Adolescent idiopathic scoliosis: spinal fusion and beyond

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2019

document version
Publisher's PDF, also known as Version of record

citation for published version (APA)
Holewijn, R. M. (2019). *Adolescent idiopathic scoliosis: spinal fusion and beyond*. [PhD-Thesis - Research and graduation internal, Vrije Universiteit Amsterdam].

Chapter 6

A prospective analysis of motion and deformity at the shoulder level in surgically treated adolescent idiopathic scoliosis

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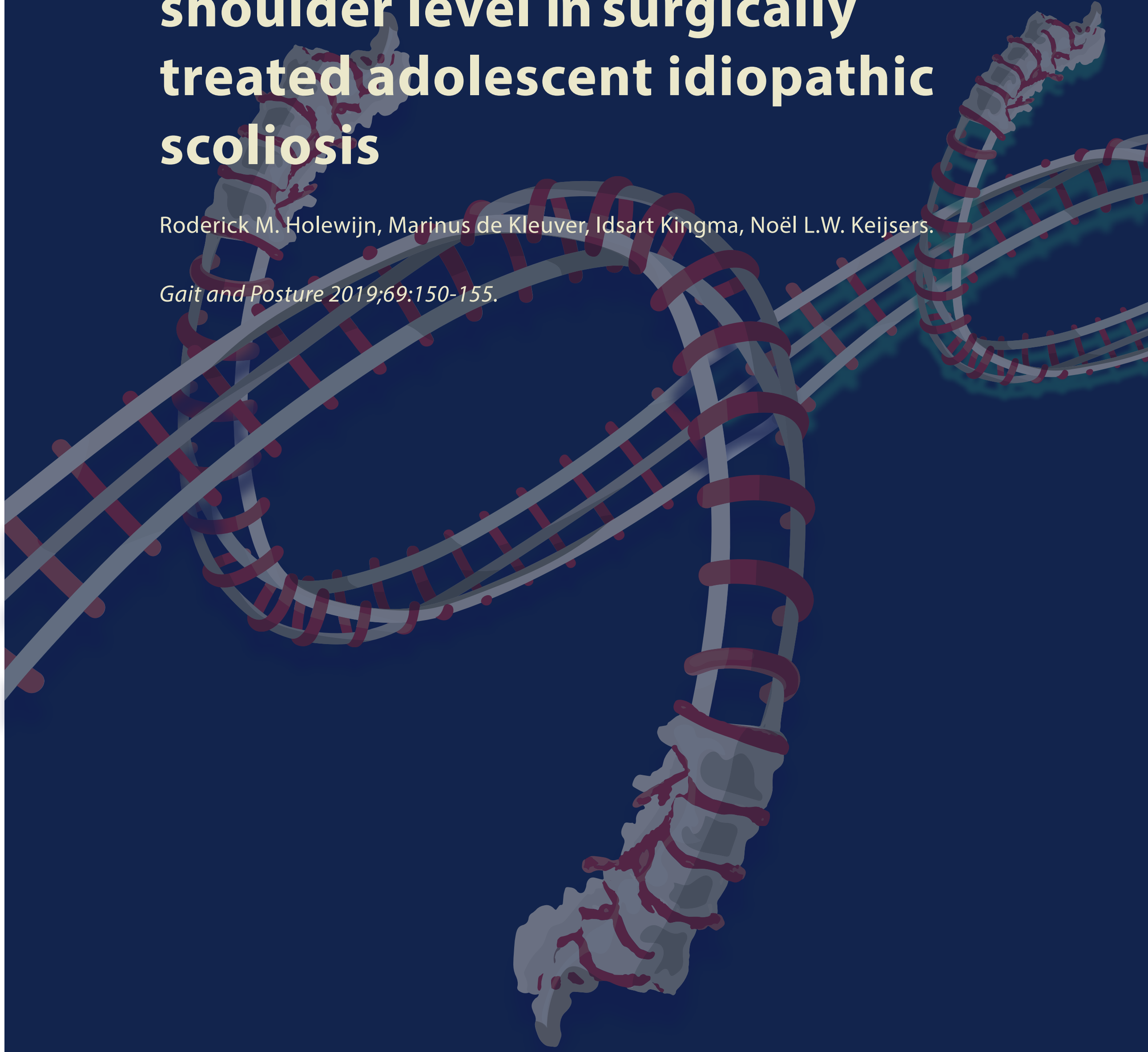
Gait and Posture 2019;69:150-155.



Abstract

Background: Although posterior spinal correction and fusion surgery (PSF) of adolescent idiopathic scoliosis (AIS) limits counter rotation between thorax and pelvis, the physical function, and more specifically gait of these patients is only slightly affected after PSF. Possibly, shoulders-thorax counter-rotation increases to compensate for the loss in thorax-pelvis motion. This would subsequently result in a higher phase-difference and range of motion (ROM) between the shoulders and thorax.

Research questions: What is the effect of PSF on the phase difference and ROM between the shoulders and thorax? What is the effect of PSF on upper body deformity?

Methods: 18 AIS patients underwent gait analysis at increasing walking speeds (0.45 to 2.22 m/s) before, and 3 and 12 months after PSF. The phase difference, ROM, and deformity between the shoulders, thorax, and pelvis were calculated.

Results: The shouldersthorax phase difference was unaffected by surgery. At 3 months postoperatively the shoulders-thorax ROM was decreased (3.5° ± 0.2° versus 2.7° ±0.2°, p=0.001). This recovered to preoperative values 12 months postoperatively (3.2° ±0.2°, p=0.213). The shoulder-pelvis phase difference was decreased 3 months postoperatively (−98.9° ±6.8° vs. −77.2° ±7.2°, p=0.010), and recovered to pre-op values at the 12 months postoperative measurement (−89.6° ±6.9°, p=0.290). Walking speed did not influence the effect of surgery on phase difference or ROM. The pre-operative shoulders-thorax asymmetry decreased from 3.4° ± 2.4° to 0.6° ± 3.1° (p < 0.001). Shoulders-pelvis and thorax-pelvis asymmetry decreased from 10.0° ±3.7° to 2.8° ±4.3° (p < 0.001) and from 6.5° ± 3.4° to 1.8° ±3.2° (p=0.006) respectively.

Significance: No compensatory mechanisms could be identified in the relative motion between the shoulders and the thorax. Possibly, compensatory mechanisms are not required for normal gait after surgery. The asymmetry of the shoulders in the transversal plane improved without specific surgical strategies.

Introduction

Adolescent idiopathic scoliosis (AIS) patients suffer from a threedimensional deformity of the trunk and spine. It is the most common type of spinal deformity. The current gold standard for treatment of severe curves with the risk of progression is posterior spinal correction and fusion (PSF) using rigid rods and screws/hooks [1]. This results in a good correction of the deformity, but negatively influences spinal motion [2]. As a result, engagement in sports is negatively influenced [3]. Similarly, patients report decreased physical function and activity after surgery, but, although statistically significant, this effect is rather small [4,5].

These rather good outcomes are surprising as the spine is presumed to play a vital role in basic human functions such as gait by functioning as a shock absorber and some authors even state that it powers the pelvis and decreases energy consumption during gait [6–8]. Moreover, thorax-pelvis counter-rotation is regarded as an important factor in reducing angular momentum during gait [9,10]. Although the motion of the fused spinal segments is reduced [11,12], studies analysing the effect of PSF surgery in AIS patients on spatiotemporal gait parameters report no change in gait speed and stride width [13,14], and no to minimal changes in stride length, step length and cadence [11,13–15]. Therefore, an increase in motion distal or proximal to the fused spinal segments could be expected to maintain the thorax-pelvis counter-rotation. A previous study reported, in contrast to this hypothesis, a decrease in motion of the in the unfused spinal segments during gait after PSF surgery [16].

Alternatively, compensatory mechanisms could occur proximal to the fusion. AIS patients could exhibit a shift in the relative timing (i.e. increase in phase difference) between shoulders and thorax motion to maintain the out-of-phase timing in the transversal plane between the shoulders and the pelvis at higher walking speeds. This could consequently result in a higher ROM between the shoulders and the thorax. However, previous studies did not differentiate between the shoulders and the thorax, and consequently lacked a detailed analysis of relative shoulders-thorax kinematics. Hence, this study focussed on the relative motion in the transversal plane between the shoulders and the thorax. It was hypothesized that the phase difference and relative range of motion (ROM) between the shoulders and the thorax increase after surgery to compensate for the loss of spinal motion.

Methods

Some parts of the methods and included patients have previously been presented in this journal [11]. To provide stand-alone readability of this paper, those portions of the methods that are similar are repeated alongside the methods specific to this study.

Subjects

The study population consisted of AIS patients 12–18 years old who all underwent posterior spinal fusion surgery. All patients had a rightthoracic curve of the spine. The subjects did not suffer from any other disorders that could alter the gait pattern, had no history of spinal surgery and did not suffer from cognitive disorders. All participants and parents/guardians signed an informed consent form prior to the study. Approval of the local medical ethics committee (Independent Review Board Nijmegen, reference number: IRBN2010026) for the study was obtained.

A total of 27 patients were included for gait analysis. Two patients were unable to walk (i.e. they started running) at 1.94 and 2.22 m/s at the pre-operative measurement. At the 3 months postoperative measurement a similar observation was made for two other patients at 1.94 and 2.22 m/s and for one patient at 2.22 m/s only. Their data was excluded from the analysis. Regrettably, an additional four patients had to be excluded because their data files were corrupt and analysis was not possible. After exclusion of these patients, a total of 18 patients were available for analysis.

Two experienced spine surgeons performed all surgeries with the aid of intraoperative neuromonitoring. The preand postoperative Cobb-angle (depicting the severity of the scoliotic curve) was measured using standard radiographs. The age at surgery was 14.2 ± 1.6 years (mean ± standard deviation). The pre-operative Cobb angle was 57 ± 11°. Fourteen patients had a single curve and 4 patients a double curve. An average of 9.7 ± 1.8 spinal levels were fused. The median upper and lower instrumented vertebra were T5 (range T3–T6) and L1 (range T12–L4) respectively. The Cobb angle at three and twelve months postoperatively was 21° ± 6° and 22° ± 6° respectively.

Gait protocol

Measurements were performed pre-operatively, 3 months post-operatively, and 1 year post-operatively. For the gait analysis, 23 markers were placed on standardized positions on the upper body and lower extremities according to the Plug-in-Gait model. To limit any errors in marker placement a single experienced gait researcher placed the skin markers during every measurement. The 3D motions of the markers were registered using 10 camera's sampling at 100 Hz (VICON, Oxford Metrics, Oxford, UK). The shoulders were defined by two markers on the acromion processes, the thorax by the markers on the sternum, xiphoid and C7, and the pelvis by the markers on the posterior and anterior superior iliac spines. Prior to each measurement the anthropometric data (shoulder offset, leg length, body length, ankle width, knee width and weight) of each subject was determined. The gait measurements were performed with the subjects walking barefooted on a treadmill at seven speeds; 0.45, 0.78, 1.06, 1.35, 1.63, 1.94 and 2.22 m/s. Each trial lasted 1 min and was afterwards labelled frame-byframe to minimalize technical errors and ensure the quality of each trial.

Data analysis

The 3D position of the markers was filtered with a fourth order low pass Butterworth filter with a cut-off frequency of 5 Hz. A heel strike was defined as the instant when the heel marker is as far as possible to the front and the period between two consecutive heel strikes of the right leg defined a stride cycle. The position of the shoulders, thorax, and pelvis segments in the global coordinate system was calculated during the stride cycles in the transversal plane. For this, the orientation of the shoulders was calculated by projecting the line between the two shoulders skin markers on the transversal plane. The orientation of the thorax and pelvis segment was calculated using Euler decomposition, in the order: sagittal plane, frontal plane, and lastly transversal plane (axial rotation), consistent with ISB recommendations [17]. The mean position of the segments was defined by the angular orientation of the segment. This was calculated for the gait trials (averaged over all stride cycle and gait speeds). The same calculations were performed for the static trials, for which the subjects were standing still with the arms hanging next to their bodies. A positive shoulders-thorax and shoulderspelvis position indicates that the right shoulder is relatively protracted in the thorax/pelvis plane. The range of motion (ROM, maximal minimal angle) of the segments was defined per stride cycle. Subsequently, the average ROM over the middle 25 strides of each oneminute measurement was calculated to avoid any start-up and stop irregularities. For visualization, kinematic parameters were time normalized using a heel-strike-to-heel-strike gait cycle.

To calculate the phase differences between shoulders, thorax, and pelvis the transversal rotation angles of these segments were used. First, the mean time series of the rotation angle over the middle 25 strides for each segment was calculated. Subsequently, from the mean rotation angles time series during a gait cycle, a Fourier phase was calculated using a discrete Fourier transform. The Fourier phase of each segment was determined at the fundamental frequency of the gait cycle. Finally, the relative phase difference between the segments (shoulders-thorax, shoulders-pelvis and thorax-pelvis) was calculated by subtracting the Fourier phase of the pelvis, thorax and shoulders from each other.

Statistical analysis

A two-way repeated measures ANOVA was used to analyse the effect of measurement (pre-operatively, 3 months post-operatively, and 1 year post-operatively) and walking speed (0.45–2.22 m/s) and the related interaction effects on the outcome parameters. A significant interaction effect between the factors measurement and walking speed would indicate that measurement (i.e. fusion) had a different effect at different walking speeds. When a significant main effect of measurement or an interaction between measurement and speed was identified, post hoc Bonferroni tests were used to identify significant differences. The statistical analyses were performed using SPSS version 23 for Mac OS X. P-values < 0.05 were considered statistically significant.

Results

Kinematics and phase

Figs. 1 and 2 present the curve patterns of the shoulders, thorax, and pelvis in the transversal plane averaged across all patients at 0.45, 1.35 and 2.22 m/s during a full gait cycle. The figures show a vertical shift of the curves towards the zero axis after surgery, indicating a more symmetrical movement. Pre-operatively the phase differences of all analysed segments increased with increasing walking speed (Table 1, main effect walking speed $P \leq 0.004$). No significant interaction was identified between measurement and walking speed for any of the analysed segments regarding the phase difference.

The shoulders thorax phase difference was unaffected by surgery. At 3 months postoperatively the shoulders-thorax ROM was decreased (3.5° ± 0.2° versus 2.7° ± 0.2°, P = 0.001). This recovered to preoperative values 12 months postoperatively (3.2° ± 0.2°, P = 0.213). The shoulder-pelvis phase difference was decreased3 months postoperatively (−98.9° ± 6.8° vs. −77.2° ± 7.2°, P = 0.010), and recovered to pre-op values at the 12 months postoperative measurement (−89.6° ± 6.9°, P = 0.290). Walking speed did not influence the effect of surgery on phase difference or ROM. The pre-operative shoulders-thorax asymmetry decreased from 3.4° ± 2.4° to 0.6° ± 3.1° (P <0.001). Shoulders-pelvis and thorax-pelvis asymmetry decreased from 10.0° ± 3.7° to 2.8° ± 4.3° (P <0.001) and from 6.5° ± 3.4° to 1.8° ± 3.2° (P= 0.006) respectively.

Range of motion

The ROM of the shoulders in relation to the thorax is presented in Table 2. An increased shoulders-thorax ROM was observed at higher waking speeds pre-operatively with ROM increasing from 1.9° ±0.5° at 0.45 m/s to 4.9° ± 1.6° at 2.22 m/s (main effect walking of speed P <0.001). Averaged across all walking speeds, the shoulders-thorax ROM showed a small, but statistically significant, decrease at the first postoperative measurement (3.5° ± 0.2° versus 2.7° ± 0.2°, P = 0.001). At the second postoperative measurement the ROM recovered and was no longer significantly different from pre-operative values (3.2° ± 0.2°, P =0.213). Walking speed did not influence the effect of surgery on shoulders-thorax ROM (measurement*walking speed interaction P =0.419).

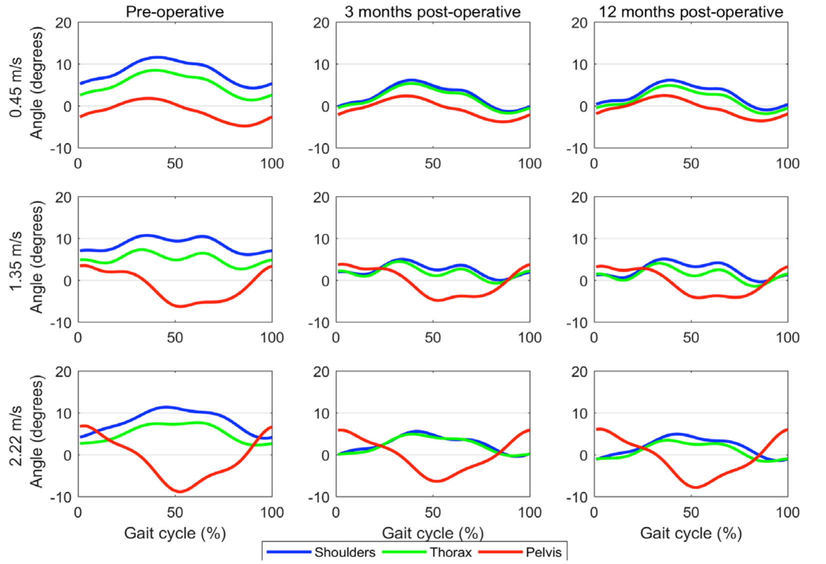


Fig. 1. Average transverse plane angle time series of the shoulders, thorax and pelvis relative to the global coordinate system.

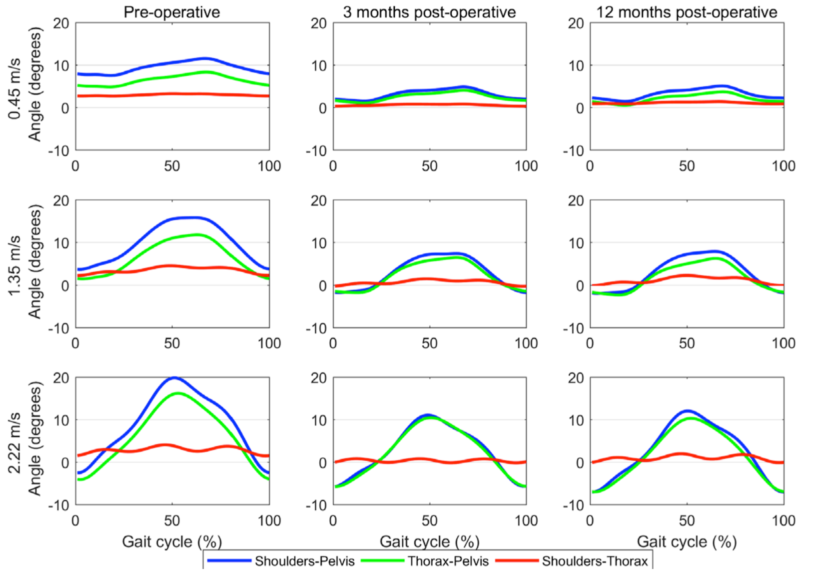


Fig. 2. Average transverse plane angle time series of the shoulders, thorax, and pelvis relative to each other.

Symmetry

Table 3 shows the mean angular position of the shoulders, thorax, and pelvis in relation to each other during gait and static trial. At baseline the shoulders were rotated 3.4° ± 2.4° (i.e. the right shoulder protruding anteriorly) in relation to the thorax during gait. This decreased to 0.6° ± 3.1° at the first postoperative measurement ($p < 0.001$) and this correction was maintained at the second postoperative measurement. Similar results were observed for the shoulders-pelvis and thorax-pelvis deformity, decreasing from 10.0° ± 3.7° to 2.8° ± 4.3° ($p < 0.001$) and from 6.5° ± 3.4° to 1.8° ± 3.2° ($P = 0.006$) respectively. During static trial there was a main effect ($P = 0.042$) for the shoulders-thorax mean position, but the post-hoc Bonferroni could not identify significant differences between the three measurements. The effect of surgery on shoulders-pelvis and thorax-pelvis mean position was similar during gait and static trials

Table 1 Effect of surgery on the phase differences between the shoulders, thorax, and pelvis.

	Measurement 1		**Measurement 2**		**Measurement 2**		**Two way RM-ANOVA**[a]	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**		
Shoulders-thorax								
0.45 m/s	−14.4	25.2	−11.4	13.0	−12.8	9.8	M:	0.240
0.78 m/s	−15.5	18.9	−14.5	18.4	−14.6	15.1	W:	0.004
1.06 m/s	−25.5	31.1	−17.0	25.3	−24.8	22.9	M*W:	0.841
1.35 m/s	−36.2	45.3	−33.2	51.5	−34.4	29.8		
1.63 m/s	−42.5	29.9	−29.1	37.6	−33.7	32.5		
1.94 m/s	−58.6	46.2	−45.6	67.1	−44.9	41.9		
2.22 m/s	−62.4	75.9	−48.8	72.9	−44.7	46.5		
Shoulders-pelvis								
0.45 m/s	−35.7	32.6	−26.0	13.6	−28.7	11.0	M:	0.003
0.78 m/s	−50.9	24.9	−52.4	32.7	−50.6	19.4	W:	< 0.001
1.06 m/s	−95.2	38.1	−83.3	29.8	−96.1	25.1	M*W:	0.143
1.35 m/s	−114.3	44.9	−91.4	47.0	−106.5	37.4		
1.63 m/s	−123.2	49.0	−83.1	55.9	−105.2	54.1		
1.94 m/s	−131.4	51.6	−96.8	64.1	−113.5	56.9		
2.22 m/s	−141.3	59.2	−107.5	73.2	−126.5	61.9		
Thorax-pelvis								
0.45 m/s	−21.3	18.4	−14.5	9.5	−15.8	16.9	M:	0.043
0.78 m/s	−35.5	19.0	−37.9	31.1	−36.0	24.6	W:	< 0.001
1.06 m/s	−69.6	35.9	−66.3	34.8	−71.3	33.2	M*W:	0.411
1.35 m/s	−78.1	32.4	−58.2	59.7	−72.1	32.3		
1.63 m/s	−80.7	39.9	−54.0	51.5	−71.5	34.3		
1.94 m/s	−72.8	37.0	−51.2	44.0	−68.5	47.5		
2.22 m/s	−79.0	59.7	−58.8	72.5	−81.8	55.2		

Results presented in degrees.

[a] M = measurement, W = walking speed, M*W = interaction. 1 = pre-operatively. 2 = 3 months postoperatively. 3 = 12 months postoperatively.

Table 2 Effect of surgery on therelative shoulders-thorax ROM.

	1		2		2		Two way RM-ANOVA[a]	
	Mean	SD	Mean	SD	Mean	SD		
0.45 m/s	1.9	0.5	1.6	0.5	1.6	0.4	M:	<0.001
0.78 m/s	2.5	21.	1.8	0.6	1.9	0.5	W:	<0.001
1.06 m/s	2.9	0.7	2.1	0.6	2.5	0.7	M*W:	0.419
1.35 m/s	3.6	1.0	2.6	0.7	3.1	0.9		
1.63 m/s	4.0	0.8	3.3	1.0	3.9	1.0		
1.94 m/s	4.7	1.3	3.8	1.2	4.4	1.3		
2.22 m/s	4.9	1.6	4.0	1.8	4.7	2.1		

1 = pre-operatively.
2 = 3 months postoperatively.
3 = 12 months postoperatively. Results presented in degrees.
[a] M = measurement, W = walking speed, M*W = interaction.

Table 3 Mean position.

	1		2		3		One way RM-ANOVA[a]	1 vs 2	1 vs 3	2 vs 3
	Mean	SD	Mean	SD	Mean	SD				
During gait trial										
Shoulders-thorax	−3.4	2.4	−0.6	3.1	−1.0	3.3	0.000	0.000	0.006	1.000
Shoulders-pelvis	−10.0	3.7	−2.9	4.6	−2.8	4.3	0.000	0.000	0.000	1.000
Thorax-pelvis	−6.5	3.4	−2.3	3.8	−1.8	3.2	0.000	0.000	0.000	1.000
During static trial										
Shoulders-thorax	−2.5	3.1	−0.5	3.0	−1.2	2.8	0.042	0.109	0.411	0.373
Shoulders-pelvis	−9.4	3.7	−3.3	3.8	−3.1	4.1	0.000	0.000	0.000	1.000
Thorax-pelvis	−6.8	3.7	−2.8	3.8	−1.9	3.1	0.000	0.002	0.001	0.762

1 = pre-operatively.
2 = 3 months postoperatively.
3 = 12 months postoperatively.
Results presented in degrees.
[a] p-Value presented for main effect of measurement.

Discussion

Previous studies provided valuable insights on the effect of posterior spinal correction and fusion of adolescent idiopathic scoliosis on gait parameters [11–16,18]. Despite inclusion of high and fixed walking speeds, no mechanisms in the lower extremities, spatiotemporal parameters or distally unfused spinal segments could be identified that compensate for the loss of motion of the fused spine [11,16]. The present study focused on possible compensatory mechanisms proximal to the fusion by analysing the relative phase differences and ROM between the shoulders, thorax, and pelvis at increasing walking speeds. Additionally, patient satisfaction with treatment is influenced by the cosmetic outcome of the surgery and conventional radiographs only allow for the analysis of the coronal and sagittal plane deformity. Therefore, the opportunity was taken to compare the asymmetry of the shoulders, thorax, and pelvis in the transversal plane before and after surgery.

In contrast to our hypothesis, the present study showed that the phase difference between the shoulders and the thorax did not significantly change after PSF surgery (Table 1). Still, a small but significant decrease in shoulders-pelvis phase difference was observed at the first postoperative measurement. This recovered to pre-operative values at the second postoperative measurement. Also contrary to our hypothesis, the shoulder-thorax ROM slightly decreased at the first postoperative measurement (Table 2). The ROM did return to pre-operative values at the latest follow-up indicating a recovery. This concurs with our previous analysis in the same patient group that demonstrated a similar decrease in thorax-pelvis ROM after scoliosis surgery, although this did not recover at the 12 months postoperative measurement [11].

Normal thorax-pelvis counter-rotation in the transversal plane is regarded as an important factor in reducing angular momentum and is essential in maintaining stability and limiting energy expenditure during gait [9,10]. Therefore, the decrease in phase difference found in the present study could result in decreased gait stability and increased energy consumption [19,20]. At the second follow-up measurement this phase difference showed a partial recovery towards pre-operative values and was no longer significantly different. It is noteworthy that, despite the decreased phase differences after spinal fusion, the AIS patients studied here were still able to transfer from a relatively inphase rotation between shoulders/thorax and pelvis at lower walking speeds to a more out-of-phase counter-rotation at higher walking speeds while at the same time demonstrating an increase in ROM, which is comparable to the pattern seen in healthy persons [21].

PSF surgery reduced the asymmetrical position of the shoulders relative to the pelvis and thorax to a nearly symmetrical movement around the zero axis during gait (Fig. 1 and Table 3). All patients had an anteriorly projected right shoulder at baseline. The nearly complete correction of this deformity after surgery was obtained without specific surgical strategies aiming at the rotational deformity of the shoulders. Previous studies demonstrated a similar reduction of shoulder-pelvis asymmetry as found here [22–25]. Additionally, this study shows that shoulder-thorax asymmetry is also spontaneously corrected after PSF (i.e. without any specific surgical techniques). In contrast to the gait trial, PSF surgery had no effect on shoulders-thorax asymmetry during standing. However subjects were asked to stand up straight and still during the static trial. Possibly, this could have led to the observed reduction in transversal asymmetry. Similar results were observed in a previous study by Nishida et al. [26]. Unfortunately, the group was too small and demonstrated too little variation in shoulder deformity for a correlation with patient reported cosmetic appearance.

For this study increasing walking speeds were applied. This was done as it was hypothesized that compensatory mechanisms would not be present during preferred walking, but could only be identified at more strenuous/faster walking speeds when more thorax-pelvis counter rotation occurs. This provided unique advantages over previous studies, but to the best of our knowledge, it is unknown what the effect of the walking speeds would have on shoulders-thorax kinematics in healthy subjects so no comparisons can be made. Also, the present study is limited by the lack of a control group of healthy subjects. The use of a larger sample size would allow for a more in-depth analysis based on curve type and curve severity. Lastly, a set of only two skin markers was applied to define the shoulders and no markers were attached to the arms. This resulted in a two-fold limitation of our analysis. First, the complexity of the shoulder girdle, with its interaction between hu merus, scapula, and thorax, could not be fully modelled. This prevented a true three-dimensional analysis of the shoulder girdle in 3D. Second, with the lack of skin markers on the arms the present study could not analyse the role of arm swing.

In summary, to explain the limited effect of PSF surgery on gait parameters, the present and previous studies sought evidence of mechanisms that compensated for the loss in spinal motion. Although total body symmetry is improved, no compensatory mechanisms could be identified in the relative motion between the shoulders and the thorax (this study), the distally unfused spine [16] or the lower extremities [11]. A reason for the lack of substantial compensatory mechanisms could be that a considerable part of the fusion includes the lower thoracic spine, which is relatively stiff during gait compared to other spinal regions [26,27]. On top of this, scoliosis induces an additional stiffness, as the scoliotic thoracic spine was shown to have a smaller transversal plane ROM compared to healthy controls and the ROM decreases with increasing curve severity [28,29]. Hence, the difference between preand postoperative spinal motion of the fused region could be so small that compensatory mechanisms are minimally required. Nevertheless, angular momentum during gait could increase in patients with reduced spinal motion. Larger arm swing and/or rotational forces between foot and floor, which were not analysed in the present study, may compensate increased angular momentum.

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