

Marquette University
e-Publications@Marquette

Biomedical Engineering Faculty Research and
Publications

Biomedical Engineering, Department of

7-1-2018

Effects of Spinal Fusion for Idiopathic Scoliosis on Lower Body Kinematics During Gait

Karen M. Kruger

Marquette University, karen.kruger@marquette.edu

Christina R. Garman

Marquette University

Joseph J. Krzak

Marquette University

Adam Graf

Shriners Hospitals for Children

Sahar Hassani

Shriners Hospitals for Children

See next page for additional authors

Accepted version. *Spine Deformity*, Vol. 6, No. 4 (July-August 2018): 441-447. DOI. © 2018 Elsevier.
Used with permission.

Authors

Karen M. Kruger, Christina R. Garman, Joseph J. Krzak, Adam Graf, Sahar Hassani, Sergey Tarima, Peter F. Sturm, Kim W. Hammerberg, Purnendu Gupta, and Gerald F. Harris

Marquette University

e-Publications@Marquette

Biomedical Engineering Faculty Research and Publications/College of Engineering

This paper is NOT THE PUBLISHED VERSION; but the author's final, peer-reviewed manuscript. The published version may be accessed by following the link in the citation below.

Spine Deformity, Vol. 6, No. 4 (July-August 2018): 441-447. [DOI](#). This article is © Elsevier and permission has been granted for this version to appear in [e-Publications@Marquette](#). Elsevier does not grant permission for this article to be further copied/distributed or hosted elsewhere without the express permission from Elsevier.

Effects of Spinal Fusion for Idiopathic Scoliosis on Lower Body Kinematics During Gait*

Karen M. Kruger

Orthopaedic & Rehabilitation Engineering Center, Marquette University, Milwaukee, WI

Christina M.R. Garman

Orthopaedic & Rehabilitation Engineering Center, Marquette University, Milwaukee, WI

Joseph J. Krzak

Orthopaedic & Rehabilitation Engineering Center, Marquette University, Milwaukee, WI

Motion Analysis Laboratory, Shriners Hospitals for Children, Chicago, IL

College of Health Sciences, Midwestern University, Downers Grove, IL

Adam Graf

Orthopaedic & Rehabilitation Engineering Center, Marquette University, Milwaukee, WI

Motion Analysis Laboratory, Shriners Hospitals for Children, Chicago, IL

Sahar Hassani

Motion Analysis Laboratory, Shriners Hospitals for Children, Chicago, IL

Sergey Tarima

Division of Biostatistics, Medical College of Wisconsin, Milwaukee, WI

Peter F. Sturm

Division of Orthopaedic Surgery, Cincinnati Children's Hospital Medical Center, Cincinnati, OH

Kim W. Hammerberg

Motion Analysis Laboratory, Shriners Hospitals for Children, Chicago, IL

Purnendu Gupta

Motion Analysis Laboratory, Shriners Hospitals for Children, Chicago, IL

Gerald F. Harris

Orthopaedic & Rehabilitation Engineering Center, Marquette University, Milwaukee, WI

Motion Analysis Laboratory, Shriners Hospitals for Children, Chicago, IL

Abstract

Objectives

The purpose of this study was to compare gait among patients with [scoliosis](#) undergoing posterior [spinal fusion](#) and instrumentation (PSFI) to typically developing subjects and determine if the location of the lowest instrumented [vertebra](#) impacted results.

Summary of Background Data

PSFI is the standard of care for correcting [spine deformities](#), allowing the preservation of [body equilibrium](#) while maintaining as many mobile spinal segments as possible. The effect of surgery on joint motion distal to the spine must also be considered. Very few studies have addressed the effect of PSFI on activities such as walking and even fewer address how surgical choice of the lowest instrumented vertebra (LIV) influences possible motion reduction.

Methods

Individuals with scoliosis undergoing PSFI (n = 38) completed gait analysis preoperatively and at postoperative years 1 and 2 along with a control group (n = 24). Comparisons were made with the control group at each time point and between patients fused at L2 and above (L2+) versus L3 and below (L3-).

Results

The kinematic results of the AIS group showed some differences when compared to the Control Group, most notably decreased range of motion (ROM) in [pelvic tilt](#) and trunk lateral bending. When comparing the LIV groups, only minor differences were observed, and the results showed decreased coronal trunk and [pelvis](#) ROM at the one-year visit and decreased hip rotation ROM at the two-year visit in the L3- group.

Conclusions

Patients with AIS showed decreased ROM preoperatively with further decreases postoperatively. These changes remained relatively consistent following the two-year visit, indicating that most kinematic changes occurred in the first year following surgery. Limited functional differences between the two LIV groups may be due to the lack of full ROM used during normal gait, and future work could address tasks that use greater ROM.

Keywords

Adolescent idiopathic scoliosis, Posterior spinal fusion, Gait, Lowest instrumented vertebra, Kinematics

Introduction

[Scoliosis](#) is the most common orthopaedic disorder among children and adolescents and the 3D deformation of the spine changes the mechanics of the whole body. Posterior [spinal fusion](#) and instrumentation (PSFI) is the standard of care for correcting [spine deformities](#) in individuals with [adolescent idiopathic scoliosis](#) (AIS), allowing the preservation of [body equilibrium](#) while maintaining as many mobile spinal segments as possible [1], [2]. The effect of surgery on body shape, pain, and decompensation phenomenon has been well documented [3]; however, there is still uncertainty on how AIS and subsequent spinal fusion to varying levels affects functional outcomes such as walking, particularly in segments other than the trunk.

Standing coronal and sagittal radiographs are the standard means of preoperative analysis and postoperative assessment of surgical results of spinal fusion [4]; however, this static assessment does not address the associated changes in functionality that may occur following fusion. Changes to trunk mobility have been measured via dynamic assessment following this procedure [5]. To date, there is not sufficient robust evidence to judge the influence of scoliosis deformity on kinematic parameters during walking [6].

Gait analysis was first used to define normal spinal and [pelvis](#) motion by Thurston and Harris in 1976 [7]. In a gait analysis of the head, trunk, and pelvis, Kramers-de Quervain et al. observed significant asymmetry in the trunk's [rotational behavior](#) in the transverse plane during double limb stance in 10 females with AIS whereas head and pelvic rotation followed a symmetric pattern [8]. While several investigators have studied gait following spinal fusion in scoliosis [9], [10], [11], it is not clear if trunk and lower extremity kinematics are impacted in follow-ups beyond the first year postoperatively. Past work has shown individuals with AIS to have decreased pelvic, hip, and knee ranges of motion during gait compared to healthy, control subjects, although the restriction of motion was relatively small [12]. Following surgery, the spine has been shown to become stiffer with decreased spinal range of motion (ROM) [9]. Short-term follow-ups post spinal fusion have shown slight increases to pelvic and hip frontal motion [11]; however, the longer-term effects of surgery on lower body gait kinematics are still unclear.

Even fewer clinical studies address how surgical choice of the lowest instrumented [vertebra](#) (LIV) influences possible reductions in motion. The lowest level to fuse the vertebra is a continued topic of clinical debate and a majority of the work addressing LIV has focused on trunk motions. Appropriate selection of the LIV is crucial to ensure positive outcomes after surgical management of patients with AIS. Failure to do so can lead to curve decompensation and "adding on" of additional vertebrae to the deformity [13]. Because of the mobility of the [lumbar spine](#) and the propensity for symptomatic degeneration, selection of the optimal LIV is believed to play a significant role in the ultimate clinical outcome of the patient. The concept of "saving a level" by stopping the fusion short must be weighed against the potential to leave an undercorrected or unbalanced spine [14]. Although several publications have described the contribution of LIV to trunk mobility [5] and volitional weight shifting [15], no studies have compared gait outcomes between varying LIV.

The goal of PSFI surgery is the preservation of body equilibrium while maintaining as many mobile spinal segments as possible. Ultimately, the purpose of this study was to (1) compare pre-, one-year, and two-year

postsurgery conditions among patients with scoliosis undergoing PSFI to assess effects on temporospatial and trunk and lower body kinematics during gait compared to typically developing subjects and (2) determine if the location of the LIV had any impact on the results. We hypothesized that the spinal fusion would result in stiffer gait (as measured by joint ROM) and that individuals with PSFI to more distal LIV (L3 and below) would experience more joint stiffening during gait.

Materials and Methods

This was a [prospective study](#) performed on 38 individuals with AIS (5 males, 33 females, age 15.0 ± 2.1 years) undergoing PSFI ([Table 1](#)). The AIS Group consisted of a sample of convenience between October 2007 and August 2012 at a single specialized pediatric orthopaedic institution ([Figure 1](#)). A consecutive series of 120 patients had a PSFI, of which 38 patients agreed to participate in the AIS Group. The average age at the time of the PSFI was 15.0 years ± 2.1 years. Participants were excluded if they required fusion outside T12 through L4. None of the participants had an L5 [vertebra](#) above the intercrestal line or L5 sacralization. Because of safety concerns, participants were excluded if they could not walk/stand independently. Patient demographics are defined in [Table 1](#). The LIV was determined by the operating surgeon using the standing radiograph, intersection of the center sacral vertical line, and correction of the LIV on [traction](#) and bending films. The goal was to have the LIV centralized, horizontalized, and neutralized postoperatively.

Table 1. Patient demographics

Study no.	Fusion levels	Sex	Age	Weight (kg)	Height (cm)	Lenke class	LIV group	Cobb angle (°)	Preoperative	Postoperative 1-year	Postoperative 2-year
4	T3–T12	Female	13.5	62.6	168.9	1(C)	L2+	53	25	18	
5	T2–T12	Female	18.3	54.0	162.6	4(C)	L2+	46	24	24	
10	T2–L2	Female	10.6	28.1	134.6	1(C)	L2+	51	16	13	
12	T2–L2	Female	14.2	37.7	156.9	4(C)	L2+	74	30	31	
15	T3–L1	Female	14.7	54.5	162.5	3(B)	L2+	40	25	23	
19	T3–L2	Male	16.8	80.9	175.5	2(B)	L2+	50	27	33	
20	T2–L2	Male	15.5	84.5	175.0	5(C)	L2+	54	22	25	
21	T4–L1	Female	14.6	52.3	157.0	1(C)	L2+	40	10	14	
26	T4–T12	Female	14.8	45.4	160.0	2(B)	L2+	57	32	33	
27	T2–L1	Female	17.4	57.2	165.1	3(C)	L2+	46	8	13	
29	T3–L1	Female	13.0	55.0	165.0	3(C)	L2+	59	18	22	
30	T3–T12	Female	18.8	61.6	165.6	3(C)	L2+	41	30	n/a	
32	T3–T12	Female	12.0	63.6	158.7	3(C)	L2+	50	29	19	
34	T3–L2	Female	16.9	55.5	154.0	1(C)	L2+	55	17	14	
1	T11–L3	Female	15.8	71.1	103.2	6(B)	L3–	47	25	28	
2	T3–L3	Female	13.0	45.0	154.0	5(C)	L3–	58	2	1	
3	T4–L3	Female	14.7	53.2	165.74	6(C)	L3–	52	26	19	
6	T3–L4	Female	13.2	60.5	170.0	6(C)	L3–	49	24	22	
7	T3–L3	Male	15.9	64.1	167.0	3(C)	L3–	80	27	31	
8	T3–L3	Female	15.4	89.7	165.0	2(C)	L3–	55	31	32	
9	T2–L4	Female	19.9	46.4	157.5	1(C)	L3–	76	33	n/a	

11	T3–L3	Male	16.2	53.2	166.4	3(C)	L3–	69	37	34
13	T3–L3	Female	17.8	50.3	157.5	1(C)	L3–	55	16	19
14	T10–L3	Female	15.1	52.3	170.2	5(C)	L3–	40	32	36
16	T2–L3	Male	15.0	50.9	152.5	1(C)	L3–	97	12	10
17	T4–L4	Female	11.9	65.9	161.9	3(C)	L3–	60	14	14
18	T4–L4	Female	15.6	65.0	160.0	6(C)	L3–	50	16	12
22	T3–L3	Female	12.3	47.7	155.0	1(C)	L3–	39	19	29
23	T2–L3	Female	15.0	44.5	155.0	2(C)	L3–	46	26	27
24	T2–L3	Female	12.8	34.8	143.0	6(C)	L3–	52	25	24
25	T2–L4	Female	13.1	56.6	159.0	3(C)	L3–	74	24	35
28	T4–L4	Female	17.4	54.1	176.0	3(C)	L3–	52	21	21
31	T2–L4	Female	16.5	71.3	170.0	2(C)	L3–	66	26	26
33	T3–L4	Female	14.2	50.0	164.0	3(C)	L3–	59	27	25
35	T3–L4	Female	12.9	44.5	142.0	6(C)	L3–	71	13	21
36	T3–L4	Female	15.7	53.6	160.0	3(C)	L3–	59	22	25
37	T3–L4	Female	12.7	61.7	167.0	2(C)	L3–	52	24	19
38	T4–L4	Female	16.8	52.7	164.4	6(C)	L3–	50	21	13

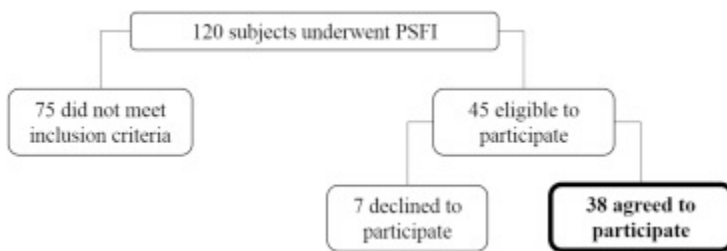


Fig. 1. Study design.

Gait analysis was performed on all patients preoperatively and at postoperative years 1 (mean, 1.15 years; range, 0.8–1.5 years) and 2 (mean, 2.2 years; range, 1.8–3.4 years). All participants freely consented in accordance with an institutionally approved IRB protocol. This group was split into two subgroups, L2+ (fusions to L2 and above, 14 subjects) and L3– (fusions to L3 and below, 24 subjects), to evaluate the effect of LIV on trunk and lower extremity gait.

Gait data were collected at 120 Hz using a passive marker 14 camera (MX model) motion capture system (Vicon; Oxford Metrics, Oxford, UK) on a 10-m walkway. Reflective spherical markers were placed at anatomical landmarks on the subject’s [pelvis](#) and lower limbs in accordance with the validated [Vicon Plug-in-Gait Model \(Figure 2\)](#) [16], [17]. All gait data were run through a Woltring filter with a mean squared error (MSE) value of 20. The system underwent calibration, ensuring accuracy of less than 1 mm [18]. Each subject was asked to walk at a self-selected pace for 10–15 trials, from which a minimum of three representative trials were selected. All data collection and analysis was performed by the same tester for reliability purposes. To minimize reviewer bias, a standardized quantitative protocol for data collection, processing, reduction, and analysis was employed. Additionally, study staff were unaware of LIV at the time of baseline testing. Kinematic parameters were calculated for every trial and then averaged for each individual.

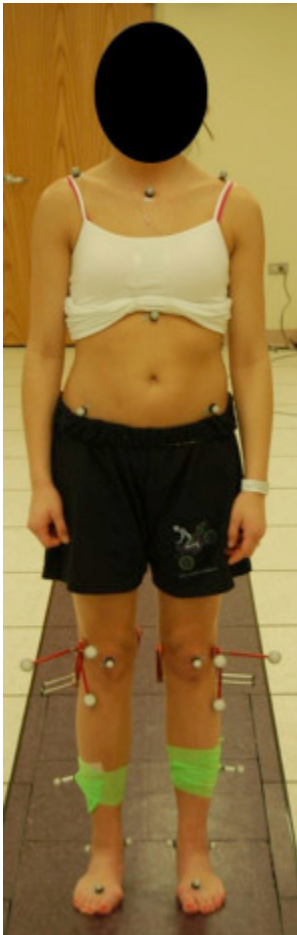


Fig. 2. [Vicon](#) PlugIn gait model markers.

Select gait parameters were compared to an age range–matched healthy, control group (11 males, 9 females, age 15.8 ± 2.4 years). Temporospacial values and ROM of the trunk, pelvis, hip, knee, and ankle were analyzed. A linear mixed model fit was used to account for within-person correlations. To evaluate the effect of PSFI on trunk/lower body gait parameters, Student *t* tests were performed to compare mean temporospacial values and kinematic excursions at preoperative, one-year, and two-year postoperative time points. To evaluate the effect of LIV on gait parameters, Student *t* tests were further used to compare participants fused at L2+ or L3–. Level of significance was set at 0.01 to control for multiple comparisons and potential for false discoveries. Statistical analysis was performed using SAS version 9.4 (IBM, Armonk, NY).

Results

Of the 38 patients initially tested, 29 returned for the one-year visit and 27 returned for the two-year visit. Results are summarized in [Table 2](#). Preoperatively, the comparison between the L2+ and L3– group showed there were no significant differences between the two surgical groups for any variables analyzed ([Figure 3](#)). Decreased cadence was observed in both LIV groups at the one- and two-year visits. Slight decreases in overall [walking speed](#) were observed; however, the difference was not statistically significant.

Table 2. Summary of temporal spatial parameters and lower body kinematics during gait for control group and each [spinal fusion](#) group (L2+, L3–) during preoperative, 1-year, and 2-year follow-up.

	Control (n = 20)	Preoperative (n = 38)		Postoperative 1- year (n = 29)		Postoperative 2- year (n = 27)	
		L2+ (n = 14)	L3- (n = 24)	L2+ (n = 9)	L3- (n = 20)	L2+ (n = 8)	L3- (n = 19)
Temporal spatial parameters							
Walking speed (m/s)	1.17 (0.03)	1.13 (0.04)	1.21 (0.03)	1.10 (0.03)	1.12 (0.02)	1.14 (0.04)	1.15 (0.03)
Cadence (step/min)	59.3 (1.3)	55.5 (1.3)*	57.3 (0.9)	54.7 (1.2)**	53.9 (0.8)**	53.6 (1.5)**	54.8 (0.9)**
Single support %	40 (0)	39 (0)	40 (0)	40 (0)	40 (0)	39 (1)	39 (0)
Double support %	21 (1)	21 (1)	19 (1)	21 (1)	21 (0)	21 (1)	22 (1)
Stride length (m)	1.2 (0.03)	1.2 (0.02)	1.3 (0.02)*	1.2 (0.02)	1.2 (0.02)	1.3 (0.02)*	1.3 (0.02)
Sagittal kinematics							
Trunk flexion range (°)	2.7 (0.7)	3.3 (1.0)	3.5 (1.1)*	3.0 (0.4)	3.3 (0.9)	3.5 (0.9)	3.3 (0.9)
Pelvic tilt range (°)	4.6 (0.4)	3.4 (0.3)**	3.5 (0.2)*	3.5 (0.3)*	3.1 (0.2)**	3.0 (0.3)**	3.1 (0.2)**
Hip flexion range (°)	44.2 (0.6)	43.1 (1.2)	42.8 (1.0)	40.1 (0.6)**	41.0 (0.9)**	43.4 (2.5)	42.6 (0.9)
Knee flexion range (°)	59.4 (0.8)	58.4 (1.4)	55.9 (1.1)*	53.1 (3.5)	55.9 (1.3)*	58.6 (1.7)	57.5 (1.0)
Ankle dorsi/plantarflexion range (°)	33.3 (0.8)	30.6 (1.2)	30.8 (1.2)	33.2 (2.2)	31.1 (1.6)	34.8 (1.6)	32.5 (1.0)
Coronal kinematics							
Trunk lateral bend range (°)	4.6 (1.6)	3.0 (2.0)**	3.1 (2.1)*	2.8 (2.4)*	2.0 (0.9)**	2.8 (1.5)**	2.4 (0.9)**
Pelvic obliquity range (°)	8.1 (0.6)	10.8 (0.9)**	8.7 (0.6)	10.1 (0.9)*	7.6 (0.5)	9.3 (0.7)	8.7 (0.6)
Hip adduction range (°)	13.4 (0.5)	14.1 (1.0)	13.2 (0.6)	14.1 (1.0)	12.1 (0.5)	13.9 (0.6)	12.9 (0.5)
Transverse kinematics							
Trunk rotation range (°)	6.8 (2.3)	5.1 (2.0)	5.7 (2.2)	5.1 (0.9)**	6.3 (2.0)	5.2 (1.2)	5.6 (2.0)
Pelvic rotation range (°)	12.0 (0.8)	10.2 (0.6)	10.5 (0.8)	7.6 (0.4)*	8.6 (0.5)*	7.3 (0.9)*	9.4 (0.6)*
Hip rotation range (°)	17.3 (1.1)	15.7 (0.6)	14.4 (0.9)*	13.8 (0.7)**	13.8 (0.6)**	16.0 (1.1)	12.9 (0.6)**
Foot progression range (°)	15.5 (0.8)	15.7 (1.1)	15.7 (0.9)	18.2 (0.9)*	15.8 (1.1)	17.0 (1.4)	16.7 (0.7)

Data are shown as mean (standard deviation).

*p < .05, **p < .01.

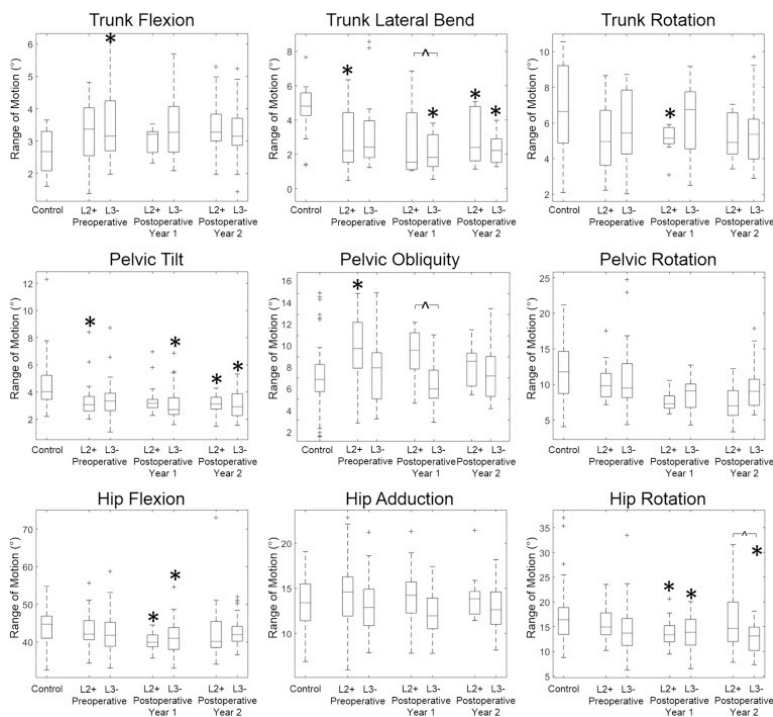


Fig. 3. Comparison of LIV groups at each visit. For each group, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the plus symbol. *Statistical difference from control group. ^Statistical difference between LIV groups ($p < .01$).

Slight differences were observed in the kinematics when compared to the Control Group, most notably in the sagittal plane of the [pelvis](#) and the coronal plane of the trunk ([Figure 3](#)). In the trunk, lateral bending ROM was lower than the control group in the L3- group preoperatively, L2+ group at postoperative year 1, and both groups at postoperative year 2. Other groups tested did not meet our strict statistical requirement of $p < .01$. The ROM was lower in the L3- group than in the L2+ group at the one-year follow-up visit.

The pelvis showed decreased sagittal ROM in both groups as compared to controls at all time points tested but the decrease was not significant in the L3- group preoperatively or the L2+ group at postoperative year 1. However, no statistically significant differences were observed for comparisons between the two surgical groups. A preoperative increase in pelvic obliquity was observed in the L2+ group, which was corrected following surgery at the two-year visit. Pelvic rotation ROM was decreased but not significantly in both groups at both the one- and two-year visits.

At the hip, there was decreased ROM in the sagittal plane in both groups at the one-year visit. ROM returned to normal ranges at the two-year visit for both groups. Decreased hip rotation was also observed at the one-year visit for both groups. The L2+ group returned to normal ROM at the two-year visit whereas that for the L3- group remained low. Only minor differences were observed in the sagittal knee ROM and foot progression angle.

Discussion

The purpose of this study was to (1) compare pre-, one-year, and two-year postsurgery conditions in [scoliosis](#) patients undergoing PSFI to assess effects on trunk and lower body kinematics during gait compared

to typically developing controls and (2) determine if the location of the lowest instrumented [vertebra](#) impacted the results. We hypothesized that the [spinal fusion](#) would result in stiffer gait (as measured by joint ROM) and that individuals with PSFI to more distal LIV (L3 and below) would experience more joint stiffening during gait. Hypothesis 1 was partially accepted in that trunk lateral bending, [pelvis](#) sagittal bending, and pelvic rotation ROM was lower at the two-year follow-up. Hypothesis 2 was partially accepted in that the L3– group showed less hip ROM in the transverse plane.

The results of this gait analysis both agree and disagree with previously published literature on patients with AIS. The results of the two-year follow-up showed that temporal spatial parameters were only slightly impacted by the spinal fusion surgery. Previous data on the impact of spinal fusion on [gait speed](#), cadence, and stride length has been contradictory. One study showed a significant increase in gait speed postsurgery [19] whereas others showed decreases in speed and step length [10], [11]. Although our results showed statistically significant lower cadence and higher stride length as compared to controls, step length, walking speed, and cadence for all time points tested were within 95% confidence intervals reported for healthy males and females aged 10–19 years [20], suggesting that the scoliosis deformity and spinal fusion did not cause clinically significant changes to these parameters. Work that compares the kinematics of subjects with AIS to a healthy control group is limited. Mahanudens et al. showed decreased frontal pelvis and hip motion and transversal hip motion [12]. Our populations showed agreement in frontal plane pelvic motion (L2+ group) and transversal hip motion (L3– group); however, we did not observe decreased hip frontal plane motion in either group. In the previous paper, gait analysis was performed on a treadmill at a set walking speed for all participants which differed from the self-selected walking speed in the current work. This controlled walking speed may have caused [gait deviations](#) which did not occur when patients were allowed to walk at a self-selected pace.

Several decreases in mobility were still observed at the two-year visit. Although the trunk lateral bending ROM during walking was decreased (average ROM 4.6°, 2.8°, and 2.0° for the control, L2+, and L3– groups, respectively), this is well below the total available lateral bending ROM, which was measured to range from 37° to 57° reported in our previous study that included the same patients [5]. Findings from the current study suggest that available ROM is not the cause of these gait deviations. It is plausible that the reduced ROM in patients with AIS is attributed to a compensatory mechanism to avoid loss of balance; however, there have been contradictory results in regard to balance capabilities of patients with AIS. Chen et al. reported decreased ROM of the pelvis in the transverse plane and the spine in the coronal plane when comparing patients with AIS to control subjects. It was noted that this decreased pelvic ROM may indicate that subjects with AIS need to restrict their movements to keep the upper body balanced because of geometric asymmetry from the deformity [21]. This work also showed patients with AIS to have poorer postural stability when compared to normal subjects [21]. This contradicts the work of Kurapati et al. [15], which showed patients with AIS to have improved volitional weight shifting over typically developing controls, suggesting they learn to improve the initial accuracy of their weight shifts despite an aberrant center of gravity.

It has been reported that spinal fusion causes an increase in the incidence of lower back pain [18]; therefore, correcting spinal alignment while maintaining normal [joint function](#) remains an important clinical concern. Although most gait abnormalities were diminished by the two-year postoperative appointment, [pelvic tilt](#), trunk lateral [bend](#), and pelvic and hip rotation range remained lower compared with the control group. Stiffness during gait may inhibit the cocontraction of the lumbo-pelvic muscles that has been noted in scoliosis patients [12]. If stiff gait is in fact only a compensatory safety mechanism to avoid loss of balance, intervention

techniques to regain this ROM may be warranted to reduce the potential for low back pain from excessive muscular strain due to cocontraction.

With respect to lowest instrumented vertebrae, the current study showed limited significant differences in gait preoperatively and at the one- and two-year follow-up between the L2+ and the L3– group. This suggests that LIV does not greatly affect functional tasks such as gait. A major limitation to this work was that patients were not randomly assigned an LIV; rather, the appropriate LIV was determined by the operating surgeon. However, there was no statistical significance between the Cobb angles between the two groups at any of the time points tested. A long-term study of individuals with AIS at least 20 years after surgery showed subjects with fusion ending at L3 or above had better lumbar mobility compared to those with more distal ending fusions [3] and a study on trunk mobility showed a trend toward greater postoperative reduction in peak forward flexion at more distal LIVs [5]. One reason for limited differences between the two groups could be that differences might only be seen at LIVs more distal than L3. Our sample size prohibited us from dividing our AIS population into more than two LIV groups. Future work could use larger patient populations to assess differences in LIVs below L3.

A further limitation of this study was that a power analysis was not completed prior to the study because of a lack of pilot data. Using the primary variable of interest (sagittal trunk ROM) based on previous literature [5], a power analysis was conducted to guide future work on this subject. Power analysis showed that to accurately capture a difference between the two LIV groups at 80% power, 2203 subjects would need to be analyzed.

In conclusion, patients with AIS showed decreased ROM preoperatively, primarily in pelvic tilt, pelvic rotation, and hip rotation. Postoperatively, further decreases in ROM were observed for these parameters as well as hip flexion. These ROM variables remained relatively consistent following the two-year visit, indicating that most of the kinematic changes occurred in the first year following surgery. It is likely that no functional differences were seen in the current study due to the lack of full ROM used during normal gait. As such, expansion of the study to include more complex tasks that utilize greater ROM in the pelvis and hip, such as running, jumping, and changing direction, may reveal group differences and as such warrant further investigation before conclusions regarding functional tasks and LIVs are made.

Acknowledgments

The contents of this manuscript were developed under a grant from the US Department of Health and Human Services–National Institute on Disability, Independent Living, and [Rehabilitation](#) Research (NIDILRR): Advanced Rehabilitation Research Training in Pediatric Mobility for Physicians and Engineers. 90AR5022-01-00 (Formerly H133P140023-14). The contents do not necessarily represent the policy of NIDILRR, ACL, and HHS, and you should not assume endorsement by the Federal Government. Support for the study also came from the Hainer Foundation and DePuy Spine.

References

- [1] R.M. Ali, O. Boachie-Adjei, B.A. Rawlins **Functional and radiographic outcomes after surgery for adult scoliosis using third-generation instrumentation techniques** *Spine (Phila Pa 1976)*, 28 (2003), pp. 1163-1169 discussion 1169–70
- [2] J.A. Byrd 3rd, P.V. Scoles, R.B. Winter, *et al.* **Adult idiopathic scoliosis treated by anterior and posterior spinal fusion** *J Bone Joint Surg Am*, 69 (1987), pp. 843-850

- [3] A.J. Danielsson, K. Romberg, A.L. Nachemson **Spinal range of motion, muscle endurance, and back pain and function at least 20 years after fusion or brace treatment for adolescent idiopathic scoliosis: a case-control study** *Spine (Phila Pa 1976)*, 31 (2006), pp. 275-283
- [4] T.R. Maher, A. Merola, R.I. Zipnick, *et al.* **Meta-analysis of surgical outcome in adolescent idiopathic scoliosis. A 35-year English literature review of 11,000 patients** *Spine (Phila Pa 1976)*, 20 (1995), pp. 1575-1584
- [5] U.I. Udoekwere, J.J. Krzak, A. Graf, *et al.* **Effect of lowest instrumented vertebra on trunk mobility in patients with adolescent idiopathic scoliosis undergoing a posterior spinal fusion** *Spine Deform*, 2 (2014), pp. 291-300
- [6] M.T. Karimi, M. Kavyani, M. Kamali **Balance and gait performance of scoliotic subjects: a review of the literature** *J Back Musculoskelet Rehabil*, 29 (2016), pp. 403-415
- [7] A.J. Thurston, J.D. Harris **Normal kinematics of the lumbar spine and pelvis** *Spine (Phila Pa 1976)*, 8 (1983), pp. 199-205
- [8] I.A. Kramers-de Quervain, R. Müller, A. Stacoff, *et al.* **Gait analysis in patients with idiopathic scoliosis** *Eur Spine J*, 13 (2004), pp. 449-456
- [9] J.R. Engsborg, L.G. Lenke, M.L. Uhrich, *et al.* **Prospective comparison of gait and trunk range of motion in adolescents with idiopathic thoracic scoliosis undergoing anterior or posterior spinal fusion** *Spine (Phila Pa 1976)*, 28 (2003), pp. 1993-2000
- [10] L.G. Lenke, J.R. Engsborg, S.A. Ross, *et al.* **Prospective dynamic functional evaluation of gait and spinal balance following spinal fusion in adolescent idiopathic scoliosis** *Spine (Phila Pa 1976)*, 26 (2001), pp. E330-E337
- [11] P. Mahaudens, C. Detrembleur, M. Mousny, X. Banse **Gait in thoracolumbar/lumbar adolescent idiopathic scoliosis: effect of surgery on gait mechanisms** *Eur Spine J*, 19 (2010), pp. 1179-1188
- [12] P. Mahaudens, X. Banse, M. Mousny, C. Detrembleur **Gait in adolescent idiopathic scoliosis: kinematics and electromyographic analysis** *Eur Spine J*, 18 (2009), pp. 512-521
- [13] M.A. Erickson, D.M. Baulesh **Lowest instrumented vertebra selection in AIS** *J Pediatr Orthop*, 31 (1 suppl) (2011), pp. S69-76
- [14] L.Y. Carreon, C.H. Crawford, L.G. Lenke, *et al.* **Optimal lowest instrumented vertebra selection for posterior instrumented fusion of Lenke type 5 and 6 adolescent idiopathic scoliosis: is there a difference in outcome between L3 and L4?** *Spine J*, 13 (2013), p. S38
- [15] N.T. Kurapati, J.J. Krzak, A. Graf, *et al.* **Effect of surgical fusion on volitional weight shifting in individuals with adolescent idiopathic scoliosis** *Spinal Deform*, 4 (2016), pp. 432-438
- [16] M.P. Kadaba, H.K. Ramakrishnan, M.E. Wootten **Measurement of lower extremity kinematics during level walking** *J Orthop Res*, 8 (1990), pp. 383-392
- [17] R.B. Davis III, S. Öunpuu, D. Tyburski, J.R. Gage **A gait analysis data collection and reduction technique** *Hum Mov Sci*, 10 (1991), pp. 575-587
- [18] K.A. Myers, M. Wang, R.M. Marks, G.F. Harris **Validation of a multisegment foot and ankle kinematic model for pediatric gait** *IEEE Trans Neural Syst Rehabil Eng*, 12 (2004), pp. 122-130
- [19] S. Khodadadeh, S.M. Eisenstein **Gait analysis of patients with low back pain before and after surgery** *Spine (Phila Pa 1976)*, 18 (1993), pp. 1451-1455
- [20] T. Oberg, A. Karsznia, K. Oberg **Basic gait parameters: reference data for normal subjects, 10-79 years of age** *J Rehabil Res Dev*, 30 (1993), pp. 210-223
- [21] P.Q. Chen, J.L. Wang, Y.H. Tsuang, *et al.* **The postural stability control and gait pattern of idiopathic scoliosis adolescents** *Clin Biomech (Bristol, Avon)*, 13 (1 suppl 1) (1998), pp. S52-S