day**

☐ Don't know/Not sure

The last question is about the time you spent **sitting** on weekdays during the **last 7 days**. Include time spent at work, at home, while doing course work and during leisure time. This may include time spent sitting at a desk, visiting friends, reading, or sitting or lying down to watch television.

7. During the **last 7 days**, how much time did you spend **sitting** on a **week day**?

_____ **hours per day**

_____ **minutes per day**

☐ Don't know/Not sure

This is the end of the questionnaire, thank you for participating.

SHORT LAST 7 DAYS SELF-ADMINISTERED version of the IPAQ. Revised August 2002.