Adolescent idiopathic scoliosis: spinal fusion and beyond

Holewijn, R.M.

2019

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

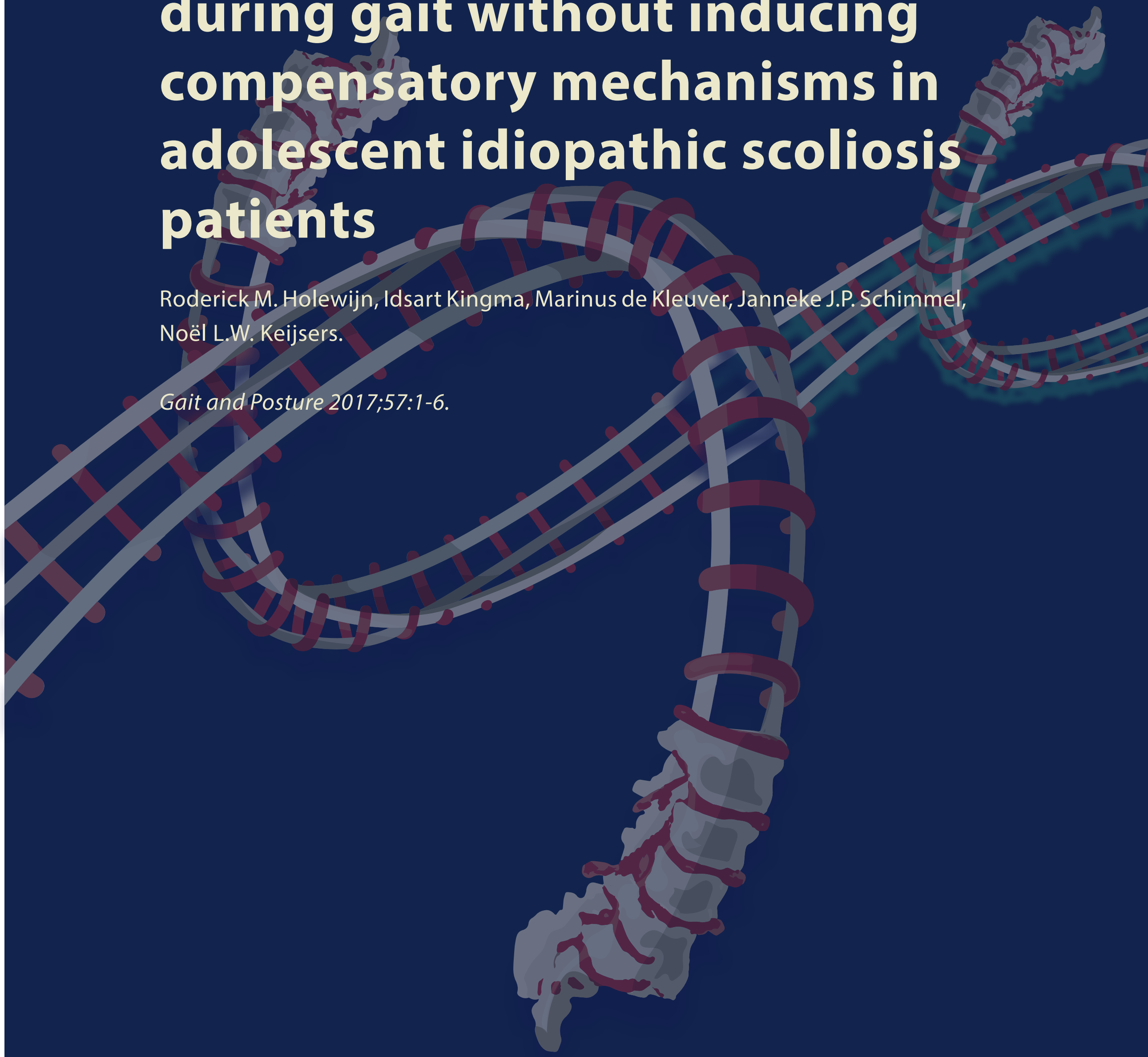
citation for published version (APA)
Holewijn, R. M. (2019). *Adolescent idiopathic scoliosis: spinal fusion and beyond*. [PhD-Thesis - Research and graduation internal, Vrije Universiteit Amsterdam].

Chapter 4

Spinal fusion limits upper body range of motion during gait without inducing compensatory mechanisms in adolescent idiopathic scoliosis patients

Roderick M. Holewijn, Idsart Kingma, Marinus de Kleuver, Janneke J.P. Schimmel, Noël L.W. Keijsers.

Gait and Posture 2017;57:1-6.



Abstract

Introduction: Previous studies show a limited alteration of gait at normal walking speed after spinal fusion surgery for adolescent idiopathic scoliosis (AIS), despite the presumed essential role of spinal mobility during gait. This study analyses how spinal fusion affects gait at more challenging walking speeds. More specifically, we investigated whether thoracic-pelvic rotations are reduced to a larger extent at higher gait speeds and whether compensatory mechanisms above and below the stiffened spine are present.

Methods: 18 AIS patients underwent gait analysis at increasing walking speeds (0.45 to 2.22 m/s) before and after spinal fusion. The range of motion (ROM) of the upper (thorax, thoracic-pelvic and pelvis) and lower body (hip, knee and ankle) was determined in all three planes. Spatiotemporal parameters of interest were stride length and cadence.

Results: Spinal fusion diminished transverse plane thoracic-pelvic ROM and this difference was more explicit at higher walking speeds. Transversal pelvis ROM was also decreased but this effect was not affected by speed. Lower body ROM, step length and cadence remained unaffected.

Discussion: Despite the reduction of upper body ROM after spine surgery during high speed gait, no altered spatiotemporal parameters or increased compensatory ROM above or below the fusion (i.e. in the shoulder girdle or lower extremities) was identified. Thus, it remains unclear how patients can cope so well with such major surgery. Future studies should focus on analyzing the kinematics of individual spinal levels above and below the fusion during gait to investigate possible compensatory mechanisms within the spine.

Introduction

Adolescent idiopathic scoliosis (AIS) is a three-dimensional deformity of the spine, which can lead to pain and a lower self-image [1]. AIS patients are imbalanced in the medial-lateral direction and have a reduced upper body range of motion (ROM) during gait [2,3]. To correct the deformity and/or to prevent deformity progression, a surgical correction and fusion of the spine is a commonly performed procedure [4]. Clinical results show a significant correction of the deformity and only a minor decrease in physical function [1]. In particular, a physical activity in daily life such as gait is hardly affected and some gait parameters even improve after surgery. Specifically, improvement in angular symmetry of the upper body and an increase in ROM of frontal plane pelvis and hip motions during gait have been reported [5,6]. However, ROM of the thorax is significantly reduced during gait [7,8]. Spatiotemporal parameters seem not to be altered by the surgery except for cadence, which shows a consistent minor decrease [6,8,9].

The limited effect of spinal fusion on gait is remarkable because the spine plays an essential role in gait. The spine functions as a shock absorber and is also seen as the engine that drives the pelvis and reduces energy consumption during gait [10–13]. Gait analysis in the currently available research has been performed at a preferred walking speed. However, gait at preferred walking speed might not be challenging enough to result in substantial effects of spinal fusion. In healthy subjects, an increase in walking speed caused an increase in cadence, step length, and angular motion in the transverse plane of the pelvis, [14,15]. The pelvic angular displacement increased while thoracic angular displacement decreased, resulting in an increased relative thoracic-pelvic angular rotation in the transverse plane [14,15].

The increased transversal thoracic-pelvic rotation at higher walking speeds that is observed in healthy subjects could be troublesome for surgically treated AIS patients since the fusion causes a limitation of spinal motion. The limited spinal motion could result in a more synchronous movement of thorax and pelvis or the inability to increase pelvic motion at higher walking speeds. Both would cause a decrease in transverse plane thoracic-pelvic rotation. As a consequence of decreased transversal pelvis motion, the ability to increase step length could be limited and cadence should increase to increase walking speed. Another possibility is that a compensatory increase in motion takes place in the unfused segments of the spine, which would limit the negative effect of spinal fusion on transversal thoracic-pelvic rotation. However, this would lead to increased rotational motion and loading of the unfused spine, potentially leading to overloading and increased disc degeneration over the years. Hence, identifying compensatory mechanisms could help understand the effect of a fused spine on physical function and possibly result in further improvement of current treatments for AIS.

The present study aimed to establish how, in AIS patients, the effect of spinal correction and fusion interacts with gait speed. More specifically, we investigated whether, after surgery, thoracic-pelvic rotations are reduced to a larger extent at higher gait speeds and what coping mechanisms take place to compensate for this limitation in adapting to higher gait speed. Results will be compared between pre-operative, and 3 months and 12 months postoperative measurements.

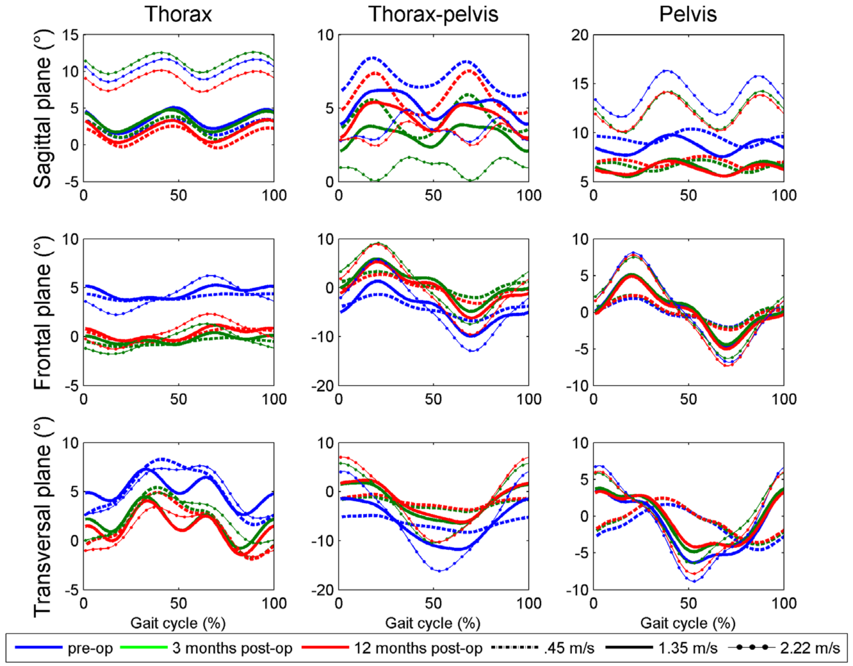


Fig. 1. Angles during the gait cycle. Blue = 0.45 m/s, green = 1.35 m/s, red = 2.22 m/s. Straight = pre-operatively, striped = 3 months post-operatively, checkered = 12 months postoperatively. The thoracic-pelvic angle was calculated by subtracting the pelvis angle from the thorax angle.

Methods

Subjects

Medical and ethical approval was obtained from the local medical ethics committee (Independent Review Board Nijmegen, reference number: IRBN2010026). All participants and parents/guardians signed an informed consent prior to the study activities.

The study population consisted of AIS patients between 12 and 18 years old who all underwent posterior spinal fusion surgery. All patients had a right-thoracic curve of the spine. The subjects did not suffer from any other disorders that could alter the gait pattern (i.e. no neurological/musculoskeletal disorders), had no history of spinal surgery and did not suffer from cognitive disorders.

In total 27 patients were selected 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 post-operative measurement two other patients were unable to walk at 1.94 and 2.22 m/s and one patient at 2.22 m/s. Four patients were excluded because of corrupt data files. After exclusion, 18 patients were included in this study.

Two experienced spine surgeons performed the surgery. All procedures were performed with the aid of intraoperative neuromonitoring. The preand postoperative Cobb-angle was measured using posterior-anterior standing radiographs of the entire spine. The age at surgery was 14.2 ± 1.6 years (mean ± standard deviation). The pre-operative Cobb angle was 57° ± 11°. 14 patients had a single curve and 4 patients a double curve. On average 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. Three months postoperatively the Cobb angle was reduced to 21° ± 6°. At 12 months post-operatively this was 22° ± 6°.

Table 1 Results of the two-way RM-ANOVA for the kinematic parameters. P-values for 'measurement' and 'speed' depict the main effects, while 'interaction' depicts the interaction between these factors. Significant values (P < 0.05) are bold. Mean values and standard deviations of the ROM are provided as Supplementary material (Table 3).

	Measurement	Speed	Interaction
Thorax			
Transversal	**0.692**	**0.001**	0.724
Frontal	**0.021**	**<0.001**	**0.026**
Sagittal	**<0.001**	0.092	0.078
Thorax-pelvis			
Transversal	**<0.001**	**<0.001**	**<0.001**
Frontal	0.319	**<0.001**	**0.027**
Sagittal	**<0.001**	**0.001**	**<0.001**
Pelvis			
Transversal	**<0.001**	**<0.001**	0.275
Frontal	0.567	**<0.001**	0.052
Sagittal	**<0.001**	**<0.001**	0.164
Hip			
Transversal	0.248	**0.002**	0.266
Frontal	0.488	**<0.001**	0.060
Sagittal	**0.004**	**<0.001**	0.749
Knee			
Sagittal	0.108	**<0.001**	0.276
Ankle			
Transverse	**<0.001**	**0.002**	0.170
Sagittal	0.510	**<0.001**	**0.043**

Gait protocol

Gait analysis was performed pre-operatively, 3 months post-operatively and 12 months 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. The 3D movements of the markers were registered using 10 camera's sampling at 100 Hz (VICON, Oxford Metrics, Oxford, UK). The pelvis is defined using the markers on the posterior and anterior superior iliac spines. The thorax is defined by the markers on the AC-joints, sternum, C7 and T10. 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 barefooted on a treadmill at seven different velocities; 0.45, 0.78, 1.06, 1.35, 1.63, 1.94 and 2.22 m/s. Each trial lasted about 1 min and was afterwards labeled 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.

The kinematic parameters of interest were the range of motion of the upper (thorax, thoracic-pelvic and pelvis) and lower body (hip, knee and ankle) and calculated using the Plug-in-Gait model. The thoracicpelvic angle was calculated by subtracting the pelvis angle from the thorax angle for every data sample. The range of motion (ROM, maximal – minimal angle) was defined per step cycle. Subsequently, the average ROM over the middle 25 strides of each one-minute measurement was calculated to avoid any start-up and stop irregularities. The ROM was calculated in the frontal, transversal and sagittal plane. The ROM was used to express the angular movement of a body segment during gait. Finally, we analyzed the spatiotemporal gait parameters stride length and cadence. For visualization, kinematic parameters were time normalized using a heel-strike-to-heel-strike gait cycle and subsequently averaged over 25 steps.

Statistical analysis

A two-way repeated measures ANOVA was used to analyze the effect of measurement (pre-operatively, 3 months post-operatively and 12 months 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 was most important because it indicates a possible effect of fusion at higher walking speeds. In case of a significant main effect of measurement or an interaction between measurement and speed, post hoc Bonferroni tests were used to identify significant differences. The statistical analyses were performed using SPSS for Mac OS X. P-values less than 0.05 were considered statistically significant. Differences between measurements were expressed in percentages.

Results

Kinematics of the upper body

Fig. 1 shows the angles of the thorax, thoracic-pelvis and pelvis in the sagittal, frontal and transversal planes averaged across all patients at 0.45, 1.35 and 2.22 m/s during a full gait cycle. The curves show a similar wave pattern for the three measurements. However, there is a visible shift between the pre-operative and the post-operative angles for the thorax and thoracic-pelvis in all three planes and for the pelvis in the sagittal plane.

The two-way repeated measures ANOVA for the ROM revealed an interaction effect between measurement and walking speed for the thoracic-pelvis in all planes and for the thorax in the frontal plane (Table 1). Subsequent post-hoc Bonferroni tests indicated a significant difference between preand post-operative measurements, which was more pronounced at higher walking speeds (Fig. 2). The exact ROM values per measurement and per walking speed are presented in Table 3, which is available as Supplementary data (see Appendix A).

No interaction between measurement and speed was detected in pelvis ROM but there was a main effect for measurement in the transversal and sagittal planes. The pelvis ROM in transverse plane decreased by 13% at 3 months post-operatively (11.8° ± 3.1°) vs. preoperatively (13.1° ± 2.7°), which remained decreased at 12 months post-operatively (11.1 ± 3.2). Similarly, the pelvis ROM in sagittal plane decreased with 11% at 3 and 15% at 12 months post-operatively (pre-operatively: 4.7° ± 1.0° vs. 3 months post-operatively: 4.2° ± 0.6° and vs. 12 months post-operatively: 4.0° ± 0.7°).

Thorax sagittal plane ROM showed a decrease of 9% at 3 months post-operatively (5.0° ± 1.0°) versus pre-operatively (5.5° ± 1.2°), which remained decreased at 12 months post-op (4.9° ± 0.9°). Thorax ROM in transverse plane was not significantly affected by the surgery.

Kinematics of the lower extremities and spatiotemporal parameters

Results of the two-way RM-ANOVA for the ROM of the lower extremities are presented in Table 1. An interaction between measure ment and walking speed was found for the sagittal ankle ROM but post hoc testing revealed no significant differences. No other interactions were identified.

Small main effects for measurement were found for hip and ankle ROM.ROMofthe hip in the sagittal plane was significantly increased at 3 months post-operatively (44.7° ± 3.4° vs. 46.8° ± 2.8°) but this was no longer significant at 12 months post-operatively (46.6° ± 1.0°). Similarly, transverse ankle ROM was increased at 3 months postoperatively (26.4° ± 4.6° vs. 28.5° ± 4.4°) but returned to pre-op values at 12 months post-operatively (25.2° ± 3.5°).

For cadence, no interaction but a significant main effect for the factor measurement was found (Table 2. However, post hoc Bonferroni tests revealed no significant differences between any of the measurements. A significant interaction between measurement and walking speed was found for stride length (Table 2). Post hoc tests could only demonstrate a significant difference at 1.35 m/s showing an increase of 4% after surgery (pre-operatively: 0.51 ± 0.002 m vs. 12 months post-operatively: 0.53 ± 0.002 m), with no difference between 3 and 12 months post-operatively.

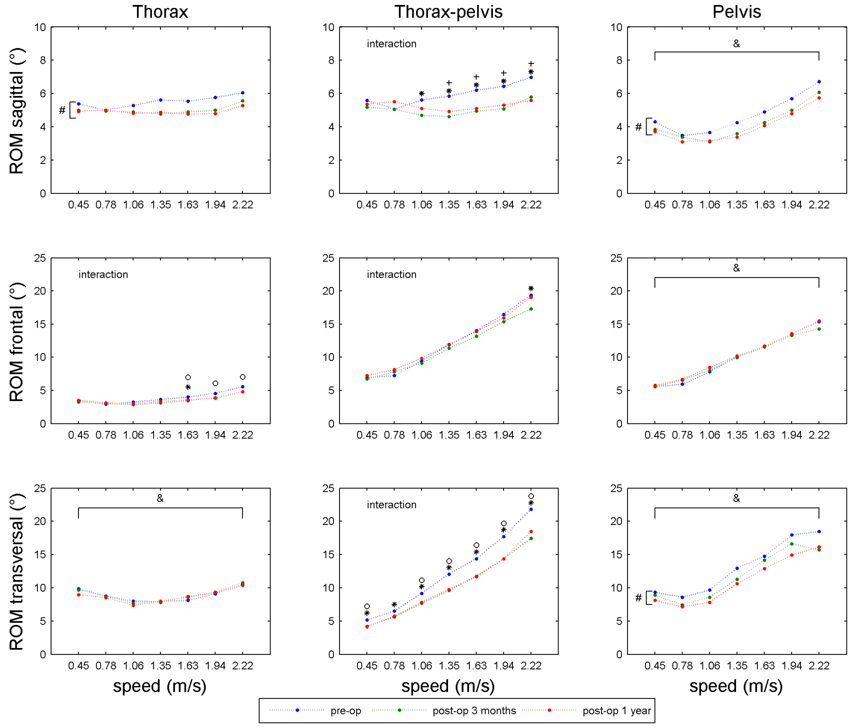


Fig. 2. Range of motion of the upper body during gait. Significant effects (P < 0.05) based on a post hoc Bonferroni analysis between measurements (pre-operatively, 3 months post- operatively and 12 months post-operatively) are marked with symbols.

*: significant difference between pre-operatively and 3 months post-operatively.

o: significant difference between pre-operatively and 12 months post-operatively.

+: significant difference between 3 months post-operatively and 12 months post-operatively. & : significant main effect for velocity.

#: significant main effect for measurement.

Discussion

The main purpose of this investigation was to establish how, in AIS patients, the effect of spinal correction and fusion interacts with gait speed. Additionally, if such limitation was present, this study tried to identify if and what coping mechanisms take place to compensate for this limitation.

This study is unique because gait analysis was performed at low, medium and high walking speeds. Gait at higher walking speeds requires an increased transverse thoracic-pelvic motion as compared to preferred walking speed [14,15]. This study demonstrates that spinal fusion indeed diminished transverse thoracic-pelvic ROM. Although this decrease was present at all walking speeds, it was more explicit at higher walking speeds. The decreased transverse thoracic-pelvic ROM was accompanied by a decrease in transversal pelvis ROM. Besides a decrease in the transversal plane, thoracic-pelvic ROM also decreased in the sagittal plane after surgery. This was in accordance with decreases found in both thorax and pelvis sagittal plane ROM. Lastly, thorax ROM in the frontal plane was also decreased at higher walking speeds after spinal fusion. It is important to note that the observed decreases in thoracic-pelvic ROM can also be partly caused by a more synchronous movement of thorax and pelvis after spinal fusion [15]. However, this was not the only reason as pelvis and thorax motion reduced as well. A more detailed analysis of phase shifts between pelvis and thorax was beyond the scope of this paper.

Because of the decrease in transversal pelvic ROM after spinal fusion, it was hypothesized that stride length should decrease as a result. As a way of coping with this decrease, patients could have increased cadence (i.e. steps/min.) to maintain the ability of walking at higher speeds. This study showed that surgery did not alter the ability of patients to walk at higher walking speeds. Before surgery, two patients were unable to walk at higher speeds without starting to run, but after surgery this problem was not observed in these two patients. After surgery, this was a similar problem for three other patients who were able to walk (i.e. and not start running) at higher speeds before surgery. Surprisingly, patients were still able to increase stride length at higher speeds. Moreover, despite the reduction of pelvis ROM at higher gait speeds, step length was not reduced and cadence was not increased. In fact, cadence actually showed a small but statistically non-significant decrease after surgery. Earlier studies demonstrated a similar but statistically significant decrease [6,9].

Thus, this study could not identify the hypothesized coping strategies in the spatiotemporal parameters.

Coping strategies could also be present in the lower body. As was described earlier, a significant interaction between measurement and walking speed was found for the thoracic-pelvic and thorax ROM; the ROM was decreased post-operatively at higher walking speeds. Therefore, an altered ROM of one of the lower body angles at higher walking speeds (i.e. also an interaction effect) could be a mechanism to cope with the decrease in upper body ROM. However, no indications of post-surgical altered ROM of the lower body at higher speeds were found in this study.

There are three remaining possible mechanisms that could explain why spinal fusion had a very limited effect on gait. Firstly, it could be possible that the non-fused segments show a compensatory increase in ROM during gait, as has also been described during static bending tests [16]. Secondly, the spinal segments operated during surgery could have a limited effect on normal gait even when not fused. Syczweska et al. have shown that the thoracic T7-T12 region is the stiffest region of the whole spine during gait [17]. While the spinal levels C7-T7 and T12-L5 bend to the support and swing leg respectively, the T7-T12 region remains in roughly the same position during the entire gait cycle. Since a large proportion of the fused levels is situated in the already stiff T7-T12 region, the effect of surgery on gait could be limited. Thirdly, compensatory mechanisms could differ between patients thus making it very difficult to identify one universal compensatory mechanism in the whole group of surgically treated AIS patients. Indeed, our patient group showed a variation in fused spine levels, single/double curves and highest/lowest instrumented vertebra. The sample size was too small to allow for a sub-group analysis.

A limitation of this study is the absence of healthy controls. However, our main purpose was to evaluate the effect of the surgery and we therefore used the pre-operative data as the own control of the patients. Also, data of normal adolescent controls is available from previous publications [2,18,19]. In this study, consecutive gait measurements were performed. Unfortunately, besides using percutaneous bone pins, there are no techniques available to replicate the exact marker position between measurements. In the present study an experienced gait researcher used bony landmarks to place the markers. This limited a possible change in marker position between measurements.

In conclusion, transversal thoracic-pelvic ROM was significantly decreased at higher walking speeds after spinal fusion. While the pelvis ROM decreased, surgery did not have substantial effects on lower limb ROM, step length or cadence. Suprisingly no general coping mechanisms for the decrease in upper body ROM could be identified, and patients were still able to walk with relatively unaltered spatiotemporal parameters at high speeds. It remains unclear how patients can cope so well with such major surgery. Future studies should focus on analyzing the kinematics of individual spinal levels above and below the fusion during gait to investigate possible compensatory mechanisms within the spine.

Table 2 Cadence, stride length and stride time (mean (SD)) and results of the two-way RM-ANOVA. Significant values ($P < 0.05$) are bold. NS: not significant. *M: Measurement, W: Walking speed.

	Pre-operatively	**3 months post-operatively**	**12 month post-operatively**	**Main effects* (P value)**	**Interaction***
Cadence (steps/min)					
0.45 m/s	40.63 (5.30)	38.74 (4.17)	37.94 (2.79)	M: 0.017	NS
0.78 m/s	48.92 (3.61)	47.67 (2.42)	47.07 (2.65)	W: < 0.001	
1.06 m/s	54.92 (2.79)	54.14 (2.11)	53.52 (2.09)		
1.35 m/s	60.24 (2.97)	59.67 (2.36)	59.01 (1.91)		
1.63 m/s	66.20 (3.63)	65.25 (2.56)	64.42 (1.96)		
1.94 m/s	72.41 (4.47)	71.88 (3.65)	70.68 (2.81)		
2.22 m/s	79.15 (4.68)	79.58 (4.29)	78.26 (4.61)		
Stride length (meters)					
0.45 m/s	0.23 (0.06)	0.23 (0.05)	0.19 (0.07)	M: 0.642	M*W: 0.047
0.78 m/s	0.31 (0.06)	0.31 (0.07)	0.34 (0.04)	W: < 0.001	
1.06 m/s	0.44 (0.03)	0.42 (0.04)	0.42 (0.05)		
1.35 m/s	0.51 (0.02)	0.53 (0.02)	0.53 (0.02)		
1.63 m/s	0.62 (0.04)	0.60 (0.04)	0.61 (0.03)		
1.94 m/s	0.71 (0.07)	0.70 (0.06)	0.71 (0.08)		
2.22 m/s	0.76 (0.08)	0.82 (0.08)	0.79 (0.10)		

Conflict of interest statement

The authors declare there are no conflicts of interest.

Appendix A. Supplementary data

Table 3. Range of motion in degrees at all walking speeds in three planes. *1: pre-operatively, 2: 3 months post-operatively, 3 = 12 months post-operatively.

		Measurement*	Walking speed						
			0.45 m/s	0.78 m/s	1.06 m/s	1.35 m/s	1.63 m/s	1.94 m/s	2.22 m/s
Thorax	Sagittal	1	5.4 (1.8)	5.0 (1.2)	5.3 (1.2)	5.6 (1.4)	5.5 (1.2)	5.8 (1.5)	6.0 (1.5)
		2	5.0 (1.4)	5.0 (1.0)	4.9 (0.9)	4.8 (1.0)	4.9 (1.1)	5.0 (1.5)	5.6 (1.5)
		3	4.9 (0.9)	5.0 (1.1)	4.8 (0.8)	4.9 (0.9)	4.8 (1.0)	4.8 (1.4)	5.3 (1.5)
	Frontal	1	3.5 (1.1)	2.9 (0.9)	3.2 (0.7)	3.6 (1.0)	4.0 (0.9)	4.6 (0.9)	5.5 (1.3)
		2	3.3 (1.2)	3.0 (0.9)	2.9 (0.7)	3.1 (0.8)	3.5 (0.9)	3.9 (1.0)	4.8 (1.3)
		3	3.5 (1.2)	3.1 (1.0)	3.0 (0.8)	3.3 (0.8)	3.6 (0.8)	3.8 (0.9)	4.8 (1.0)
	Transversal	1	9.9 (4.4)	8.8 (3.9)	8.0 (2.7)	8.0 (2.0)	8.1 (2.4)	9.1 (2.9)	10.6 (3.1)
		2	9.7 (3.4)	8.7 (2.2)	7.7 (1.7)	7.8 (1.7)	8.7 (2.4)	9.4 (2.8)	10.8 (4.7)
		3	8.9 (2.7)	8.5 (2.0)	7.4 (1.6)	8.0 (1.9)	8.6 (2.8)	9.3 (3.3)	10.4 (3.8)
Thorax-pelvis	Sagittal	1	5.6 (1.8)	5.0 (1.1)	5.6 (1.1)	5.8 (1.8)	6.2 (1.6)	6.4 (1.4)	7.0 (1.9)
		2	5.2 (1.8)	5.0 (1.4)	4.7 (1.2)	4.6 (1.0)	4.9 (1.1)	5.1 (1.2)	5.8 (1.4)
		3	5.4 (1.5)	5.5 (1.5)	5.1 (1.2)	4.9 (1.1)	5.1 (1.3)	5.3 (1.3)	5.6 (1.6)
	Frontal	1	6.9 (2.4)	7.3 (2.3)	9.5 (2.3)	11.9 (2.5)	14.0 (2.8)	16.5 (3.3)	19.4 (4.9)
		2	6.7 (2.5)	7.8 (2.2)	9.1 (1.9)	11.3 (2.2)	13.2 (2.5)	15.4 (2.9)	17.3 (3.7)
		3	7.2 (2.3)	8.2 (2.3)	9.8 (2.3)	11.9 (2.6)	13.9 (3.0)	15.9 (3.4)	19.0 (4.3)
	Transversal	1	5.2 (1.6)	6.5 (2.0)	9.2 (2.3)	12.1 (3.5)	14.4 (3.7)	17.7 (4.5)	21.8 (4.3)
		2	4.2 (1.5)	5.6 (1.5)	7.7 (2.4)	9.6 (3.0)	11.8 (3.5)	14.4 (3.8)	17.4 (4.5)
		3	4.2 (1.1)	5.7 (1.8)	7.8 (2.3)	9.8 (2.8)	11.6 (3.5)	14.4 (3.8)	18.5 (5.3)
Pelvis	Sagittal	1	4.3 (0.8)	3.5 (0.9)	3.7 (1.0)	4.3 (1.4)	4.9 (1.3)	5.7 (1.2)	6.7 (1.7)
		2	3.9 (0.7)	3.4 (0.8)	3.1 (0.6)	3.6 (0.8)	4.3 (0.8)	5.0 (0.8)	6.1 (1.1)
		3	3.7 (0.9)	3.1 (0.7)	3.1 (0.7)	3.4 (0.7)	4.1 (0.8)	4.8 (1.0)	5.7 (1.1)
	Frontal	1	5.5 (1.7)	5.9 (1.9)	7.8 (2.3)	10.1 (2.5)	11.7 (2.6)	13.5 (2.8)	15.4 (3.8)
		2	5.5 (1.7)	6.6 (1.8)	8.0 (2.0)	10.0 (2.1)	11.6 (2.2)	13.3 (2.5)	14.3 (3.4)
		3	5.8 (1.7)	6.7 (2.0)	8.5 (2.4)	10.2 (2.7)	11.7 (2.9)	13.5 (2.9)	15.5 (3.6)
	Transversal	1	9.3 (3.5)	8.6 (2.5)	9.7 (2.3)	13.0 (4.1)	14.8 (3.9)	17.9 (4.5)	18.5 (5.4)
		2	8.9 (2.7)	7.4 (2.1)	8.6 (2.8)	11.3 (4.0)	14.2 (4.3)	16.6 (5.1)	15.7 (5.1)
		3	8.1 (2.5)	7.2 (2.0)	7.8 (2.1)	10.6 (3.6)	12.9 (5.2)	14.9 (5.7)	16.1 (6.4)
Hip	Sagittal	1	31.4 (4.0)	35.3 (3.1)	40.0 (3.5)	46.2 (3.6)	49.6 (3.8)	53.5 (4.2)	56.7 (4.7)
		2	33.9 (3.1)	38.1 (3.1)	42.3 (3.2)	47.6 (3.2)	51.8 (3.3)	55.5 (3.3)	58.6 (4.9)
		3	33.3 (3.3)	37.6 (2.8)	42.3 (3.2)	47.6 (3.5)	51.8 (2.9)	55.6 (2.8)	58.3 (3.4)
	Frontal	1	9.2 (1.9)	10.0 (1.8)	12.3 (2.3)	14.8 (2.5)	16.3 (2.5)	17.9 (2.8)	19.8 (3.4)
		2	9.9 (2.3)	11.4 (2.2)	13.0 (2.6)	15.0 (2.5)	16.5 (2.5)	18.5 (3.0)	19.7 (3.3)
		3	9.7 (2.4)	11.1 (2.5)	13.0 (2.8)	14.8 (2.9)	16.4 (2.9)	18.0 (2.8)	20.0 (3.2)
	Transversal	1	17.0 (6.0)	19.4 (7.0)	20.9 (7.6)	20.4 (7.6)	19.1 (7.4)	18.3 (6.5)	19.0 (6.5)
		2	18.1 (4.2)	20.4 (5.3)	21.7 (5.3)	21.2 (5.2)	20.4 (4.8)	18.8 (4.6)	18.4 (3.5)
		3	15.8 (5.3)	17.9 (6.2)	18.9 (6.4)	18.1 (6.1)	17.4 (5.5)	16.3 (5.2)	16.3 (5.9)
Knee	Sagittal	1	46.7 (5.0)	51.2 (4.1)	54.3 (3.5)	55.9 (3.4)	57.4 (4.1)	60.1 (4.1)	62.9 (5.5)
		2	47.8 (5.3)	53.0 (5.0)	55.8 (3.9)	56.7 (4.6)	58.3 (4.6)	61.4 (4.5)	63.8 (6.6)
		3	47.2 (4.6)	51.7 (4.6)	55.5 (4.6)	56.7 (3.8)	59.0 (4.2)	61.9 (3.7)	65.1 (4.9)
Ankle	Sagittal	1	20.6 (4.9)	24.0 (5.4)	26.8 (5.5)	29.2 (5.5)	28.7 (5.3)	29.4 (5.7)	33.0 (6.9)
		2	21.9 (4.7)	25.1 (5.4)	27.6 (5.1)	28.6 (4.5)	28.5 (3.9)	28.9 (4.7)	35.3 (6.4)
		3	22.1 (4.8)	25.1 (5.4)	27.7 (5.1)	29.4 (5.1)	29.0 (4.5)	30.3 (6.0)	33.0 (6.8)
	Transversal	1	23.6 (5.8)	26.1 (5.5)	26.9 (5.6)	26.6 (4.8)	26.0 (4.3)	27.0 (5.4)	28.5 (5.9)
		2	25.5 (4.8)	27.5 (5.9)	28.8 (4.7)	29.0 (4.9)	28.6 (4.1)	29.5 (5.4)	30.6 (6.7)
		3	21.3 (3.7)	23.9 (4.0)	24.9 (3.4)	24.9 (3.1)	25.6 (4.2)	27.1 (4.9)	28.4 (6.1)

References

1. Asher M a, Burton DC. Adolescent idiopathic scoliosis: natural history and long term treatment effects. Scoliosis 2006;1:2.
2. Mahaudens P, Banse X, Mousny M, Detrembleur C. Gait in adolescent idiopathic scoliosis: Kinematics and electromyographic analysis. Eur Spine J 2009;18:512–21.
3. Giakas G, Baltzopoulos V, Dangerfield PH, Dorgan JC, Dalmira S. Comparison of gait patterns between healthy and scoliotic patients using time and frequency domain analysis of groud reaction forces. Spine (Phila Pa 1976) 1996;21:2235–42.
4. Kleuver M De, Lewis SJ, Germscheid NM, Kamper SJ, de Kleuver M, Lewis SJ, et al. Optimal surgical care for adolescent idiopathic scoliosis : an international consensus. Eur Spine J 2014;23:2603–18.
5. Paul JC, Patel A, Bianco K, Godwin E, Naziri Q, Maier S, et al. Gait stability improvement after fusion surgery for adolescent idiopathic scoliosis is influenced by corrective measures in coronal and sagittal planes. Gait Posture 2014;40:510–5.
6. Mahaudens P, Detrembleur C, Mousny M, Banse X. Gait in thoracolumbar/lumbar adolescent idiopathic scoliosis: Effect of surgery on gait mechanisms. Eur Spine J 2010;19:1179–88.
7. Engsberg JR, Lenke LG, Reitenbach AK, Hollander KW, Bridwell KH, Blanke K. Prospective evaluation of trunk range of motion in adolescents with idiopathic scoliosis undergoing spinal fusion surgery. Spine (Phila Pa 1976) 2002;27:1346–54.
8. Lenke LG, Engsberg JR, Ross S a, Reitenbach A, Blanke K, Bridwell KH. Prospective dynamic functional evaluation of gait and spinal balance following spinal fusion in adolescent idiopathic scoliosis. Spine (Phila Pa 1976) 2001;26:E330-7.
9. Engsberg JR, Lenke LG, Uhrich ML, Ross SA, Bridwell KH. 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) 2003;28:1993–2000.
10. Gracovetsky S. An hypothesis for the role of the spine in human locomotion: A challenge to current thinking. J Biomed Eng 1985;7:205–16.
11. Gracovetsky SA, Iacono S. Energy transfers in the spinal engine. J Biomed Eng 1987;9:99–114.
12. Capozzo A. Analysis of the linear displacement of the head and trunk during walking at different speeds. J Biomech 1981;14:411–25.
13. Kubo M, Holt KG, Saltzman E, Wagenaar RC. Changes in axial stiffness of the trunk as a function of walking speed. J Biomech 2006;39:750–7.
14. Yang Y-T, Yoshida Y, Hortobágyi T, Suzuki S. Interaction between thorax, lumbar, and pelvis movements in the transverse plane during gait at three velocities. J Appl Biomech 2013;29:261–9.
15. Bruijn SM, Meijer OG, van Dieën JH, Kingma I, Lamoth CJC. Coordination of leg swing, thorax rotations, and pelvis rotations during gait: The organisation of total body angular momentum. Gait Posture 2008;27:455–62.
16. Marks M, Newton PO, Petcharaporn M, Bastrom TP, Shah S, Betz R, et al. Postoperative Segmental Motion of the Unfused Spine Distal to the Fusion in 100 Patients With Adolescent Idiopathic Scoliosis. Spine (Phila Pa 1976) 2012;37:826–32.
17. Syczewska MB, Öberg T, Karlsson D. Segmental movements of the spine during treadmill walking with normal speed. Clin Biomech 1999;14:384–8.
18. Frigo C, Carabalona R, Dalla Mura M, Negrini S. The upper body segmental movements during walking by young females. Clin Biomech 2003;18:419–25.
19. Mahaudens P, Detrembleur C, Mousny M, Banse X. Gait in adolescent idiopathic scoliosis: Energy cost analysis. Eur Spine J 2009;18:1160–8.