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CHOOSING THE LOWEST INSTRUMENTED VERTEBRA IN ADOLESCENT IDIOPATHIC SCOLIOSIS

The Added Value of 3D and Dynamic Measures

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Table of Contents

LIST OF ABBREVIATIONS ……..III

SUMMARY ……V

CHAPTER 1: INTRODUCTION ……1

1.1 AIS - Definition and epidemiology
1.2 AIS - Etiology, natural history and clinical presentation
1.3 AIS - Current treatment
1.4 AIS - Planning fusion levels in posterior scoliosis fusion
1.5 AIS - Outcome evaluation in posterior scoliosis fusion
1.6 References

CHAPTER 2: RESEARCH OBJECTIVES ……33

CHAPTER 3: THREE- INSTEAD OF TWO-DIMENSIONAL EVALUATION OF KEY PARAMETERS ALTERS THE CHOICE OF THE LOWEST INSTRUMENTED VERTEBRA IN LENKE 1 AND 2 AIS PATIENTS ……37

CHAPTER 4: MONITORING THE INITIAL RECOVERY AFTER FUSION SURGERY USING ACTIVITY TRACKERS IN ADOLESCENT IDIOPATHIC SCOLIOSIS: GOING IN THE LUMBAR SPINE DECREASES THE DAILY STEP COUNT……57

CHAPTER 5: POSTOPERATIVE TRUNK MOBILITY RECOVERY AND THE PREDICTIVE ROLE OF THE LOWEST INSTRUMENTED VERTEBRA IN ADOLESCENT IDIOPATHIC SCOLIOSIS FUSION SURGERY ……75

CHAPTER 6: CONCLUDING DISCUSSION AND FUTURE PERSPECTIVES….101

6.1 LIV selection in 3D instead of 2D
6.2 Objective activity tracking versus LIV
6.3 Quantitative trunk ROM analysis versus LIV
6.4 Final Conclusion
6.5 References

APPENDIX ……119

Scientific Acknowledgements and Personal Contributions
Statements and Declarations
Curriculum Vitae
List of Publications
Personal Acknowledgements

List of abbreviations

2D - Two-dimensional

3D - Three-dimensional

AIS - Adolescent Idiopathic Scoliosis

AO - Adding-On

AP - anteroposterior

CHVA - Central Hip Vertical Axis

CSVL - Central Sacral Vertical Line

CT - Computed Tomography

DJK - Distal Junctional Kyphosis

EV - End Vertebra

FDI - The Functional Disability Inventory

FL - Fusion Length

HRQOL - Health-related Quality of Life

IPAQ - International Physical Activity Questionnaire

L - Lumbar

L-group - Lumbar Fusion Group

LF-group - Long Fusion Group

LIV - Lowest Instrumented Vertebra

LLD - Leg Length Discrepancy

MRI - Magnetic Resonance Imaging

NV - Neutral Vertebra

PA - Posteroanterior

PAQ-A - IPAQ in Adolescents

PAQ-C - IPAQ in Children

PCS-C - Pain Catastrophizing Scale

PEDSQL - Pediatric Quality of Life Inventory

PiG - Plug in Gait Model

PJK - Proximal Junctional Kyphosis

Post-1Y - 1 Year after Surgery

Post-3W - 3 Weeks after Surgery

Post-6W - 6 Weeks after Surgery

Pre-op - Preoperatively

PROMS - Patient Reported Outcome Measures

PSF - Posterior Spinal Fusion/Posterior Scoliosis Correction and Fusion

RoM - Range of Motion

ROM - Range of Motion

SagSV - Sagittal Stable Vertebra

SC - Step Count

SF-group - Short Fusion Group

SRS - Scoliosis Research Society

STV - Substantially Touching Vertebra

SV - Stable Vertebra

T - Thoracic

T-group - Thoracic Fusion Group

TAPS - Trunk Appearance Perception Scale

TL - Thoracolumbar

TV - Touching Vertebra

UIV - Upper Instrumented Vertebra

VAS - Visual Analog Scale

VAS - Visual Analogue Scale

VBT - Vertebral Body Tethering

Summary

Adolescent idiopathic scoliosis (AIS) is recognized as a complex three-dimensional (3D) structural deformity of the spine that occurs during peak growth puberty in otherwise healthy children between the ages of 10 and 18. This condition is not only visually apparent - characterized by uneven shoulders, a prominent scapula, rib hump, and/or asymmetrical waistline - but it also doubles the likelihood of back pain, potentially leading to significant cosmetic and psychological distress, and, although rare, cardiopulmonary complications.

Management of AIS varies from observation in mild cases, to bracing in moderate and skeletally immature cases, to surgery in severe cases. The primary goal of all surgical interventions is to halt the progression of the curve, achieve as much deformity correction as possible, and ensure spinal balance and alignment. Posterior Scoliosis correction and Fusion (PSF) is the predominant surgical approach and is considered the gold standard because of its effectiveness in long-term correction of the deformity and overall good clinical outcome.

However, current surgical treatments for AIS exhibit significant variability, particularly in the selection of the Lowest Instrumented Vertebra (LIV), especially notable in Lenke 1 (main thoracic) curves where choices may vary by up to four spinal levels. Furthermore, this variability is coupled with an important trade-off—balancing between longer constructs that offer sustained control of the deformity versus shorter constructs that rather aim at preserving lumbar motion— which underscores the need for further research and standardized guidelines.

Therefore, this doctoral thesis aims to refine surgical treatment and decision-making of AIS by transitioning from static, 2D to dynamic, 3D-informed LIV selection in PSF. It identifies three key knowledge gaps: (1) the oversimplification of the spine's complex 3D dynamics into simplistic 2D parameters in today's preoperative planning concepts, (2) the limitations of subjective functional outcome measures that drive current decision-making and outcome assessments, (3) and the insufficient insights into the correlation between, on one hand, functional outcomes and the extent of spinal motion reduction and, on the other hand, fusion length, and LIV location.

By addressing these knowledge gaps, this thesis reveals that accurate 3D assessment of the stable vertebrae can alter LIV selection towards more proximal levels in 20% of cases compared to current 2D assessment of the stable vertebra. Furthermore, thoracic-only fusions were found to exhibit a lesser reduction than thoracolumbar fusions in step count in the early recovery phase which was not detectable through patient-reported outcome measures (PROMs), suggesting the added value of objective activity measurement over subjective assessments. Finally, our research revealed that thoracic-only fusions demonstrate a smaller reduction in range of motion (ROM) compared to thoracolumbar fusions, and that factors such as the presence of a structural lumbar curve and fusion length are more predictive of ROM loss than LIV itself, albeit without any clear effect on patient-reported functional outcomes.

Based on the findings of this thesis, future research directions include investigating the clinical impact of 3D-based LIV selection on improving postoperative outcomes and developing more comprehensive activity tracking methods to better understand patient activity levels after surgery. The thesis also highlights the need to consider spinal ROM

reduction in functional outcome assessments, particularly as it relates to mechanical limitations, rather than focusing solely on LIV position.

In conclusion, this thesis represents an important step towards integrating 3D and dynamic assessment into routine clinical practice for AIS patients. Future studies should focus on further validating these findings and exploring the long-term impact of dynamic, 3D-informed LIV selection on patient outcomes. The thesis underscores the necessity for advanced, non-invasive and robust segmental analysis of spine-specific range of motion (ROM) to enhance our understanding of the dynamic, functional implications of LIV selection and surgical methods overall. Furthermore, it highlighted the challenges of objectively measuring activity among growing adolescents. The ongoing development of sophisticated 3D dynamic assessment tools is crucial to further refine surgical techniques tailored to individual patient needs.

Samenvatting

Adolescente idiopathische scoliose (AIS) wordt gezien als een complexe driedimensionale (3D) structurele misvorming van de wervelkolom die optreedt tijdens de puberteit bij verder gezonde kinderen tussen de 10 en 18 jaar. Deze aandoening is niet alleen visueel duidelijk - gekenmerkt door ongelijke schouders, een prominent schouderblad, ribbenbult en/of asymmetrische taille - maar verdubbelt ook de kans op rugpijn, kan mogelijk leiden tot aanzienlijk cosmetisch en psychologisch leed en, hoewel zeldzaam, kunnen er cardiopulmonale complicaties optreden.

De behandeling van AIS varieert van observatie in milde gevallen tot bracing in matige en onvolgroeide gevallen en chirurgie in ernstige gevallen. Het primaire doel van alle chirurgische ingrepen is om de progressie van de curve te stoppen, zoveel mogelijk misvorming te corrigeren en te zorgen voor een gebalanceerde en goed gealigneerde wervelkolom. Posterieure scoliosecorrectie en fusie (PSF) is de meest voorkomende chirurgische benadering en wordt beschouwd als de gouden standaard vanwege de effectiviteit voor langetermijncorrectie van de misvorming en het algehele goede klinische resultaat.

De huidige chirurgische behandelingen voor AIS vertonen echter een aanzienlijke variabiliteit, met name in de keuze van de laagst geïnstrumenteerde wervel (LIV), vooral opvallend bij Lenke 1 (thoracale curve) curve, waar de keuze kan variëren tot wel vier verschillende wervels. Bovendien gaat deze variabiliteit gepaard met een belangrijke afweging tussen ‘langere constructies die duurzame controle van de misvorming bieden versus kortere constructies die eerder gericht zijn op het behouden van de lumbale beweging’, wat de noodzaak voor verder onderzoek en de nood aan gestandaardiseerde richtlijnen onderstreept.

Daarom heeft dit proefschrift als doel de chirurgische behandeling en besluitvorming van AIS te verfijnen door de overgang te maken van statische, 2D naar dynamische, 3D-geïnformeerde LIV-selectie in PSF. Het identificeert drie belangrijke hiaten in de kennis: (1) de oversimplificatie van de complexe 3D-dynamica van de wervelkolom in simplistische 2D-parameters in de huidige preoperatieve planningsconcepten, (2) de beperkingen van subjectieve functionele uitkomstmaten die de huidige besluitvorming en uitkomstbeoordelingen sturen, (3) en het onvoldoende inzicht in de correlatie tussen enerzijds functionele resultaten en de mate van spinale bewegingsreductie, en anderzijds, fusielengte en LIV-locatie.

Door deze kennislacunes aan te pakken, onthult dit proefschrift dat nauwkeurige 3D beoordeling van de 'stabiele wervel' , LIV selectie kan veranderen naar meer proximale niveaus in 20% van de gevallen in vergelijking met de huidige 2D beoordeling van de stabiele wervel. Verder bleek dat puur thoracale fusies in de vroege herstelfase een geringere afname van het aantal stappen vertoonden in vergelijking tot de thoracolumbale fusies, wat niet kon worden gedetecteerd via patiënt-gerapporteerde uitkomstmaten (PROM's), wat de toegevoegde waarde van objectieve activiteitsmeting ten opzichte van subjectieve beoordelingen suggereert. Tot slot toonde ons onderzoek aan dat puur thoracale fusies een kleinere afname in range of motion (ROM) laten zien in vergelijking met thoracolumbale fusies, en dat factoren zoals de aanwezigheid van een structurele lumbale curve en fusielengte meer voorspellend zijn voor ROM-verlies dan LIV zelf, zij het zonder duidelijk effect op patiënt-gerapporteerde functionele uitkomsten.

Op basis van de bevindingen van dit proefschrift omvatten toekomstige onderzoeksrichtingen het onderzoeken van de klinische impact van 3D-gebaseerde LIV-selectie op het verbeteren van postoperatieve uitkomsten en het ontwikkelen van uitgebreidere methoden voor het

volgen van activiteiten om de activiteitsniveaus van patiënten na de operatie beter te begrijpen. Het proefschrift benadrukt ook de noodzaak om de vermindering van de ROM van de wervelkolom mee te nemen in functionele uitkomstbeoordelingen, met name als het gaat om mechanische beperkingen, in plaats van alleen te focussen op de positie van de LIV.

Concluderend, dit proefschrift vertegenwoordigt een belangrijke stap in de richting van het integreren van 3D en dynamische beoordeling in de routinematige klinische praktijk voor AIS patiënten. Toekomstige studies moeten zich richten op het verder valideren van deze bevindingen en het onderzoeken van de langetermijneffecten van dynamische, 3D-geïnformeerde LIV-selectie op de resultaten van patiënten. Het proefschrift onderstreept de noodzaak van geavanceerde, niet-invasieve en robuuste segmentale analyse van wervelkolom-specifieke range of motion (ROM) om ons begrip van de dynamische, functionele implicaties van LIV-selectie en chirurgische methoden in het algemeen te verbeteren. Bovendien benadrukte het de uitdagingen van het objectief meten van activiteit bij opgroeiende adolescenten. De voortdurende verbetering van geavanceerde 3D dynamische beoordelingsinstrumenten is essentieel voor het verder verfijnen van chirurgische technieken, afgestemd op de individuele behoeften van de patient.

Chapter 1: Introduction

Chapter 1: Introduction

1.1 Adolescent idiopathic scoliosis - Definition and epidemiology

Adolescent idiopathic scoliosis (AIS) is a complex structural three-dimensional (3D) deformity of the spine characterized by rotation of the vertebrae around the longitudinal axis, resulting in a lateral curvature of the spine, termed scoliosis (See Figure 1.1). The amount of lateral curvature is typically measured using the Cobb angle, i.e. angle between upper and lower end vertebrae of a spinal curve (See Figures 1.1 & 1.3), of at least 10 degrees (°). It is termed 'idiopathic' if there are no underlying abnormalities such as congenital or neuromuscular problems[1, 2]

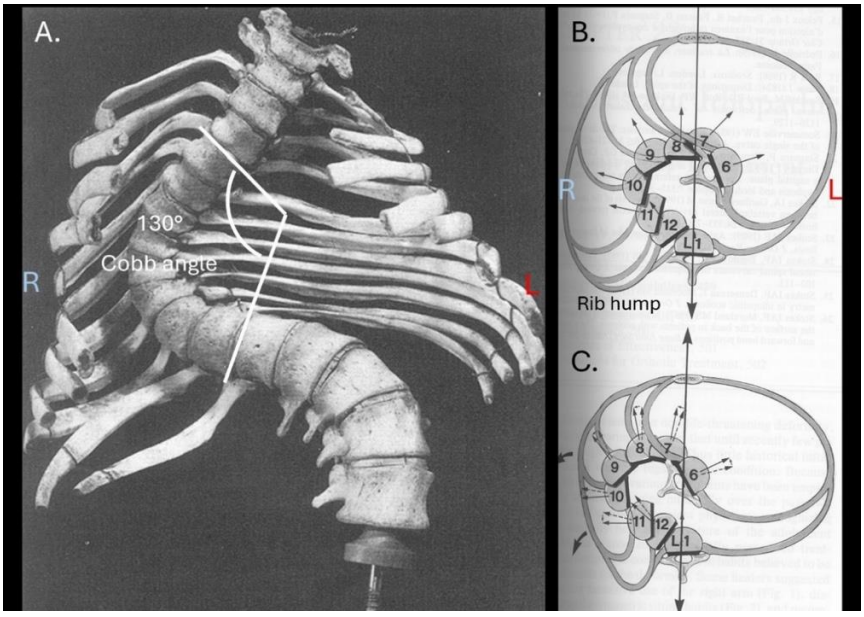


***Fig. 1.1**: AIS is a complex structural 3D spinal deformity. (A) Shows a frontal view of a specimen with extreme dextroconvex thoracic curvature with a Cobb angle greater than 90°. (B) Demonstrates an axial view from below, highlighting the rotational deformity along the longitudinal axis, creating a rib hump and often a lordotic thoracic sagittal profile. (C) Presents an axial view in which the increased rotation to the right contributes to a pronounced overall trunk deformity. (Figure used with permission from Moens, 'spine round' UZ Leuven 2021, unpublished PowerPoint presentation)*

This growth deformity occurs during the second growth spurt in otherwise healthy children between the ages of 10 and 18 years, hence the term 'idiopathic', and is the most common form of scoliosis, accounting for approximately 80% of all pediatric scoliosis cases. The prevalence of AIS in the general adolescent population is estimated to be between 1% and 5%, with a higher incidence in females compared to males. This female-to-male ratio increases with the severity of the curve, and can be as high as 8:1 for curves greater than 40 degrees.[3, 4]

1.2 AIS - Etiology, natural history and clinical presentation

As mentioned above, "Idiopathic" refers to the fact that a specific cause cannot be identified, and this is unfortunately still the case in the majority of cases today. Indeed, the **etiology** of Adolescent Idiopathic Scoliosis (AIS) remains largely unknown, despite extensive prior research into potential genetic, hormonal, and environmental factors. Although various theories have been proposed, including genetic predisposition, neuromuscular dysfunction, abnormal skeletal growth, and biomechanical factors, to the best of our knowledge, none have been conclusively proven thus far[5]. Nevertheless, several studies do suggest a genetic aspect[6]. For example, prior studies showed an increased risk of developing AIS in individuals with first-degree relatives affected by AIS, with a prevalence of 6–11%. Furthermore, twin studies show that monozygotic twins have higher AIS concordance rates (73%) compared with dizygotic twins (36%). Nevertheless, idiopathic scoliosis remains a diagnosis of exclusion, meaning it is diagnosed after ruling out other forms such as congenital, neuromuscular, or syndromic scoliosis.[4–6]

The **natural history** of AIS varies widely, with some curves remaining stable while others progress rapidly, particularly during periods of rapid

growth. The risk of progression is influenced by several factors, including the patient's age at diagnosis (See Table 1.1)[7], sex, curve magnitude and pattern, and skeletal maturity. In general, the risk of curve progression is known to positively correlate with residual spinal growth and magnitude of the curve.

Curve Magnitude Cobb angle	Age at detection		
	10-12 years	13-15 years	16 years
<19°	25%	10%	0%
20°-29°	60%	40%	10%
30°-39°	90%	70%	30%
>40°	100%	90%	70%

Table 1.1*: Probabilities of major curve progression in % for skeletally immature patients.*[7]

Based hereon, there is consensus that early detection in skeletally immature patients and appropriate management are crucial to prevent severe deformity and associated complications. The need for early detection is further stressed by the fact that, even in skeletally mature patients, curves with Cobb angles between 30° and 50° have been shown to progress, on average, 10° to 15° over a patient's lifetime[8, 9]. Furthermore, curves above 50° can progress at a rate of 1 to 2 degrees per year, necessitating follow-up every 3 to 5 years.[8, 9]

Clinically, AIS may be asymptomatic or present itself with physical signs such as uneven shoulders, a protruding scapula, a rib hump, and an asymmetrical waistline (Figure 1.2). In terms of **symptoms**, back pain is approximately twice as prevalent in patients with AIS compared to non-scoliosis patients[10, 11], with higher intensity in more severe curves. Large lumbar curves are associated with an increased incidence of back

pain, particularly if the apical vertebra develops significant lateral translation[12].

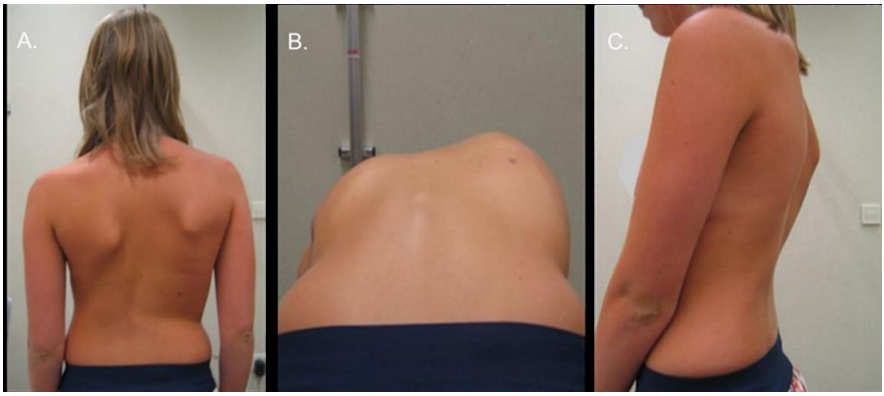


Fig. 1.2 *Spinal deformity in a mild to severe scoliosis patient: (A) standing, (B) forward-bending view, and (C) left lateral view of a typical AIS patient. Notice the shoulder imbalance, waist asymmetry, rib hump in forward flexion, but also in lateral view. (Figure used with permission from Moens, UZ Leuven, unpublished)*

In severe cases, AIS can lead to significant cosmetic deformity, psychological distress, and, rarely, cardiopulmonary complications. Indeed, thoracic curves greater than 100° have been shown to reduce forced vital capacity, i.e. the total volume of air that can be exhaled during a maximal forced expiration effort, to less than 70% to 80% of the reference value[12]. The decrease in pulmonary function is secondary to restrictive lung disease, and if the pulmonary compromise is severe, the patient is theoretically at risk for early death from cor pulmonale. In severe thoracic scoliosis, also myelomalacia (i.e. softening of the spinal cord tissue due to spinal cord injury) may develop on the concave side at the apex of the curve due to tethering of the spinal cord (see Figure 1.3).

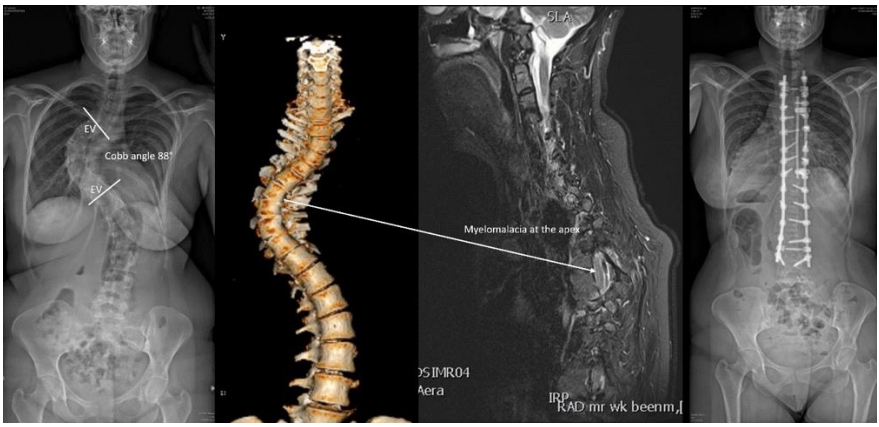


Fig. 1.3: *A 22-year-old woman with neglected severe scoliosis with a Cobb angle of 88° for the main thoracic curve presenting with restrictive pulmonary disease and gait disturbance due to myelomalacia at the rigid apex. She underwent posterior scoliosis fusion, including a vertebral column resection at the rigid apex for spinal cord decompression. The procedure resulted in good aesthetic correction and an overall positive clinical outcome, despite its high risk. (Figure used with permission from Schelfaut, UZ Leuven, unpublished)*

The physical examination for AIS includes evaluation of the curve pattern, shoulder height, and waist asymmetry. Also gait and posture are assessed, with particular attention to any leg length discrepancy and coronal or sagittal imbalance. The Adams forward bending test may reveal a rib rotation deformity (rib hump) on the convex side of the curve. This test uses a scoliometer to measure the angle of vertebral rotation (See Figure 1.4). A rotation asymmetry of 5 to 7° indicates the need for referral for scoliosis evaluation. Given the known correlation between residual spinal growth and the risk of curve progression in AIS, it is essential to monitor the rate of growth at each clinical examination, with simple height measurements being highly reliable[4]

Standard medical imaging assessments for AIS includes upright standing posteroanterior (PA) and lateral two-dimensional (2D) radiographs. Based on the PA full spine radiograph, the primary **Cobb angle** is measured by identifying the maximally tilted vertebrae cephalad and caudal to the

curve's apex and drawing lines along the superior border of the upper End Vertebra (EV) and the inferior border of the lower EV (See Figure 1.3 – left)[13]. The most significant curvature is referred to as the main curve, and its classification as thoracic, thoracolumbar, or lumbar is determined by the location of the apex vertebra. Typically, AIS manifests with one to three structural curves. The main thoracic curve is commonly dextroconvex, characterized by a rightward convexity and an associated rib hump on the right side. Additional imaging modalities, such as magnetic resonance imaging (MRI), are reserved for patients presenting with atypical features of AIS that may suggest alternative underlying etiologies[13] The emphasis on minimizing radiation exposure is crucial in the management of AIS, given the potential risks associated with repeated exposure and the need for regular follow-up[14]. The EOS® slot-scanning 2D/3D system is increasingly favored as it reduces radiation dose by 50–80% compared to conventional radiography. This system also provides the advantage of simultaneous bi-planar imaging, which facilitates three-dimensional reconstruction of spinal deformities[15]. For optimal imaging results using this system, patients are advised to adopt the SRS free-standing position. This posture entails standing upright in a relaxed manner with fingertips positioned on the clavicles or chin, as depicted in Figure 1.4. This specific positioning ensures clear spinal visibility, minimizing obstruction caused by arm placement.[16]

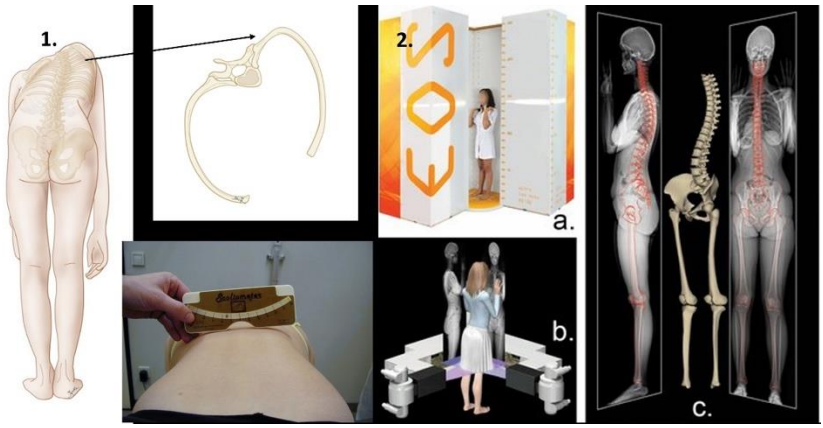


Fig. 1.4: *(1) The Adams forward bending test may reveal rib rotational deformity (rib hump) on the convex side of the curve. A scoliometer is used during this test to measure the angle of vertebral rotation. (2) The EOS 2D/3D Imaging System with a patient in SRS free standing position. (a) The EOS 2D/3D Imaging System and the typical positioning during examination. (b) The basic operation of the imaging system: upright biplanar slot-scanning X-ray imaging. (c) 3D reconstruction opportunities of the full body (source: www.eos-imaging.com).*

1.3 AIS - Current treatment

Treatment of AIS depends on the severity of the curve, the patient's age, and the risk of progression. Early detection and regular follow-up are there for critical. Mild cases may require only observation, moderate skeletally immature cases often benefit from bracing, and severe cases may require surgery. The **overall goal** is not only to correct the deformity, but also to slow or halt the progression of scoliosis, prevent health problems and improve the quality of life in severe scoliosis. Each treatment plan should be tailored to the individual patient. However, as will be detailed hereunder, current clinical practice is largely trichotomous, based largely on the progression of the Cobb angle of the principal curve.[4]

In skeletally immature patients with a Cobb angle of less than 20-25°, observation for suspected curve progression is recommended at 6 to 12 month intervals until skeletal maturity by physical examination

(scoliometer) and complementary low-dose full spine radiographs. In skeletally immature patients, physiotherapy that includes specific therapeutic exercises may help slow the progression of smaller spinal curves [17], though evidence supporting the effectiveness of these exercises is currently limited[18, 19]. However, after skeletal maturity, curves with a Cobb angle greater than 30° may still progress and require follow-up every 2-5 years.[4, 20]

For skeletally immature AIS patients with curves between 20° and 45°, bracing is often recommended to at least slow the progression of scoliosis during growth. Specifically, the deformity must be sufficiently flexible, and the patient must be skeletally immature, with an Risser stage between 0 and 2. It is recommended that the brace be worn for a minimum of 18 hours per day; success is defined as a curve progression of less than 5° at the end of treatment. The Boston underarm brace (thoraco-lumbo-sacral brace) is the most commonly utilized brace for thoracolumbar or lumbar curves and is well tolerated due to its ability to be hidden under clothing. Another option is the Chêneau orthosis, which is designed to combine biomechanical forces in three dimensions, including curve derotation, which is particularly useful for thoracic curves [21, 22]. Nocturnal braces are worn for eight to ten hours a night. The use of these braces may be considered for skeletally immature patients with a single major curve of 25 to 35° and an apex below T8, according to current guidelines. Bracing is continued until the patient has reached the end of their major growth spurt, as indicated by Risser 4 or two years after menarche for females or Risser 5 for males. Following skeletal maturity, curves of less than 30° may be considered for release from systematic follow-up, given the low probability of progression without symptoms before the onset of menopause.[4, 20]

For skeletally mature AIS patients with a Cobb angle greater than 50°, surgery is generally considered. Surgery can even already be preferred at 40-45° in a skeletally immature patient where progression is expected and further waiting may lead to more invasive surgical treatment (longer fusion, exclusion of selective fusion or vertebral body tethering, ...). Low back pain is not an indication for surgery, but apical pain due to early facet joint degeneration may be considered. In cases of borderline curves[9], it is of paramount importance to consider the potential benefits of performing a "prophylactic" fusion procedure at an early age, as opposed to waiting until adulthood to observe whether the curve will reach a critical size or become symptomatic. The decision-making process is dependent on two key factors: the probability of progression and the likelihood of achieving favorable outcomes in an adolescent or adult patient. It is evident that younger patients may experience less difficulty with surgical procedures and demonstrate superior baseline SRS (Scoliosis Research Society) scores. In addition to reduced pain scores, adolescents often have no dependents, are not engaged in full-time employment, have extended school breaks and receive greater familial support. In addition to the better tolerated rehabilitation of surgery in adolescents, the overall outcome of surgery in adolescents may be better than in adults, from better correction to shorter fusion length to better SRS outcome scores[9]. On the other hand, any complication resulting from unnecessary surgery is extremely significant, and non-fused, painless scoliosis consistently maintains greater mobility than fused scoliosis[23]. As such, this preservation of mobility can be an effective guarantee for maintaining activity levels, as can be further illustrated by a comparison of two surgical cases in Figure 1.5.

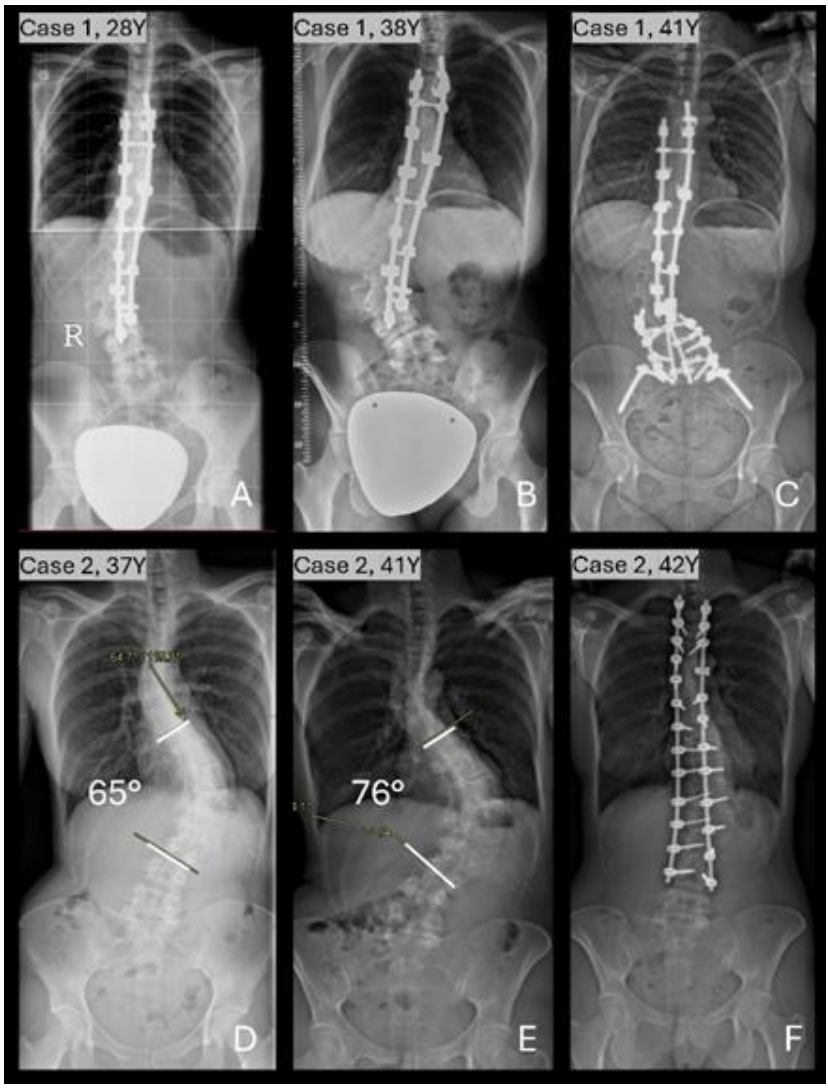


Fig. 1.5. *AIS surgery in* ***adolescence versus adulthood****. Fused spine at a young age versus maintaining spinal motion as long as possible.*
Female 1: Fusion surgery for thoracolumbar AIS curve at 16 years of age.(A) 12 years postoperatively (age 28): No pain, no limitations in daily activities, limited sports participation since fusion.(B) 23 years postoperatively (age 38): Mechanical low back pain for the past 2 years due to adjacent level degeneration.(C) 2 years post-extension of fusion to pelvis: No pain, full-time work with adaptations (e.g., standing desk), limitations in daily activities.
Female 2: Surgery was considered at age 16, but opted for conservative treatment due to fear of limitations in sports activities. (D) At age 37, the curve increased by 10 degrees to 65°, no complaints, very athletic since childhood. (E) At age 41, further curve increase to 76° with a feeling of collapsing spine, limited pain. (F) One year post-fusion surgery: No pain, full-time work resumption with limited adjustments, resumption of all sports activities 6 months postoperatively. (Figure used with permission from Schelfaut, UZ Leuven, unpublished)

The **primary goals of all surgical procedures** are to prevent further progression of the curve, correct the existing deformity as much as possible, and maintain balance and alignment of the spine. Spinal fusion has been the predominant surgical procedure for AIS for over 100 years and involves the fusion of the curved vertebrae from either the anterior or posterior approach to halt curve progression. A combination of metal rods, hooks, screws, or wires are employed to correct and maintain spinal alignment. In spinal fusion, all vertebrae within the curved area are thus realigned and permanently attached to each other through this surgical instrumentation, ultimately forming one large or fused bone (see Figure 1.6), albeit with loss of mobility in all spinal segments involved in the fusion.

In the past 20 years, there has been a significant shift towards the all-posterior approach in AIS fusion surgery. This approach, utilizing modern pedicle screw instrumentation systems, offers comparable correctional outcomes to anterior scoliosis correction, and has a lesser negative impact on pulmonary function[24]. As a result, posterior Scoliosis correction and Fusion (**PSF**) is currently the most used surgical technique in AIS and counts as the golden standard due to the proven long-term and overall effectiveness to correct the Cobb angle[25]. Additionally, outcomes after PSF for AIS are excellent in general. PSF has a low risk of adverse events such as respiratory complications, massive blood loss and neurological deficits[26]. The reoperation rate varies between studies but is generally reported to be between 4% and 13% due to pseudarthrosis, hardware failure or progression/recurrence of the scoliotic curve[27].

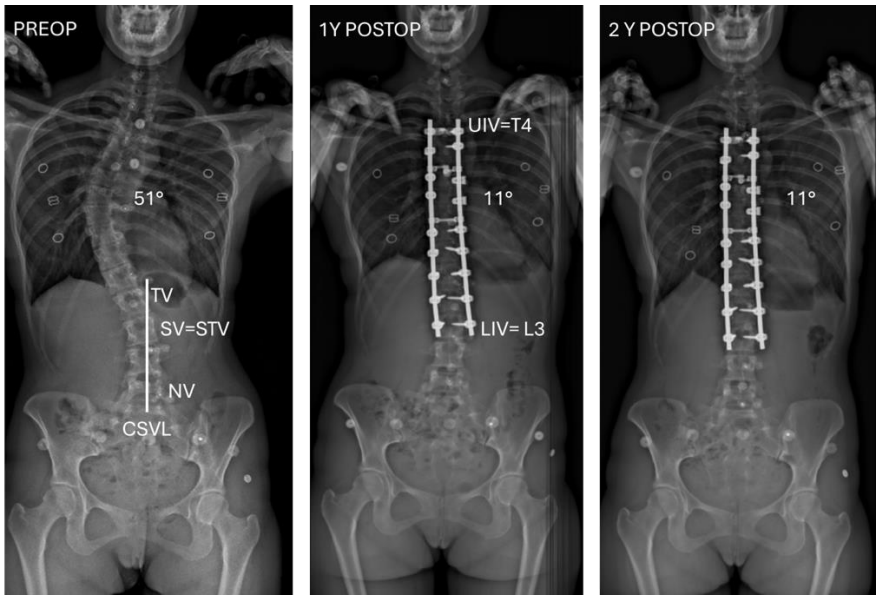


Fig. 1.6 *A* ***Lenke 1 A-R thoracic curve*** *with a Cobb angle of 51° in a 22-year-old skeletally mature woman. Note the marked asymmetry of the waist and the CSVL (central sacral vertical line). The SV (stable vertebra) is the same as the STV (substantially touching vertebra) = L3, the NV (neutral vertebra) is L5. Postoperatively there is fusion from T4 (UIV) to L3 (LIV). The coronal imbalance is well corrected, but the left shoulder is now slightly higher. The motion analysis markers are also evident. The 2Y postoperative result is similar to the 1Y postoperative result, no signs of AO. (Figure used with permission from Schelfaut, UZ Leuven, unpublished)*

Currently, there is an increasing focus on preserving spinal motion segments during fusion, especially in the lumbar spine, through selective thoracic fusions and selecting the lowest instrumented vertebra (LIV) as cranially as possible in thoracic and thoracolumbar curves. As mentioned above, spinal fusion inherently results in a significant reduction in trunk mobility, presenting the surgeon with **an important trade-off**. Shorter fusion lengths, while preserving more mobility, are associated with a higher risk of complications such as the "adding-on" phenomenon and distal junctional kyphosis[28, 29], but also with lower patient satisfaction primarily due to persistent waistline asymmetry and/or truncal translation[30]. Conversely, longer fusions provide better deformity

control at the expense of reduced mobility and increased risk of adjacent level disc degeneration[31].

As an illustration of this increasing focus on preventing loss of spinal mobility and adjacent level degeneration, a newer surgical technique has been recently introduced called dynamic anterior scoliosis correction, or vertebral body tethering (**VBT**) (see Figure 1.7). It has been developed for limited indications, namely skeletally immature patients with flexible AIS curves and makes use of a flexible polyethylene terephthalate cord which is attached to the anterior convex side to straighten the spine. It targets the patient's growth to provide additional correction of the curve after the initial correction by the cord[32–34]. It thus applies the Hueter-Volkmann principle, which states that increased mechanical compression on the convex side of the vertebral body impairs skeletal growth on the convex side. Or in other words, the patient's remaining growth potential will promote concave sided growth, thereby creating a corrective effect during spinal growth[35]. The biomechanical basis of VBT has been established through cadaveric and animal studies, highlighting the preservation of trunk Range Of Motion (ROM) and the potential for significant spinal curve correction[36–39]. However, patients undergoing VBT are at risk of developing complications that we do not see with modern PSF, such as pulmonary complications (5.5%), overcorrection (4-8%), or tether breakage (20-30%), and are at risk for revision surgery (13-17%), most commonly due to overcorrection or tether breakage with loss of correction[40, 41], also shown in figure 1.7. Although the radiographic outcome, in the form of curve correction, is usually inferior to modern spinal fusion, potential advantages over spinal fusion have been reported in terms of spinal mobility, less invasive surgical procedure, and overall faster recovery[42].

However, the benefit of motion preservation in AIS fusion (or using newer surgical techniques like VBT) on overall functionality has not yet been demonstrated in the literature. As a result there is insufficient evidence, let alone guidelines, to determine whether preserving trunk ROM in AIS patients justifies the increased risk of complications linked to a higher proximal LIV in PSF. Likewise, in VBT, the benefits of preserving ROM against a possibly higher rate of complications and revisions remain uncertain[43–45].

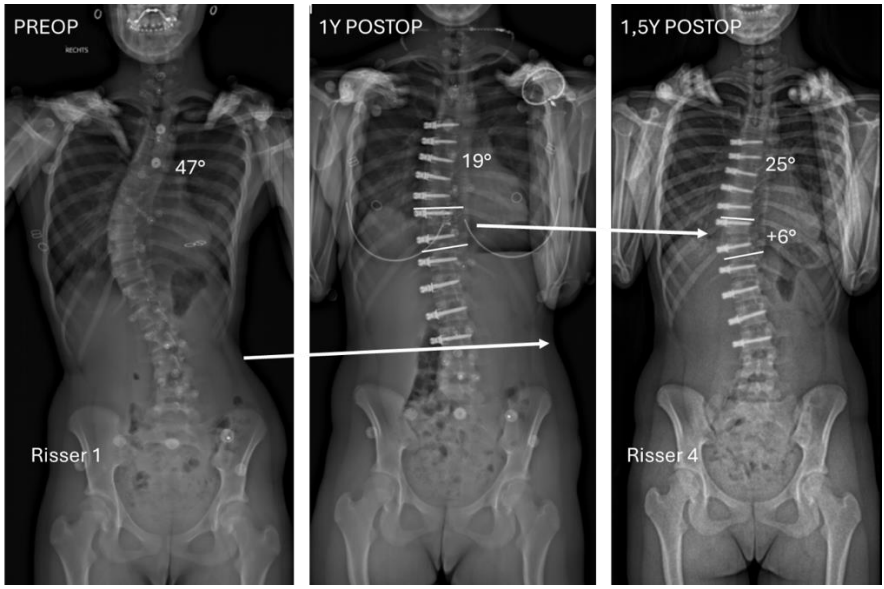
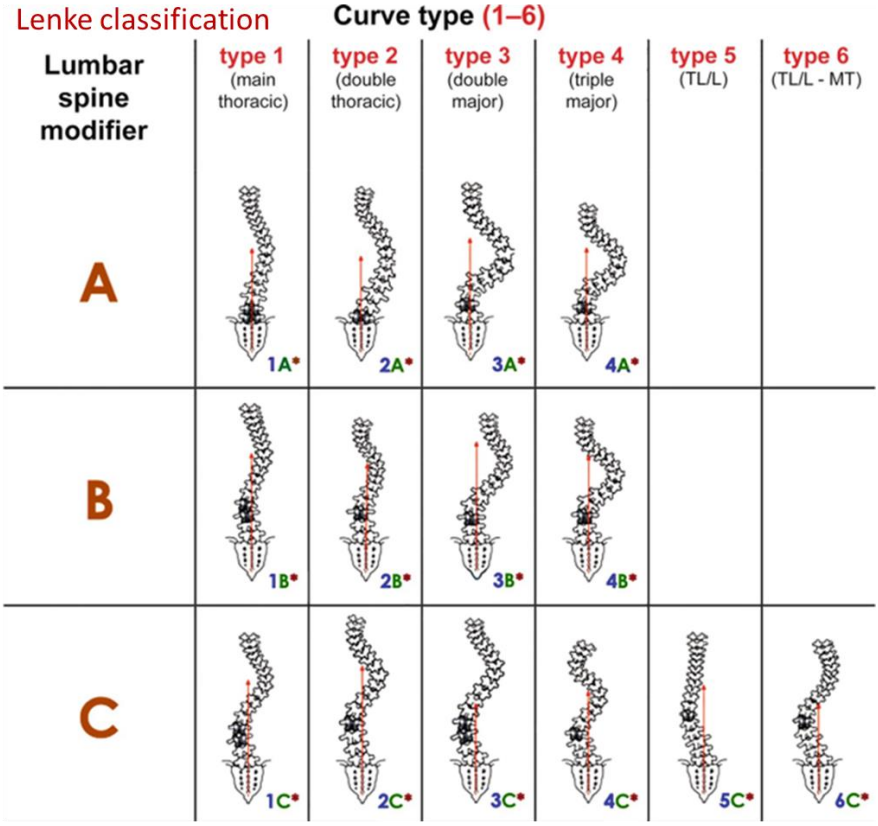


Fig. 1.7 *A* ***Lenke 1 A-R type thoracic curve*** *with a Cobb angle of 47° in a 13-year-old skeletally immature (Risser 1, Sanders 4) girl. The curve was dynamically corrected with anterior vertebral body tethering (VBT) with UIV (T5) and LIV (L3). Note the preoperative waist asymmetry, which is nicely corrected postoperatively. The postoperative Cobb angle is 19° at 1 year postop, and at 1.5 years postop, the Cobb angle has increased to 25° due to cord rupture at T10-T11 (+6° disc wedging). (Figure used with permission from Schelfaut, UZ Leuven, unpublished)*

1.4 AIS - Planning fusion levels in PSF

1.4.1 Selecting fusion length

Current guidelines for selecting fusion length in AIS correction surgery typically relies on the use of the 2D static radiography-based Lenke classification[24]. This system classifies AIS into six major types (see Figure 1.8), based on the location and direction of the curve(s) in the spine. Additionally, the Lenke classification considers the sagittal thoracic profile (flat, normal, or kyphotic) and the lumbar spine's reaction to the main thoracic curve (Lumbar Modifiers A, B, C). In addition, the flexibility of the spinal curve is evaluated through bending and/or traction-elongation X-rays. If the curve does not reduce below a 25° Cobb angle, it is considered structural and generally integrally included in the fusion, from cranial EV to caudal EV. However, if not all structural curves are included in the fusion in an attempt to maximally preserve mobility, this is termed a 'selective' fusion. For example, a patient demonstrating two (thoracic and lumbar) structural curves wherein only a fusion of the more pronounced thoracic curve is performed.



Redline = CSVL, black vertebra = the lumbar apical vertebra, Modifier B = CSVL touching pedicle of lumbar apical vertebra

***Fig. 1.8**: The Lenke classification for AIS categorizes spinal curves into six types based on their location and direction. It also considers the sagittal profile and the lumbar spine's reaction (lumbar modifier), helping to guide surgical treatment by providing a detailed structural analysis of the spine in 2 dimensions (2D). The Central Sacral Vertical Line (CSVL) is a vertical line drawn from the center of the sacrum on an anteroposterior spine radiograph, used to assess lateral deviations of the spine. In this classification, modifier C indicates that the lumbar apical vertebra does not contact the CSVL, showing significant deviation. Conversely, modifier A indicates that the lumbar apical vertebra touches the CSVL between the pedicles, reflecting minimal deviation.(https://doi.org/10.1007/978-981-99-3017-3_4)*

1.4.2 Choosing the upper instrument vertebra

The specific choice of the **upper instrumented vertebra (UIV)** primarily depends on the alignment of the shoulders and targets the prevention of proximal junctional kyphosis. In general, the UIV can be determined based on the necessity of proximal thoracic curve fusion, which can include

either fusion to T2, fusion to T3 or exclusion of the proximal thoracic curve and starting fusion at T4 or T5. T2 is selected if the left shoulder is higher and T1 is tilted in the same direction, while T4 or T5 is chosen if there is only one structural dextroconvex thoracic curve and the right shoulder is higher. However, shoulder balance is highly position dependent. It is also not recommended to end the construct immediately adjacent to a kyphotic disc space.[46] Alternatively, +/- T10 is chosen if only a structural lumbar or thoracolumbar curve is present.

1.4.2 Choosing the lower instrumented vertebra

The **lower instrumented vertebra (LIV)** is usually the first vertebra beneath the structural curve that intersects with the so-called central sacral vertical line (CSVL, see Figure 1.6 & 1.8), which is the stable vertebra (SV). However, in current practice, the substantially touching vertebra (STV) is often chosen instead of the SV, being the vertebra being crossed by the CSVL line on the inside of the pedicle. The STV may correspond to the SV (see figure 1.6) or can be more proximal[47]. However, the position of the neutral vertebra (NV), defined as the first vertebra beneath the structural curve with no apparent rotation, also affects the choice of LIV. In cases involving isolated thoracic curves, the options typically range from T12 to L3, and the eventual choice can vary by as much as four spinal levels between experts[48]. Lenke type 1 (thoracic) and type 2 (double thoracic) with a lumbar C modifier (apex of nonstructural lumbar curve not bisected by the CSVL) include the minor nonstructural lumbar curve in the fusion if there is substantial clinical truncal translation, waist asymmetry, or significant rotation of the apical vertebra. For lumbar and thoracolumbar curves, the lumbar part is included with the distal lumbar EV as the most caudal level. However, surgeons may deviate from the above principle and opt for L3 to preserve at least three vertebral

segments distal to the fusion to improve long-term outcomes[46]. An LIV lower than L4 is very rarely chosen, except for AIS fusion during adulthood. Here fusions up to the sacrum/pelvis are preferred in up to 41% of the case[9].

1.4.3 Impact of inadequate fusion level selection

Both the selection of fusion levels and the correction of the structural curve are acknowledged as **crucial determinants of the final radiographic outcome**. Inadequate selection of fusion levels can lead to complications such as adjacent level issues and overall misalignment of the spine and/or shoulders, potentially resulting in inadequate radiographically-assessed outcomes and, occasionally, the need for further surgery. Adjacent level problems may include postoperative curve progression above or below the fused area ("adding-on"), junctional kyphosis (either proximal or distal), and long-term adjacent level disease. Choosing an LIV that is too proximal may result in extension of the spinal deformity in the form of distal adding-on or distal junctional kyphosis. The incidence of these undesirable radiographic outcomes in thoracic curves ranges from 13.6%[28] to 20.5%[49]. This is an unsustainably high range given the scientific insights accumulated over the last decades regarding the choice of LIV in fusion of thoracic curves[49] and warrants future research.

1.4.4 Limitations of current **fusion level selection in PSF**

This suboptimal outcome may be due to the oversimplification of a complex 3D dynamic deformity into a few simple 2D static parameters such as CSVL (and associated determination of SV, STV, TV and lumbar modifier) and rotation assessment on a 2D radiograph (Nash-Moe method[50]). Dubousset et al. [51] highlight that relying exclusively on static, biplanar (coronal and sagittal) measurements undermines the

efficacy of the Lenke classification approach by failing to incorporate the dynamic, rotational, and horizontal dimensions of the deformity[52, 53]. Over the past two decades, researchers have attempted to overcome the limitations of 2D approaches and improve surgical decision making by developing various methods to model the spine in 3D from bi-planar radiographs[54, 55]. To overcome the limitations of the CSVL, the SRS 3D Scoliosis Committee proposed the central hip vertical axis (CHVA), a true vertical bisection of the line segment joining the centers of the two femoral heads, as a reference line for 3D evaluation of the spinal deformity[56]. In addition, Illes et al.[57] developed a method to calculate vertebral rotation based on 3D vertebral vectors. Although the potential of these novel 3D approaches is clear, several limitations remain, such as the lengthy and complex 3D reconstruction procedure of most methods. One way to overcome the complexity and limitations of most 3D approaches is to adhere to the definition of currently used 2D parameters that are familiar to clinicians. However, it remains unclear whether the clinical decision-making process would undergo significant changes when planning the LIV through straightforward 3D analytical methods that directly translate conventional 2D key parameters into the third dimension.

In summary, AIS is a complex 3D deformity[53] of a flexible (i.e., not rigid in shape during motion), trunk with the axial deformity being the main driver of the global malalignment[58]. Relying exclusively on static, biplanar (coronal and sagittal) measurements to select the LIV, undermines the efficacy of the Lenke classification approach by failing to incorporate the dynamic, rotational, and horizontal dimensions of the deformity[51, 52]. **The first knowledge gap** identified regarding the current AIS surgical treatment pathway for LIV selection in PSF concerns the oversimplification of a complex 3D dynamic deformity into a few

simple 2D static parameters during preoperative LIV planning. Specifically, the first knowledge gap relates to whether the incorporation of simple 3D analysis techniques that convert traditional two-dimensional (2D) key LIV planning parameters into the third dimension could significantly alter the LIV planning and outcomes.

1.5 AIS - Outcome evaluation in PSF

Currently, outcome assessment in AIS is mainly limited to documenting surgical complications, 2D radiographic outcomes, and patient reported outcome measures (PROMS). Whereas surgical complications have already been discussed in detail in section 1.3 *AIS-Current treatment,* this section will discuss the other types of outcome assessments.

1.5.1 Radiographic outcome

The 2D radiographic outcome focuses on the assessment of the pre- to post-operative Cobb angle correction, with PSF showing a more favorable Cobb angle correction of approximately 75%, compared to less than 50% correction with VBT[4, 33]. Poor radiographic outcomes include complications like global malalignment (trunk shift/shoulder imbalance >1.5-2 cm), adding-on phenomena (>5-10° wedging AP view) and both distal (>5-10° kyphosis lateral view) and proximal junctional kyphosis (>10-15° kyphosis lateral view), which still occur in about one in five cases[28, 59].

Assessments of axial rotation, such as the Nash-Moe method applied to 2D radiographs, typically provide only approximate measures of actual rotation. While some methods can accurately measure minor rotational deviations on 2D radiographs, they fail to consider variations in pelvic positioning (e.g., when the two femoral heads are not aligned in profile)[50]. Furthermore, assessing postoperative rotation is challenging

in clinical settings, largely due to the difficulty in visualizing rotation through instrumentation on 2D radiographs and the lack of Computed Tomography (CT) scans. Illes et al. developed an alternative approach using bi-planar radiographs that calculates vertebral rotation based on three-dimensional vectors of the vertebrae[57].

The same limitations discussed in section 1.4.4 *Limitations of current fusion level selection in PSF,* apply to the radiographic outcome assessment of AIS, with the horizontal, rotational dimension missing by default in the current clinical setting of 2D radiographic assessment.

1.5.2 Patient Reported Outcome Measures (PROMS)

In AIS surgery, commonly used PROMs include the Visual Analogue Scale (VAS) for self-reported pain, the Scoliosis Research Society (SRS)-22 score[60, 61] for assessing health-related quality of life, and age-adjusted physical or sport-specific activity questionnaires for measuring activity levels. These tools offer insights into various aspects of patient well-being and recovery. These PROMs are further discussed below, with a particular focus on how the LIV affects these outcomes.

First, the Visual Analog Scale (**VAS**) is a commonly used method to evaluate pain, where patients rate their pain on a scale from 0 (no pain) to 10 (worst pain imaginable). Studies indicate that 34% of patients may report higher preoperative pain scores, averaging 5.6, compared to those without pain who average 0.5, though this isn't directly correlated with the severity or location of the deformity[62]. Postoperatively, there is a significant reduction in pain scores, from an average of 6.0 preoperatively to 4.0 two years post-surgery in this AIS patient population[63]. However, Regarding the influence of the LIV, no correlation has been found

between postoperative VAS scores and the extent of vertebral fusion (LIV location)[64].

Next, also the health-related quality of life (HRQOL) is routinely assessed in AIS patients, primarily using the **SRS-22** questionnaire[60], which is also validated in Dutch[61]. It evaluates the following five key aspects: Pain, Function, Self-Image, Mental Health, and Satisfaction, on a scale from 0 (worst) to 5 (best). Generally, AIS patients report high scores, typically above four, indicating sustained post-surgical improvements across all domains [9]. However, a notable ceiling effect[65] exists due to the high compensatory capabilities of this group, both physically and mentally. Regarding the influence of the LIV, LIV below L1 tends to negatively impact outcomes, primarily due to significant reductions in spinal mobility, which can be 50% in some cases, compared to less than 20% in thoracic-only fusions with LIV at L1 or higher[66].

Finally, also self-reported activity levels are commonly assessed in this population. Hereto, age-adjusted levels should be used due to changes in school, work, and leisure activities across different age groups. The International Physical Activity Questionnaire (**IPAQ**) and its adaptations such as the PAQ-C for children under 12 and the PAQ-A for adolescents aged 12-18, are examples of such measures validated in Dutch[67, 68]. These will be discussed in more detail in Chapter 5. Regarding the influence of the LIV, studies indicate that fusions stopping at L1 or above allow a greater return to pre-fusion sport activity levels compared to fusions extending to L2 or lower. Additionally, fusions with LIV at L2 or below restrict the types of sports that can be performed post-surgery[69, 70].

1.5.3 Limitations of current **outcome evaluation in PSF**

The effect of fusion length and LIV on short-term rehabilitation/function is less clear. The impact of this early rehabilitation in AIS fusions on later function is also not well understood. However, this is an important issue in this young active population in terms of preoperative information as well as postoperative guidance for return to school/work/sports activities. Currently, the majority of studies have relied on self-report measures to assess postoperative recovery in AIS, which may be a reason for some of the conflicting results. All of the above **PROMS** may face the problem of a ceiling effect[65], where they fail to capture nuanced differences between different LIV groups due to their **subjective** nature and limited sensitivity. The SRS-22 does not adequately capture important concepts related to HRQOL in adolescents with AIS; for example, in the study by Alamrani et al.[71], no patients reported any limitation of RoM after fusion surgery for AIS, but the terms "stiffened" and "inflexibility" were used by some during interviews. Due to this subjective nature of the questionnaire-based PROMS and limited sensitivity to patient-specific functional limitations, the **second knowledge gap** we identify is “the limitations of subjective measures to assess functional outcomes in AIS fusion surgery”, such as the SRS-22 score (function item) and other activity questionnaires. As an alternative, **objective** monitoring using **accelerometers** or wearables has emerged as a promising method to assess pre- and postoperative physical activity levels[72]. This approach provides a more accurate and quantifiable measure of functional recovery, reflecting the patient's return to normal activity levels after surgery[73].

A second key limitation of current outcome assessments is that routine clinical follow-up after PSF generally does not include systematic,

objective, quantitative assessments of spinal ROM. Nevertheless, the importance of preserving spinal motion segments when selecting the LIV was already emphasized in the above section on current surgical treatments using PSF. This method attempts to limit fusion of the mobile lumbar spine, although its definitive impact on patient functionality remains unproven because of the lack of spinal ROM assessments[43, 44]. This lack of extensive spinal ROM data further complicates this issue, as most studies have small numbers of participants. Furthermore, the availability of such assessments could elucidate how preoperative spinal ROM, objective activity levels, and *LIV selection* decisions influence *patient-specific ROM reduction and overall functional outcomes*. This knowledge could guide more personalized surgical approaches, such as identifying candidates who may benefit most from selective thoracic fusion for a Lenke 1C curve, potentially improving long-term outcomes for patients with AIS. In an attempt to fill this gap, studies have suggested the assessments of ROM by using a measuring tape(1) to track changes in distance or a goniometer to track changes in angle[66, 74]. Nevertheless, the most accurate measurement is angle determination using deep bending radiographs(2). However, the utility of this method is often limited by the physical limitations of biplanar microdosage radiography settings[75, 76] and provides only unidirectional insight, unlike the multidirectional movements encountered in daily activities. Alternatively, marker-based(3) motion capture provides another method[45, 77, 78] that can mimic more complex motions such as those that combine flexion and rotation (e.g., putting on socks) and may better delineate compensatory mechanisms such as those observed during walking[79, 80]. This marker-based 3D gait and motion analysis tool will be our method of choice, as it serves as a crucial evaluation technique in assessing the functional outcomes of AIS, particularly when assessing

changes before and after spinal fusion surgery. This technique utilizes advanced imaging technologies to create detailed models of the spine, allowing clinicians to examine the range of motion, alignment, and mechanical loading of various spinal segments. Skalli et al.[53] highlighted the importance of using such comprehensive biomechanical assessments to understand the impact of spinal deformities on overall motion dynamics. Mahaudens et al[81] reported a significant increase in pelvic tilt (i.e., reduced drop and rise of the pelvis due to scoliosis) in AIS patients after surgery, contributing to a more balanced and symmetrical gait. In addition, advances in spinal fusion techniques have been shown to restore spinal alignment in the coronal and sagittal planes[82] and reduce rotational deformity, resulting in improved biomechanical efficiency during movement[83–85]. Collectively, these studies highlight the value of 3D gait and motion analysis in not only assessing RoM, but also demonstrating improvements in both anatomical alignment and functional mobility during gait.

The availability of such dynamic assessments could elucidate how preoperative spinal ROM, objective activity levels, and LIV selection decisions influence patient-specific ROM reduction and overall functional outcomes postoperatively. Thus, the **third knowledge gap** identified in the current surgical management of AIS concerns the structural lack of spinal range of motion assessment and its relation with functional outcome and fusion length, including LIV selection.

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Chapter 2: Research Objectives

Chapter 2: Research Objectives

The overarching aim of this thesis is to advance the surgical treatment of AIS by shifting from static, 2D- to dynamic, 3D-informed decision-making, particularly in improving the selection of the LIV in PSF. To achieve this, we have identified 3 important knowledge gaps in the current surgical management.

The first knowledge gap concerns the oversimplification of a complex 3D dynamic deformity into a few simple 2D static parameters during preoperative LIV planning.
The second knowledge gap focuses on the limitations of subjective measures to assess functional outcomes in patients undergoing AIS fusion to more objectively identify the impact of LIV on patient function.
The third knowledge gap concerns the structural lack of spinal range of motion assessments and its relation with functional outcome and fusion length, including LIV selection.

Based on these knowledge gaps, the following three objectives of this thesis have been defined:

The first objective is to address the limitations of current 3D reconstruction methods by introducing a simple **3D analysis** method that directly translates the traditional 2D key parameters for LIV selection (such as CSVL, SV, Lenke lumbar modifier, NV) into the third dimension. Second, to quantitatively compare and clinically interpret these 3D corrected parameters in relation to their corresponding traditional 2D

assessment and the potential impact on LIV selection. This first objective is addressed in Chapter 3.

Our second objective is to document the added value of objective activity measurement in the outcome assessment of AIS patients undergoing PSF. Hereto, the very early (3 & 6 weeks post-operatively) functional recovery of AIS fusion patients will be assessed using an **accelerometer**. Furthermore, we will investigate the relationship with patient characteristics, patient reported outcome measures (PROMS), pain and fusion levels. This second objective will be explored during the short-term recovery period of AIS fusions in Chapter 4 and also during the later (3 & 12 months postoperative) recovery period in Chapter 5.

Our third objective is to document the added value of the non-invasive assessment of spinal range of motion in the outcome assessment of AIS patients. Hereto, we will conduct a comparative analysis of global **trunk mobility** and functional outcomes in AIS patients who have undergone thoracic (T) fusion (with LIV at L1 or higher) versus those who have undergone thoracolumbar (TL) fusion (with LIV at L2 or lower). In addition, we aim to evaluate potential predictors of postoperative global trunk mobility impairment in the cohort of AIS patients undergoing spinal fusion.

Chapter 3: Three- instead of two-dimensional evaluation of key parameters alters the choice of the Lowest Instrumented Vertebra in Lenke 1 and 2 AIS patients

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Three- instead of two-dimensional evaluation of key parameters alters the choice of the Lowest Instrumented Vertebra in Lenke 1 and 2 AIS patients

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3.1 Abstract

Purpose: Treatment of AIS, a three-dimensional spinal (3D) deformity, is guided by a two-dimensional (2D) evaluation. Novel 3D approaches that address the 2D limitations have not been adopted in AIS care due to their lengthy and complex 3D reconstruction procedures. This study aims to introduce a simple 3D method that translates the 2D key parameters (Stable vertebra (SV), Lenke lumbar modifier, Neutral vertebra (NV)) into 3D and to quantitively compare these 3D corrected parameters to the 2D assessment.

Methods: The key parameters of 79 surgically treated Lenke 1 and 2 patients were measured in 2D by two experienced spine surgeons. Next, these key parameters were measured in 3D by indicating relevant landmarks on biplanar radiographs and using the 'true' 3D CSVL which was perpendicular to the pelvic plane. Differences between the 2D and 3D analysis were examined.

Results: A 2D-3D mismatch was identified in 33/79 patients (41.8%) for at least one of the key parameters. More specifically, a 2D-3D mismatch was identified in 35.4% of patients for the Sag SV, 22.5% of patients for the SV and 17.7% of patients for the lumbar modifier. No differences in L4 tilt and NV rotation were found.

Conclusion: The findings highlight that a 3D evaluation alters the choice of the LIV in Lenke 1 and 2 AIS patients. Although, the true impact of this more precise 3D measurement on preventing poor radiographic outcome needs further investigation, the results are a first step toward establishing a basis for 3D assessments in daily practice.

3.2 Introduction

The choice of the lowest instrumented vertebra (LIV) in Adolescent Idiopathic Scoliosis (AIS) surgery has a major impact on conservation of spinal mobility, sports participation and long-term outcome. A pure thoracic fusion holds an advantage over fusions that stop at, for example, L2 or lower [1–3]. Nevertheless, a too proximal selection of LIV can lead to extension of the spinal deformity in the form of adding-on or distal junctional kyphosis. The incidence of these undesirable radiographic outcome ranges from 13.6% [4] to 20.5% [5]. This is a relatively high range given the scientific insights accumulated over the last decades with regards to the choice of LIV in fusion of thoracic curves [5].

The key reference axis for the choice of LIV is the central sacral vertical line (CSVL [6]), which is a 2D anteroposterior radiography-based reference axis. The majority of the parameters relevant for the choice of LIV are determined using this reference axis, such as the stable vertebra (SV), substantial touching vertebra (STV), touching vertebra (TV) and Lenke lumbar modifier [4, 5]. However, the CVSL is conventionally only defined in the coronal radiographic view and has no corresponding definition in the sagittal view [7]. As a result, the CSVL represents a two-dimensional (2D) evaluation of the three-dimensional (3D) deformity.

Moreover, quantification of the vertebral axial rotation, in particular the determination of the neutral vertebra (NV) [4, 8], is another key parameter for the selection of LIV [9]. Axial rotation evaluations such as the widely used Nash-Moe method on 2D radiography are often rough approximations of effective rotation. Other attempts to quantify rotation on 2D radiography, are accurate in case of limited rotational deviations, but do not account for position variations of the pelvis (i.e. the two femoral heads not on top of each other in profile) [10].

For the past two decades, researchers have been striving to overcome the limitations of the 2D approaches and improve surgical decision-making by creating different methods to model the spine in 3D from bi-planar X-ray images [11–17]. To overcome the limitations of the CSVL, the SRS 3D scoliosis committee proposed the central hip vertical axis (CHVA), a true vertical bisecting the line segment joining the centers of the two femoral heads, as a reference line for the 3D evaluation of the spinal deformity [7]. Nevertheless, the CHVA does not account for potential height differences between the femoral heads, as it is drawn perpendicular to floor instead of perpendicular to the hip axis. This contradicts with the original definition of King et al. [18] in 1983, who states the following: 'The central vertical line must always be based on a horizontal pelvis'. Moreover, Illes et al. [9] developed a method to calculate the vertebral rotation based on 3D vertebral vectors. Even though the potential of these novel 3D approaches is clear, various limitations, such as the lengthy and complex 3D reconstruction procedure of most methods have precluded the use of 3D measures in AIS daily clinical care [12, 13].

A way to overcome the complexity and constraints of most 3D approaches is to adhere to the definition of the presently used 2D parameters, which are familiar to the clinicians. Nevertheless, it remains unknown if the clinical decision-making is directly affected by this novel 3D analysis.

Therefore, the main objective of this study is to address the limitations of current 3D reconstruction methods, by introducing a simple 3D analysis method that directly translates the traditional 2D key parameters (such as, CSVL, SV, Lenke lumbar modifier, NV [6]) into the third dimension. Secondly, to quantitively compare and clinically interpret these 3D corrected parameters in relation to their corresponding traditional 2D assessment. It is hypothesized that the 3D analysis can complement the current 2D assessment in the selection of the Lumbar modifier and stable

vertebra, and that a mismatch between 2D and 3D methods exists in terms of the vertebral rotation. These 3D-corrected key parameters could have a direct impact on the surgical decision making for some thoracic AIS patients potentially resulting in shorter (or longer) fusions according to common theories around choice of LIV.

3.3 Methods

3.3.1 Participants

Seventy-nine surgically treated Lenke 1 (n=57) and Lenke 2 (n=22) AIS patients (age: 16.9 ± 4.5 yrs.) were retrospectively selected from the clinical database of the University Hospital. All selected participants were aged between 11 and 35 years old, surgically treated with a spinal fusion surgery that corresponded to the initial 2D planning and completed preoperative low-dose biplanar radiographic imaging (EOS Imaging System, France). Exclusion criteria were (1) prior spinal fusion surgery, (2) patients with a Lenke 3-5 curve, or (3) patients with a leg length discrepancy (LLD) of more than 15 mm. The study was approved by the institution's research ethics committee (S63053) and was conducted in accordance with the Declaration of Helsinki.

3.3.2 Procedures

The selected patients were first measured in 2D by two experienced spine surgeons according to the radiographic measurement manual of the spinal deformity study group [6]. In case of disagreement consensus was sought. Once the 2D measurements were finalized, the 3D measurements were executed in custom-made software [19], again by two experienced users of the software who had an excellent understanding of the anatomy of the spine.

3.3.3 2D Analysis

The following 2D radiographic parameters were determined on the preoperative radiographs of each patient using the standard of care software and in accordance with the radiographic measurement manual of the spinal deformity study group [6]:

1) Primary curve and Lenke Lumbar modifier. First the steps of the Lenke Classification [20] were followed to identify the primary curve and assign the Lumbar modifier.

2) The Stable vertebra. In the present study, the SV is the most proximal vertebra where the CSVL either intersected the pedicle outline or was medial to the pedicle outline. We adopted this broader sense of the SV (= SV and STV [21]) according to the recent paper by Fischer et al. [4] instead of the narrow definition by Erickson et al. [22].

3) The Sagittal Stable Vertebra (SagSV). The SagSV was defined as the vertebral level at which 50% of the vertebral body was in front of the posterior sacral vertical line (PSVL) [23].

4) The Neutral Vertebra. The NV is the most cephalad vertebra below the apex of the major curve whose pedicles are symmetrically located within the radiographic silhouette of the vertebral body.

5) L4 tilt. The L4 tilt angle was calculated by the intersection of a line drawn tangential to the superior end plate and a horizontal reference line (left side up is positive by convention).

6) Leg length discrepancy. The LLD was determined in order to take possible differences in leg length into account.

All parameters (1,2,4-6) are measured on the frontal radiograph, accept the SagSV (3) which is measured on the sagittal radiograph.

3.3.4 3D analysis

The 3D analysis was performed using a custom-made software tool that has previously been used in Adult Spinal Deformity patients to develop subject-specific models and calculate 3D parameters [19, 24], but also to account for spinal palpation error [25]. The biplanar radiographic images of each patient were loaded and spatially calibrated into the software's 3D environment. Next, the relevant landmarks necessary to calculate the 3D parameters of interest were indicated on both radiographs. The simultaneous agreement of both 2D projections on their respective radiograph plane, provides the 3D position of each landmark. The 3D location of these landmarks was imported in MATLAB software (MATLAB 2013b, MathWorks Inc., USA) for further analysis.

First a rotational correction of the pelvis was performed in 3D (i.e. the pelvis was set as the reference plane (Figure 3.1B)) using the relevant landmarks (right and left femur heads, and sacrum) indicated on both radiographs (Figure 3.2AB). The outline of both femur heads was delineated using at least five points in both radiograph planes (2D), after which an ellipse fitting algorithm provided the 3D position of each femur landmark (Figure 3.2A). One point was placed on both radiographs to obtain the 3D sacrum landmark (Figure 3.2B). Based on these landmarks the 'true' 3D CSVL line was identified as a combination of the 2D CSVL and PSVL line with the starting point at the sacrum. Importantly, this new line is, as originally described by King et al. [26], per definition perpendicular to the pelvic plane and not to the floor (Figure 3.1A).

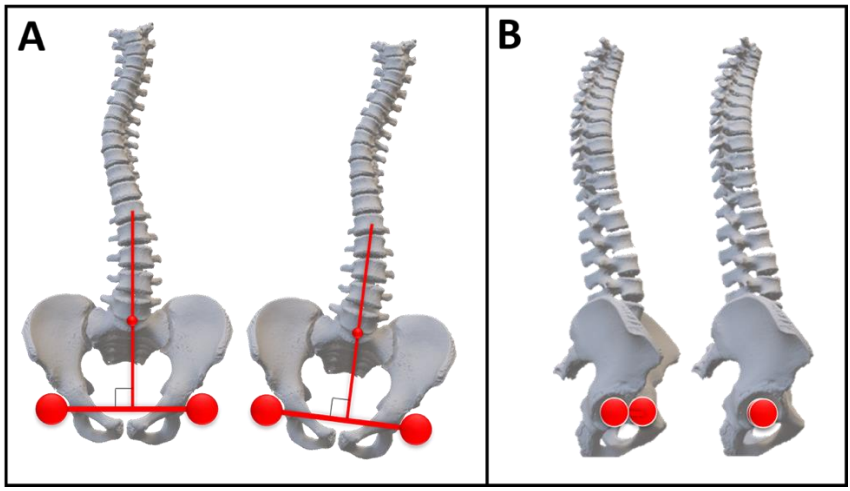


Fig. 3.1. *Schematic overview to illustrate the fact that the in the present study used true 3D CSVL line was perpendicular to the pelvic plane (as originally described by King et al. [22]) and not the floor (A) and that a rotational correction of the pelvis was performed in 3D (B).*

This 'true' 3D CSVL was used to determine the relevant parameters in 3D. The following, already determined in 2D, parameters were re-calculated in 3D by indicating landmarks on both spatially calibrated radiographs (Figure 3.2): 1) Lenke Lumbar modifier. Relevant landmarks were placed in the center of both pedicles; 2) SV. Relevant landmark was placed on the center of the pedicle of the two vertebras above and two vertebras below the 2D determined SV. 3) SagSV. Using the ellipse fitting algorithm, the midpoint of the vertebral body was determined of the two vertebras above and two vertebras below the 2D determined SagSV. 4) L4 tilt. Landmarks were placed on the superior end plate (left side up is positive by convention). In addition, 5) the Neutral Vertebra (NV) rotation was also analysed in 3D to evaluate whether the neutral vertebra was indeed the vertebra with the least rotation. Hereto, landmarks were placed above the left and right pedicle on the superior end plate, and on the spinous processes. The rotation was determined (in a similar manner as the method proposed by Illes et al. [9]) with respect to the pelvis landmarks

(right and left femur heads, and sacrum) and using a vector between the landmarks on the superior end plate and the spinous processes landmark.

3.3.5 Statistics

A crosstabulation was performed for the Lumbar Modifier in order to examine differences between the 2D and 3D analysis using a Chi-Square test. The 'true' SV and SagSV were determined in 3D using the relevant landmarks and compared to the 2D SV. To examine differences between the 2D and 3D analysis in terms of tilt a paired samples T-test was performed. Statistical analyses were performed using SPSS (version 28, SPSS Inc., Irvine, CA) and the significance level was set at p = 0.05.

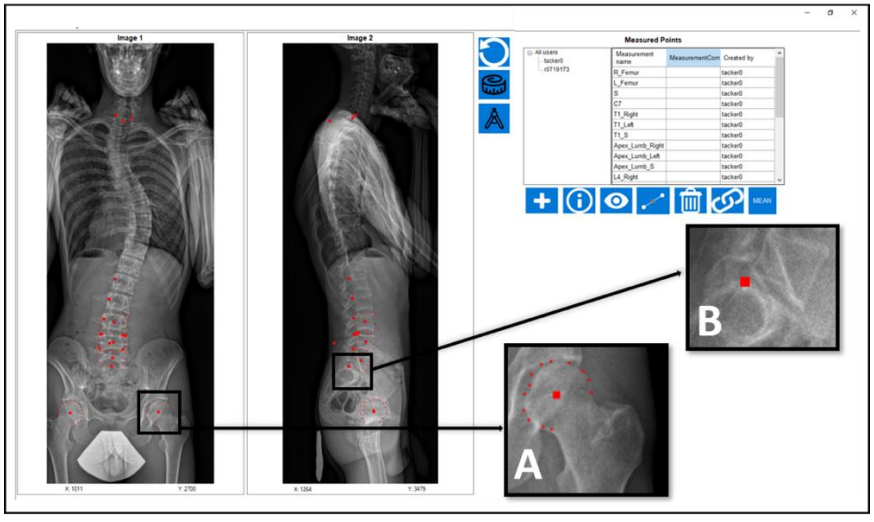


***Fig. 3.2**. Overview of the custom-made software tool used to indicate the relevant landmarks on both spatially calibrated biplanar radiographic images, such as the Femur heads (A) and Sacrum (B).*

3.4 Results

3.4.1 Lumbar Modifier

The pearson Chi-Square test identified a significant ($p<0.05$) mismatch for the Lumbar Modifier between the 2D and 3D analysis (Table 3.1). For 13

out of the 79 patients (16.5%) the modifier differed between analysis methods (Table 3.1). More specifically, for 7 patients the modifier changed from B (2D assessment) to A (3D assessment). In addition, for 5 patients the modifier changed from B (2D assessment) to C (3D assessment). For the remaining patient the modifier changed from C (2D assessment) to B (3D assessment).

	2D Modifier A	**2D** Modifier B	**2D** Modifier C	**Total**
3D Modifier A	49	7	0	56
3D Modifier B	0	6	1	7
3D Modifier C	0	5	11	16
Total	49	18	12	79

Table 3.1. *Crosstabulation for the Lenke Lumbar Modifier for both analysis methods (2D vs 3D).*

3.4.2 Stable Vertebra

For the SV a mismatch between the 2D and 3D analysis was identified for 18 out of the 79 patients (22.5%). For 16 patients the SV determined in 3D was one vertebra above the SV determined in 2D. For the other 2 patients the SV determined in 3D was one vertebra below the SV determined in 2D.

3.4.3 Sagittal Stable Vertebra

The 2D SagSV was similar to the 3D SagSV in 51 out of the 79 patients (64.6%), for 22 of the patients (27.8%) the 3D SagSV was one or two vertebras above the 2D SagSV and for the remaining 6 patients the SagSV was one vertebra below the 2D SagSV. When comparing the SV determined in 3D with the 3D SagSV it was found that for 10 out of the 79 patients (12.7%) the 3D SagSV was one or more vertebras below the 3D SV.

3.4.4 Overall 2D-3D mismatch

A 2D-3D mismatch for the SagSV, SV, & lumbar modifier was identified for 33 out of the 79 patients (41.8%). For 26 patients a 2D-3D mismatch in one out of the three parameters was identified. Whereas 6 patients had a 2D-3D mismatch in two out of the three parameters (Lenke Modifier & SV: 1 patient; Lenke Modifier & SagSV: 4 patients; SV & SagSV: 1 patient). One patient had a 2D-3D mismatch for all three outcome measures.

3.4.5 L4 tilt

The paired samples T-test did not identify significant differences between the 2D and 3D analysis for the L4 tilt (2D = 6.6° vs 3D = 6.9°) (Figure 3.3).

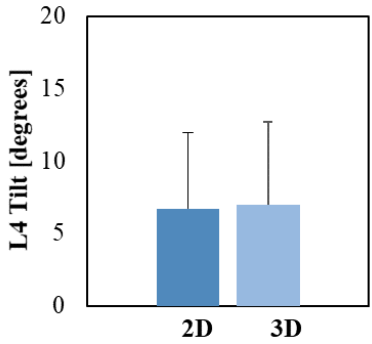


Fig. 3.3. The L4 tilt determined according to the 2D radiographic measurement manual and the 3D method.

3.4.6 Neutral Vertebra rotation

The average rotation of the neutral vertebra determined in 3D was: 5.67° (SD=4.95°); one vertebra above the neutral vertebra: 8.86° (SD=5.98°); and one vertebra below the neutral vertebra was: 4.92° (SD=3.92°). For two patients the 3D analysis revealed that the vertebra above the NV was 'more neutral' and had a rotation closer to zero (difference in rotation > 10°). In addition, for four patients the vertebra below the NV was 'more neutral' and had a rotation closer to zero (differences in rotation > 10°).

3.5 Discussion

To overcome the limitations of the current 2D radiographic parameters and address the limitations of recent 3D reconstruction methods in AIS, the present study aimed to provide a simple 3D analysis method to correct the traditional 2D key parameters (CSVL, SV, NV, etc.) in 3D whilst taking their definition into account[6]. The proposed method started from biplanar radiographs (EOS) and used the pelvis as a reference plane. The hypothesis that a 3D analysis of key parameters in the choice of LIV in thoracic AIS can complement the current 2D assessment, is supported for the lumbar modifier, SV and SagSV as a 2D-3D mismatch was identified in 33 out of the 79 patients (41.8%) for at least one of these parameters.

3.5.1 Lumbar Modifier

For the Lumbar modifier a significant ($p<0.05$) mismatch between methods was identified. More specifically, for 13 out of the 79 patients (16.5%) the modifier differed between analysis methods and in 7 out of the patients the modifier changed from B (2D assessment) to C (3D assessment). This is in line with the findings of the SRS 3D scoliosis committee who also found an increase in modifier C from 4 out of 68 patients towards 14 out of 68 when using their proposed CHVA instead of the CSVL [7]. This finding could have a direct impact on the proposed fusion length as a modifier B can be perfectly fused purely thoracically, whereas a modifier C would result in a possible selective thoracic fusion under certain conditions [22]. Thus, for 7 of the patients the shift in modifier corresponding with our proposed 3D assessment would have resulted in a possible ‘longer’ fusion.

3.5.2 Stable Vertebra

For the Stable Vertebra a mismatch between the 2D and 3D outcome was identified for 18 out of the 79 patients (22.5%). For 16 of the patients the 3D-determined SV was one vertebra above the one determined in 2D. In the attempt to preserve mobility in AIS fusions, LIV should be as proximal as possible, of course, while also taking care to avoid poor radiographic outcome (e.g. adding on). According to the literature the SV-1 (corresponding to substantially touching vertebra) is often a safe option [5, 27], but the SV-2 can also be selected [4] (exceptions to this are Lenke 1 A-R curves). For the findings of the present study this implies that for 16 patients (20.3%) a potentially shorter fusion could have been performed and, thus, preserving more mobility without additional risk of poor radiographic outcome.

3.5.3 Sagittal Stable Vertebra

The SagSV also plays an important role in the choice of LIV. Especially for the prevention of distal junctional kyphosis, with a sharp increase in risk with fusions not including the SagSV [28]. The 3D SagSV was one or two vertebras above the 2D SagSV in 22 out of the 79 patients (27.8%). Thus, in the sagittal plane, this 2D-3D mismatch finding could also lead to a more proximal LIV choice. However, since AIS is a hypokyphotic condition, this sagittal parameter is only important when the SagSV is more distal than the SV, which was the case in 12.7% of the patients. For these patients the introduction of a 'true' stable vertebra in 3D could be of added value.

3.5.4 L4 tilt

L4 tilt is also an important parameter in the choice of LIV in thoracic AIS curves, with a tilt to the right (Lenke 1 A-R curves) typically resulting in longer fusions [22]. Nevertheless, this parameter did not differ between our measurement in 2D versus 3D. However, only for patients with a large LLD, we would have expected such a change in tilt between 2D (border of radiograph/floor as a reference) versus 3D measurements (pelvis as reference plane). However, in the present study patients with an LLD of more than 15 mm were excluded. Overall, this finding shows that in a levelled pelvis, the measurement of tilt is not affected by the choice of being performed on 2D coronal radiographs or in 3D.

3.5.5 Vertebral rotation

The rotation of the NV determined in 3D was relatively small: 5.67° and suggests that there was a good agreement between the 2D radiographic observation and the measurement in 3D. This is in line with existing literature that also reported small rotational differences [8,9]. In the present study, only for four patients the vertebra below the NV was 'more neutral' and had a rotation closer to zero. Although, determining the NV in 3D has a small impact on the surgical decision-making, this more objective method could counteract the poor agreement between surgeons in selecting the NV [29].

3.5.6 Limitations

For the 3D measurements, no inter- and intra-observer reliability was determined. However, previous literature performing similar 3D measurements [14] and using the same software [25] reported excellent reproducibility. Moreover, the positional artifacts of the EOS free standing positioning could have had an impact on the results, especially

in terms of rotation. However, the average rotation of the pelvis in the EOS was 1.39 degrees and, thus, we are confident that the patient positioning at the time of EOS acquisition did not influence the results of the present study. Furthermore, we use the pelvic plane for perpendicular positioning ('true' 3D CSVL) instead of the floor. However, as noted large pelvic misalignment based on LLD was excluded. Thus, a well-leveled pelvis also remains important here as it also applies to the classical 2D assessment introduced by King in 1983 [26] to minimize non-spine related positional factors on the CSVL determination.

3.6 Conclusion

The findings of the present study highlight that a simple three- instead of two-dimensional evaluation alters the choice of the LIV in Lenke 1 and 2 AIS patients. More specifically, a mismatch exists when determining the key parameters (Sag SV, SV, & lumbar modifier) for the selection of LIV. For some of the patients this 3D visualization and quantitative evaluation would retrospectively have resulted in a shorter fusion when adhering to the current 2D-based surgical guidelines. Although, the true impact of this more precise 3D measurement on preventing poor radiographic outcome needs further investigation, the results are nevertheless, a first step toward establishing a basis for 3D assessment of the scoliotic spine in daily practice.

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Chapter 4: Monitoring the initial recovery after fusion surgery using activity trackers in Adolescent Idiopathic Scoliosis: Going in the lumbar spine decreases the daily step count

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Monitoring the initial recovery after fusion surgery using activity trackers in Adolescent Idiopathic Scoliosis: Going in the lumbar spine decreases the daily step count

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Conflicts of interest: The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethics Approval: The multi-centric study was approved by the Central Ethical Committee with permission of all local ethical committees to collect data at each site, and was carried out according to the guidelines for Good Clinical Practice (ICH/GCP) and the declaration of Helsinki for the protection of people who participate in clinical studies.

4.1 Abstract

Purpose: Although the functional outcome (e.g. the return to daily activities) plays an important role in the evaluation of treatment success for the paediatric patient, clinicians currently cannot make accurate and objective predictions regarding the very early (≤ 6 weeks) functional outcome and its recovery over time. The purpose of the present study is to objectively measure initial postoperative physical activity levels and examine the relationship with patient characteristics, fusion levels and pain.

Methods: Step count (SC) was obtained pre- (Pre-Op) and postoperatively (Post-3W: 3 weeks after surgery; Post-6W: 6 weeks after surgery) using an accelerometer. Patients were grouped based on LIV (thoracic (T-group) and lumbar (L-group)) and fusion length (FL≤10 levels = SF-group and FL≥11 levels=LF-group). Differences in the daily SC between groups (LIV and FL) and the three timepoints was investigated using a two-way ANOVA.

Results: The SC was significantly lower at both Post-3W ($p<0.001$) and Post-6W ($p<0.001$) compared to the preoperative SC, and significantly ($p<0.001$) increased from Post-3W to Post-6W (Pre-Op = 13049 ± 3214 steps/day; Post-3W = 6486 ± 2925 steps/day; Post-6W = 8723 ± 3020 steps/day). At both post-op timepoints the T-group had a higher SC compared to the L-group.

Conclusion: A fusion surgery with the LIV at L2 or below has a negative impact on the very early postoperative activity levels. The initial functional outcome level of AIS patients was not related to the presently collected patient characteristics. This suggests that objective activity trackers provide novel information and could have an added value in very early rehabilitation programs.

4.2 Introduction

AIS is a progressive growth defect of the spine that primarily occurs in prepubertal children between the age of 10 to 14 years, affecting approximately 3% of these otherwise healthy children [1]. The spine, which is normally straight in a posterior view, forms one or two lateral curves with associated turns around its longitudinal axis, like a spiral staircase. The current treatment recommendation for an immature patient with a scoliosis curve (measured as the cobb angle, which is a measurement of the degree of side-to-side spinal curvature) of approximately 50 degrees and which is clinically expected to further progress is a "scoliosis fusion" [2]. This type of surgery permanently attaches all vertebrae in the area to be corrected to each other by surgical instrumentation [3]. The ultimate goal of this scoliosis surgery is to obtain a well-balanced stable spine by means of a solid arthrodesis, but at the price of losing all spinal mobility in the segments of the fusion area.

The choice of the LIV (lowest instrumented vertebra) affects the loss of spinal mobility. More specifically, fusions lower than L1 lead to a more pronounced loss of spinal mobility (half of spinal mobility lost vs. less than 20%) [4]. Moreover, the loss of spinal mobility in the lumbar spine has in the longer follow-up (10 years) a negative impact on the patient-reported outcome items for pain, function, satisfaction [4]. Similar findings were observed for the return to sport after AIS fusion, where patients with a pure thoracic scoliosis fusion showed a greater return to pre-fusion sport levels compared to fusions to L2 or below [5]. In addition, there are more restrictions in terms of the type of sporting activity that is still possible after AIS fusion surgery for fusions with the LIV at L2 or below [5, 6]. In contrast, the impact of the length of fusion and the LIV on short-term rehabilitation/function is less clear. Nor is the impact of this early rehabilitation in AIS fusions on later functioning well known. This is

nevertheless an important point in this young active population in terms of preoperative information, as well as postoperative guidance in returning to school/work/sports activities.

Presently, the majority of studies relied on self-report measures to assess the postsurgical recovery in AIS which could be an underlying reason explaining some of the contradicting results. Objective monitoring using accelerometers of pre- and postsurgical physical activity levels has been suggested as a useful tool to indirectly assess functional recovery in terms of re-engagement in physical activities after surgery in pediatric patients [7]. The added value of accelerometers to quantify the decrease of physical activity level and to assess the recovery of the physical activity level has previously been shown in adolescents with lower limb fractures [8].

The aim of the present study is therefore to objectively assess the very early (3 & 6 weeks postoperative) functional recovery of AIS fusion patients with an accelerometer and to investigate the relationship to patient characteristics, patient reported outcome measures (PROMS), pain, and fusion levels. We hypothesize that accelerometers can reveal different recovery patterns in the initial physical activity levels for AIS patients with a thoracic or lumbar fusion, which can presently not be captured by the typically used PROMs.

4.3 Methods

4.3.1 Participants

Forty-eight AIS patients (Cobb angle: 52.2 ± 10.7 degrees) were retrospectively selected from a prospective multi-centric study (Age: 15.2 ± 1.6 years; Height: 165.9 ± 8.0 cm; Weight: 55.1 ± 10.3 kg) [9]. The AIS patients were initially scheduled for spinal fusion surgery and recruited from four orthopedic units between December 2016 and December 2018.

Inclusion criteria for the AIS patients of the original study included (1) aged between 12 and 18 years; (2) free from a severe comorbid neurological, developmental or another (mental) health condition; and (3) did not undergo a prior spinal fusion surgery. A more detailed overview of the recruitment procedure of the primary multi-centric study is provided in Figure 1 of Beeckman et al [10]. For the present retrospective analysis all patients with complete accelerometer measurements and questionnaires at all timepoints were included. The multi-centric study was approved by the Central Ethical Committee with permission of all local ethical committees to collect data at each site, and was carried out according to the guidelines for Good Clinical Practice (ICH/GCP) and the declaration of Helsinki for the protection of people who participate in clinical studies. Parental informed consent and adolescent informed assent were obtained online at the start of the study.

4.3.2 Procedures

As part of the primary study [10] the AIS patients completed a range of questionnaires (related to health-related quality of life and pain) at different timepoints of which the following timepoints were selected for the present study (Pre-Op: 1-3-week(s) prior to surgery; Post-3W: 3 weeks after surgery; Post-6W: 6 weeks after surgery) and wore a waist accelerometer (to assess physical activity) for 7 consecutive days at all three timepoints. It should be noted that in the original study no accelerometer data was collected after the Post-6W timepoint. In addition, the surgeon reported the surgical details of the spinal fusion procedure.

4.3.3 Surgical procedure

The following details of the spinal fusion surgery were provided by the treating surgeon: 1) The Lowest Instrumented Vertebra (LIV) and 2) the Fusion length (FL). For further analysis, the patients were grouped based on their LIV, as sparing of lumbar motion segments was found to demonstrate clinically significant benefits [4]. The thoracic fusion (T-group) was defined as a fusion with the LIV at L1 or above, whereas a lumbar fusion (L-group) was defined as a fusion with the LIV at L2 or below [4]. In addition, the patients were grouped based on their fusion length: The short fusion group (SF-group) had 10 or less vertebras fused and the long fusion group (LF-group) had 11 or more vertebras fused.

4.3.4 Questionnaires

A range of validated questionnaires were completed, which were selected due to their relevance regarding the post-surgical recovery in AIS [9].

1) The Functional Disability Inventory (FDI) [11]: The FDI assesses adolescents' perceived difficulty in physical and psychosocial functioning that is due to physical health. Higher scores indicate greater disability. The FDI scores were included at all timepoints (Pre-Op, Post-3W and Post-6W).

2) Health-related quality of life (HRQOL) was assessed by means of the Pediatric Quality of Life Inventory (PedsQL 4.0) [12]. Higher total scores indicate better HRQOL. The PedsQL scores were included at all timepoints (Pre-Op, Post-3W and Post-6W).

3) Average pain intensity was rated on an 11-point numerical rating scale (0 = no pain, 10 = worst possible pain) and used to calculate a characteristic pain intensity score at each time point.

4) The child version of the Pain Catastrophizing Scale (PCS-C) [13] was completed pre-surgically (Pre-Op) to assess the AIS patient's worrisome

thinking associated with pain. Higher scores indicate a higher degree of worrisome thinking about pain.

4.3.5 Physical activity data

The procedure to acquire and analyze the physical activity data has been described in detail in the primary study [10]. Briefly, at Pre-Op, Post-3W and Post-6W all AIS patients wore an accelerometer (ActiGraphTM (GT3X+), Pensacola, Florida) over a period of seven consecutive days to register daily physical activity. The AIS patients were asked to wear the device at the right side of the body during day and night and to remove it only for showering, swimming or activities that involve the risk to potentially damage the device. Verbal instructions on how to wear the device were given by a member of the research team during the house visit prior to the start of the study and additionally summarized on an information leaflet. Accelerometers have been shown to be valid, objective measures to characterize physical activity levels in adolescents and children in clinical [8, 14] and postsurgical settings in particular [15]. The number of steps (i.e., total physical activity volume) was averaged over a period of seven consecutive days using ActiLife software (version 6.13.3) and included as indicators of physical activity recovery. AIS patients were asked to wear the accelerometer for at least 8 hours per day to reliably estimate their step count (SC) on that day. Data of participants with less than 4 out of 7 registration days were considered as invalid and excluded from further analyses.

4.3.6 Statistics

In order to investigate differences in the daily SC between surgical procedure and the three timepoints (Pre-Op, Post-3W and Post-6W) a two-way Repeated Measures Analysis of Variance (ANOVA) followed by

Bonferroni post-hoc testing was conducted separately for both the LIV-groups (T-group and L-group) and FL groups (SF-group and LF-group). In order to investigate whether the early postoperative SC could be predicted by commonly used patient reported outcome measures, an univariate linear regression analysis was conducted for the SC at Post-3W (model 1) and, secondly, for the SC at Post-6W (model 2). The following predictors at each relevant timepoint were included in the analysis: age, average pain intensity, PCS-C score, FDI-score and PedsQL-score. Statistical analyses were performed using SPSS (version 28, SPSS Inc., Irvine, CA) and the significance level was set at p = .05.

4.4 Results

The LIV was fairly equally distributed over the patients (T12=6 patients; L1=15 patients; L2=10 patients; L3=7 patients; and L4=10 patients). This resulted in the following LIV groups: T-group = 21 patients, and L-group= 27 patients. The fusion length of the AIS patients ranged from 4-15 levels. This resulted in a SF-group of 19 patients and a LF-group of 29 patients.

4.4.1 Recovery of Step count

The ANOVA showed a significant ($p<0.001$) timepoint effect for the SC. The SC of both LIV groups was significantly lower postoperatively at both Post-3W ($p<0.001$) and Post-6W ($p<0.001$) compared to the preoperative SC (T-group: Pre-Op = 13044 ± 3514 steps/day; Post-3W = 7743 ± 2800 steps/day; Post-6W = 9494 ± 2752 steps/day; and L-group: Pre-Op = 12921 ± 3259 steps/day; Post-3W = 5367 ± 2336 steps/day; Post-6W = 7765 ± 2674 steps/day). Postoperatively the SC significantly ($p<0.001$) increased for both groups from Post-3W to Post-6W.

4.4.2 LIV and Fusion length groups

Pre-Op no significant difference in SC was identified between LIV groups. Postoperatively, the ANOVA showed a significant group effect for the SC at both Post-3W (p=0.002) and Post-6W (p=0.033) (Figure 4.1). At both timepoints the T-group had a higher SC compared to the L-group (Figure 4.1).

The repeated ANOVA revealed no significant (p=0.080 - 0.394) differences between the SF- and LF-group in SC for the three timepoints (Pre-Op, Post-3W and Post-6W) (Figure 4.2).

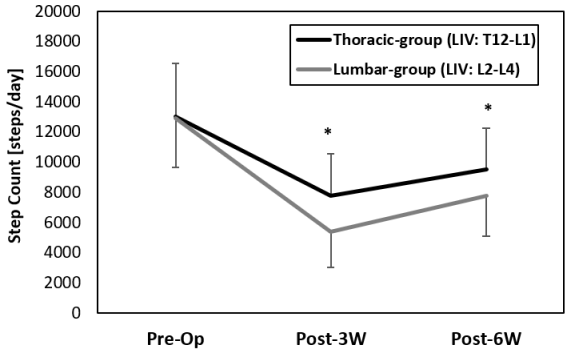


Fig. 4.1. *The average daily step count for the three timepoints (Pre-Op: 1-3-week(s) prior to surgery; Post-3W: 3 weeks after surgery; Post-6W: 6 weeks after surgery) of the AIS patients who were grouped based on their lowest instrumented vertebra (LIV)*

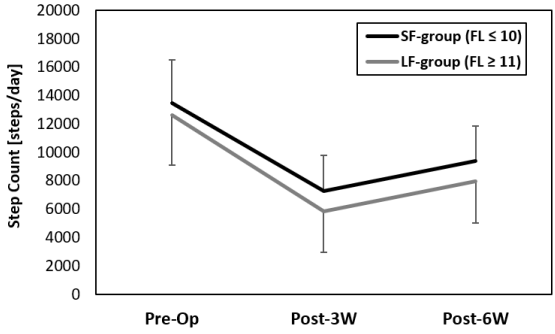


Fig. 4.2. *The average daily step count for the three timepoints (Pre-Op: 1-3-week(s) prior to surgery; Post-3W: 3 weeks after surgery; Post-6W: 6 weeks after surgery) of the AIS patients who were grouped based on their fusion length (FL)*

4.4.3 Step count at Post-3W and at Post-6W

The linear regression model (p=0.011) with the SC at Post-3W as the dependent variable revealed that the FDI-score at Post-3W was the only significant (p = 0.011) predictor variable (Table 4.1). The remaining variables (Age, Avg. Pain at Post-3W, PCS-C score at Pre-Op and PedsQL-score at Post-3W) did not significantly contribute to the prediction of the SC at Post-3W. Overall, the model revealed that the predictors were able to explain 17.6% of the variance in the SC at Post-3W (Table 4.1).

No significant multiple linear regression model (p=0.485) with the SC at Post-6W as the dependent variable was obtained. Thus, none of the variance in the SC at Post-6W (adjusted R^2 = -0.003) could be explained by any of the predictor variables.

Variables	Regression coefficient	95% Confidence interval	P-value	R^2 Value	Adjusted R^2 Value
Multiple regression model: SC at Post-3W			**0.022**	0.266	0.176
Constant	15378	4381, 263760	0.007		
Age	-190	-750, 370	0.497		
Avg. Pain at Post-3W	206	-252, 665	0.369		
PCS-C score at Pre-Op	-68	-145, 8	0.079		
FDI-score at Post-3W	-153	-269, -37	**0.011**		
PedsQL-score at Post-3W	-37	-120, 45	0.369		

Notes: SC: Step count; avg.: Average; PCS-C: Pain Catastrophizing Scale for children; FDI: Functional Disability Inventory; PedsQL: Pediatric Quality of Life Inventory.

Table 4.1. Multivariate linear regression analysis with SC at Post-3W as dependent variable and age, LIV-score, Fusion length, average pain intensity at Post-3W, PSC-C score at Pre-Op, FDI-score at Post-3W and PedsQL-score at Post-3W as independent variables.

4.5 Discussion

In the present study, for the first time the initial postoperative physical activity levels were measured objectively using a waist-worn accelerometer (ActiGraphTM (GT3X+), Pensacola, Florida). We additionally examined the relationship between physical activity in terms of daily step count (SC) at 3 and 6-weeks postoperative and patient characteristics (i.e., age), fusion levels (i.e. FL and LIV) or pain.

4.5.1 Step count recovery

The preoperative SC (Pre-Op = 13049 ± 3214 steps/day) of the AIS patients was in line with the recommended daily SC of 12.000 steps for adolescents in the literature [16] and suggests that the AIS patients met the current physical activity guideline [17]. As expected, the SC was lower postoperatively at Post-3W and Post-6W compared to Pre-Op (Pre-Op = 13049 ± 3214 steps/day; Post-3W = 6486 ± 2925 steps/day; Post-6W = 8723 ± 3020 steps/day). The SC did increase from Post-3W towards Post-6W, but did not reach the recommended levels yet in this very early postoperative phase.

4.5.2 Step count and Fusion levels

A factor that affected the postoperative recovery was the LIV-level. A fusion surgery with the LIV at L2 or below (L-group) had a negative impact on the SC at Post-3W and Post-6W (Figure 4.1), which was in line with the hypothesis. The length of the fusion, and thus the UIV selection, did not impact the postoperative SC. This shows that shorter fusions do not necessarily result in a higher activity level in the very early recovery phase compared to longer fusions. Overall, these findings highlight that the choice of LIV is not only important for long-term spinal mobility [4], but

also, affects the early recovery phase (Post-3W and Post-6W), at least in terms of step count.

4.5.3 Step count and PROMS

The regression model revealed that a small proportion of variance (17.6%) in the SC at Post-3W could be predicted by the variables included in the model (age, avg. pain intensity at Post-3W, FDI-score at Post-3W and PedsQL-score at Post-3W) of which the FDI-score was the only significant predictor. This relatively low relationship reveals that a very large portion of the SC at Post-3W remains unexplained. For the SC at Post-6W, the regression model could not explain any of the variance and no significant predictors were identified amongst the included variables (age, avg. pain intensity at Post-6W, FDI-score at Post-6W and PedsQL-score at Post-6W). Overall, these findings highlight that the initial recovery in physical activity levels cannot be predicted by the currently available information, which is in line with our hypothesis and a proportion of the literature that focused on the return to daily life activity and sports [5, 18]. Thus, in the very early recovery phase (Post-3W and Post-6W) questionnaires on physical functioning (FDI) and HRQOL (PedsQL) are not related to objective data of physical activity. Once more, this shows the added value of accelerometers that collect objective data such as SC in this very early postoperative phase, as these could act as threshold values for the functional recovery of the AIS patient. This information could allow the clinician to determine if the AIS patient is recovering as expected and intervene when necessary.

4.5.4 Limitations

A potential limitation of the present study is the fact that high levels of compliance among patients wearing accelerometers is required to

prevent great portions of missing data. The present technological developments provide several alternatives to overcome this limitation, as SC data is presently collected almost effortless by more 'attractive' and easy to use alternatives for the patient, such as smartphones or other wrist worn devices, with sufficient accuracy and providing immediate feedback [19]. Furthermore, the lacking accelerometer data at a later timepoint, such as three, six or twelve months postoperatively, is a limiting factor and prevents any conclusions regarding the further development of the SC over time. However, it should be noted that we specifically focused on the very early postoperative phase (three and six weeks postoperatively) and the findings of the present study will, therefore, provide valuable information concerning the functional recovery within this period.

4.6 Conclusion

The findings of the present study show that the LIV selection and not the fusion length, is important for the very early recovery phase, at least in terms of step count (at 3 and 6-weeks postoperatively). A fusion surgery with the LIV at L2 or below has a negative impact on the very early postoperative (at 3 and 6-weeks) activity levels. Furthermore, this objective functional outcome parameter in the form of a step count is not predicted by questionnaires on physical functioning in the very early recovery phase.

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Chapter 5: Postoperative Trunk Mobility Recovery and the Predictive Role of the Lowest Instrumented Vertebra in Adolescent Idiopathic Scoliosis Fusion Surgery

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Postoperative Trunk Mobility Recovery and the Predictive Role of the Lowest Instrumented Vertebra in Adolescent Idiopathic Scoliosis Fusion Surgery

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Keywords: AIS, LIV, Spinal Fusion, Trunk Motion, Functional outcome

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(The study protocol was submitted to and approved by KOOR & SRS, followed by intermittent updates on the progress of the study without significant interference.)

Conflicts of interest: The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethics Approval: The study was approved by the institution's research ethics committee (S64400), and was carried out according to the guidelines for Good Clinical Practice (ICH/GCP) and the declaration of Helsinki for the protection of people who participate in clinical studies.

Consent to participate: Written informed consent was obtained from all legal guardians/parents and/or the individual participants in the study.

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5.1 Abstract

Background Spinal fusion is a common treatment for severe, progressive Adolescent Idiopathic Scoliosis (AIS). Maximum safe preservation of motion segments, particularly in the lumbar spine, is a fairly widely accepted surgical goal. However, the specific relationship between reduced spinal motion and fusion length/LIV (lowest instrumented vertebra) and its negative impact on functional outcomes remains largely unexplored.

Research question Do AIS patients undergoing thoracolumbar (TL) fusion have greater loss of trunk mobility and worse functional outcomes compared to their thoracic (T) fusion counterparts with an LIV at L1 or higher? Additionally, can we identify predictors of decreased postoperative trunk mobility at 1-year follow-up to improve preoperative planning and counseling?

Methods This study includes 37 AIS patients (11-29y), with a mean follow-up of 1-year. Data collected preoperatively, at 3-months, and 1-year included structural, motion, and functional assessments (PROMs and activity tracking). Differences in trunk mobility, PROMs, and step counts between the T- and TL-fusion groups were analyzed. A multivariate linear regression was utilized to identify predictors of reduced global trunk mobility.

Results At 3-month follow-up, the TL-group showed greater reductions in global trunk mobility (28%) compared to the T-group (15%), with no marked improvements at 1-year. No significant differences in SRS-function scores, (I)PAQ results, and daily step counts were noted between the groups. The presence of a structural lumbar curve and overall fusion

length were key predictors, explaining 31% of the variance in range of motion reduction.

Significance The findings indicate that structural factors, specifically fusion length and the presence of a structural lumbar curve (not LIV), negatively influence global trunk mobility. The study underscores the intricate relationship between subjective functional assessments and objective mobility outcomes, suggesting that enhanced trunk mobility measurement could refine our understanding and impact future surgical strategies.

5.2 Introduction

Current guidelines recommend spinal fusion for adolescent idiopathic scoliosis (AIS) patients with Cobb angles equal or greater than 50 degrees, especially when curve progression is anticipated[1, 2]. Spinal fusion inherently results in a significant reduction in trunk mobility and thus confronts the surgeon with an important trade-off. Shorter fusion lengths, although preserving more mobility, are associated with a higher risk of complications such as "adding-on" phenomenon and distal junctional kyphosis[3, 4]. Conversely, longer fusions offer better deformity control but at the expense of mobility and increased risk of adjacent level disc degeneration[5]. Most of the AIS literature has focused on the structural outcome following spinal fusion, with more recent efforts evaluating this structural outcome in 3D[6, 7]. However, outcome following spinal fusion also includes the intrinsic loss of spinal motion due to the arthrodesis of a certain number of spinal motion segments. This reduction in spinal motion can be objectively measured in a non-invasive manner by clinical assessment or can be quantified in more detail using advanced marker-based motion analysis[8, 9]. In more general terms,

functional outcome is evaluated in this adolescent population through two distinct approaches: patient-reported outcome measures (PROMs), which emphasize self-assessed functional abilities and physical activity levels, and objective assessments employing wearable activity trackers. The latter provides quantifiable data on physical activity, offering a complementary perspective to the subjective insights gathered from conventional PROMs[10]. Based on such assessments, literature has demonstrated that, on average, positioning the lowest instrumented vertebra (LIV) below L1 adversely affects functional capability in certain daily and sports-related activities, as evidenced by questionnaire-based assessments[11–13]. Also objective measurements of daily activity, such as step counts recorded by activity trackers, indicate an increased level of physical activity at 6 weeks postoperatively among patients undergoing spinal fusion with an LIV located at or above L1[14]. However, the specific relationship between reduced spinal mobility and fusion length and its negative impact on functional outcomes during the first year of postoperative recovery remains poorly documented. Similarly, the patient-specific structural and functional factors that predict loss of global trunk mobility after fusion remain largely unexplored. Therefore, this study aims to conduct a comparative analysis of global trunk mobility and functional outcome in AIS patients who have undergone thoracic (T) fusion (with the LIV at L1 or higher) versus those who have received thoracolumbar (TL) fusion (with the LIV at L2 or lower). The comparison will be based on loss of trunk mobility (e.g. seated forward flexion task), as assessed by marker-based motion analysis, and functional outcomes, as assessed by patient-reported outcome measures (PROMs) and objective measures of daily activity, at three months and one year postoperatively relative to preoperative levels. We hypothesize that AIS

patients subjected to TL fusion will exhibit more mobility loss and inferior functional outcomes compared to their T fusion counterparts.

Additionally, this study seeks to assess potential predictors of postoperative global trunk mobility impairment in the cohort of AIS patients undergoing spinal fusion. We aim to answer the following research questions: (1) Can preoperative structural variables predict loss of global trunk Range of Motion (RoM) (2) Is the postoperative decrease in global trunk RoM less in patients who were more active preoperatively? (3) Can any of the postoperative PROMS predict a loss in global trunk RoM? Identifying these predictors is critical for tailoring preoperative planning (e.g. selective fusion), preoperative counseling and postoperative management to mitigate fusion-related reductions in trunk mobility.

5.3 Methods

5.3.1 Participants

This study includes 37 patients (11-29y) with a mean of 1-year (and a minimum of 3-month) postoperative follow-up from an ongoing prospective AIS pilot study approved by our institution's research ethics committee (S64400) and conducted according to the Declaration of Helsinki.

5.3.2 Data collection

Data were collected for all AIS patients (N=37) at the following three different time points: Pre-op (N=37), 3-months post-op (Post-3M, N=37), and 1-year post-op (Post-1Y, N=29). Data collection consisted of:

5.3.2.1 Patient characteristics

Demographic parameters (age, Body Mass Index (BMI), radiographic parameters in the SRS free standing position (Lenke classification, Risser classification, Cobb angles of all structural curves) using low-dose biplanar radiographic images (EOS Imaging System, France) as well as surgical parameters (instrumentation length and LIV-score (T12=0;L1=1;L2=2;L3=3;L4=4)) were documented by the treating surgeon for each patient.

5.3.2.2 PROMS

The following validated questionnaires were completed by the patient at all three timepoints: the Scoliosis Research Society Score (SRS-22)[15] which covers five aspects (Pain, Function, Self-Image, Mental Health and Satisfaction), the Trunk Appearance Perception Scale (TAPS)[16] to evaluate the perception patients have of their trunk deformity, the International Physical Activity Questionnaire (IPAQ) which is a self-reported measure of physical activity (PAQ-C in children (<12y), PAQ-A in adolescents (12-18y) and IPAQ in adults [17, 18]) and the Visual Analog Scale (VAS) to assess the pain perception at each timepoint.

5.3.2.3 Objective level of activity

The level of activity in terms of average daily step count was collected using a commercial activity tracker (Xiaomi Mi Band 5, Xiaomi Inc, China), which was worn around each patient's wrist for at least 7 consecutive days prior to visiting the motion analysis laboratory at each of the three timepoints.

5.3.2.4 Motion analysis

To assess the level of global trunk RoM, the seated maximal forward trunk flexion angle is measured at all three timepoints (preoperative, post-3M and post-1Y), using a previously validated spinal deformity-specific motion analysis (Vicon Motion systems, Oxford Metric, UK) [9]. First markers were attached to the body of the patient according to the Plug-in Gait (PiG) model, supplemented by a spine model consisting of at least 6 individual markers (Figure 5.1)(including markers on the spinal processes of C7 and S1, which we use to determine the seated maximum forward flexion angle of the trunk). Next, the patients were instructed to perform a maximal seated forward trunk flexion, starting with the patient in upright position with the fingertips placed just above their ears. When the patients reached maximal flexion, they were instructed to hold that positions for three seconds, to thereafter move back to the starting position (Figure 5.1). Each flexion task was performed in duplicate and the marker locations were captured using a 10-camera motion capture system sampling at 100 Hz (VICON Motion systems). Global trunk flexion RoM was calculated between maximum flexion and the upright position using the trajectory of the markers placed at C7 and the patient's sacrum.

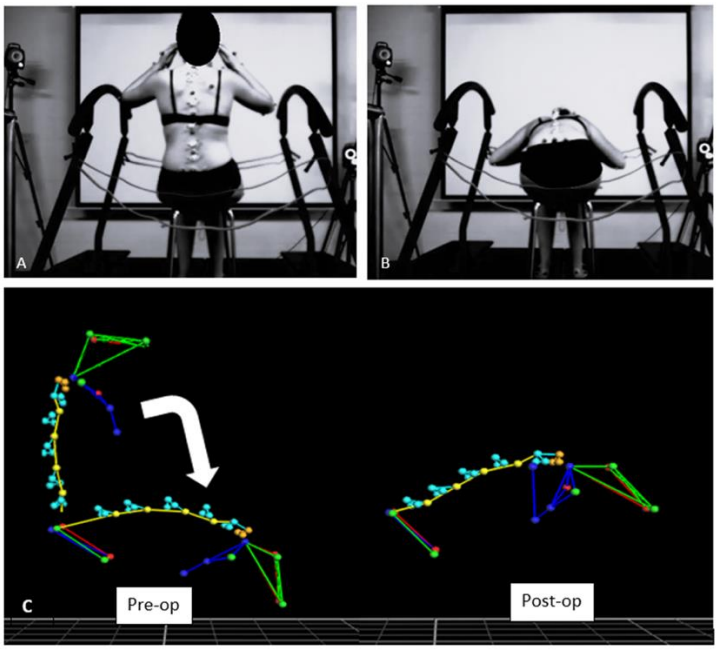


Fig. 5.1. illustrates the methodology for assessing global trunk flexion range of motion through maximal forward trunk flexion in a seated position performed in a gait laboratory setting. Panel (A) illustrates the initial upright position adopted by the participants at the beginning of the assessment, while panel (B) captures the moment of maximum flexion achieved by the participants. Panel (C) shows maximal forward flexion of the trunk in the seated position in sagittal view before and after thoracolumbar AIS fusion. Note the loss of kyphosis or preservation of lumbar lordosis during maximal forward flexion in the postoperative image.

5.3.3 Statistical analysis

In the first part patients were categorized based on LIV into T (with the LIV at L1 or higher) and TL (with the LIV at L2 or lower) groups. Then differences in preoperative characteristics between T and TL-group were evaluated using two-sample t-tests or Wilcoxon signed-rank tests, followed by Bonferroni correction for multiple tests.

Differences in functional abilities, physical activity levels, and spinal motion ((I)PAQ, SRS-function score, daily step count, seated forward trunk flexion angle) between T and TL-group at preoperative vs 3-month and preoperative vs 1-year follow-up were analyzed. Negative percentages signify reductions post-surgery. Since we have one value for

each difference (Pre vs Post-3M, Pre vs Post-1Y), again a two-sample t-test or Wilcoxon signed-rank test, followed by Bonferroni correction for multiple testing, was used to compare the differences between the T and TL-group.

In the second part, predictors for the level of postoperative global trunk RoM (dependent variable) were sought using multivariate linear regression with forward selection using the Aike Information Criterion (AIC). Analyses were performed for changes at 3-months and 1-year post-surgery, considering radiographic and surgical, functional, and demographic factors in separate models. Statistical analyses were done in R (version 4.2.3), with p = .05 as significant. No violation was made against assumptions of linear regression (normality, homoscedasticity, independence of observations and multicollinearity). Missing values were not excluded from the dataset but were handled using a mean impute. This resulted in one imputation in the preoperative Cobb angle, 10 for the pre-operative step count, 5 in the SRS-22 total score at 1 year, and 8 of global trunk RoM reduction percentage at 1 year.

5.4 Results

5.4.1 Study population

The detailed preoperative characteristics for the T-group and the TL-group can be found in the supplement (table 5.8.1 supplement). The only significant ($p<0.001$) difference between the two groups was observed in their LIV scores, with the T-group having a score of 1 and the TL-group having a score of 3 on average. No differences were found in age, BMI, Cobb angle, VAS, TAPS or fusion length. At 3-month follow-up, the T-group consisted of nine patients, while the TL-group had 28 patients. At

1-year follow-up, the T-group had seven patients, while the TL-group had 22 patients.

5.4.2 Differences in absolute values of RoM

Significant differences in global trunk flexion RoM were observed between preoperative (91° ± 10.7°) and 3-month (68.1° ± 15.7°) ($p<0.001$). A similar result was found between the preoperative (91° ± 10.7°) and 1-year follow-up (68.2° ± 13.7°) ($p<0.001$). This indicates a postoperative reduction in maximal trunk flexion for all patients.

5.4.3 Percentual reduction in RoM and functional outcomes (T-&TL-group)

Percent changes in trunk flexion angle, SRS-function score, (I)PAQ, and daily step count at 3-month and 1-year follow-up showed no significant differences between fusion groups (Table 5.1). The detailed absolute values of the preoperative, 3-month and 1-year functional outcome scores and step count for the T and TL-group can be found in the supplement (Table 5.8.2 supplement).

Both fusion groups exhibited a decrease in global trunk RoM 3-month follow-up being more pronounced in the thoracolumbar fusion group (T-group: -15%, TL-group: -28%). Till 1 year follow-up, no increase in RoM was observed (T-group: -16%; TL-group: -26%). Data suggest a difference between both groups, yet due to the large variances, results are not statistically significant (Figure 5.2)

Percentual reduction		T-group (n=9) (LIV : T12-L1)	TL-group (n=28) (LIV: L2-L4)	p-value
Trunk RoM (%)	Pre vs Post-3M (n=37)	-15.1±19.2	-28.2 ± 17.6	0.095[b]
	Pre vs Post-1Y (n=29)	-16.3 ± 17.9	-26.2 ± 18.8	0.134[b]
SRS Function (%)	Pre vs Post-3M (n=37)	-11.1 ± 12.5	-7.7 ± 16.5	0.519[b]
	Pre vs Post-1Y (n=32)	0.6 ± 7.2	6.1 ± 16.0	0.414[a]
Step count (%)	Pre vs Post-3M (n=19)	-24.4 ± 21.6	0.48 ± 68.8	0.080[a]
	Pre vs Post-1Y (n=19)	-2.22 ± 31.8	18.6 ± 35.9	0.137[a]
IPAQ (%)	Pre vs Post-3M (n=27)	-30.3 ± 29.6	-28.4 ± 27.7	0.881[b]
	Pre vs Post-1Y (n=17)	-21.4 ± 13.5	3.8 ± 29.4	0.059[b]

After applying a Bonferroni correction the statistical significance is set at p-value = 0.003. The number of participants per group is indicated by 'n'. 'Pre vs Post-3M' is the difference between preoperative and 3 months after surgery. 'Pre vs Post-1Y' is the difference between preoperative and 1 year after surgery. Statistical tests were performed on the mean imputed dataset (no missing values). The original numbers of participants for each parameter are next to their timepoint. (a) The nonparametric Wilcoxon signed-rank test used to test potential difference . (b) A two-sample t-test used to test potential difference
Table 5.1. *Percentual reduction for several variables between different time points in follow-up for the thoracal group (T-group) and the thoracolumbar group (TL-group).*

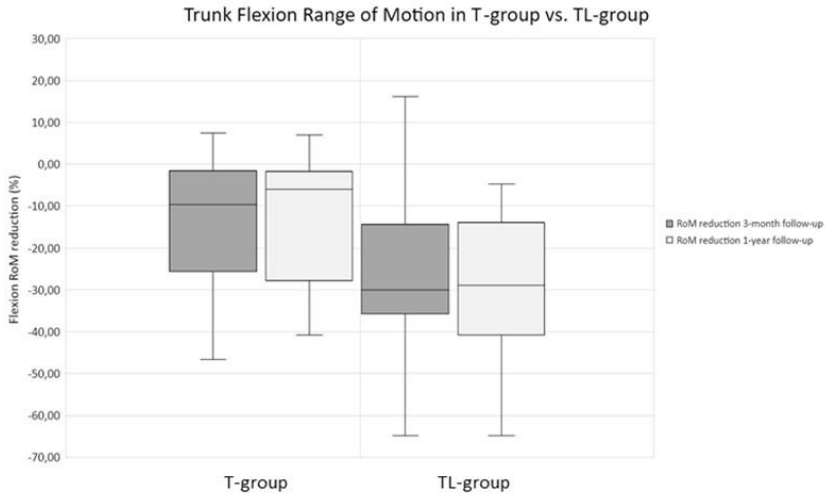


Fig. 5.2. *T-group vs. TL-group: RoM reduction at 3-month and 1-year follow-up*

5.4.4 Prediction of postoperative reduction in trunk RoM in spinal fusion (all patients)

Model 1: Preoperative radiographic patient characteristics and surgical parameters

At 3-months follow-up the selected predictive variables for the postoperative mobility reduction included Lenke type (β= -18.2, t= -3.298, p=0.002), fusion length (β= -3.9, t= -3.298, p= 0.002), and preoperative Cobb angle (β= 0.5, t= 2.222, p=0.033), each showing a significant impact on reduction in flexion RoM percentages. Other variables, e.g., Risser classification and LIV score, did not have a significant effect (See table 5.8.3 supplement). Overall, the model could explain **31% of the variance** for reduction in seated forward trunk flexion RoM percentages from preoperative to 3-months follow-up (F=6.387, p =0.002, Adj. R^2 = 0.310). As stated before, a negative percentage indicates a reduction in global trunk flexion postoperative compared to the baseline preoperative assessment. Therefore, at 3 months postoperative a change in Lenke type group (Lenke 3-6 ~ structural lumbar curve) results in an 18.2% reduction of flexion RoM. Similarly, an increase in fusion length is associated with a 3.9% reduction in flexion RoM. Conversely, a higher preoperative Cobb angle is linked to a 0.5% increase in flexion RoM.

At 1-year follow-up, the selected predictive variables were consistent with those identified in the 3-month follow-up model, again including Lenke type (β= -12.4, t= -2.245, p=0.032), fusion length (β= -4.7, t= -3.980, p<0.001), and the preoperative Cobb angle (β= 0.5, t= 2.119, p=0.042). Other variables, e.g., Risser classification and LIV score, did not have a significant effect (Table 5.2). The model could explain **30.8% of the**

variance in the reduction of global trunk RoM percentages from preoperative to 1-year postoperative (F=6.365, p=0.002, Adj. R^2 Value=0.308). Our data analysis suggests that the Lenke-type group (structural lumbar curve) is associated with a 12.4% reduction in global trunk flexion RoM. An increase in fusion length is linked to a 4.7% reduction in global trunk flexion RoM.Conversely, a higher preoperative Cobb angle is linked to a 0.5% increase in flexion RoM. It's important to note the slight differences in the impact of Lenke type and fusion length on RoM reduction between the 3-month and 1-year follow-ups, which may reflect the longer-term adaptation or recovery processes.

Variables	Regression coefficient	95% Confidence interval	P-value
Constant	5.1	-32.0, 42.3	0.78
Lenke type (grouped)	-12.4	-23.7, -1.2	0.032*
Fusion Length	-4.7	-7.1, -2.3	<0.001*
Preoperative Cobb angle	0.5	0.02, 1.0	0.042*
Excluded variables			
Risser classification (grouped)			
LIV-score (grouped)			

** indicates statistical significance (p= 0.05). The number of participants per group is indicated by 'n.'*

Table 5.2. *A multivariate linear regression analysis with forward selection using AIC and the reduction in global trunk RoM (%) from preoperative to 1-year follow-up as the dependent variable and the radiographic patient characteristics and surgical parameters as the independent variables.*

Model 2: Preoperative functional PROMS and activity level

As we have 2 different activity questionnaires with different scales and questionnaires, due to different age groups, 2 different populations were extracted based on this questionnaire. This resulted in the PAQ(<18Y) selection (n=28) and the IPAQ(>18Y) selection (n=9). For each of these populations, two regression analyses were executed for the reduction in global trunk RoM (%) from preoperative to 3-month and 1-year follow-up.

For the PAQ selection (n=28), no significant variable could be found for the model at 3-month follow-up. For the 1-year follow-up, the SRS-22 function domain score was selected but did not significantly affect the reduction in RoM (%) (t=1.722, p-value= 0.097).

For the IPAQ(>18Y) selection (n=9), the 3-month follow-up model selected the SRS-22 function domain score, but this score did not significantly affect the reduction of global trunk RoM percentages (t= -2.274, p-value= 0.057). However, the 1-year follow-up model showed an overall significant effect and could explain **55.7% of the variance** in the reduction of global trunk RoM percentages from preoperative to 1-year post-operation (F=11.09, p=0.013, Adj. R^2 Value= 0.557). The SRS-22 function domain score itself had a significant effect on the reduction in RoM (β= -33.92, t= -3.330, p-value= 0.0126) (Table 5.3). Interpreting this result yields that an increase in the preoperative SRS-22 function domain score by 1 point increases the reduction in flexion RoM by 33%. Therefore, our data suggest that if the preoperative level of function is higher, the impact of fusion on spinal mobility may be more pronounced.

Variables	Regression coefficient	95% Confidence interval	P-value
Constant	5.1	-32.0, 42.3	0.78
SRS-22 function domain	-33.9	-58.0, -9.8	0.0126*
Excluded variables			
IPAQ questionnaire Average daily step count			

** indicates statistical significance (p= 0.05). The number of participants per group is indicated by 'n.'*

Table 5.3. *A multivariate linear regression analysis with forward selection using AIC and the reduction in global trunk RoM (%) from preoperative to 1-year follow-up as the dependent variable and the preoperative functional PROMS as the independent variables.*

Model 3: Demographic patient characteristics and postoperative PROMS

No significant variable was selected for the model at 3-month follow-up. However, at 1-year follow-up model, the total SRS-22 score was selected. This model could explain **8% of the variance** reduction in global trunk RoM (%) (F= 4.125, p =0.0499, Adj. R^2 Value = 0.080) (Table 5.4). The total SRS-22 score significantly affected the reduction in global trunk RoM (%) (β= 16.145, t=2.031 p-value= =0.0499). Interpreting this result yields that an increase in the total SRS-22 score (scale 1-5) of 1 point is linked to a 16% increase in flexion RoM, highlighting the potential role of PROMS in the assessment of postoperative reduction of flexion RoM.

Variables	Regression coefficient	95% Confidence interval	P-value
Constant	-92.403	-183.5, -33.1	0.006*
Total SRS-22 score	16.145	<0.001, 32.5	0.050
Excluded variables			
Age			
BMI			
VAS-score			
TAPS-score			

* indicates statistical significance (p= 0.05). The number of participants per group is indicated by 'n'.

Table 5.4. A multivariate linear regression analysis with forward selection using AIC and the reduction in global trunk RoM (%) from preoperative to 1-year follow-up as the dependent variable and demographic patient characteristics and postoperative PROMS as independent variables.

5.5 Discussion

This study is one of the first to assess short-term recovery in Adolescent Idiopathic Scoliosis (AIS) patients post-thoracic versus thoracolumbar fusion, focusing on mobility loss and functional outcomes via PROMs and objective activity measures. Our findings support the hypothesis that thoracolumbar fusions result in a greater loss of global spinal mobility at 3-months and 1-year postoperative follow-up compared to thoracic fusions. Specifically, the TL-group exhibited a greater reduction in global trunk RoM at 3-months (28% vs. 15% in the T-group), with no notable improvements by 1 year. This aligns with previous research indicating more substantial mobility impairments when instrumentation extends into the lower lumbar spine [19–22]. However, in our study, the discrepancy in mobility between the TL- and T-group at 1-year follow-up did not reach statistical significance. The percentage changes in SRS function score, (I)PAQ, and daily step count at 3-month and 1-year follow-up also showed no significant differences between the two fusion groups. Additionally, our analysis aimed to identify predictors of postoperative trunk mobility loss. Preoperative structural variables, notably the presence of a structural lumbar curve (not LIV) and fusion length, were significant predictors. However, the explained variance in global trunk mobility loss at 3-month and 1-year follow-up by these preoperative structural variables, was consistently small (R^2 = 0.31), suggesting that additional variables might be required to account for the observed reductions in RoM. Our data suggest that even a more proximal LIV within a structural lumbar curve—achieved through selective thoracic fusion or by opting for the touching rather than the substantially touching vertebra as the LIV—may not adequately preserve forward flexion.

In contrast, preoperative functional status inversely predicted mobility loss, with more functional patients experiencing proportionally greater

impairments, challenging the notion that higher preoperative activity levels protect against postoperative mobility loss. However, this relationship was observed only in a small subgroup of adult patients and not in the larger group of patients under 18 years old, who were analyzed separately due to differing functional score assessments. So, interpretation should be done cautiously. Postoperative PROMs, meanwhile, showed limited efficacy in predicting RoM loss, underscoring the complex interplay between subjective functional assessments and objective mobility outcomes. This inconsistency is further corroborated by a recent study by Pahys et al.[22], which compared vertebral body tethering (VBT= a polyethylene cord based dynamic scoliosis correction technique) and fusion in AIS patients. Despite substantial differences in postoperative mobility loss between VBT and fusion, the SRS scores remained largely similar across both groups.

Study limitations and future directions. This study had several limitations. In particular, the thoracic fusion group had a smaller sample size, and our focus was limited to trunk motion in the sagittal plane without considering pelvic compensation[23]Future research should include a broader evaluation of spinal and pelvic motion to improve the clinical relevance of our findings.

In the current study, our marker-based motion analysis does not differentiate between "hip users" (those with the majority of flexion RoM in the hips) and "spine users"[24]. However, spinal arthrodesis is likely to have a more significant impact on the RoM of "spine users". Currently, direct measurement using deep-flexion radiographs is the most accurate method for differentiating between spinal RoM and hip flexion. However, this approach results in additional radiation exposure. To address this limitation, future research is exploring the use of patient-specific spine

modeling. A previously published polynomial method between anatomically corrected spinal skin markers may offer a viable solution[9]. These approaches could help distinguish between RoM in the spine and hips, providing more accurate and clinically relevant data.

In addition to the limitations of the study in terms of motion analysis, there is a need to address the challenge of accurately assessing physical activity over time, especially with the transition from school to work-related activities and the limitations of wearable technology [14].

5.6 Conclusion

This study showed that thoracolumbar fusion results in greater trunk mobility reduction compared to thoracic fusion, without significant differences in functional outcomes as measured by subjective surveys and objective activity measures at 3-month and 1-year follow-ups. Key predictors of mobility loss were the presence of a structural lumbar curve and the extent of fusion, not LIV. Postoperative PROMs had limited predictive value for RoM loss, highlighting the complex relationship between subjective functional assessments and objective mobility outcomes. Enhancing trunk mobility measurement may improve our understanding of these dynamics, benefiting future preoperative counseling and surgical planning.

5.7 References

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5.8 Supplement

Table 5.8.1 supplement *Preoperative characteristics for the T-group and the TL-group*

Characteristic	T-group (n=9) (LIV: T12-L1)	TL-group (n=28) (LIV: L2-L4)	p-value
Age (yrs.)	16.4 ± 3.8	16.9 ± 3.4	0.497[a]
BMI	21.0 ± 3.3	19.2 ± 3.5	0.100[a]
Main Cobb angle (°)	56.8 ± 5.6	60.8 ± 12.4	0.412[a]
VAS score (0-10) *	2.0 ± 2.0	1.8± 2.2	0.533[a]
TAPS (0-5) *	3.3 ± 0.5	3.0 ± 0.5	0.080[b]
LIV score (0-4)	1 ± 0.9	3 ± 0.9	**<0.001**[a]
Fusion length	11.1 ± 1.3	11.1± 2.5	0.146[a]

After applying a Bonferroni correction the statistical significance was set at p-value = 0.003. The number of participants per group is indicated by 'n'. (a) The nonparametric Wilcoxon signed-rank test used to test potential difference. (b) A two-sample t-test used to test potential difference

Table 5.8.2 supplement *Absolute values of preoperative, 3-month and 1-year functional outcome scores and step count for the T and TL-group (IPAQ (adult), PAQ (child)).*

	T-group (LIV : T12-L1)	TL-group (LIV: L2-L4)
Pre-op		
SRS function	4.38 ±0.50	4,19 ±0.61
Step count	7137 ±2587	5699 ±2919
IPAQ	8763 ±547	3052 ±1800
PAQ	2.48 ±0.56	2,12 ±0.67
3 months		
SRS function	3.84 ±0.31	3,79 ±0.39
Step count	5784 ±2162	4704 ±2199
IPAQ	3125 ±2114	1887 ±1506
PAQ	1.71 ±0.88	1,39 ±0.34
1 year		
SRS function	4.23 ±0.23	4,36 ±0.46
Step count	5999 ±1325	4689 ±2414
IPAQ	3660 ±1358	5590 ±1931
PAQ	1.93 ±0.86	2,05 ±0.62

Table 5.8.3 supplement *A multivariate linear regression analysis with forward selection based on AIC using the reduction in global trunk RoM (%) from preoperative to 3-months follow-up as the dependent variable and the radiographic patient characteristics and surgical parameters as independent variables.*

Variables	Regression coefficient	95% Confidence interval	P-value
Constant	-4.4	-41.7, 32.8	0.8
Lenke type (grouped°)	-18.3	-29.6, -6.9	0.002*
Fusion Length	-3.9	-6.3, -1.5	0.002*
Pre operative Cobb angle	0.5	0.04, 1.0	0.033*
Excluded variables			
Risser classification (grouped°)			
LIV-score (grouped°)			

** indicates statistical significance (p= 0.05). The number of participants per group is indicated by 'n'.*

° Lenke type grouped: group A (Lenke1&2), group B (Lenke 3-6~structural lumbar curve)

° Risser grouped: group A (Risser 0-2), group B (Risser 3-5)

Chapter 6: Concluding discussion and future perspectives

CONCLUDING DISCUSSION AND FUTURE PERSPECTIVES

To date, the surgical treatment of adolescent idiopathic scoliosis has shown considerable variability, primarily caused by a lack of uniform evidence-based treatment guidelines. A major source of this variability lies in the selection of the Lowest Instrumented Vertebra (LIV) when performing posterior spinal fusion (PSF). For example, in Lenke 1 (main thoracic) the choice of LIV during PSF can vary by up to four spinal levels between experts[1]. As was outlined in the general introduction, this specific variability in LIV selection is fueled by the absence of scientific evidence, and hence guidelines, with regards to an **important trade-off when selecting the LIV**: whereas longer constructs provide sustained deformity control at the expense of preserving less lumbar motion, shorter constructs preserve more lumbar motion[2, 3] but risk further deformity progression below the fusion and global spinal malalignment[4, 5].

With regards to this lack of scientific evidence, three specific knowledge gaps were identified, ranging from surgical planning to outcome evaluation which this doctoral thesis aims to address:

I. The first knowledge gap concerns the oversimplification of a complex 3D dynamic deformity into a few simple 2D static parameters during preoperative LIV planning.
II. The second knowledge gap focuses on the limitations of subjective measures to assess functional outcomes in patients undergoing AIS fusion to more objectively discern the impact of LIV on patient function.

III. The third knowledge gap concerns the structural lack of spinal range of motion assessments and its relation with functional outcome and fusion length, including LIV selection.

Based on these knowledge gaps the overall aim of this thesis was to explore the potential added value of **3D** planning, objective **activity** measurement and non-invasive quantitative spinal **ROM** measurement to provide the currently missing scientific evidence underlying LIV in AIS fusions.

Moreover, specific research objective were identified to address each of the above gaps.

The first objective was to address the limitations of current 3D reconstruction methods by introducing a simple 3D analysis method that directly translates the traditional 2D key parameters for LIV selection (such as CSVL, SV, Lenke lumbar modifier, NV) into the third dimension. Second, to quantitatively compare and clinically interpret these 3D corrected parameters in relation to their corresponding traditional 2D assessment and the potential impact on LIV selection. This first objective was addressed in **Chapter 3**.

Our second objective was to document the added value of objective activity measurement in the outcome assessment of AIS patients undergoing PSF. Hereto, the very early (3 & 6 weeks post-operatively) functional recovery of AIS fusion patients was assessed using an accelerometer. Furthermore, we investigated the relationship with patient characteristics, patient reported outcome measures (PROMS), pain and fusion levels. This second objective was explored during the short-term recovery period of AIS fusions in **Chapter 4** and also during the later (3 & 12 months postoperative) recovery period in **Chapter 5**.

Our third objective was to document the added value of the non-invasive assessment of spinal range of motion in the outcome assessment of AIS patients. To this aim, in **Chapter 5**, we performed a comparative analysis of global trunk mobility and functional outcomes in AIS patients who underwent thoracic (T) fusion (with LIV at L1 or higher) versus those who underwent thoracolumbar (TL) fusion (with LIV at L2 or lower). In addition, we aimed to evaluate potential predictors of postoperative global trunk mobility impairment in the cohort of AIS patients undergoing spinal fusion.

In the remainder of this general discussion the main findings, remaining discussion points, and suggestions for further research for each of these three research objectives are summarized below. In the final section of this chapter, the contribution to the overall aim of this thesis is summarized in a final conclusion.

6.1 LIV selection in 3D instead of 2D

In Chapter 3, we addressed the first knowledge gap regarding the oversimplification of a complex 3D dynamic deformity into a few simple 2D static parameters during preoperative LIV planning. Hereto, we first developed a straightforward 3D analysis method that redefines existing traditional 2D key parameters for LIV selection, such as the CSVL, SV, and NV, within a 3D framework. The developed method used biplanar radiographs (EOS imaging) with the pelvis as the reference plane and thus overcomes an important limitation of the central hip vertical axis (CHVA) previously proposed by the SRS 3D scoliosis committee[6] which does not take into account the horizontality of the pelvis as prescribed by the original definition of King et al.[7]. Furthermore, in our approach, NV is based on a rotation measurement between vectors (similar to those

proposed by Illes et al.[8]) with respect to the pelvic landmarks and a vector between the landmarks on the superior endplate and the spinous process landmark, thus overcoming the subjective and categorical nature of vertebral rotation assessment underlying the Nash-Moe method. To assess the added value of this novel 3D analysis method over the conventional 2D approach, a retrospective analysis was performed on 79 patients diagnosed with Lenke 1 or 2 AIS, comparing key parameters for LIV selection based on the novel 3D framework with conventional 2D parameters. This analysis revealed a significant discrepancy between 2D and 3D assessment in 33 of 79 patients (41.8%) for at least one key parameter [9]. This finding suggests that 3D evaluation may significantly alter LIV selection in patients with Lenke 1 and 2 AIS and may potentially explain poor radiographic outcomes such as additional or distal junctional kyphosis [4, 5]. The most relevant discrepancy between 2D and 3D analysis in terms of key parameters for LIV selection was found for the Stable Vertebra (SV). A different SV was identified in 18 of the 79 patients (22.5%). In 16 of these patients, the 3D SV was one vertebral level higher than the 2D SV. This means that in 16 patients (20.3%), a potentially shorter fusion could have been performed, preserving more motion without additional risk of poor radiographic results according to current LIV selection guidelines. Conversely, in *2 of 18 patients*, the SV determined in 3D was one vertebral level lower than that determined in 2D, as shown in Figure 6.1 in *one* of these cases. This could explain the suboptimal radiographic results at five years in this specific case, characterized by a noticeable adding-on (AO) phenomenon just below the fusion area. In the *second* case, a more conservative LIV approach was applied, with the chosen LIV more distal than the 2D-SV-1, with a good radiographic outcome. This fact directly highlights the limitations of the retrospective approach to explore the association between poor

radiographic outcome (AO and DJK: 19/79) and 2D-3D mismatch in key parameters for LIV selection (33/79) in this cohort of 79 Lenke 1 & 2 fusions. An exercise we performed, but without reasonable conclusions, also due to the fact that many cases were operated in a rather conservative way (LIV = SV or even more distal) according to the guidelines for LIV selection. However, to confirm this assumption of a possible safe - without additional risk of AO or DJK - more proximal LIV selection in 16/18 cases, based on 3D-SV , further research is needed, specifically through prospective studies in larger cohorts that focus on 3D planning of the LIV followed by detailed outcome evaluations.

Limitations and future research directions: Clearly, the clinical impact of 3D-based LIV selection on reducing suboptimal postoperative radiographic outcomes requires further investigation. If positive, the widespread conversion from 2D to 3D assessment in clinical settings requires that commercially available surgical planning software packages include a tool that produces an accurate "true" 3D CSVL to define the 3D SV and Lenke lumbar modifier. This tool should also facilitate the rapid identification of the most neutral vertebra and the most rotated apical vertebra relative to a de-rotated pelvis, thus eliminating the need for labor-intensive 3D reconstructions of the entire spine[8, 10–12].

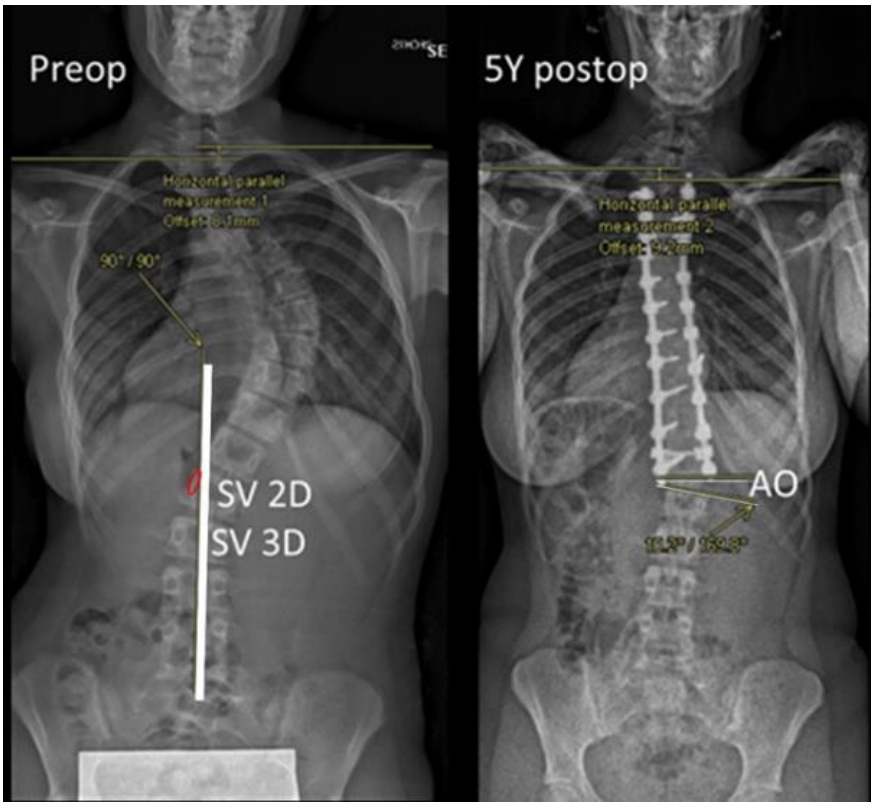


Fig. 6.1. *A double thoracic curve type Lenke 2 A-L in a 13-year-old girl with Cobb angle of 65°. Fusion of T3 to L1 with large correction of the curve to 9° and inversion of mild shoulder imbalance (-8mm preop to +9mm postop). Obvious phenomenon of Adding-On (AO)(continuing curve below fusion, 10° wedging of LIV/LIV+1 disc). LIV is SV-1 according to 2D measurement, however, SV-2 according to 3D measurement. Other drivers for this poor radiographic outcome may also be the slight shoulder imbalance +/- the large correction of the curve.*

6.2 Objective activity tracking versus LIV

The second knowledge gap of this work was addressed in Chapters 4 and 5, and concerned the limitations of subjective measures to assess functional outcomes in patients undergoing AIS fusion, to more objectively identify the impact of LIV on patient function. More specifically, wearable accelerometers were employed in both chapters to quantify physical activity in terms of step count as a potential novel and objective addition to the routine functional outcome assessment in AIS

patients pre- and post-surgery. To our knowledge, while the benefits of using accelerometers to monitor perioperative recovery have been shown in other conditions affecting adolescents[13], this approach has not yet been explored in adolescents undergoing AIS fusion surgery. Furthermore, chapter 4 specifically examined the added value of documenting step count in the early post-operative phase of 48 AIS patients as part of a prospective multi-centric study[14]. The analysis revealed that a spinal fusion at or below the L2 vertebra adversely affected early postoperative activity levels, a difference that could not be detected by state-of-the-art PROMs documenting function, pain or HRQOL[15]. As such, these findings indicate a potential complementary role of activity trackers to objectively document early post-operative recovery. Indeed, the information they provide could have an added value in the patient-specific design and monitoring of very early rehabilitation programs. However, Chapter 5 focused on longer postoperative follow-ups and compared functional outcomes, including accelerometer-measured activity, between thoracic and thoracolumbar (LIV at or below L2) fusions. In contrast with the early post-operative phase, no significant differences in step counts or PROMs were observed three months postoperatively between the two fusion types within a reduced cohort of 37 patients. Therefore, further research is needed to determine the possible benefits of objective activity tracking during later recovery phases. Indeed, the lack of observed differences in chapter 5 may have been due to the small sample size, particularly in the thoracic-only fusion group. Also the sole reliance on step counts to document activity, as well as the incomplete data might have confounded our results and will be further discussed below.

Limitations and future research directions: As mentioned, Chapters 4 and 5 focused solely on the analysis of daily step counts as an output of the

accelerometers that were used in this study. Clearly, this only provides a first, basic estimate of a patient's actual activity level. A more comprehensive approach to activity tracking, including detailed activity registration in addition to physical parameters such as those recorded by sports watches, would greatly enhance our understanding of the true activity levels of individual patients.

Furthermore, the Chapter 5 daily step count dataset was notably incomplete, with recorded step counts from only 19 of the 37 patients (51%). In Chapter 4, only 48 of 100 patients had a complete step count dataset[14, 15]. Accurate activity measurement was attempted using commercially available wrist-worn activity trackers in Chapter 5 (instead of the Actigraph® in Chapter 4), but still required seven consecutive days of wear. As a result, compliance was suboptimal in our study and rendered many data sets unusable for further analysis. While smartphone-based[16] accelerometers or biometric rings[17] may offer higher compliance, their accuracy in measuring specific types of physical activity remains inferior. However, in terms of daily step count only, the pedometer on smartphones is a cost-effective and user-friendly tool for assessing walking distance in adolescents[18]. Addressing these challenges is critical to effectively and more comprehensively assess physical activity over time, especially considering the transition from school to work activities and the limitations of current wearable technologies.

Activity questionnaires may still offer an alternative. Nevertheless, they also come with limitations such as challenges in querying the rapidly changing interests of adolescents, such as sports activities, which vary with age, schooling, and possibly work-related activities[19, 20]. Additionally, postoperative PROMS were compared to preoperative responses in both our studies, but patients were blinded to preoperative

responses when completing the postoperative questionnaires. Consequently, the intense and painful recovery period immediately following surgery might have negatively biased their subsequent responses with regards to their activity levels. Patients were indeed more likely to compare their current state to the painful postoperative period rather than to the preoperative baseline, thus complicating the interpretation of longitudinal data with regards to their activity levels and overall functional outcome. Providing preoperative scores to patients upon completion of postoperative PROMs has been suggested as a possible solution for future study designs[21].

Ultimately, it is the reduction in spinal range of motion (ROM) that must be considered when assessing functional outcomes and specifically activity levels in AIS fusion patients with respect to the LIV. This reduction, not the LIV position itself, is the direct cause of mechanical/physical limitations. This approach addresses what we have identified as the third knowledge gap, and was discussed further in Chapter 5.

6.3 Quantitative trunk ROM analysis versus LIV

In Chapter 5, we focused on the third knowledge gap, concerning the structural lack of spinal range of motion assessments and its relation with functional outcome and fusion length, including LIV selection. First, our research revealed that thoracolumbar fusion results in a greater reduction in trunk mobility compared to thoracic fusion. This confirms the hypothesis that was formulated in this chapter and is in accordance with prior studies[3, 22–24]. Yet, no significant differences were observed in functional outcomes based on subjective questionnaires. As already discussed in the previous section, also daily step count at 3-month and 1-year follow-up did not reveal any possible functional impact of the reduced mobility. Thus, the question remains whether the differences in

trunk mobility between thoracic (T) and thoracolumbar (TL) fusion has a significant and clinically relevant impact on functional outcome. Secondly, significant differences in global trunk flexion ROM were observed between preoperative (91 ± 11°) and 1-year follow-up (68.2 ± 14°) assessments ($p<0.001$) for both surgical groups (T & TL). This confirms how fusion is always at the expense of spinal mobility, an especially important point in borderline indications (as discussed in figure 1.5 in the general introduction). Nevertheless, the amount of mobility loss was highly variable between patients for both groups (T: -16% ± 18%; TL: -26% ± 19%). In an attempt to explain this variability, the primary predictive determinants of mobility loss were identified as the presence of a structural lumbar curve and the extent of the fusion, rather than the LIV. Nevertheless, as already mentioned above, the mobility loss seemed to have an overall limited impact on functional outcomes as measured today. The fact that also the predictive value of postoperative PROMs for this range of motion loss was limited, again underscores the complex interplay between subjective functional assessments and objective mobility outcomes.

Limitations and future research directions: A first important limitation is that the current study's marker-based motion capturing in this Chapter 5 did not allow to distinguish between individuals who predominantly utilize hip flexion ("hip users") and those who primarily use spinal motion ("spine users") to enable trunk flexion. Such information can be highly relevant for surgical decision making as spinal arthrodesis is expected to impact "spine users" more significantly than hip users. Prior research in hip biomechanics suggests that a high pelvic incidence with more lumbar lordosis results in an extended range of motion arc typical of "spine users"[25, 26]. Nevertheless, this relationship remains to be validated in the adolescent population. Improvements in techniques for measuring

trunk mobility can help us better understand the factors involved in using proportionally more of the spine when bending, for example, but also when walking and performing other activities of daily living. Today, direct measurement using deep-flexion radiographs remains the most precise method for differentiating spinal RoM from hip flexion, despite the associated increase in radiation exposure[27, 28]. Although low-dose biplanar radiographs are commonly used for these assessments, limitations of the EOS system's cabin often prevent capturing the full range of motion in most patients[29]. Moreover, these assessments only assess postural changes at the global spinal level and in a semi-static way. This cannot be considered to be fully representative of dynamic motions during daily-life activities. To address these challenges, current research, including in our own research group, is exploring the use of patient-specific spine modeling[30] to assess more complex movements typical of daily activities and allowing precise examination of changes at the level of the individual intervertebral joints - where surgical changes occur. This method also aims to improve understanding of compensatory actions at the hip level. However, this approach is currently still time consuming and its effectiveness in accurately distinguishing between spine and hip motion has not been fully validated yet. An alternative and less time-demanding approach such as a previously published polynomial method involving anatomically corrected spinal skin markers, may thus provide a clinically feasible solution[31]. This method aims to more accurately distinguish between RoM in the spine and hips, offering data that is both precise and clinically relevant. For dynamic evaluations from sit to stand, the accuracy of the polynomial method appears satisfactory[31]; however, piloting its use in kinematic analysis of deep flexion movements resulted in non-physiologic behavior as illustrated in figure 6.2B.

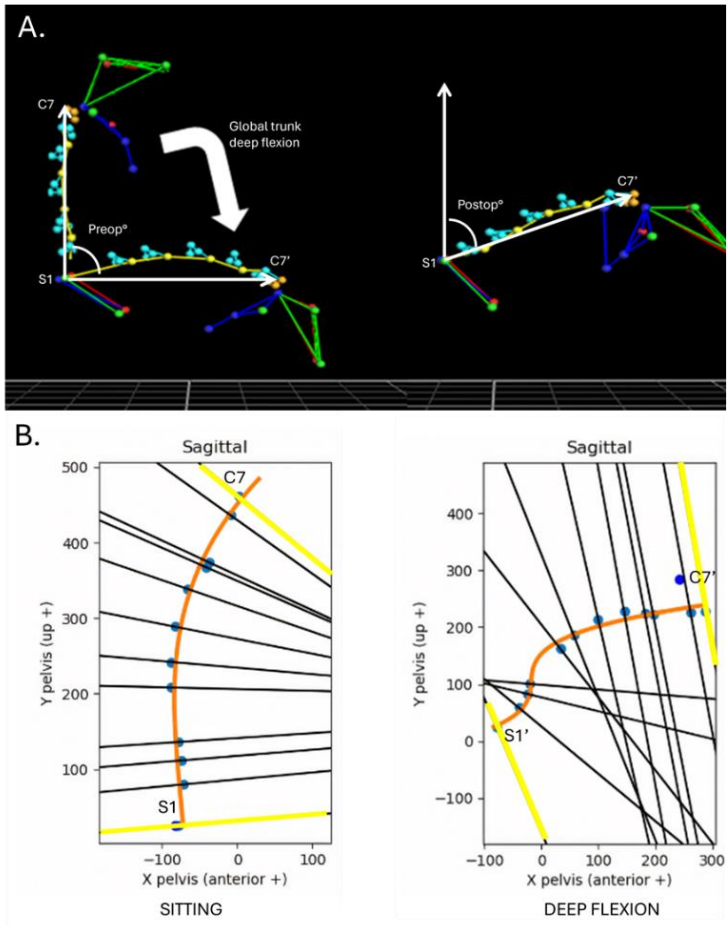


Fig. 6.2*: Measurement of global trunk flexion, method (A) including hip flexion (A) versus method (B) pure spinal ROM without hip flexion.*
A. Chapter 5 method: Global trunk flexion RoM was calculated between maximum flexion and upright position using the trajectory of markers placed at C7 and the patient's sacrum (S1). The preoperative angle (C7S1-C7'S1) and the substantially reduced postoperative global trunk flexion angle are shown.
B. Polynomial method: Measurement of the Cobb angle between C7 and S1 by measuring the angle between the normal (in yellow) to the polynomial (3rd degree) at C7 and S1 in the sitting position[31] *and then in the deep flexion position (C7' and S1'). Currently, there is still a* ***non-physiological behavior*** *of the polynomial in the deep flexion position. In the deep flexion drawing we observe a strange fitting of the polynomial in the lumbar region with a residual lordotic fit in the lower lumbar spine as well as a non-physiological fit in the thoracolumbar region. We also notice a large increase in the sacral slope represented by the normal at S1, which shows more forward pelvic flexion than expected. Necessary corrections and associated validations are currently ongoing to further improve the accuracy of this polynomial approach in motor tasks that involve deep flexion.*

An additional advantage of marker-based motion capture over deep-flexion radiographs is that it provides not only information on spinal ROM, but also detailed insight into dynamic alignment. Global spinal alignment, trunk shift and shoulder alignment are captured during various motor tasks of daily living, including walking at various speeds[32–35]. Currently, the selection of the upper instrumented vertebra (UIV) still heavily relies on static two-dimensional (2D) radiographic parameters and only static clinical assessments[36, 37]. Based on previous research on sagittal alignment and dynamic compensation in adult spinal deformity[38], the assessment of dynamic factors such as trunk shift or shoulder balance during motor activities of daily living, particularly walking, requires further developments and refinement. Nevertheless, dynamic shoulder and trunk balance is a promising direction for future research as it more accurately reflects real-world conditions that may be more relevant to patients' quality of life. Similarly, the claimed beneficial effects of specific therapeutic exercises on waist asymmetry and overall spinal appearance[39] need to be confirmed in a more dynamic manner. To provide a more concrete illustration, the spontaneous corrections observed postoperatively, often mentioned in previous studies regarding shoulder alignment or trunk shift [40], eventually facilitated by specific postural exercises, could be transient phenomena captured during static radiography. Once the patient begins to move, these compensations may disappear. Further research is needed to determine the validity of these assumptions.

6.4 Final Conclusion

The main findings of this doctoral thesis on the added value of 3D and dynamic measures in the selection of the LIV were that the selection of the LIV can be effectively changed when key parameters such as stable vertebrae are assessed in 3D, resulting in a more proximal LIV in 20% of cases according to existing guidelines. Furthermore, our research shows that in the early recovery phase, there is no difference in PROMS on function between thoracic-only (LIV at L1 or above) and thoracolumbar fusions, although step count (accelerometer) is significantly less reduced in the thoracic fusion group. This indicates the potential added value and complementarity of objective activity measurement to subjective questionnaires in the perioperative evaluation of this adolescent population. Further we confirmed that thoracic-only fusions have less reduction in ROM than thoracolumbar fusions, but the presence of a structural lumbar curve and fusion length, rather than the LIV itself, appear to be more predictive of the amount of spinal ROM loss due to fusion. Nevertheless, there was no impact on functional outcome as it is measured today. These findings could direct future research towards identifying which patients might benefit more from a more proximal LIV. Distinguishing between hip and spine users may help to improve this understanding. In conclusion, this work represents an important step in advancing the surgical treatment of AIS by shifting from static, 2D- to dynamic, 3D-informed decision-making, particularly in improving LIV selection in posterior scoliosis correction and fusion. Future studies should focus on further validating these findings and exploring the long-term impact of 3D-guided LIV selection on patient outcomes. The continued development of advanced assessment tools and methods will be critical to optimizing surgical strategies and improving quality of life for patients with adolescent idiopathic scoliosis.

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APPENDIX

APPENDIX

SCIENTIFIC ACKNOWLEDGEMENTS AND PERSONAL CONTRIBUTIONS

The summary, general introduction, research objectives and general discussion of this thesis were written by Sebastiaan Schelfaut and critically revised by Lennart Scheys, Anja Van Campenhout and Lieven Moke.

Chapter 3 & 5 was written by Sebastiaan Schelfaut and critically revised by all actively involved co-authors.
Chapter 4 was written together with Thijs Ackermans as shared first author, and critically revised by all actively involved co-authors.

Chapter 3: Three- instead of two-dimensional evaluation of key parameters alters the choice of the Lowest Instrumented Vertebra in Lenke 1 and 2 AIS patients

	Study Design	Data Acquisition	Data analysis	Data Interpretation	Drafted the work	Revised the work	Approved this version	Agree to be accountable
SS	X	X	X	X	X		X	X
PM	X	X	X	X		X	X	X
TO		X	X	X		X	X	X
SC		X	X	X		X	X	X
AVC	X			X		X	X	X
LM	X			X		X	X	X
LS	X	X	X	X		X	X	X
TA	X	X	X	X		X	X	X

Chapter 4: Monitoring the initial recovery after fusion surgery using activity trackers in Adolescent Idiopathic Scoliosis: Going in the lumbar spine decreases the daily step count

	Study Design	Data Acquisition	Data analysis	Data Interpretation	Drafted the work	Revised the work	Approved this version	Agree to be accountable
TA	X	X	X	X	X		X	X
SS	X	X	X	X	X		X	X
MB	X	X	X	X		X	X	X
JM		X		X		X	X	X
PM		X		X		X	X	X
LG	X	X	X	X		X	X	X
FP	X	X		X		X	X	X

Chapter 5: Postoperative Trunk Mobility Recovery and the Predictive Role of the Lowest Instrumented Vertebra in Adolescent Idiopathic Scoliosis Fusion Surgery

	Study Design	Data Acquisition	Data analysis	Data Interpretation	Drafted the work	Revised the work	Approved this version	Agree to be accountable
SS	X	X	X	X	X	X	X	X
TA	X	X	X	X	X		X	X
TL			X	X		X	X	X
PM		X				X	X	X
AVC	X					X	X	X
LM	X			X		X	X	X
LS	X			X		X	X	X

STATEMENTS AND DECLARATIONS

Chapter 3: Three- instead of two-dimensional evaluation of key parameters alters the choice of the Lowest Instrumented Vertebra in Lenke 1 and 2 AIS patients

Competing Interests and Funding

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Conflicts of interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethics Approval

The study was approved by the institution's research ethics committee (S63053) and was carried out according to the guidelines for Good Clinical Practice (ICH/GCP) and the declaration of Helsinki for the protection of people who participate in clinical studies.

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Chapter 4: Monitoring the initial recovery after fusion surgery using activity trackers in Adolescent Idiopathic Scoliosis: Going in the lumbar spine decreases the daily step count

Competing Interests and Funding

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Conflicts of interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethics Approval

The multi-centric study was approved by the Central Ethical Committee with permission of all local ethical committees to collect data at each site and was carried out according to the guidelines for Good Clinical Practice (ICH/GCP) and the declaration of Helsinki for the protection of people who participate in clinical studies.

Chapter 5: Postoperative Trunk Mobility Recovery and the Predictive Role of the Lowest Instrumented Vertebra in Adolescent Idiopathic Scoliosis Fusion Surgery

Competing Interests and Funding

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(The study protocol was submitted to and approved by KOOR & SRS, followed by intermittent updates on the progress of the study without significant interference.)

Conflicts of interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethics Approval

The study was approved by the institution's research ethics committee (S64400) and was carried out according to the guidelines for Good Clinical Practice (ICH/GCP) and the declaration of Helsinki for the protection of people who participate in clinical studies.

Consent to participate

Written informed consent was obtained from all legal guardians/parents and/or the individual participants in the study.

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EDUCATION

High School

- Sint Laurensinstituut, Zelzate, Belgium, Sciences-Mathematics, Magna cum Laude

University

- Katholieke Universiteit Leuven, Belgium, Faculty of Medicine
  - 2000-2007, Degree of Doctor in Medicine, Magna cum Laude
  - 2007-2013, Medical Specialist in Orthopaedic and trauma surgery, Prof. Dr. J Bellemans.

European Education Plan

- 2015, European Spine Course Diploma, Strasbourg, France

PROFESSIONAL EXPERIENCE

University Hospitals Leuven – 2013-present:

- Deputy Head of Clinic in Orthopaedic Surgery: Spine surgery and scoliosis.
- My spine practice includes all spinal pathologies, except intramedullary pathology. My particular interest is in paediatric spinal deformity, primary bone tumors and spinal trauma.

Spine fellowship – 2013-2014:

- AO spine fellowship, Zentrum für Wirbelsäulenchirurgie und Neurotraumatologie, Berufsgenossenschaftliche Unfallklinik, Frankfurt am Main, Germany, Prof. Dr. med. F. Kandziora (sept 2013-dec 2013).
- Full licence Spine deformity fellowship, Hospital for Sick Children (SickKids) and Toronto Western Hospital, Toronto, Canada, Dr. R. Zeller and Dr. S. Lewis (jan 2014-april 2014).

Orthopaedic and trauma surgery residency – 2007-2013:

- 2007-2009 General surgery **resident**, General Hospital Sankt-Nikolaus Eupen, Belgium, Dr. A. Geukens
- 2009-2010 Orthopedic and trauma surgery **resident**, General Hospital Sint-Lucas Assebroeck, Brugge, Belgium, Prof. Dr. J. Victor
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International internship in general and orthopaedic surgery – 2004-2006:

- 2006 Voluntary **internship** trauma surgery (5 weeks), General Hospital Saint-Luc Kisantu, RDC (Congo), Dr. D. Makiadi.
- 2005 Surgery **internship** (4 months), University Hospitals Genève (HUG), Switzerland, Prof. Dr. P. Hoffmeyer.
- 2004 Voluntary **internship** (9 weeks), General Hospital Saint-Luc Kisantu, RDC (**Congo**), Dr. D. Makiadi.

UNIVERSITY/HOSPITAL TEACHING POSITIONS

2013- present:

- Lector at the Catholic University of Leuven, faculty of medicine
- Multiple 'spine' lectures for the Flemish interuniversity orthopaedic resident training
- Internship supervisor at the university hospital of Leuven
- Co-responsible for selection procedure of orthopaedic training candidates

RESEARCH EXPERIENCE

Candidate PhD

- 2018-2024. IORT under supervision of Prof. Ir. Lennart Scheys, department of orthopaedics UZ Leuven, Catholic University of Leuven.

Reviewer/Chairman

- Co-chairman/co-riewer: Annual **Eurospine** scientific Meeting of 2018 in Barcelona & 2019 in Helsinki.
- Reviewer for Brain & Spine
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Member of scientific organization

- BVOT (Belgische Vereniging voor Orthopedie en Traumatologie) Active member
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- EUROSPINE: Active member. Past Delegate to Membership Committee
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LANGUAGES

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Journal Publications

Thys T, Bogaert L, Dankaerts W, Depreitere B, Van Wambeke P, Brumangne S, Bultheel M, Vanden Abeele V, Moke L, Spriet A, Schelfaut S, Janssens L, Swinnen TW. Qualitative study exploring the views of patients and healthcare providers on current rehabilitation practices after lumbar fusion surgery. **BMJ Open.** 2024 May 30;14(5):e077786. doi: 10.1136/bmjopen-2023-077786. PMID: 38816040; PMCID: PMC11141188.

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