

Titre: Automatic Analysis of the Scoliotic Trunk for Surgery Planning and Outcome Assessment

Auteur: Maryam Khani

Date: 2023

Type: Mémoire ou thèse / Dissertation or Thesis

Référence: Khani, M. (2023). Automatic Analysis of the Scoliotic Trunk for Surgery Planning and Outcome Assessment [Thèse de doctorat, Polytechnique Montréal].
Citation: PolyPublie. <https://publications.polymtl.ca/55986/>

 **Document en libre accès dans PolyPublie**
Open Access document in PolyPublie

URL de PolyPublie: <https://publications.polymtl.ca/55986/>
PolyPublie URL:

Directeurs de recherche: Farida Cheriet, Hubert Labelle, & Stefan Parent
Advisors:

Programme: Génie informatique
Program:

POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

**Automatic Analysis of the Scoliotic Trunk for Surgery Planning and Outcome
Assessment**

MARYAM KHANI

Département de génie informatique et génie logiciel

Thèse présentée en vue de l'obtention du diplôme de *Philosophiæ Doctor*
Génie informatique

Octobre 2023

POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

Cette thèse intitulée :

**Automatic Analysis of the Scoliotic Trunk for Surgery Planning and Outcome
Assessment**

présentée par **Maryam KHANI**

en vue de l'obtention du diplôme de *Philosophiæ Doctor*
a été dûment acceptée par le jury d'examen constitué de :

Thomas HURTUT, président

Farida CHERIET, membre et directrice de recherche

Hubert LABELLE, membre et codirecteur de recherche

Stefan PARENT, membre et codirecteur de recherche

Luc DUONG, membre

Mathias ADANKON, membre externe

DEDICATION

This thesis is dedicated to my lovely family, my father Abolghasem Khani, my mother Tahereh Yousefi, my husband Jafar Soltani and my sister Mina Khani and my brother Khosro Khani who believed in me and supported me with their love and patience every moment. I sincerely seek their blessing for the path ahead.

ACKNOWLEDGEMENTS

I'm grateful to my supervisor, Prof. Farida Cheriet, for giving me the valuable opportunity to work with her as a PhD student and for granting me the freedom to pursue research topics according to my interests and passion. Also, I would like to express my deepest appreciation to her for her kindness and patience.

I'm thankful to my co-supervisors, Prof. Hubert Labelle and Prof. Stefan Parent for transferring their valuable knowledge in scoliosis surgery of AIS patients and their passion for developing scoliosis surgery planning in clinical settings.

I would like to thank Prof. Lama Seoud for her valuable lessons on image processing and generously sharing her expertise on AIS patients to complete follow-up study. Also, I would like to thank Prof. Marie Beauséjour for her help in the analyzing of the questionnaires.

A special thank you to Philippe Debanné for his support, availability and sharing his valuable experiences in research studies of AIS patients. Without his support, the presentation of SPIE would have been not possible.

Thank you to Prof. Mohamed Cheriet, who gave out a unique course on pattern recognition and thank you to Prof. Aaron Courville for providing an excellent course on deep representation learning which helped me to have a strong foundation knowledge to complete this research.

I would like to extend my thanks to all the members of the LIV4D lab at École Polytechnique of Montreal. I have consistently appreciated their insightful feedback and willingness to share knowledge.

Also I would like to thank the personnel of the Orthopaedics Research Clinical Unit (URCO, CHU Sainte-Justine) for their help with collecting clinical data.

I'm grateful to the Canadian Institutes of Health Research (CIHR) and the TransMedTech Institute for providing me with their funding support during the entire research project.

Finally, special recognition goes out to my family, for their support and patience. More importantly, I would like to thank my father, Abolghasem, and my mother, Tahereh, who have always supported me with their love, support, and encouragement during my whole life. To my incredible sister, Mina and my brother Khosro for encouraging me to reach the end of my potential and for believing in me. To my amazing husband Jafar, who always got my back during hard times with his support and love, without hesitation. Without their love, unwavering support and inspiration, I never could follow my wishes.

RÉSUMÉ

La préoccupation la plus importante des patients atteints de scoliose idiopathique adolescente (SIA) sévère, à qui il est conseillé de subir une correction chirurgicale, est l'apparence de leur tronc après la procédure et les améliorations esthétiques potentielles après la chirurgie. Ces facteurs influencent directement leur santé mentale et leur bien-être émotionnel. Par conséquent, les patients souhaitent comprendre l'impact de la correction de la colonne vertébrale sur l'apparence de leur tronc avant de procéder à la chirurgie. De plus, les chirurgiens doivent planifier leurs approches chirurgicales en tenant compte de l'aspect externe postopératoire du tronc avant d'effectuer la chirurgie. Cette planification aide à identifier la stratégie chirurgicale la plus appropriée pour le patient. Par conséquent, dans la planification chirurgicale pour le traitement de la scoliose sévère, les orthopédistes et les patients obtiendraient des informations précieuses en visualisant le résultat prévu de la chirurgie de la colonne vertébrale ainsi que son impact sur l'apparence externe du patient.

Pour atteindre cet objectif, les chercheurs ont développé plusieurs simulateurs de chirurgie de la colonne vertébrale. Une première méthode consiste en une modélisation biomécanique des structures osseuses ainsi que de leur réponse à différentes stratégies opératoires. Le chirurgien peut ainsi visualiser l'effet d'une stratégie sur la géométrie 3D de la colonne vertébrale. Une deuxième méthode consiste en la propagation de la correction de la colonne vertébrale à travers les tissus mous du tronc afin de visualiser l'effet de la stratégie opératoire sur l'apparence externe du tronc. Ce simulateur utilise une modélisation physique des structures anatomiques du tronc et simule la surface externe du tronc en propageant les déplacements de la colonne vertébrale obtenus suite à la correction chirurgicale à travers un maillage tétraédrique des structures anatomiques du tronc. Afin d'utiliser ce simulateur avant d'effectuer la chirurgie, un modèle postopératoire 3D de la colonne vertébrale est requis. Étant donné que les simulateurs biomécaniques développés pour la simulation de la forme postopératoire de la colonne vertébrale ont été validés sur des cohortes restreintes de patients, une approche d'apprentissage basée sur l'ensemble des données acquises sur des patients opérés au CHU Sainte-Justine serait très utile. Des modèles d'apprentissage automatique ont déjà été utilisés pour prédire le résultat de la chirurgie de la scoliose sur la colonne vertébrale mais les résultats de ces modèles ne sont pas personnalisés pour chaque patient et se limitent à prédire quelques groupes de configurations.

L'objectif principal de cette thèse est d'abord de prédire la forme postopératoire de la colonne vertébrale en utilisant les données de patients ayant subi une chirurgie de la scoliose durant

les dernières décennies au CHU Sainte-Justine. Cette prédiction pourra être utilisée comme entrée au simulateur physique afin de visualiser l'apparence externe de la forme du tronc après la chirurgie. Dans ce contexte, nous avons créé une architecture d'apprentissage en profondeur appelée Controlled Point Deformation Network (CPDNet). Ce nouveau réseau exploite les propriétés de forme pour prédire avec précision la forme postopératoire de la colonne vertébrale à la suite d'une chirurgie corrective de la scoliose. CPDNet apprend les transformations rigides entre les points de repère 3D de vertèbres consécutives de la colonne vertébrale représentée à l'aide d'un modèle articulé. Nous concaténons un ensemble de métadonnées cliniques des patients avec les coordonnées 3D de chaque point de la forme de la colonne vertébrale préopératoire. Ces informations multimodales fusionnées constituent l'entrée d'un réseau entièrement convolutif qui permet de prédire des vecteurs de déplacement ponctuels 3D. Ces déplacements sont additionnés aux coordonnées 3D des repères anatomique de chaque vertèbre de la colonne vertébrale préopératoire pour obtenir la forme de la colonne vertébrale postopératoire. Nous avons proposé une fonction de perte qui calcule les différences de rotation et de translation entre deux vertèbres consécutives, conduisant le réseau à apprendre les caractéristiques du modèle articulé de la colonne vertébrale. Les expériences effectuées démontrent que le modèle proposé surpasse le modèle de P2P-NET. D'un point de vue clinique, CPDNet a le potentiel de servir de base au développement d'un outil de planification chirurgicale pour la scoliose. Cet outil permettrait aux chirurgiens et aux patients de visualiser les résultats postopératoires de diverses techniques chirurgicales avant d'effectuer l'opération. Les autres contributions de la thèse se concentrent sur l'évaluation des résultats de simulation de la forme postopératoire du tronc. De plus, proposer des métriques quantitatives est indispensable pour évaluer la forme externe du tronc chez les patients SIA après leur chirurgie et lors des suivis cliniques. Des études antérieures ont souligné l'importance de détecter les mesures d'asymétrie du tronc gauche-droite dans des régions locales spécifiques, telles que les épaules et la taille. L'identification et le traitement de ces asymétries sont essentiels pour une meilleure satisfaction du patient et pour garantir des stratégies de traitement plus efficaces. Par conséquent, nous avons introduit de nouveaux indices 3D qui détectent l'asymétrie gauche-droite dans la région locale de la surface arrière du tronc. Nous avons identifié les zones d'asymétrie comme des régions de déviation significative entre les côtés gauche et droit de la surface 3D du dos du patient. De nouveaux paramètres appelés taux de déformation (DR) et asymétrie maximale (MA) ont été mesurés dans différentes régions en fonction des zones d'asymétrie. Nous avons également mesuré la courbure de la colonne vertébrale à l'aide d'angles de Cobb mesurés sur des radiographies, de mesures de gibbosités effectuées à l'aide d'un scoliomètre ainsi que du déjettement coronal. Par la suite, nous avons utilisé les mesures standard de la rotation de la surface du dos (BSR) et du

déjettement latéral du tronc (TLS) pour évaluer l'asymétrie globale du tronc (GTA). Fait intéressant, nos indices peuvent ainsi évaluer les asymétries locales du tronc afin de quantifier objectivement le degré de leur amélioration ou aggravation après la chirurgie de la scoliose.

Grâce à la mise en œuvre de nouveaux indices 3D, nous avons complété une étude qui a permis d'évaluer les attentes et la satisfaction du patient et de ses parents concernant l'amélioration de l'apparence du tronc suite à une chirurgie de la colonne vertébrale. Les patients et leurs parents ont l'habitude de compléter deux types de questionnaires SAQ et SRS afin d'exprimer leur appréciation de l'apparence externe du tronc avant et après la chirurgie. Nous avons alors étudié la relation entre chaque question des deux questionnaires et chaque indice 3D développé. Un expert dans le domaine de la santé publique a aidé pour établir la correspondance entre chaque question des deux questionnaires SAQ et SRS avec les mesures 3D du tronc et de la colonne vertébrale. Les résultats de l'étude démontrent l'utilité des indices 3D développés dans l'évaluation quantitative des déformations de régions locales spécifiques du tronc, en particulier les épaules et la taille, qui revêtent une importance significative pour les patients et leurs parents, selon l'analyse de leurs réponses aux questions posées dans les deux questionnaires SAQ et SRS.

Enfin, nous avons documenté l'impact à long terme de la chirurgie de la colonne vertébrale sur la forme postopératoire du tronc après un suivi de deux ans. Pour évaluer la forme postopératoire du tronc, la rotation de la surface du dos (BSR) et le déjettement latéral du tronc (TLS) ont été calculés le long du tronc. Nous avons analysé l'effet de l'âge, de la taille, du poids, et de l'angle de Cobb mesuré sur les radiographies, de la durée du suivi et de la technique chirurgicale. Nous avons également comparé les taux de correction des mesures de la colonne vertébrale et du tronc après six mois et deux ans de suivi. Nos résultats révèlent que bien qu'il y ait eu une correction de plus de 55% du déjettement latéral du tronc (TLS) après un suivi de deux ans, la rotation de la surface du dos (BSR) est restée inchangée au fil du temps. De plus, malgré la correction du TLS, la gibbosité sur la surface du dos a persisté même après la période de suivi de deux ans. Ces résultats mettent en évidence la nature complexe de la scoliose et l'importance de prendre en compte les résultats et les effets à long terme dans la planification du traitement.

Les méthodes développées dans ce projet contribueront de manière significative au développement d'outils de planification de la chirurgie de la scoliose pour prédire le résultat de la chirurgie de la colonne vertébrale ainsi que son impact sur l'apparence externe du patient. Les travaux futurs devraient se concentrer sur l'ajout de plus de contraintes au modèle CPDNet afin de préserver la topologie de chaque vertèbre ainsi que la topologie globale de la colonne vertébrale. En outre, davantage de patients présentant tous les types de courbes vertébrales

devraient être considérés dans l'ensemble d'entraînement. Suite à une validation exhaustive de la forme prédite de la colonne vertébrale postopératoire, davantage d'efforts doivent être déployés pour valider les résultats de simulation de la surface du tronc suite à une chirurgie de la colonne vertébrale.

ABSTRACT

The most significant concern of patients with severe Adolescent Idiopathic Scoliosis (AIS) who are recommended to have a surgical correction is the appearance of their trunk after the procedure and the potential cosmetic improvements following surgery. These factors directly influence their mental health and emotional well-being. As a result, patients wish to understand the impact of spinal correction on the appearance of their trunk before proceeding with the surgery. Furthermore, surgeons need to plan their surgical approaches considering the postoperative external aspect of the trunk prior to performing the surgery. This planning helps identify the most appropriate surgical strategy for the patient. Therefore, in surgical planning for severe scoliosis treatment, orthopedic surgeons and patients would gain valuable insights by visualizing the predicted outcome of spinal surgery as well as its impact on the patient's external appearance.

To achieve this goal, researchers have developed several spinal surgery simulators. The first category involves biomechanical modeling of the bone structures as well as their response to different surgical strategies. The surgeon can thus visualize the effect of a strategy on the 3D geometry of the spine. The second category involves the propagation of spinal correction through the soft tissues of the trunk to visualize the effect of the surgical strategy on the external appearance of the trunk. This simulator utilizes a physical modeling of the anatomical structures of the trunk and simulates the external surface of the trunk by propagating the spinal displacements obtained as a result of surgical correction through a tetrahedral mesh of the anatomical structures of the trunk. In order to use this simulator before performing surgery, a 3D postoperative model of the spine is required. Since the biomechanical simulators developed for simulating the postoperative shape of the spine have been validated on limited patient cohorts, a learning approach based on the dataset acquired from patients operated on at Sainte Justine Hospital would be very useful. Machine learning models have already been used to predict the outcome of scoliosis surgery on the spine, but the results of these models are not personalized for each patient and are limited to predict a few groups of configurations.

The main objective of this thesis is to predict the postoperative shape of the spine using data from patients who have undergone scoliosis surgery over the past decades at Sainte Justine Hospital. This prediction can be used as input for a physical simulator to visualize the external appearance of the trunk's shape after surgery. In this context, we have developed a deep learning architecture called Controlled Point Deformation Network (CPDNet). This

novel network leverages shape properties to accurately predict the postoperative shape of the spine following corrective scoliosis surgery. CPDNet learns rigid transformations between consecutive 3D landmark points of the spine represented using an articulated model. We concatenate a set of clinical metadata from the patients with the 3D coordinates of each point of the preoperative spine shape. These fused multimodal inputs are fed into a fully convolutional network that predicts 3D point displacement vectors. These displacements are added to the 3D coordinates of anatomical landmarks of each preoperative vertebral body to obtain the postoperative spine shape. We proposed a loss function that calculates rotation and translation differences between two consecutive vertebrae, guiding the network to learn the characteristics of the articulated spine model. Experiments demonstrate that the proposed model outperforms the P2P-NET model. From a clinical perspective, CPDNet has the potential to serve as a foundation for the development of a surgical planning tool for scoliosis. This tool would enable surgeons and patients to visualize postoperative outcomes of various surgical techniques before the actual procedure.

The other contributions of the thesis focus on evaluating the simulation outcomes of the postoperative trunk shape. Additionally, proposing quantitative metrics is essential to assess the external trunk shape in AIS patients after their surgery and during clinical follow-ups. Previous studies highlighted the importance of detecting left-right trunk asymmetry measures in specific local regions, such as the shoulders and waist. Identifying and addressing these asymmetries are crucial for improved patient satisfaction and more effective treatment strategies. Therefore, we introduced new 3D indices that detect left-right asymmetry in the local region of the back surface of the trunk. We identified asymmetry areas as regions with significant deviation between the left and right sides of the patient’s 3D back surface. New parameters called Deformation Ratios (DR) and Maximum Asymmetry (MA) were measured in different regions based on the asymmetry areas. We also measured spinal curvature using Cobb angles from X-rays, hump measurements using a scoliometer, and coronal offset. Subsequently, we used standard measurements of Back Surface Rotation (BSR) and Trunk Lateral Shift (TLS) to evaluate Global Trunk Asymmetry (GTA). Interestingly, our indices can assess local trunk asymmetries to objectively quantify the degree of their improvement or worsening after scoliosis surgery.

By implementing new 3D indices, we conducted a study to assess patient and parental expectations and satisfaction regarding the improvement of trunk appearance following spinal surgery. Patients and their parents typically complete two types of questionnaires, the SAQ and SRS, to express their perception of the external appearance of the trunk before and after surgery. We then examined the relationship between each question in the two SAQ and SRS questionnaires and each developed 3D index. An expert in the field of public health assisted

in establishing the association between each question in the SAQ and SRS questionnaires and the spine and 3D trunk measurements. The study results demonstrate the utility of the developed 3D indices in quantitatively evaluating deformations of specific local trunk regions, especially the shoulders and waist, which hold significant importance for patients and their parents, as analyzed from their responses to the questions in the SAQ and SRS questionnaires.

Finally, we documented the long-term impact of spinal surgery on the postoperative trunk shape after a two-year follow-up. To assess the postoperative trunk shape, Back Surface Rotation (BSR) and Trunk Lateral Shift (TLS) were calculated along the trunk. We analyzed the effect of age, height, weight, Cobb angle measured on X-rays, follow-up duration, and surgical technique. We also compared the correction rates of spinal and trunk measurements after six months and two years of follow-up. Our results reveal that, although there was a correction of over 55% in Trunk Lateral Shift (TLS) after a two-year follow-up, Back Surface Rotation (BSR) remained unchanged over time. Additionally, despite the correction of TLS, the hump on the back surface persisted even after the two-year follow-up period. These findings highlight the complex nature of scoliosis and the importance of considering long-term outcomes and effects in treatment planning.

The methods developed in this project will significantly contribute to the development of scoliosis surgery planning tools, allowing for the visualization of the predicted outcome of spinal surgery and its impact on the patient’s external appearance. Future work should focus on adding more constraints to the CPDNet model to preserve the topology of each vertebra as well as the overall topology of the spine. Additionally, a larger number of patients representing all types of spinal curves should be included in the training dataset. Following a comprehensive validation of the predicted postoperative spine shape, further efforts should be directed towards validating the simulation results of the trunk surface following spinal surgery.

TABLE OF CONTENTS

DEDICATION	iii
ACKNOWLEDGEMENTS	iv
RÉSUMÉ	v
ABSTRACT	ix
TABLE OF CONTENTS	xii
LIST OF TABLES	xv
LIST OF FIGURES	xvi
LIST OF SYMBOLS AND ACRONYMS	xx
LIST OF APPENDICES	xxii
CHAPTER 1 INTRODUCTION	1
1.1 Adolescent Idiopathic Scoliosis (AIS)	1
1.2 General Research Objectives	3
1.3 Manuscript Overview	5
CHAPTER 2 LITERATURE REVIEW	7
2.1 Scoliosis Surgery Planning	7
2.1.1 Prediction of the 3D Spine Shape	7
2.1.2 Prediction of the 3D Trunk Shape	10
2.2 Assessment of the Scoliosis Surgery Outcome	12
2.2.1 2D and 3D Clinical Measurements	12
2.2.2 Expectation and Satisfaction of Patients and Parents (SAQ and SRS)	21
2.3 Prospective Follow-up Studies of AIS Surgery	23
2.4 3D Shape Prediction using Deep-Learning	25
2.4.1 Prediction Networks of Pointwise Displacements	25
CHAPTER 3 OBJECTIVES AND GENERAL METHODOLOGY	28
3.1 Problem Statement	28

3.2	Objectives	29
3.2.1	Objective 1	29
3.2.2	Objective 2	29
3.2.3	Objective 3	30
3.2.4	Objective 4	30
3.3	General Methodology	30
CHAPTER 4 ARTICLE 1: PREDICTION OF POSTOPERATIVE 3D SPINE SHAPE USING CONTROLLED POINT DEFORMATION NETWORK (CPDNet)		33
4.1	Abstract	33
4.2	Introduction	34
4.2.1	Related Work	34
4.2.2	Objective of Our Work	35
4.3	Methodology	35
4.3.1	Controlled Point Deformation Network (CPDNet)	35
4.3.2	Loss Function	37
4.4	Data	39
4.5	Results	39
4.6	Conclusion	43
4.7	Acknowledgments	44
CHAPTER 5 ARTICLE 2: AUTOMATIC ASSESSMENT of SCOLIOSIS SURGERY OUTCOME ON TRUNK SHAPE USING LEFT-RIGHT TRUNK ASYMMETRY		45
5.1	Abstract	45
5.2	Introduction	46
5.3	Materials and Methods	47
5.4	Results	52
5.5	Discussion	56
5.6	Conclusion	57
5.7	Acknowledgments	57
CHAPTER 6 ANALYSING THE RELATIONSHIP BETWEEN 3D TRUNK MEA- SUREMENTS AND SATISFACTION AND EXPECTATION OF THE SCOLI- OTIC PATIENTS		58
6.1	Introduction	58
6.1.1	Questionnaires	59
6.1.2	Patient Data	65

6.1.3	3D Trunk Measurements	65
6.1.4	Finding Association Between Questionnaires and Trunk Measurements	66
6.1.5	SAQ Analysis using 3D Measurements	71
6.1.6	SRS Analysing using 3D Measurements	72
6.2	Results	73
6.2.1	Patients and Parents' Expectations	75
6.2.2	Patient's Satisfaction	89
6.3	Discussion	93
CHAPTER 7 ARTICLE 3: CHANGES IN TRUNK APPEARANCE AFTER SCO-		
LIOSIS SPINE SURGERY: TWO-YEARS FOLLOW-UP STUDY		94
7.1	Abstract	94
7.2	Introduction	95
7.3	Materials and Methods	96
7.4	Results	98
7.5	Discussion	102
7.6	Acknowledgments	104
CHAPTER 8 GENERAL DISCUSSION		105
8.1	Prediction of Postoperative Shape Of the Spine using Deep Learning Approaches	105
8.1.1	Limitations	106
8.2	Automatic Assessment of Scoliosis Surgery Outcome	106
8.2.1	Limitations	107
8.3	Two-Years Follow-up Study of Scoliosis Surgery Outcome	108
8.3.1	Limitations	108
CHAPTER 9 CONCLUSION		109
REFERENCES		111
APPENDICES		125

LIST OF TABLES

Table 4.1	Summary statistics for the whole patient dataset and for the training, validation, and testing subsets. Cobb angles are for the main thoracic curvature in the frontal plane.	39
Table 4.2	Comparison of the three models tested.	40
Table 5.1	Demographic and radiological information of AIS and non-scoliotic cohorts.	47
Table 5.2	Numbers of patients for each outcome based on Cobb angles, GTA and LRTA measurements.	53
Table 6.1	Demographic and Radiological Information of Selected Cohort	65
Table 6.2	The correlation between the Correction Rates (CRs) of 3D trunk measurements (BSR, Coronal Lateral Shift, Coronal Balance, and Shoulder Level) and 2D spine measurements (Scoliometer T, Scoliometer L, Cobb PT, Cobb MT, Cobb TLL) are computed. The correlation values bigger than 0.20 are highlighted.	66
Table 6.3	Association between questions SAQ and SRS with Spine and Trunk measurements	69
Table 7.1	Demographic and Radiological Information of Selected Cohort	96
Table 7.2	BSR, TLS, and MT Cobb angle CRs, overall and per surgeon (two years follow-up).	99
Table 7.3	Association of CRs with clinical variables (regression model, two-year follow-up).	99
Table 7.4	Correlation between spine and trunk CRs (n=46) after two-years follow-up. (*: $p < 0.05$)	100

LIST OF FIGURES

Figure 1.1	(a) The Adams forward-bending test, (b) the scoliometer (used under licence CC BY) [14]	2
Figure 1.2	Cobb PA and LAT angles	2
Figure 1.3	Adolescent idiopathic scoliosis in a female patient. Photograph and X-ray preoperatively (left) and postoperatively (right) (used under licence CC BY) [22]	3
Figure 2.1	Simulator Spine [47]	9
Figure 2.2	(a) Flowchart and (b) Results of simulation in [27].	11
Figure 2.3	(a) Algorithm and (b) Results of simulation in [28].	11
Figure 2.4	The Spine3D software is utilized to create 3D representations of the spine and pelvis from calibrated standing posterior-anterior and lateral radiographs [60].	12
Figure 2.5	Thoracic apical vertebral translation (A) and lumbar apical vertebral translation (B) [64].	14
Figure 2.6	Coronal Parameters (used under licence CC BY) [71].	14
Figure 2.7	Sagittal Parameters (used under licence CC BY) [71]	15
Figure 2.8	This diagram compares a 3D curve with low (a) and high (b) values of writhe [77]	16
Figure 2.9	This diagram compares low (a) and high (b) values of torsion obtained from a twisting ribbon illustrating the analogy of the parametric geometric torsion. In this analogy, as the length between consecutive loops (H) decreases, the torsion value increases. This relationship highlights how a shorter distance between successive loops leads to higher torsion values in the ribbon	16
Figure 2.10	Spinal parameters were measured [63]	17
Figure 2.11	3D reconstruction process [86]	19
Figure 2.12	Graphical user interface for trunk measurements visualization [32] . .	21

Figure 4.1	Architecture of proposed CPDNet. n represents the number of points in the spine (6 landmarks per vertebra, 18 vertebrae from C7 to L5 levels, thus $n = 108$). In our formalism, a rigid transformation is expressed as $T = \{R, t\}$, applied to a point x to yield $y = R \cdot x + t$, where $x, y \in \mathbb{R}^3$ define input and output points, $R \in SO^3$ defines a rotation matrix and $t \in \mathbb{R}^3$ defines a translation vector. Pairs of consecutive vertebrae are related by a transformation T , each vertebra having a local axis system computed from a set of known anatomical landmarks [61,62].	37
Figure 4.2	Clinical indices: (a) Coronal Balance, (b) Cobb PA and LAT angles. .	41
Figure 4.3	RMSE errors by the three models.	41
Figure 4.4	Comparison of 3D postoperative spine shapes predicted by the different models, for two patients from the test set. In all cases, the real postop spine shape is shown in green, and each predicted-real pair is displayed in the frontal and sagittal planes. Columns show predictions by (a) P2P-NET; (b) PDNet; (c) proposed CPDNet with no patient meta-data; (d) CPDNet with patient metadata. The last column superimposes all the spine models. The red arrows indicate large discrepancies between the predicted and real postop spine shapes for each network.	43
Figure 5.1	3D reconstruction process to obtain whole trunk shape.	48
Figure 5.2	Illustration of steps to obtain the distance map, using a depth threshold of 9 mm.	49
Figure 5.3	Sample of pre- and post-operative distance maps computed for a patient. (a) full distance map with area colours corresponding to depth index at left; (b) LRTA areas when applying depth threshold.	49
Figure 5.4	Comparison of distance maps of a set of non-scoliotic patients against threshold values in the range [3,15] mm.	50
Figure 5.5	Definition of measurement regions spanning the back surface for LRTA indices.	51
Figure 5.6	Violin plots showing spinal, GTA, and LRTA corrections preoperatively (blue) and postoperatively (orange).	54
Figure 5.7	X-rays, depth maps, and GTA measurements (BSR and TR) of two selected patients: (a) good correction for GTA; (b) poor correction for GTA.	55
Figure 5.8	LRTA corrections (DR) of two selected patients: (a) good correction for LRTA; (b) satisfactory for LRTA.	56
Figure 6.1	SAQ: section one	60

Figure 6.2	SAQ: section two	61
Figure 6.3	SRS: section one	63
Figure 6.4	SRS: section two	64
Figure 6.5	Horizontal cross-sections along the trunk (A). The BSR and TLS are calculated on each cross-section [29].	69
Figure 6.6	Association between questions of SAQ and Spine and Trunk Measurements	70
Figure 6.7	A sample of scoring the answers of questions 8 and 9 from SRS . . .	73
Figure 6.8	The <i>Expectation and Perception Values</i> for each measurement related to SAQ questions	74
Figure 6.9	The evaluation of patients and parents ‘expectations (under, fit, or over-evaluation)	75
Figure 6.10	Evaluation question 1 (body curve associated with Cobb angle) of pre-operative SAQ.	76
Figure 6.11	Evaluation question 1 (body curve associated with Cobb angle) of post-operative SAQ.	77
Figure 6.12	Evaluation question 2 (Rib Prominence associated with BSR (Thoracic)) of preoperative SAQ.	78
Figure 6.13	Evaluation question 2 (Rib Prominence associated with BSR (Thoracic)) of postoperative SAQ.	79
Figure 6.14	Evaluation question 3 (Flank Prominence associated with BSR (Thoracic Lumbar)) of preoperative SAQ.	80
Figure 6.15	Evaluation question 3 (Flank Prominence associated with BSR (Thoracic Lumbar)) of postoperative SAQ.	81
Figure 6.16	Evaluation question 4 (Head Chest Hips associated with Coronal Lateral Shift) of preoperative SAQ.	82
Figure 6.17	Evaluation question 4 (Head Chest Hips associated with Coronal Lateral Shift) of postoperative SAQ.	83
Figure 6.18	Evaluation question 5 (Position of head over hips associated with Coronal Balance) of preoperative SAQ.	84
Figure 6.19	Evaluation question 5 (Position of head over hips associated with Coronal Balance) of postoperative SAQ.	85
Figure 6.20	Evaluation question 6 (Shoulder Level associated with Maximum Asymmetry of Height in Shoulder-Neck) of preoperative SAQ.	86
Figure 6.21	Evaluation question 6 (Shoulder Level associated with Maximum Asymmetry of Height in Shoulder-Neck) of postoperative SAQ.	87

Figure 6.22	Evaluation question 7 (Spine Prominence associated with BSR (Thoracic, Thoracic Lumbar, lumbar)) of preoperative SAQ.	88
Figure 6.23	Evaluation question 7 (Spine Prominence associated with BSR (Thoracic, Thoracic Lumbar, lumbar)) of postoperative SAQ.	89
Figure 6.24	Evaluation of patients' satisfaction in Function Domain	90
Figure 6.25	Evaluation of patients' satisfaction in Pain Domain	91
Figure 6.26	Evaluation of patients' satisfaction in Self-Image Domain	91
Figure 6.27	Evaluation of patients' satisfaction in Mental-Health Domain	92
Figure 6.28	Evaluation of patients' satisfaction in Satisfaction Domain	92
Figure 7.1	Box plots for thoracic scoliometer, MT Cobb, BSR and TLS: preop (blue), postop six months (orange) and postop two years (green). Individual black diamonds are outliers. Red asterisks “*” at the top indicate significant improvements between patient visits.	101
Figure 7.2	Box plots and distributions for BSR (a) and TLS (b) per surgeon: O1 (blue), O2 (orange), and O3 (green) are shown for preop, six months, and two years follow-up. Outliers are individual black diamonds. . . .	101
Figure A.1	Three area of interest (used under licence CC BY) [14]	125
Figure A.2	General Body Coordinate System (used under licence CC BY) [14] .	127
Figure B.1	Correlations between CRs of spinal and GTA measurements and those of LRTA indices (n=49). Highlighted numbers indicate significant correlations; asterisks indicate that regression analysis was applied for two measurements (results in Figure B.2). Red asterisks indicate the highest correlation values in this figure.	129
Figure B.2	Regression analysis for the significant correlations found between spinal clinical measurements or GTA corrections and LRTA corrections . . .	130
Figure B.3	Spinal measurement (Cobb angle), trunk measurements (BSR and TLS), and visualization of the 3D trunk shape of two selected patients from our cohort: a) good correction of trunk indices; b) poor correction of trunk indices.	132

LIST OF SYMBOLS AND ACRONYMS

AIS	Adolescent Idiopathic Scoliosis
ISIS	Integrated Shape Imaging System
FEM	Finite Elements Method
MBM	Multi-Body Modeling
CD	Cotrel-Dubousset
DLT	Direct Linear Transformation
AVT	Apical Vertebral Translation
TC	Thoracic Cobb angle
LC	Lumbar Cobb angle
GCB	Global Coronal Balance
CPT	Coronal Pelvic Tilt
AT	Apical Translation
TK	Thoracic Kyphosis
LL	Lumbar Lordosis
SVA	Sagittal Vertical Axis
PI	Pelvic Incidence
PT	Pelvic Tilt
SS	Sacral Slope
GTA	Global Trunk Asymmetry
SAQ	Spinal Appearance Questionnaire
SRS	Scoliosis Research Society
NCSS	Non-Clinically Significant Scoliosis
SRS-22r	Scoliosis Research Society 22r instrument
MISS	Minimally Invasive Scoliosis Surgery
MLP	Multi-Layer Perceptron
P2MAT-Net	Point-to-MAT Net
MAT	Medial Axis Transform
PSS	Postoperative Spine Shape
CPDNet	Control Point Deformation Net
BMI	Body Mass Index
LRTA	Left-Right Trunk Asymmetries
BSR	Back Surface Rotation
TR	Trunk Rotation

TLS	Trunk Lateral Shift
DR	Deformation Rate
MD	Maximum Deformity
MA	Maximum Asymmetry
PT	Proximal Thoracic

LIST OF APPENDICES

Appendix A	Scoliosis	125
Appendix B	Complementary Experiments	128

CHAPTER 1 INTRODUCTION

1.1 Adolescent Idiopathic Scoliosis (AIS)

Adolescent Idiopathic Scoliosis (AIS) is a three-dimensional deformation of the spine leading to the asymmetry of the external shape of the trunk with one or more trunk lateral curvatures deviating from the mid-line in the coronal plane [1–3] (see Appendix A). AIS is more common among children aged from 10 to 18 years old and it usually develops rapidly. The incidence rate of AIS in the general population is estimated to range from 0.47% to 5.2% according to a study [4].

In AIS patients, there is a lateral curvature of the spine accompanied by the rotation of the vertebral and rib cage [5] that affects the external appearance of the trunk [6]. Therefore, there are two important clinical observable signs of scoliosis that reveal the problem of scoliosis: 1) a lateral deviation of the spine at least 10 degrees; 2) a rotation of the vertebra around the vertical axis. The latter results in an asymmetric trunk contour from a rib hump due to the connection of the vertebral bodies with the rib cages. Other clinical signs of scoliosis are detected in pelvic discrepancy, trunk shape, and shoulder height. Generally, the scoliotic deformations on the trunk shapes involve global asymmetries such as back surface rotation, trunk rotation, and trunk imbalance as well as left-right asymmetries in local regions in the back surface of the trunk such as the shoulders, scapulae, waist, hips, and thoracic prominence.

To assess trunk deformity commonly, clinicians apply the principle screening test including Adam forward bending test which is a physical examination of the back surface using scoliometer (see Figure 1.1) [7–10]. It is a surface measurement, a multi-segmental analysis of the trunk deformity which is used to measure the angle of the trunk inclination between C7 and S1 in 10 levels (see Appendix A) [11]. The scoliometer measurement value shows the degree of asymmetry if it is not equal to 0 (symmetry). It shows the rotational component of scoliosis. However, it has several limitations. There is controversial evidence about the scoliometer reliability and validity [12,13]. The results obtained from a scoliometer can vary depending on factors such as the location and magnitude of the curve, and the skills of the examiner. Moreover, this test method is time-consuming.

To overcome these limitations, clinicians examine the global balance of the trunk shape using radiographic measurements (clinical measurements), mainly the Cobb Angle which is considered as the golden standard. The Cobb Angle shows the degree of curvature in the

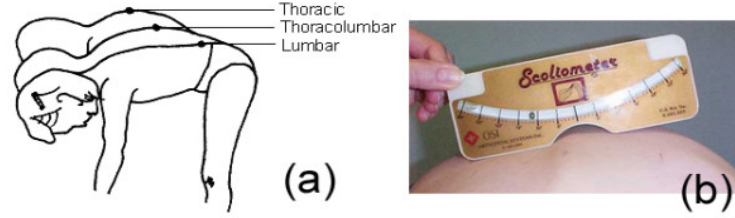


Figure (1.1) (a) The Adams forward-bending test, (b) the scoliometer (used under licence CC BY) [14]

coronal plane [15,16]. “This is defined as the included angle between the upper and lower end plates of the most tilted vertebrae around the apex of the spinal curvature in the frontal view” [17]. Figure 1.2 illustrates the Cobb angles in frontal and sagittal planes. Also, the Cobb angle shows the severity of scoliosis. However, it shows the degree of deformity in only one plane which it describes only one aspect of the 3D deformity. It is a bidimensional measurement, which is not sufficient for assessing the whole trunk appearance after surgery. Therefore, the Cobb angle alone cannot reveal the whole trunk surface deformity.

Generally, radiography measurements such as Cobb angle are limited to quantifying the spinal curvature and cannot evaluate the changes in the external asymmetries of the trunk [18].

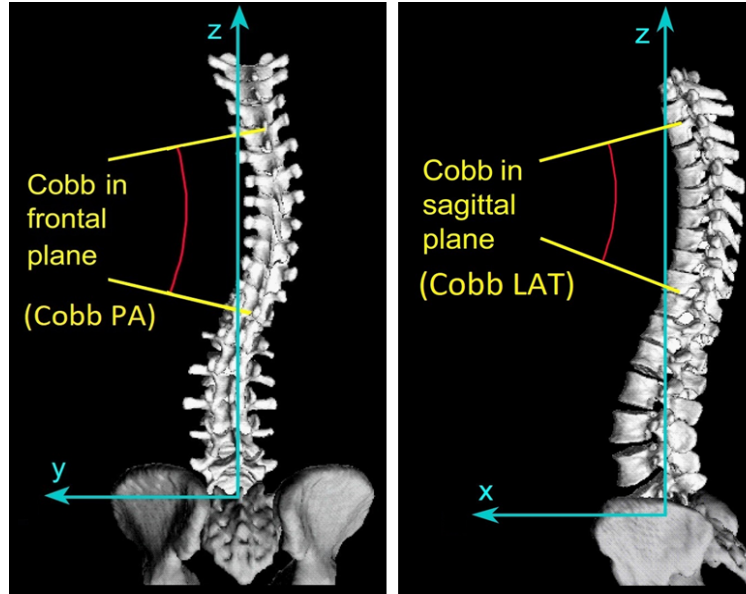


Figure (1.2) Cobb PA and LAT angles

In addition, frequent radiographies with clinical measurements are required during the follow-up examinations. As a result, patients are at risk of potential health problems associated with radiation exposure. Therefore, it is essential to develop noninvasive, radiation-free

techniques for evaluating spinal deformities during follow-up appointments to minimize the risk of ionizing radiation exposure [17]. The noninvasive radiation-free methods include Moire fringes, raster stereography, 3D optical methods, and laser triangulation. Roy *et al.* [17] proposed an ionizing radiation-free body scanner. Optical techniques are non-invasive image techniques that capture the deformity of the trunk using optical systems such as Moire-fringe mapping (structured light Integrated Shape Imaging System (ISIS), Quantec system, ultrasound system, and body scanners). Since Adolescent Idiopathic Scoliosis (AIS) is a three-dimensional spinal deformity that affects the trunk shape and alignment of the spine, researchers have developed 3D models of the spine and trunk to evaluate their 3D deformities:

1.2 General Research Objectives

Patients with severe scoliosis have functional problems, in addition to trunk shape deformations (e.g., cardiac, pulmonary dysfunction, cause common backaches) [19, 20]. Therefore, a surgical correction becomes necessary for these patients to stop its progression and to improve their quality of life by improving their trunk appearance [21]. Figure 1.3 shows a photograph and X-ray of an AIS sample case in a female patient before surgery (left) and after surgery (right).

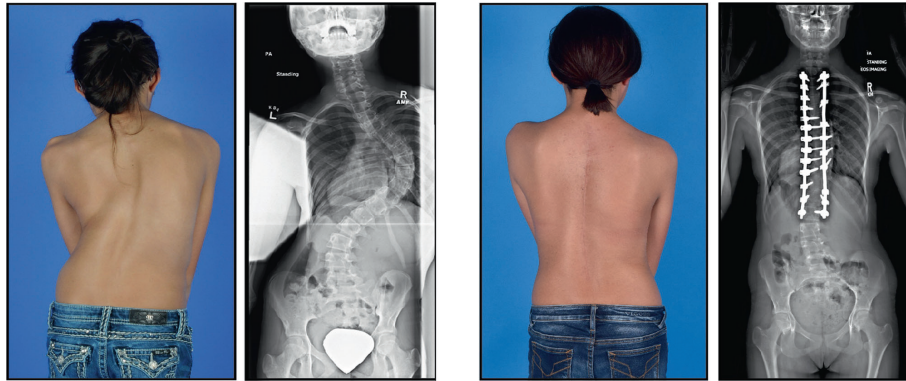


Figure (1.3) Adolescent idiopathic scoliosis in a female patient. Photograph and X-ray pre-operatively (left) and postoperatively (right) (used under licence CC BY) [22]

By introducing advanced instrumentation systems and techniques for spinal surgery, a significant range of differences in AIS instrumentation strategies among a group of experienced spine surgeons is reported [23–25]. Even for similar deformity correction priorities, different spinal surgeons may apply different instrumentation configurations. Therefore, the surgical decision-making process has more complexity in many ongoing debates over the choices of

fusion levels, selection of the instrumentation system, and suitable guidelines for surgical correction [26]. To evaluate various instrumentation systems and choose an optimal solution, computer modeling and simulations of instrumentation have become important for assessing surgeons to maximize a given patient's benefit. Therefore, much researches have been done in computer biomechanical modeling and simulations of patient-specific spinal instrumentation [26]. While correction of the spine and achieving frontal and sagittal trunk balance are the top priorities for surgeons, the trunk appearance and its cosmetic improvement after the surgery are the most important concerns for children and their parents since it is related to the mental health of patients [27]. Therefore, patients and parents want to understand the effect of spine correction on the external shape of the trunk before surgery. Moreover, surgeons need to optimize their surgical strategies based on the postoperative external shape of the trunk before surgery. Therefore, researchers have developed a trunk simulator [27,28] which is an AIS surgical tool that propagates the spine correction towards the external shape of the trunk through the soft tissues of the trunk to visualize the effect of the surgical strategy on the external appearance of the trunk. This simulator employs a physical modeling of the trunk's anatomical structures and simulates the external surface of the trunk by propagating the spinal displacements achieved from surgical correction through a trunk mesh. To utilize this simulator prior to performing surgery, a three-dimensional postoperative spinal model is necessary. The biomechanical simulators, designed to simulate the postoperative spinal shape, have only been validated on a small number of patients. Therefore, it would be greatly beneficial to implement a learning approach that utilizes the dataset of patients who have undergone scoliosis surgery. Although machine learning models have already been used to predict the postoperative shape of spine, the results of these models are not personalized for each patient.

Also, it is important to assess the accuracy of the AIS surgical tool in predicting the postoperative trunk shape to ensure that it is accurate and reliable. Therefore, it is important to have quantitative metrics to assess the postoperative trunk shape of AIS patients after surgery, and throughout the clinical follow-ups. However, the traditional methods of assessing the surgery outcome from X-rays will not reflect the correction of the trunk surface asymmetry. Moreover, since there is no clear evidence of a direct link between the curvature of the spine and the deformity of the trunk, the results of the radiological examination cannot determine on their own to what extent the surgery improved the appearance of the trunk [29]. To overcome these limitations, many research studies have been done to evaluate scoliosis surgery outcomes to find the significant global corrections between preoperative and postoperative trunk shapes or during the follow-ups [29–33]. However, the existing studies cannot be applied to assess left-right asymmetries in local regions in the back surface of the trunk due

to their natural global assessment. Therefore, automatic assessment of the left-right trunk asymmetry in local regions, in the back surface of the trunk shape, highlights which aspects of the trunk appearance are more important for patients and parents.

After scoliosis surgery, it needs to assess and document the global deformity of the trunk appearance after scoliosis spinal surgery for AIS patients through follow-ups. However, immediate follow-up after scoliosis surgery is not enough since it needs to evaluate the long-term correction and assess the stability of the trunk after a minimum two-year follow-up.

The overall goal of this project is to develop a surgical planning tool for the treatment of AIS patients, allowing surgeons and patients to visualize the predicted result of spinal surgery and to document and automatically assess scoliotic surgery outcomes. Firstly, the research will propose a new tool to help in planning surgery taking into account the effect of scoliosis surgery on the appearance of the trunk shape. Secondly, the research will propose new 3D indices and an automatic assessment tool to quantify global and left-right trunk asymmetries in the local regions of the trunk shape.

1.3 Manuscript Overview

The thesis is structured as follows:

- Chapter 2 reviews related works on scoliosis surgery planing. Then, the existing research studies on the assessment of scoliosis surgery outcomes including 2D and 3D clinical measurements, and questionnaires are presented. After that, prospective follow-up studies of AIS Surgery are summarized. Finally, well-established methods aiming at predicting the 3D shapes using deep learning models are summarized.
- Chapter 3 first describes the problem statement and research objectives which aim to develop a surgical planning tool that will enable surgeons and patients to visualize the predicted result of spinal surgery. Additionally, it will provide a tool to document and automatically evaluate the outcomes of scoliotic surgery.
- Chapter 4 presents our proposed deep learning model which exploits shape properties to predict a postoperative spine shape as the outcome of corrective surgery to treat scoliosis. It could serve to develop a surgical planning tool for scoliosis treatment, allowing surgeons and patients to visualize the predicted result of spinal surgery.
- Chapter 5 presents the second contribution which details our method for automatic assessment of the postoperative appearance of the trunk shape using proposed new 3D indices. Its main goal is to reveal left-right trunk asymmetries corrections in local

regions on the postoperative trunk shape using these new 3D indices which can help surgeons to evaluate the outcome of the surgery.

- Chapter 6, in connection to the above study, presents the evaluation of the patient and parent's expectations and satisfaction from SAQ and SRS questionnaires using the spine and 3D trunk measurements including the proposed new 3D indices. Its main goal is to document which aspects of the trunk appearance are more important for both patients and parents.
- Chapter 7 provides documentation of the changes of the postoperative trunk shape after a two-year follow-up. The goal is to help clinicians by providing complementary information.
- Chapter 8 discusses the advances of our works as well as its limitations in relation to previous studies.
- Chapter 9 summarizes the main contributions and suggests some potential research directions for future work.

CHAPTER 2 LITERATURE REVIEW

Some studies have been done on developing physical and statistical-based models as scoliosis surgery planning techniques. Furthermore, many researches have been done to document the evaluation of scoliosis surgery outcomes. A group of studies focused on proposing new indices to evaluate spine and trunk deformations. Another group of studies focused on questionnaires as practical instruments to assess the outcome of spinal surgery and health-related quality of life for AIS patients. This chapter will, therefore, review the literature on these existing research studies of scoliosis surgery outcomes in the following order: scoliosis surgery planning, outcome assessment, and prospective follow-up studies.

In addition to applying biomechanical modeling to develop surgery planning tools, machine learning models also are used. Therefore, finally, this chapter will review machine learning and deep learning models that have been used in 3D shape analysis and modeling.

2.1 Scoliosis Surgery Planning

Scoliosis surgery planning tool which predicts the outcome of scoliosis surgery lets clinicians, patients, and their parents see the different results of postoperative surgery outcome shapes based on selecting different surgical strategies. Then, they will have more flexibility to accept or reject the surgery. Scoliosis surgery planning can be beneficial in selecting appropriate surgical correction methods and reaching favorable surgical results. Generally, this surgery planning tool is patient-specific, and obtaining it through X-rays is impossible. Therefore, the use of computational biomechanical modeling has demonstrated potential in delivering a patient-specific surgery outcome and has become increasingly important in treatment processes. Utilizing biomechanical modeling provides significant benefits for surgeons in enhancing their comprehension of the biomechanics involved in the correction procedure and offering guidance before the surgery.

2.1.1 Prediction of the 3D Spine Shape

Different research groups have developed simulations of the postoperative spine shape using biomechanics methods. Finite Elements Method (FEM) and Multi-body modeling (MBM) systems, and their combinations have been used widely to model the spine.

Biomechanical models based on the Finite Elements Method (FEM) have been used to simulate different instrumentation procedures [34, 35]. Stokes *et al.* have developed a 3D FEM of

the thoraco-lumbar spine to simulate the Harrington [36] and Cotrel-Dubousset (CD) [37] corrections. Using stereo-radiographic reconstruction and DLT technique (Direct Linear Transformation), they made personalized geometry of the spine whereas the mechanical properties were obtained from existing literature that deals with the behavior of non-scoliotic specimens. Lafage *et al.* [38] proposed a simulation of the Cotrel-Dubousset (CD) scoliosis surgery conducted for 10 AIS patients utilizing a 3D Finite Element Model (FEM) of the spine. The 3D geometry of the FEM was obtained from a stereo-radiographic reconstruction and the mechanical properties were tailored to each patient using lateral bending X-rays. Borgne *et al.* [39] worked on the comparison of the 3D reconstruction geometry in standing and bending positions with a numerical simulation of the personalized Finite Element Model (FEM). Their model effectively predicts the behavior of a healthy spine. Aubin *et al.* [40] proposed a simple computer-based method for evaluating the correction of 3D spinal deformities using segmental instruments. Their model simulated spine deformations under a given set of load forces, by combining analytical solutions with numerical iteration procedures. This approach is aimed at reducing the number of finite elements required for accurate simulation. Duke *et al.* [41] have used finite element simulations to simulate patient positioning in spinal instrumentation surgery. They assessed different trunk adjustment factors and recommended the most suitable patient positioning both before and during the surgical procedure. More recently, Henao *et al.* [42] presented a personalized biomechanical model of the spine and spinal cord to simulate surgical instrumentation procedures. They customized a detailed finite element model (FEM) according to the geometry of the patient using a 3D biplanar radiographic reconstruction method and 3D dual kriging. Subsequently, the procedure of surgical instrumentation maneuvers was simulated to evaluate the neurological risks associated with each maneuver. The outcomes demonstrated that the patient-specific hybrid model effectively replicated the biomechanics of neurological injury during scoliosis correction procedures.

Surgical simulations that utilize FEMs often encounter problems with convergence due to differences in stiffness and discontinuities between elements. Moreover, the number of elements in a Finite Element Method (FEM) model is important and affects the computational power and processing time needed. By increasing the number of elements, the required computational power is also increased, and convergence issues may arise during the simulation runs [43]. Compared to FEM models, the Multi-body models (MBM) are simpler and less computationally demanding. Additionally, these models are easier to validate.

Biomechanical models based on Multi-body modeling (MBM) such as flexible mechanisms have been also used to simulate different instrumentation procedures [34]. Poulin *et al.* [44] proposed a simulation of the CD correction with a rigid-body model of the spine. They adjusted a modeling method through the analysis of flexible mechanisms and assess its via-

bility. The model integrates rigid bodies to represent the vertebrae and flexible components to represent the intervertebral structures. Moreover, Aubin *et al.* [45] developed a kinetic model incorporating flexible mechanisms which demonstrated its application in simulating surgical procedures involving the Cotrel-Dubousset Horizon. Also, Desroches *et al.* [46] developed a biomechanical model utilizing a flexible mechanism to examine instrumentation techniques for anterior spine surgeries. Aubin *et al.* [47] have also proposed a spine surgery simulator that is reliable, user-friendly, and safe to predict the correction of scoliosis spine deformity after surgery. This simulator provided advanced spinal surgery planning which works based on both patient's characteristics and different instrumentation configurations. Using this proposed spine surgical simulator, Robitaille *et al.* [48] have demonstrated the effectiveness of using alternative instrumentation strategies on the surgical results and Majdouline *et al.* [26, 49] have proposed a method that determines the best surgical instrumentation strategy personalized to each surgeon's correction objectives. Petit *et al.* [50] proposed a method to characterize the mechanical properties of the scoliotic spine. They used a flexible multi-body model, considering the spine's flexibility as a significant biomechanical factor to consider when planning surgical instrumentation.

In the existing studies, researchers have documented a spine surgery simulator [47] that is reliable to simulate the correction of scoliosis spine deformity after surgery. However, they need to define the mechanical properties of the spine and the properties of each element. Also, they are validated only for a limit cohort of the patients while this is important to predict the postoperative spine shape for general population.

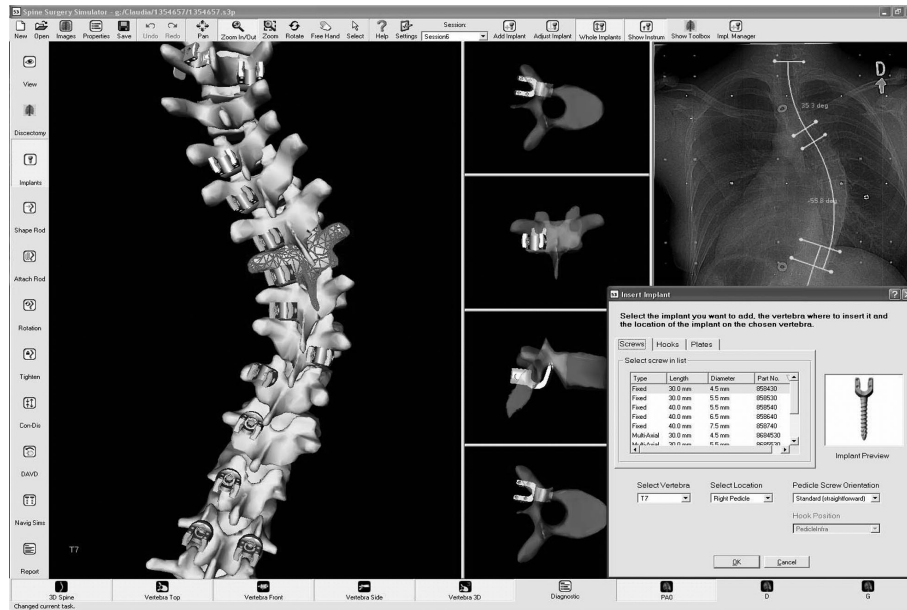


Figure (2.1) Simulator Spine [47]

learning based models have been also used to predict the scoliosis surgery outcome. Pasha *et al.* [51,52] have developed a 3D classification system for AIS patients before and two years after spinal fusion surgery which is applicable to develop predictive models for the outcomes of AIS surgery. More recently, Pasha *et al.* [53] have developed a machine learning method to predict scoliosis surgical outcomes, showing the overall 3D spinal alignment at two-year postoperative follow-up. However, that approach's outputs are not personalized to each patient; rather, the projected outcomes are clustered into three groups.

2.1.2 Prediction of the 3D Trunk Shape

Physical modeling of soft tissues is utilized in biomedical applications, specifically for simulating surgeries [28]. Visual and physical realism is crucial for these applications, but the underlying biomechanical properties are not always well known. Few research studies have worked on the simulation of postoperative trunk shape as scoliosis surgery planning [27,28] which are summarised in this section.

To simulate the postoperative trunk shape, Dionne *et al.* [28] have used a physical method to model soft tissue physical behavior after spinal surgery. They have used transformation functions to transform pre-to-post sets of anatomical landmarks of the spinal bone structures and then to transform mesh vertices corresponding to soft tissues. Then, a geometric transformation of the trunk shape is obtained and its accuracy has been improved using energy minimization transformation. The proposed approach avoids the high-complexity computation of FEM for shapes with a large number of tetrahedra. Figure 2.3 shows the proposed algorithm of interactive simulation of the postoperative shape of the trunk. As a follow-up study, Assi *et al.* [27] have proposed a novel incremental approach to simulate the postoperative shape of the trunk. Dealing with large deformations of soft tissue generally involves introducing non-linearity into the formulation of the tissue properties. In the case of large deformities, nonlinear elasticity has been shown to deliver better results than linear elasticity [54,55]. However, it leads to an increase in computational complexity. Therefore, Assi *et al.* [27] have proposed a surgery planning simulation of the postoperative trunk shape which simulated the propagation of the spine correction towards the external shape of the trunk by proposing a new incremental method that reduced the large nonlinear deformities into a set of small deformities to keep the linear elastic behavior of the soft tissue properties. The proposed method breaks down the nonlinear deformation process into a sequence of small deformations where the linear elastic behavior remains valid. So, it can keep the original linear formalism throughout the simulation. Figure 2.2 shows its flowchart and simulation results. This postoperative trunk shape simulator can help find the optimal scoliosis surgery

strategy by considering the outcome of surgery on the external shape of the trunk.

However, before starting, the postoperative shape of the spine is needed to feed into this simulator of the external shape of the trunk. Moreover, it needs to validate the simulated external shape of the trunk. To validate the outcome of this simulator, some metrics are needed that can detect the local asymmetry deformities along the trunk.

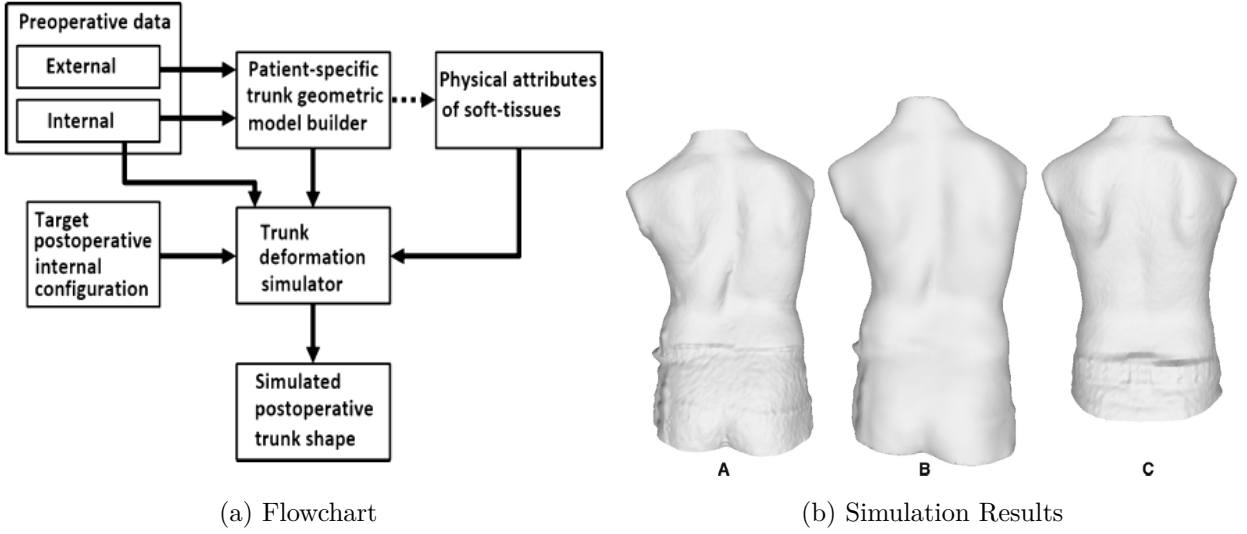


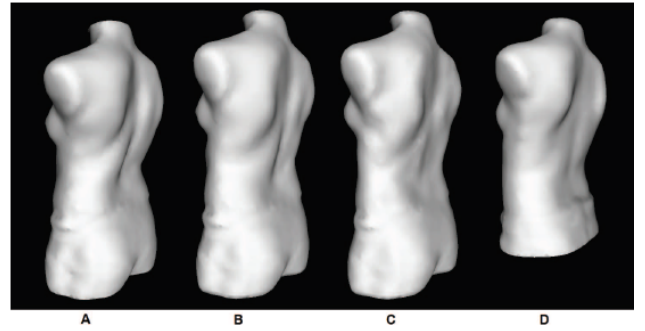
Figure (2.2) (a) Flowchart and (b) Results of simulation in [27].

Algorithm 1 Postoperative appearance simulation

```

1: Input :  $B, B'$  and  $S_V$ 
2: Output:  $S_{V'}$  {Equilibrium configuration}
3: BEGIN
4: Generate the preoperative volumetric trunk model:
    $V \leftarrow \text{GenVolMesh}(S_B, S_V)$ 
5: Assign model parameters
6: Find  $\mathcal{T}$  knowing  $L^0$  and  $L^1$ 
7: Compute  $V'' \leftarrow \mathcal{T}(V)$  {Thin-plate spline interpolation}
8: Minimize soft tissue energy:  $V' \leftarrow \tau(V'')$ 
9: Extract  $S_{V'}$  from  $V'$ 
10: Return  $S_{V'}$ 
11: END

```



(a) Algorithm © 2012, IEEE [28]

(b) Simulation Results © 2012, IEEE [28]

Figure (2.3) (a) Algorithm and (b) Results of simulation in [28].

2.2 Assessment of the Scoliosis Surgery Outcome

2.2.1 2D and 3D Clinical Measurements

Surgeons prioritize correcting the spine and achieving balance in the frontal and sagittal planes, but the most crucial concerns for children and parents are the cosmetic improvement and appearance of the trunk after surgery, as this is linked to the patient's mental well-being. Therefore, to analyze the outcome of the surgery, many studies have documented the assessment of the spine and trunk correction after scoliosis surgery. They are two categories of research works on the evaluation of the scoliosis surgery outcome: assessment of the spine and trunk shapes

Assessment of the Spine Shape:

To assess the spine shape, first, the 3D spine shape is need to be reconstructed. The spine is made up of both flexible and rigid elements, each of which plays a crucial role in maintaining the stability, flexibility, and mobility of the spine as a whole. The vertebra is a rigid component that performs different functions and has varying structures in different regions of the spine, known as the cervical, thoracic, lumbar, and sacral regions [34].

Researchers have developed 3D models of the spine using bi-planar X-ray images using calibration objects [56] or self-calibration techniques [57,58]. These models aim to provide a more accurate representation of the spinal deformity that can be used for surgical planning [59]. Figure 2.4 shows the steps of 3D reconstruction of the spine proposed in [60].

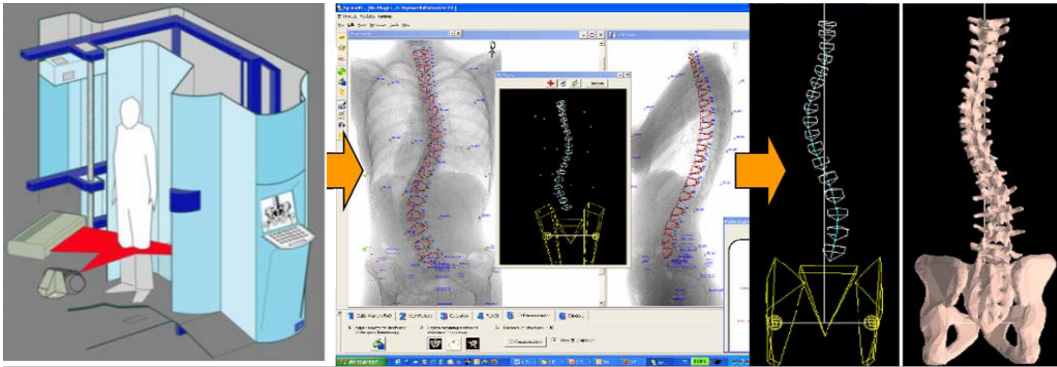


Figure (2.4) The Spine3D software is utilized to create 3D representations of the spine and pelvis from calibrated standing posterior-anterior and lateral radiographs [60].

3D spine models are typically simple and consist of 3D anatomical landmarks. The number of these points, ranging from six to fourteen on each vertebra, is determined by clinical requirements and research goals. The advantage of only using landmarks is simplicity because

the resulting models belong to a vector space where all standard statistical and analytical methods can be employed. Moreover, the spine's individual vertebrae are composed of hard, bony structures that can be regarded as rigid bodies, in contrast to the spine as a whole, which retains its flexibility. Complex deformations can occur in the spine due to its structure as a combination of multiple rigid bodies (the vertebrae) connected by soft tissues like joint capsules, intervertebral discs, ligaments, and muscles. Thus, it is also reasonable to model the spine shape using relative rigid transformations between consecutive vertebrae. Therefore, Boisvert *et al.* [61,62] proposed an articulated model that can be used for spine shape modeling.

As 2D measurements of the spine, Christophe *et al.* [63] have done an intra-observer and inter-observer reliability study to determine the accuracy and consistency of radiographic measurements for global sagittal balance parameters and sagittal spine curves, including the cervical spine. Based on their research, excellent intra-observer and inter-observer reliability in all parameters including pelvic parameters, sagittal curvatures, and global sagittal balance is reported. Figure 2.10 shows the spinal parameters were measured in [63].

Different 2D measurements of the spine have been used to assess the spine deformity. The measurement known as thoracic apical vertebral translation (AVT) [64] refers to the distance between the C7 plumb line and the center of the thoracic apical vertebra. Lumbar apical vertebral translation (AVT) refers to the distance between the center of the vertebral body located at the apex of the lumbar curve and the vertical line that passes through the center of the sacral vertebral line (see figure 2.5). Another significant parameter is vertebral rotation which different methods have need developed to measure it. The most studied methods are those that involve identifying specific landmarks. The Cobb method [65] uses the position of the spinous process, or other techniques [66–68] that utilize pedicle shadows, or the method [69] which combines multiple landmarks, is often clinically used to determine the degree of vertebral rotation.

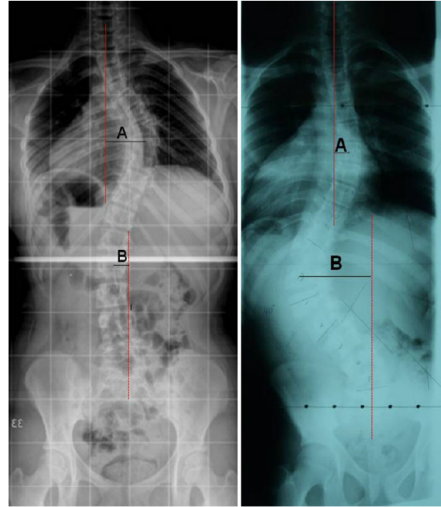


Figure (2.5) Thoracic apical vertebral translation (A) and lumbar apical vertebral translation (B) [64].

There are different coronal and sagittal radiographic parameters that are used to evaluate the spine and pelvic measurements [70, 71]. Figure 2.6 illustrates the coronal parameters including the thoracic Cobb angle (TC), lumbar Cobb angle (LC), global coronal balance (GCB), coronal pelvic tilt (CPT), and apical translation of the major curve (AT). Figure 2.7 shows the sagittal parameters including thoracic kyphosis (TK), lumbar lordosis (LL), the sagittal vertical axis (SVA), pelvic incidence (PI), pelvic tilt (PT), and sacral slope (SS).

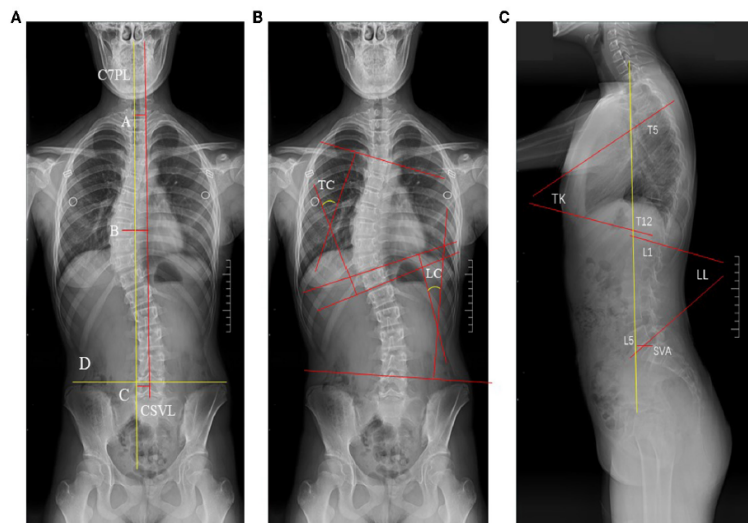


Figure (2.6) Coronal Parameters (used under licence CC BY) [71].

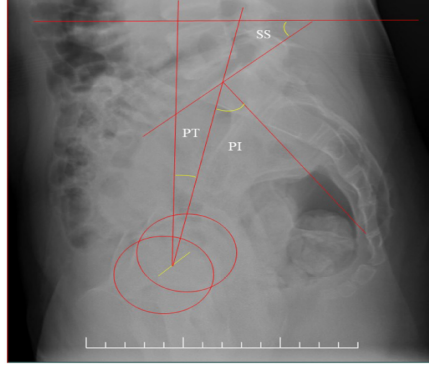


Figure (2.7) Sagittal Parameters (used under licence CC BY) [71]

Anterior–posterior and lateral X-ray images of the spine have been used to identify and follow-up on deformity of the spine in AIS patients [59]. However, using 2D measurements to assess the curvature of the spine in Adolescent Idiopathic Scoliosis (AIS) may not accurately reflect the true curve patterns, leading to potentially negative impacts on clinical treatment and surgical planning [72, 73]. The importance of describing the 3D scoliotic curve has been discussed by researchers [60, 74, 75]. Somoskeoy et al [76] reported an existing high correlation between 2D and 3D measurements of scoliotic curves in Adolescent Idiopathic Scoliosis (AIS) patients. Moreover, the 3D indices of the spine have been used to evaluate surgical outcomes for AIS patients [59]. Therefore researchers have been using a combination of 2D and 3D indices with mathematical and statistical models to improve AIS outcome assessments.

As 3D measurements of the spine, Pasha *et al.* [77] have proposed writhe (quantifying how large the projection of the 3D curve on a unit sphere is) [78] and torsion (quantifying how fast the 3D curve twists off-plane) [79] to describe the true characteristics of a 3D spine for AIS. They reported that there is a weakly correlation between these two indices. Writhe [78, 80] proposed a method for quantifying the curvature of the entire spine as a single value, which is obtained by measuring the surface area enclosed by the 3D curve of the spine when projected onto a spherical surface that is fitted to the length of the spine. Figure 2.8 illustrates the concept of writhe. Geometric torsion is a numerical measure that enables the quantification of the spine's tendency to be twice off-plane [79, 81]. Figure 2.9 shows two twisting ribbons illustrating the analogy of the parametric geometric torsion with high and low values.

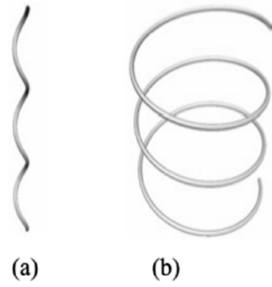


Figure (2.8) This diagram compares a 3D curve with low (a) and high (b) values of writhe [77]

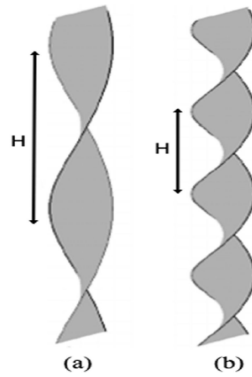
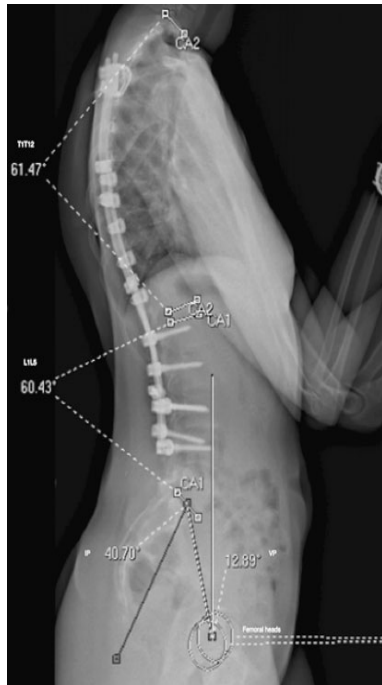


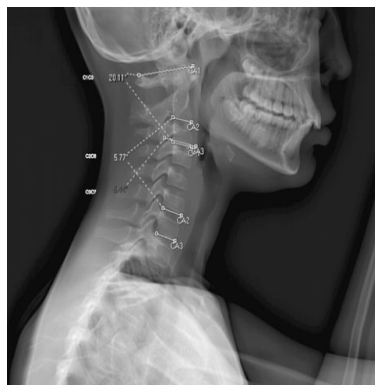
Figure (2.9) This diagram compares low (a) and high (b) values of torsion obtained from a twisting ribbon illustrating the analogy of the parametric geometric torsion. In this analogy, as the length between consecutive loops (H) decreases, the torsion value increases. This relationship highlights how a shorter distance between successive loops leads to higher torsion values in the ribbon



(a) Thoracic kyphosis (T1T12), lumbar lordosis (L1L5), pelvic incidence (IP), pelvic version (VP)



(b) External auditory canal plumb line (CAEPL), external auditory canal-C7 translation (CAEC7), external auditory canal-hips distance (CAEH), C7 plumb line



(c) Upper cervical lordosis (C1C3), global cervical lordosis (C2C6), lower cervical lordosis (C3C7) on plain EOS lateral radiographs

Figure (2.10) Spinal parameters were measured [63]

Assessment of the Trunk Shape:

In order to use unharmful visible light instead of radiographic acquisition, 3D reconstruction systems have been introduced [82–84]. Then, the 3D reconstructed trunk shape is used to assess the 3D deformities of the trunk shape. The procedure of reconstructing a 3D mesh of trunk is described by Pazos *et al.* [84]. They described the acquisition protocol of a calibrated system composed of four 3D optical digitizers which each digitizer captures four fringe images by projecting on the trunk’s external shape. Then, the depth of each point on the surface corresponding to the reference plane of the digitizer is computed. A fifth image which shows the surface texture captured without fringes and mapped on the surface. Resulting the acquisition process by using the phase-shifting interferometry principle combined with active triangulation, four partial 3D surface shapes of the trunk are reconstructed. Finally, a complete 3D reconstruction shape of the trunk is produced by merging and registering the four partial 3D surface shapes. Figure 2.11 shows the steps of 3D reconstruction of the trunk. The constructed triangulated mesh has a poor quality of triangles in some areas, especially in the regions tangential to digitizers and under the surface of the arm due to occlusion. Therefore, the surface of the mesh is not homogeneous in the whole trunk shape. In addition, the graph of mesh in the boundaries of the trunk such as the head, arms, and pelvis are not entirely connected and there are some holes due to the cropping off in these areas. It is important to improve the quality of meshes before starting the process of trunk mesh using the Laplacian matrix. The fact is that to extract the intrinsic features of the mesh, the Laplacian-Beltrami operator using the Laplacian matrix, sensitive to the mesh quality, is used. Therefore, mesh preprocessing to remove the noises and solve missing data should be applied to have a stable spectral representation of the trunk surface. It is important to improve the quality of meshes before starting to process trunk mesh. Therefore, Ahmad *et al.* [85] has proposed a sequential algorithm to extract the torso shape from the whole captured body.

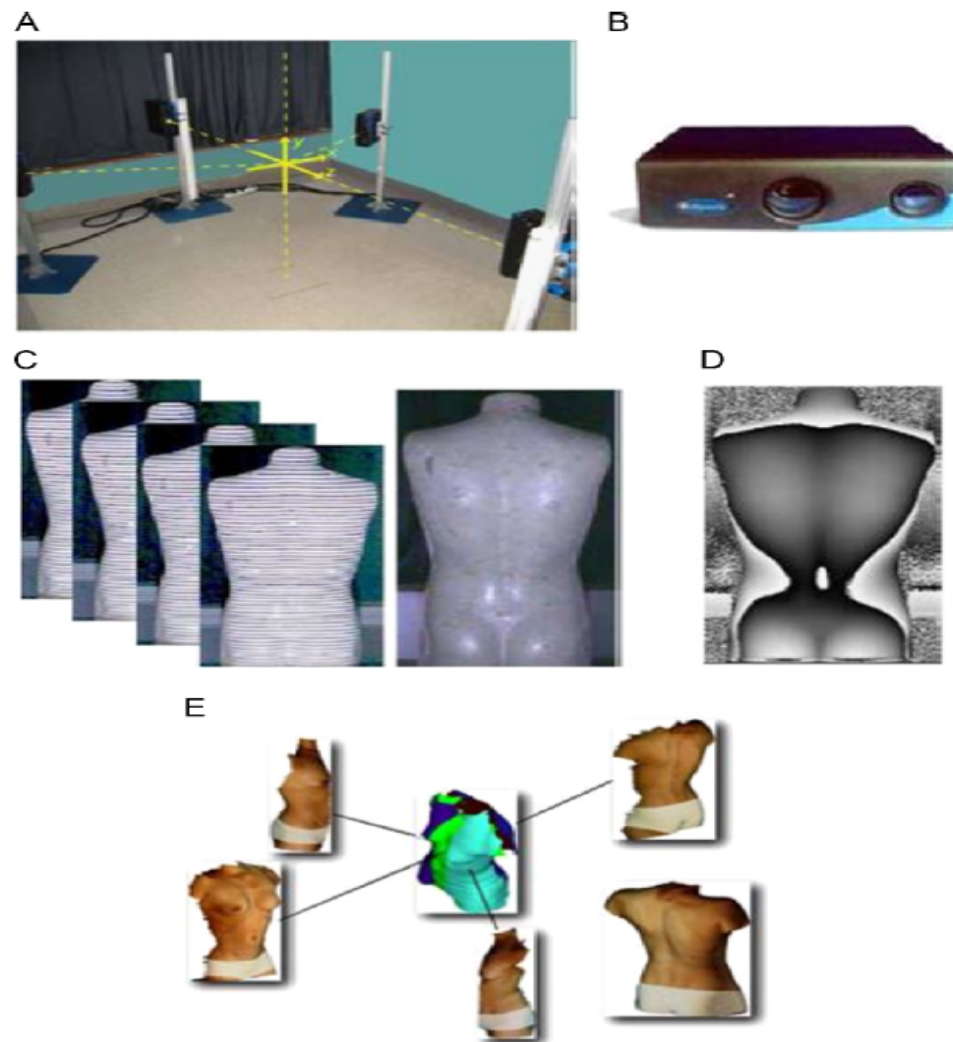


Figure (2.11) 3D reconstruction process [86]

Moreover, posture evaluation software tools using a generalizability theory are developed [87–89] to analyze the posture indices taken from digital photographs. Fortin *et al.* [87] has developed a research study on the assessment of the overall reliability, repeatability, and consistency of posture measurements among AIS patients. The operator using the software chooses a marker from the graphical interface and positions it directly onto the designated anatomical landmark or reference point on a participant's photo. Then, the program automatically computes and displays the angles or distances when markers corresponding to the calculation of this index are selected. Despite the good reliability of the marker placement, further studies are required to minimize measurement errors and establish an effective tool for monitoring changes in posture over time.

Many research studies have been proposed to assess the Global Trunk Asymmetry (GTA)

correction. Some research studies based on topographic measurements have been proposed to assess the back valley line [90] and trunk cross-sections centroid line [91]. However, they only documented the deformity in the coronal plane. Patias *et al* have summarized clinical measurements which have been proposed to assess trunk deformities [14]. Ajemba *et al.* [30] have proposed the structured splines model to analyze trunk deformity. The proposed model is used to represent the trunk as a distribution of dominant points that are extracted from a B-spline representation of the trunk cross-sections. Then, they introduced clinical measurements including three rotations in the lateral axial and posterior-anterior plans including bend, tilt, and twist asymmetries to assess local deformities of the trunk surface.

Some studies evaluated trunk deformity by computing local measurements on the trunk cross-sections along the trunk on each section as multi-level measurements including trunk rotation and back surface rotation [31,90,91]. However, to simplify the statistical analysis in the previous works, the entire multi-level measurement profile is reduced to a single measurement as the maximum value along the trunk which provides the idea of the severity of the deformations. However, this maximum value of the deformity is the same for different trunk surface acquisitions, while changes may occur locally elsewhere along the trunk. Therefore, it is significant to consider the whole measurement profile for analyzing trunk surface deformations. To overcome this limitation, Seoud *et al.* proposed a functional representation of the multilevel measurements [32]. Then, the back surface rotation, trunk rotation, trunk lateral shift, and coronal and sagittal trunk deviation are computed on the cross-sections of the trunk shape to evaluate trunk deformity *et al.* [29,32,33]. To evaluate a redundancy between the measurements, a functional correlation analysis is applied. Therefore, a novel representation of the trunk is used to assess the global changes in trunk deformity. Generally, to have a broader view of the trunk deformity, techniques based on the functional representation of the multilevel measurements provided three main objectives including (1) proposing new multi-level trunk surface measurements to assess the trunk deformities, (2) assessing the reliability of the proposed measurement for all trunk levels not only the maximum values, (3) proposing a compact set of measurements by evaluating the correlation between the proposed measurements.

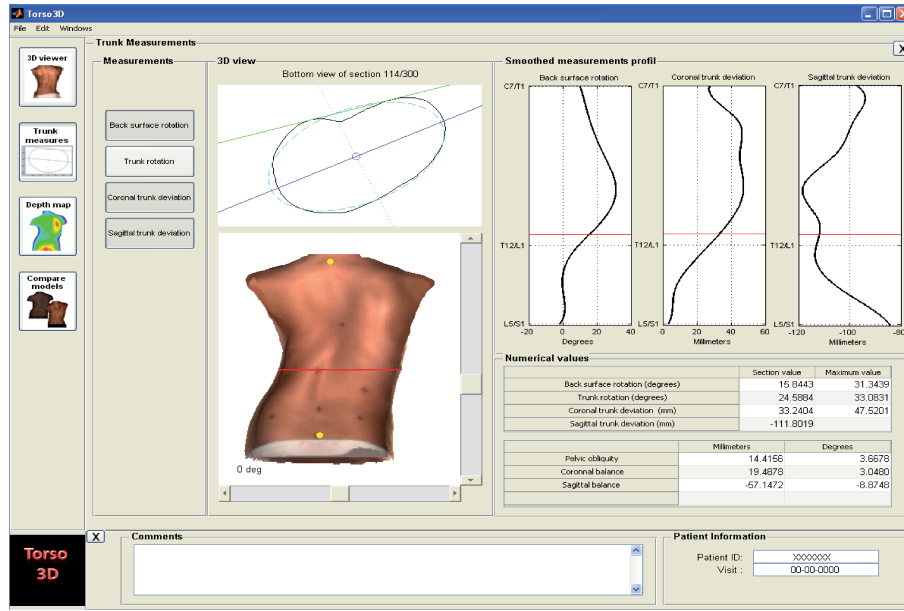


Figure (2.12) Graphical user interface for trunk measurements visualization [32]

2.2.2 Expectation and Satisfaction of Patients and Parents (SAQ and SRS)

Evaluation of the expectation and satisfaction of the patients and their parents about patients' trunk appearance as well as pain, self-perceived images, function, and mental health after scoliosis surgery is important for clinicians. To optimize the satisfaction of the patients and parents and improve the outcome of AIS surgery, it would be beneficial to consider preoperative mental health, pain, and expectations of the patients and their parents.

Two commonly used patient-reported outcomes are the Spinal Appearance Questionnaire (SAQ) and Scoliosis Research Society (SRS) questionnaires. SAQ involves selecting drawings of the body image aspects including rib prominence, body curve, and shoulder asymmetry, and extra questions on self-image satisfaction and expectations. SRS involves questions about pain, physical activity, and mental health and a total score as a measure of the patient's overall quality of life.

Sanders *et al.* [92] have proposed SAQ based on the Walter Read Visual Assessment Scale. The SAQ reflects the expectation of the patients and their parents including two sections with a total of 19 and 20 questions to be answered by patients and their parents respectively: 1) drawing questions showing the severity levels of different components of the spinal deformity; 2) texting questions scoring the dissatisfaction with other spinal deformity components. The SAQ is more related to the self-perceived images domain in the SSQ by asking questions about general (three questions), curve (two questions), prominence (two questions), trunk shift (two

questions), waist (three questions), shoulders (two questions), kyphosis (one questions), and chest (two questions). Haider *et al.* [93] have proposed SRS questionnaire as a practical instrument to assess the outcome of spinal surgery and health-related quality of life for AIS patients. The SRS questionnaire reflects the patient's perspective about his or her spinal surgery and satisfaction covering five domains including Pain (five questions), self-perceived images (five questions), function (five questions), mental health (five questions), and satisfaction with management (two questions).

Although SAQ and SRS are introduced more than a decade, still some studies are only focusing on language translation, validation, and adoption of SAQ with other languages. Authors developed specific language versions of SAQ and SRS and evaluated their reliability and validity to provide the questionnaires based on the patient's primary language [94–99].

Beausejour *et al.* [98] have published a research study of validation of the SAQ. They reported that the SAQ can provide useful clinical information to manage AIS patients by making discrimination between relevant clinical values. Moreover, Beausejour *et al.* [99] published a validation study of SRS by doing a cross-cultural adaption for three groups of patients including 145 AIS, 44 non-Clinically Significant Scoliosis (NCSS), and 64 healthy patients. They have done a prospective validation study by asking 214 patients to fill out the SRS-22-fv, then the results have been analyzed by measuring the reliability, construct, concurrent, and discriminant validities for three groups of patients. Their analyses of the result showed that SRS-22-fv can reveal the level of satisfaction in reliability, construct, concurrent, and discriminant validities.

Moreover, some studies focused on the evaluation of different body image patient-reported outcomes preoperatively and postoperatively by comparing them with topography measurements, radiographic measurements, and quality of life surveys [100–104]. Sieberg *et al.* [105] documented how preoperative expectations can impact post-surgical satisfaction for AIS patients by analyzing the correlation between demographic variables, preoperative functioning, surgical variables, and postoperative satisfaction. Although there were no significant correlations between any of the surgical variables, sex, age, or preoperative self-image, there was a significant correlation between preoperative pain, mental health, and surgical expectations with postoperative satisfaction. It can help surgeons to monitor preoperative mental health and pain as well as consider patients with high expectations about their appearance [105].

Some researchers analyzed specific parameters such as back pain reported by Charalampidis *et al.* [106]. They analyzed patient-reported questionnaires related to back pain, as well as Scoliosis Research Society 22r instrument (SRS-22r) to report preoperative factors including high preoperative back pain and low preoperative mental health can predict the persistent

postoperative back pain in AIS patients after surgery. Although these studies analyzed the AIS patients-reported outcome after scoliosis surgery over time, they analyzed SAQ and SRS scores without computing 3D trunk surface measurements.

Furthermore, there are few studies, which reported a moderate or weak correlation between patient-reported SRS and external deformity of the trunk. Brewer *et al.* [107] reported there is a better correlation between patient-reported SRS in self and mental-health domains with a volumetric asymmetry metric rather than only using the Cobb angle. Cheshire *et al.* [103] have proposed using the shoulder balance, scapula prominence and waistline asymmetry to find the correlation between questionnaires and the external deformity of the trunk. They demonstrated a weak correlation between the SRS-22 mental health and self-image domains and the external deformity of the trunk.

Although the existing studies concentrated on evaluating SRS via metrics related to volumetric asymmetry, there remains a necessity to assess both SAQ and SRS questionnaires using the spine and 3D trunk measurements. This involves identifying the associations between each question of questionnaires and the spine and 3D trunk measurements.

2.3 Prospective Follow-up Studies of AIS Surgery

Prospective follow-up studies of AIS patients after scoliosis surgery over time are valuable in the clinic because it documents the effect of the surgery in the long term which is important for both clinician and patients. Previous studies [16] reported the importance of having a minimum follow-up period of two years to ensure vertebral stability and minimal loss of correction over time. Therefore, many studies have focused on the evaluation of the outcome of surgery in follow-up studies.

Yang *et al.* [108] evaluated 84 AIS patients who underwent the Minimally Invasive Scoliosis Surgery (MISS) technique with a minimum follow-up of more than one year. They analyzed Cobb angle, kyphosis at T2 to T12, operation time, estimated blood loss, and mean length of stay, and SRS-22 questionnaire to report MISS as a valid alternative technique to the posterior approach. They reported significant correction rates for the Cobb angle and the sagittal vertical axis. Generally, they reported a notable improvement in the correction of the deformity in both the sagittal and frontal planes. The patients were monitored for a minimum of one year after their surgery using standard radiographs, and their spine correction was effectively maintained throughout the years. Uehara *et al.* [109] documented a good correction over a long follow-up study period of ten years of the outcomes of 30 AIS patients who underwent skip pedicle screw fixation for AIS patients which requires fewer screws with

reducing the risk of neurovascular injury. They reported a significant improvement in the mean Cobb angle of the main curve at each follow-up point (immediately, 2 years, and 10 years) compared to the preoperative measurement. Moreover, there was a significant improvement observed in the Cobb angle of the lumbar curve immediately after the surgery, and this improvement persisted for a period of 10 years after the surgery. Overall, Their study concluded that using the skip pedicle screw fixation technique resulted in a substantial correction of the AIS deformity, which remained well maintained during a 10-years follow-up period. Furthermore, Newton *et al.* [110] documented a prospective 10-year follow-up study of 174 AIS patients who underwent spinal fusion surgery. They evaluated preoperative, initial postoperative, and 10-year postoperative radiographic measurements including coronal cobb angles of main thoracic and thoracic lumbar/lumbar, coronal balance, sagittal thoracic kyphosis, lumbar lordosis, sagittal vertical axis. They reported an overall improvement in radiographic measurements and patient-reported outcomes which were largely maintained for 10 years. However, around 10-15% of patients experienced a loss of correction less than 10° . These studies evaluated the improvement of spine correction over time. However, they did not document the changes in the deformities of the trunk appearance over time which is a concern for the patients and their parents.

Some studies documented the changes in trunk deformities between preoperative and postoperative assessments by evaluating the patient's questionnaires and non-medical evaluations [100–105,107,111,112]. These documents are qualitative to assess how well, the surgery improved the trunk appearance over time. Therefore, Seoud *et al.* [29,32] have investigated the quantitative assessment of trunk deformities by computing multilevel trunk surface measurements. However, they reported the changes in the trunk shape after a six-month follow-up.

To document the effect of the surgery in the long term, there are also a few studies that have been done by analyzing the questionnaires. Chau *et al.* [111] documented longitudinal changes of SAQ and SRS-22 scores for AIS patients, who underwent the surgery, two years postoperatively. The improvement of all domains of SAQ including curve, prominence, trunk shift, shoulders, and over two years is reported. A continuous improvement in the patients' appearance perception was observed over two years. Although function, pain, and other factors decreased after surgery, they recovered over two years. Moreover, Chau *et al.* [112] investigated long-term longitudinal follow-up of cosmetic trunk appearance for AIS patients who underwent the surgery, seven years postoperatively. Their results showed that AIS patients were highly satisfied with the results of surgery on their general appearance, waist, and chest. Also, they reported that female patients were more satisfied with their spinal curve, and trunk shift after four years postoperatively.

Clinicians, patients, and their parents are more concerned about the appearance, the rib hump prominence, and the curve of the spine after surgery. Therefore, it needs to document the correction rates of these indices after two-year follow-ups and then compare them with the changes after a six-month follow-ups study to document the new results which could not be conducted by less than two-year follow-ups study [29].

2.4 3D Shape Prediction using Deep-Learning

By emerging deep learning techniques, recent studies have been using the capability of deep learning to exploit the intrinsic structure of deforming 3D shapes and then, generate new 3D shapes not belonging to the original dataset [113–123]. These group of research studies focused on learning the structure of 3D mesh to generate a new 3D shape. There are various methods for representing 3D shapes, including point clouds [124, 125], volumetric grids [126, 127], mesh [128], and implicit surfaces [129–131]. Pointsets are a fundamental shape representation and have the advantage of being directly available from 3D shape acquisition devices. They also can show shape deformations with more flexibility than other representations. We did a literature review of the existing works on point clouds that have focused on learning point-wise features and then predicting point-wise displacements to apply transformations between two 3D shapes.

2.4.1 Prediction Networks of Pointwise Displacements

The point cloud representation maintains the original geometric information within a three-dimensional space, thus allowing point clouds to be applied in a wide range of fields [132]. Despite its versatility, the processing of point clouds is a highly complex task that faces several major challenges, such as the limited size of datasets, the high dimensionality, and the unorganized and orderless structure of 3D point clouds [132]. Therefore, Qi *et al.* [133] presents the innovative PointNet method, which is able to operate directly on irregular point clouds. PointNet learns per-point features through a shared Multi-Layer Perceptron (MLP) and obtains global features using a symmetrical pooling function known as max-pooling [134]. The MLP in PointNet only learns the local features of each point, disregarding any connections between points.

As a result, PointNet [135] struggles to capture the local features of neighboring points, limiting its ability to perform well in complex scenes. Given this limitation in local feature extraction, PointNet++ was introduced to solve it by implementing a hierarchical feature aggregation strategy using a class pyramid feature aggregation scheme [136]. The set ab-

straction level, which is the core of the PointNet++ hierarchy, consists of three layers: the sampling layer, the grouping layer, and the PointNet-based learning layer. By building multiple set abstraction levels on top of each other, PointNet++ gradually extracts features from the local geometric structure and abstracts the local features at each layer [135]. PointNet++ is also used in classification and segmentation.

Some networks have been established based on the architecture of PointNet++ to predict point-wise displacements. Yin *et al.* [137] presented a bidirectional point displacement network (P2P-NET) to learn geometric transformations between two point-based shape representations. P2P-NET is a general-purpose model that can learn different shape transformation tasks: between shape skeletons and surfaces, between simplified and detailed surfaces, and between incomplete and complete scans. Although the network learns point-wise displacement vectors from the data, it is geared toward learning large deformations; thus some effort would be needed to adapt it to smaller shape changes. Moreover, P2P-NET cannot learn point-wise displacements dependently since neighborhood constraints within the overall shape are not considered.

Recently, Yang *et al.* [138] proposed a novel Point-to-MAT Net (P2MAT-Net) to transform a point cloud to an output set of medial spheres with the same cardinality. This is achieved by using point-wise displacement vectors learned from the points to approximate the medial spheres. The Medial Axis Transform (MAT), introduced by Blum *et al.* [139], is used to represent a 3D shape using maximally inscribed spheres providing a comprehensive and concise description of the shape. Each point on the MAT is called a medial sphere which consists of a center (c) and a radius (r) denoting by $m=(c,r)$. The points on the MAT can be linked to the local thickness, symmetry information, and part-structure of the object, which makes it possible to reconstruct the original shape from these points. They used a single directional branch of P2P-NET together with a geometric loss between the supervising spheres and the learned spheres. However, P2MAT-Net cannot learn global shape properties since its loss function does not force the network to learn the constraints between point neighborhoods within the shape. In summary, existing pointset-based networks [137,138] are not appropriate for our context since they learn point-wise feature vectors independently and don't extract regional and global shape properties.

In the present work, we address the spine shape prediction task within the general framework of 3D pointset deformation. In our case, the 3D pointset represents a set of landmarks describing the shape of the vertebrae composing the spine. Although there is a surgical spine simulator however it works based on the physical model and has its limitations. Therefore, the Prediction of Postoperative Spine Shape (PSS) using the existing data of patients who

underwent scoliosis surgery is still a challenging problem. This challenge can be considered as a learning transformation between preoperative and postoperative spine shapes by learning point-wise displacements between landmarks.

CHAPTER 3 OBJECTIVES AND GENERAL METHODOLOGY

3.1 Problem Statement

The most significant concern of the patients is related to the appearance of their trunk and the potential cosmetic improvements following surgery, as these factors have a direct impact on their mental health. As a result, patients want to understand the influence of spine correction on the appearance of the trunk prior to undergoing surgery. Furthermore, surgeons are required to optimize their surgical strategies based on an assessment of the postoperative external appearance of the trunk before the surgery. In addition, the persistence of residual external trunk asymmetry after scoliosis surgical treatment is frequent and difficult to predict by clinicians. Therefore, in surgical planning for the treatment of severe scoliosis, orthopedists, and patients would benefit from visualizing the predicted result of spinal surgery. To reach this goal, researchers have developed a trunk simulator [27, 28] which propagates the spine correction toward the external shape of the trunk by using a physical-based method. However, before starting, the postoperative shape of the spine is needed to be fed into this simulator of the external shape of the trunk. Although there are spinal simulators [45–49], they need to define the mechanical properties of the spine and the properties of each element. Considering that the validation of these biomechanical simulators designed to simulate the postoperative spinal shape has been established using a restricted number of patient groups, utilizing a learning strategy based on the dataset collected from patients who underwent the scoliosis surgery would be valuable. Machine learning models [51–53] have been also used to predict the scoliosis surgery outcome. However, that approach’s outputs are not personalized to each patient; rather, the projected outcomes are classified or clustered into different groups. Therefore, there are no tools to predict the postoperative spine shape that can be used in the existing simulator.

It is important to assess the accuracy of the AIS surgical tool in predicting the postoperative trunk shape to ensure that it is accurate and reliable. Consequently, proposing quantitative metrics becomes essential for evaluating the external shape of the trunk in AIS patients after their surgery and during clinical follow-ups. Also, previous studies have highlighted the need of detecting left-right trunk asymmetry measurements in local regions such as shoulders and waist [140]. However, the traditional methods of assessing the surgery outcome from X-rays will not reflect the correction of the trunk surface asymmetry. Therefore, it is important to introduce new 3D indices which detect left-right asymmetry in the local region of the back surface of the trunk.

Evaluation of both the expectation and satisfaction of the patients and their parents about patients' trunk appearance after scoliosis surgery is important for clinician. However, there is no research study related to finding the association of each question of SAQ and SRS with spine and 3D trunk measurements then evaluating patient's and parent's expectation and satisfaction from those associated measurements. Although the existing studies focused on analyzing SRS using volumetric asymmetry metrics, still it needs to analyze both questionnaires of SAQ and SRS using spine and 3D trunk measurements by finding the association between each question of questionnaires and these measurements. To find the association between each question of SAQ and SRS with those indices, more comprehensive 3D trunk measurements are needed that can compute both global deformities (such as back surface rotation) and left-right trunk asymmetries in local regions (such as shoulders).

Besides, a two-year follow-up is important since previous studies have reported the importance of a minimum two-year follow-up to have vertebral stability and to observe the spine correction without loss [141]. Nonetheless, existing studies have documented scoliosis surgical outcomes after a six-month follow-up and there is currently no documentation of assessing the effect of the spinal surgery on the global trunk surface deformities after a two-year follow-up [29]. Therefore, evaluating the deformities in the trunk appearance after scoliosis surgery in a two-year follow-up could be useful to document the long-term surgical outcome that takes into account the perception of the patients and their parents.

3.2 Objectives

3.2.1 Objective 1

Our first objective consists of developing a deep learning model which predicts postoperative spinal shape. The proposed model learns the pattern between the preoperative and the postoperative spine shapes of the patients who underwent the scoliosis surgery to predict postoperative spine shape for new patients. After the training process, these networks should be able to predict the postoperative spine shape of a new patient. Therefore, this can assist in the planning of scoliosis surgery by visualizing the 3D shape of postoperative of spine . In addition, it can be used in the trunk simulator.

3.2.2 Objective 2

Our second objective consists of proposing new 3D indices and an automatic assessment tool to highlight the left-right trunk asymmetry in different local areas such as shoulder neck, shoulder blades, waist also proximal thoracic main thoracic, and thoracolumbar areas.

3.2.3 Objective 3

Our third objective is using the spine and 3D trunk measurements including the proposed new 3D indices to evaluate the patient and parent's expectations and satisfaction from SAQ and SRS questionnaires.

3.2.4 Objective 4

Finally, our fourth objective consists of evaluation and documentation of the deformities of the postoperative shape of the trunk after a two-year follow-up to provide complementary information to the currently available documentation for AIS patients to address the surgeon's concerns.

3.3 General Methodology

To visualize the postoperative spinal shape after scoliosis surgery in objective 3.2.1, we proposed CPDNet (Control Point Deformation Net) to learn geometric deformation between preoperative and postoperative spine shapes. The aim is to learn geometric deformation between preoperative and postoperative spine shapes. This network learns point-wise displacement vectors which are controlled by the shape properties. CPDNet has a high potential to solve problems of point-based rigid shape transformation, learning transforms between any two shape skeletons. CPDNet learns deformation using geometric loss and rigid loss without the need to do inverse mapping, unlike networks such as P2PNet. CPDNet concatenates the meta-data (age, height, weight, BMI, and surgery strategy) containing the necessary information for correctly learning deformation with coordinates of each point and then extracting point-wise features vector leading to learning deformation between source and target. To enhance the training model, the extra rigid loss is used. We have different preoperative spine shapes and different postoperative spine shapes, and our goal is to learn the deformation between each pair of preoperative and postoperative spine shapes for each patient. Therefore, we want to force the network to learn the deformation from preoperative to postoperative spine shapes and consider the rigid transformation between consecutive vertebrae which enhances its learning. We evaluate the performance of the proposed model and compare it with the existing work by using our dataset. The clinical metrics are used to record the performance of the model. The first contribution was published in the proceedings of "SPIE Medical Imaging" conference and it is presented in chapter 4.

Then, for the assessment of scoliotic surgery outcome, the difference between preoperative and postoperative trunk surfaces should be accurately compared. Previous studies have high-

lighted the need for detecting both global and local corrections. Therefore in objective 3.2.2, we introduced new 3D indices which evaluate the Left-Right Trunk Asymmetries (LRTA) which are combined with Global Trunk Asymmetries (GTA) indices, in a retrospective cohort of surgical AIS patients. First, we computed the Cobb angles from spinal X-rays, and scoliometer readings, and coronal balance to measure the spinal asymmetry. Then, we measured the Global Trunk Asymmetry (GTA) by computing Back Surface Rotation (BSR), Trunk Rotation (TR), and Trunk Lateral Shift (TLS) along the trunk. Finally, we computed the Left Right Trunk Asymmetry (LRTA) by proposing new parameters called Deformation Rate (DR), Maximum Deformity (MD), and Maximum Asymmetry (MA). These new parameters were measured in different regions based on the asymmetry areas. Asymmetry areas are defined as regions of the back surface where the deviation (outward or inward) between the left and right sides is greater than 9 mm (the threshold to identify scoliotic patients). Subsequently, the DR is computed for cross-sections along the trunk as the ratio of the number of 3D surface points belonging to asymmetry regions inside of the slice and the total number of 3D points in that slice. We compute LRTA measurements that can reveal the deformity of different areas of the back and can be interpreted based on 2D spinal measurements. Therefore, we defined different local areas in the trunk back surface such as shoulder neck/Cervical & Proximal Thoracic (PT), shoulder blades/Main Thoracic, and waist/Lumbar. Finally, we compared GTA (BSR, TR, and TLS) and LRTA (DR, MD, and MA) changes in trunk deformities with changes in spinal measurements before and at least 6 months after surgery. This second contribution was submitted to the "European Spine Journal". Also, complementary experiments are provided in Appendix B.

For objective 3.2.3, the proposed 3D indices as well as the proposed automatic assessment method of the trunk asymmetry are applied to validate the SAQ and SRS from the 3D trunk shape analysis to show the satisfaction and expectation of both patients and their parents. At first, we computed the correlation between the correction rates of 3D measurements (BSR, Coronal lateral Shift, Coronal Balance, and Shoulder Level) and correction rates of 2D clinical measurements (Scoliometer T and L, Cobb PT, Cobb MT, and Cobb TLL) from the preoperative to the postoperative for the cohort of this study to confirm that these 3D indices are related to the 2D clinical measurements. Then, we analyzed the existing SAQ and SRS questionnaires to find the associations between their questions and spine and trunk measurements. Referring to analyzing the SAQ, we found that each question of SAQ is associated with one spine or trunk measurements. We calculated the *Expectation Values* (referring to the comparison of the answers of patients and their parents with our computed measurements on the 3D shapes of patients' trunks) and the *Perception Values* (referring to real answers of patients and their parents). We analyzed both *Expectation Values*

and *Perception Values* from the answering of the patients and their parents. Referring to analyzing the SRS, the existing SRS covers 5 domains including function activity, pain, self-image, mental health, and satisfaction management. We found questions of each domain of SRS is associated with a group of trunk measurements. We focused on the first 22 items which were used for treatment. Each domain is scored by more than one item. Therefore, we could calculate the sub-score for each domain and those are the mean scores that we used for calculation. We used the sub-scores instead of individual scores. Therefore, we have *Score Domain* for each domain per patient. Then, we analyzed the SRS using the *Score Domain* and the *Expectation Values* (as explained in the previous steps of analyzing the SAQ) for each question. Also, patients answer questions from 24 to 30 after surgery which generally shows the satisfaction of the management and how the surgery improved their condition. In this step, we computed individual scores for each question because these questions are separated. Therefore, we could analyze patients' expectations and satisfaction from association between the scores of SAQ and SRS, with spine and 3D trunk measurements. This third contribution was presented in chapter 6.

Finally, in order to document the deformities in the trunk appearance after scoliosis spine surgery as a two-year follow-up study in objective 3.2.4, we computed the Cobb angles from the spinal X-rays to measure the spinal deformity. Then, the Back Surface Rotation (BSR) and the Trunk Lateral Shift (TLS) are computed along the trunk to measure the trunk deformity. These indices have been computed along the trunk surface acquisitions before, six months, and two years after surgery for each patient. We analyzed the effect of age, height, weight, cobb angle, length of surgery, and surgical technique. We also compared the trunk deformity changes with two-dimensional (2D) spinal measurements. For our cohort, we compared the correction rate of the spinal and trunk measurements after six-month and two years of follow-up. This fourth contribution was submitted to the Journal "Spine Deformity". Also, complementary experiments are provided in Appendix B.

CHAPTER 4 ARTICLE 1: PREDICTION OF POSTOPERATIVE 3D SPINE SHAPE USING CONTROLLED POINT DEFORMATION NETWORK (CPDNet)

Maryam Khani ^{a,b}, Philippe Debanné ^{a,b}, Hubert Labelle ^b, Stefan Parent ^b, Farida Cheriet ^{a,b}

^a Polytechnique Montréal, Department of Computer and Software Engineering, P.O. Box 6079, Montréal, H3C 3A7, Québec, Canada

^b Sainte Justine Hospital Research Center, 3175, Chemin de la Côte-Sainte-Catherine, Montréal, H3T 1C5, Québec, Canada

Presentation This work was published in the conference proceedings of “SPIE Medical Imaging 2023: Image Processing” on April 3, 2023 [142].

4.1 Abstract

3D pointset deformation controlled by shape properties is still a challenging task in shape modelling. Existing neural networks learn point-wise feature vectors, then predict point displacements to deform 3D shapes. However, these solutions often learn features independently between points, i.e. without considering neighborhood constraints. In this paper, we propose a deep learning architecture named Controlled Point Deformation Network (CPDNet), which exploits shape properties to predict a postoperative spine shape as the outcome of corrective surgery to treat scoliosis. CPDNet learns the rigid transformations between the 3D landmarks of consecutive vertebrae in the spine. Point-wise feature vectors are extracted from the 3D preoperative spine and concatenated with patients’ selected clinical metadata using a fully convolutional network. Then, 3D point-wise displacement vectors are predicted and added to the input points to obtain the postoperative spine shape. Geometric shape loss computes the differences between the 3D geometric coordinates of the predicted and target spine shapes. Rigid transformation loss computes the differences in rotation and translation between consecutive vertebrae, leading the network to learn spinal shape properties. We trained and validated our model on 99 patients who previously underwent posterior spinal fusion surgery. On the test set, our model achieves average errors of 1.5°, 7.6°, and 4.9° for three clinical indices, namely coronal balance and Cobb angles in the sagittal and coronal

planes, respectively, outperforming the state-of-the-art P2P-NET model. Our model could serve to develop a surgical planning tool for scoliosis treatment, allowing surgeons and patients to visualize the predicted result of spinal surgery.

Keywords: 3D pointset deformation, Rigid transformation, Neural networks, Supervised learning, Scoliosis.

4.2 Introduction

Adolescent Idiopathic Scoliosis (AIS) is a three-dimensional deformation of the spine, with one or more lateral curvatures deviated from the midline in the coronal plane [3]. AIS is more common in children aged 10 to 18 years old and it usually develops rapidly. A severe scoliosis causes functional problems, and a surgical correction becomes necessary for these patients to stop its progression and to improve their quality of life. In the surgical planning phase, orthopedists and patients would benefit from visualizing the spine shape resulting from treatment.

4.2.1 Related Work

A research group has previously developed a spine surgery simulator, based on biomechanical modeling [47, 49] which is used to plan surgical strategies and to simulate the postoperative correction of the spine deformity. However, they used a physical model that requires the mechanical properties of the spine and of each element in the simulation. Recently, a machine learning method was applied to predict scoliosis surgical outcomes, showing the overall 3D spinal alignment at two-year postoperative follow-up [53]. However, that approach’s outputs are not personalized to each patient; rather, the projected outcomes are clustered into three groups. In surgery planning, 2D classification of spinal curves based on radiographs is commonly used as a guideline for posterior spinal fusion surgery [143]. Meanwhile, predicting the 3D postoperative spine shape is still a challenging problem.

In the present work, we address the spine shape prediction task within the general framework of 3D pointset deformation. In our case, the 3D pointset represents a set of landmarks describing the shape of the vertebrae composing the spine. Pointsets are a fundamental shape representation and have the advantage of being directly available from 3D shape acquisition devices. They also can show shape deformations with more flexibility than other representations. Relatively few works in the literature have focused on learning transformations between shapes by predicting point-wise displacements. One paper [137] presented a

bidirectional point displacement network (P2P-NET) to learn geometric transformations between two point-based shape representations. P2P-NET is a general-purpose model that can learn different shape transformation tasks: between shape skeletons and surfaces, between simplified and detailed surface, and between incomplete and complete scans. Although the network learns point-wise displacement vectors from the data, it is geared toward learning large deformations; thus some effort would be needed to adapt it to smaller shape changes. Moreover, P2P-NET cannot learn point-wise displacements *dependently* since neighborhood constraints within the overall shape are not considered. Recently, a novel Point-to-MAT Net (P2MAT-Net) [138] was used to transform a point cloud to an output set of medial spheres by applying a single directional branch of P2P-NET together with a geometric loss between the supervising spheres and the learned spheres. However, P2MAT-Net cannot learn global shape properties since its loss function does not force the network to learn the constraints between point neighborhoods within the shape. In summary, existing pointset-based networks [137, 138] are not appropriate for our context since they learn point-wise feature vectors independently and don't extract regional and global shape properties. Therefore, we propose a novel rigid transformation loss that enhances the training by learning the existing transformations (translations + rotations) between consecutive vertebrae. The aim of this loss function is to help the network learn global spine shape properties. This in turn avoids predicting implausible spine topologies.

4.2.2 Objective of Our Work

Our objective is to predict the 3D shape of a patient's spine after surgery, based on the patient's preoperative 3D spine configuration combined with selected clinical metadata. To do so, we learn the deformation between preoperative and postoperative 3D spine shapes in a dataset of previously treated AIS patients, using point-based shape representations. We propose a Controlled Point Deformation Network (CPDNet) to learn point-wise features dependently in semi-rigid shapes such as the spine. The proposed network learns the inter-vertebral geometric transformations describing the spine shape, and how to displace the input points to model the target configuration.

4.3 Methodology

4.3.1 Controlled Point Deformation Network (CPDNet)

Our goal is to learn the deformations between pairs of preoperative and postoperative spine shapes in the training set. Therefore, we want the network to obtain point-wise displacement

vectors related to the shape properties. Patient clinical information serves as additional input data to help the network. We consider selected patient clinical metadata in our model, including gender, age, height, weight, BMI, and operating surgeon as a proxy for surgical strategy (categorical variable). CPDNet concatenates the selected patient metadata with the coordinates of each point in the preop spine, then extracts point-wise feature vectors. The model learns deformations using geometric loss without needing to do inverse mapping, unlike cyclical networks such as P2P-NET [137]. Although CPDNet works in one direction, we consider the same displacement for all the landmarks on a given vertebra to preserve the global shape topology. In addition, the geometric loss alone cannot help the network to learn the existing neighborhood constraints within the overall shape. Therefore, we propose a novel rigid transformation to help the network to learn global spine shape properties from the existing transformations (translations + rotations) between consecutive vertebrae.

Figure 4.1 illustrates CPDNet. Let S_{Pre} denote the known preop spine pointset, S_{Post}^* the predicted postop pointset, and S_{Post} the real postoperative point set. The known preop and postop point sets are ordered: they correspond to known landmarks on each vertebra and follow a fixed order. The spatial coordinates of the points in S_{Pre} are concatenated with the metadata vector and noise, then the point-wise feature vectors are fed to a set of Fully Convolutional Neural Networks (F-CNNs). This block is made of three layers of 1D CNNs having 128, 64, and 3 output channels respectively. By applying F-CNNs on the point-wise feature vectors, the latter outputs a set of 3D displacement vectors $\Delta_{pre-to-post}$ that serve to predict the output point set ($S_{Post}^* = S_{Pre} + \Delta_{pre-to-post}$). Since points that are spatially close together will often have similar features, the network tends to map them to the similar displacement vectors. This does not give enough flexibility to the network to learn a variety of deformations. Adding independent Gaussian point-wise noise of length 32 provides enough degrees of freedom to the predicted displacements for individual points [137].

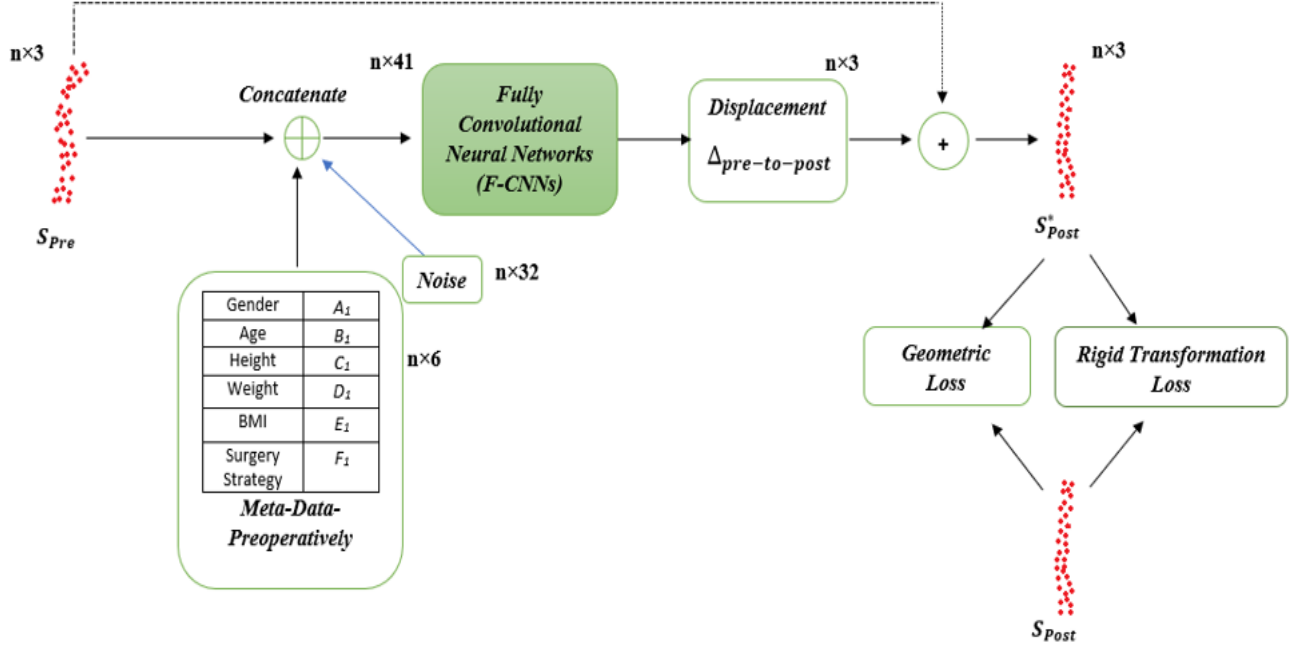


Figure (4.1) Architecture of proposed CPDNet. n represents the number of points in the spine (6 landmarks per vertebra, 18 vertebrae from C7 to L5 levels, thus $n = 108$). In our formalism, a rigid transformation is expressed as $T = \{R, t\}$, applied to a point x to yield $y = R \cdot x + t$, where $x, y \in \mathbb{R}^3$ define input and output points, $R \in SO^3$ defines a rotation matrix and $t \in \mathbb{R}^3$ defines a translation vector. Pairs of consecutive vertebrae are related by a transformation T , each vertebra having a local axis system computed from a set of known anatomical landmarks [61, 62].

4.3.2 Loss Function

We define the loss function for training so as to lead the predictions S_{Post}^* as close as possible to the target shapes (S_{Post}). Equation 4.1 shows the loss function, which combines two terms: Geometric Loss ($L_{Geometric}$) and Rigid Transformation Loss ($L_{Rigid\ Transformation}$):

$$L(S_{Post}^*, S_{Post}) = L_{Geometric}(S_{Post}^*, S_{Post}) + L_{Rigid\ Transformation}(S_{Post}^*, S_{Post}) \quad (4.1)$$

The Geometric Loss is used to compute the differences between the predicted and target postoperative spine shapes. It has the following expression:

$$L_{Geometric}(S_{Post}^*, S_{Post}) = \sum_{p \in S_{Post}^*, q \in S_{Post}} d(p, q) \quad (4.2)$$

where $d(p, q)$ measures the L2-norm distance between points p and q from the predicted

and target pointsets respectively. Since our model is supervised, we have the labels of the points (landmarks) in the different pointsets. Thus, we know the correspondence between the predicted and target points.

The Rigid Transformation Loss is defined as the sum of distances between the intervertebral rotation vectors and translation vectors of S_{Post}^* and S_{Post} overall vertebrae. Here, $d(r, r^*)$ measures the L2-norm distance between rotation vectors (r) of corresponding vertebrae of S_{Post} and S_{Post}^* . Likewise, $d(t, t^*)$ measures the L2-norm distance between translation vectors (t) of corresponding vertebrae of S_{Post} and S_{Post}^* :

$$L_{\text{Rigid Transformation}}(S_{Post}^*, S_{Pre}) = \sum_{p \in S_{Post}^*, q \in S_{Post}} d(t, t^*) + \sum_{p \in S_{Post}^*, q \in S_{Post}} d(r, r^*) \quad (4.3)$$

The rotation r and translation t are calculated between consecutive vertebrae. However, r and t are then assigned to all 6 points in a given vertebra. Thus, the summations in Eq. 4.3 are over all points p and q in the predicted and real postop shapes respectively. The translation vector, $t = (\Delta x, \Delta y, \Delta z)$ gives the translation from one vertebra to the next consecutive one. It is computed along the three axes XYZ by equation 4.4:

$$\Delta x = x_{\text{vertebra}_i} - x_{\text{vertebra}_j}, \Delta y = y_{\text{vertebra}_i} - y_{\text{vertebra}_j}, \Delta z = z_{\text{vertebra}_i} - z_{\text{vertebra}_j} \quad (4.4)$$

where i and j are the indices of two consecutive vertebrae. The rotation matrix, R , gives the rotation from the matrix of axes of one vertebra to the matrix of axes of the next consecutive one [144]. Then, the rotation matrix is converted to the rotation vector since the 3D rotation can be represented by a unit length vector n and a rotation angle of θ . In the axis-angle formalism, the rotation vector r is then defined as the product of n and θ ($r = n\theta$) [61]. Rodrigues rotation formula [145] is used to convert between the rotation vector ($r = n\theta$) and a 3x3 rotation matrix ($R \leftrightarrow r = n\theta$):

$$R = \cos(\theta) \cdot I + \sin(\theta) \cdot S(n) + (1 - \cos(\theta)) \cdot S^2(n), S(n) = \begin{bmatrix} 0 & -n_z & n_y \\ n_z & 0 & -n_x \\ -n_y & n_x & 0 \end{bmatrix}, n = \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} \quad (4.5)$$

The opposite conversion, i.e. from a rotation matrix to an axis and angle, is likewise straightforward.

4.4 Data

Our dataset comprised 99 AIS patients who underwent a posterior spinal fusion (PSF) between 2009 and 2018 at Sainte-Justine University Hospital Center, Montreal, Canada, performed by one of three orthopedic surgeons. Table 4.1 illustrates the summary statistics for the patient cohort. For this study, our inclusion criteria were: Lenke 1A main thoracic curve type5, full preoperative and postoperative spine radiographs taken at 6 months before and after surgery respectively. For each patient, 3D preop and postop spine shapes were available, along with clinical information including gender, age, height, weight, BMI, and operating surgeon. 3D spine shapes are obtained in the form of digitized landmarks reconstructed from biplanar X-ray scans [62]. In this study, we used 18 vertebral levels from L5 (lumbar) to C7 (cervical). Then, the 3D geometric coordinates of six landmarks per vertebra were extracted to have a 3D point set representing the spine shape. The extracted 3D point sets of the spine shape pairs were registered based on a global coordinate system located at L5. For the ground truth intervertebral rigid transformations, we applied the mathematics introduced in the articulated spine model [61, 62].

Table (4.1) Summary statistics for the whole patient dataset and for the training, validation, and testing subsets. Cobb angles are for the main thoracic curvature in the frontal plane.

	Age (years)	Height (cm)	Weight (kg)	Sex	Surgeon	Cobb Preop (°)	Cobb Postop (°)
(Number of patients)	Mean $\pm$ Std (min, max)	Mean $\pm$ Std (min, max)	Mean $\pm$ Std (min, max)	(N_F , N_M)	(N_{S1} , N_{S2} , N_{S3})	Mean $\pm$ Std (min, max)	Mean $\pm$ Std (min, max)
Dataset (N=99)	16 $\pm$ 2 (12, 20)	161.7 $\pm$ 7.5 (137.5, 187.5)	55.0 $\pm$ 10.0 (35.0, 83.8)	(86, 13)	(38, 42, 19)	60.2 $\pm$ 11.5 (37.4, 89.9)	18.3 $\pm$ 8.1 (0.7, 42.5)
Train (N=79)	16 $\pm$ 2 (12, 20)	162.2 $\pm$ 7.3 (143.0, 187.5)	55.5 $\pm$ 9.8 (35.0, 83.8)	(70, 9)	(31, 35, 13)	60.7 $\pm$ 11.8 (38.7, 89.9)	18.6 $\pm$ 8.5 (0.7, 42.5)
Validation (N=10)	15 $\pm$ 2 (13, 17)	156.4 $\pm$ 8.0 (137.5, 162.4)	51.3 $\pm$ 11.4 (40.0, 73.3)	(9, 1)	(5, 0, 5)	62.2 $\pm$ 10.5 (44.3, 82.9)	17.8 $\pm$ 7.6 (6.6, 32.1)
Test (N=10)	15 $\pm$ 1 (13, 20)	162.7 $\pm$ 7.8 (152.5, 176.5)	55.0 $\pm$ 10.7 (41.0, 72.3)	(7, 3)	(2, 7, 1)	54.3 $\pm$ 7.7 (37.4, 66.4)	16.7 $\pm$ 4.8 (10.9, 25.6)

4.5 Results

We used 80% of our data for training, 10% for validation, and 10% for testing. As a standard from the literature, we compared the results of our model with P2P-NET [137], a state-of-the-art method. A third model, Point Deformation Network (PDNet), is a simplified version of CPDNet that excludes the rigid transformation loss. Table 4.2 presents the details of each

model in the experiments. To train the networks, we used a batch size of 6 and a learning rate of 0.005 with a decay rate 0.5 after 400 epochs.

We trained and tested each model with both noise and clinical metadata concatenated to the 3D coordinates of the input points. To evaluate the accuracy of the predicted spine shapes, we calculated standard clinical measurements of spinal deformity [146] and compared these between the real and predicted spine shapes. The three clinical indices we computed were the coronal balance (in the frontal plane) and the Cobb angles in the frontal and sagittal planes (Cobb PA and Cobb LAT).

Figure 4.2 presents three clinical indices. The Cobb angle quantifies the amplitude of scoliotic curvature as the angle between two lines tangential to the upper and lower limit vertebrae of the deformed spine region. The coronal balance evaluates the angular offset between the vertical line going through the lowest vertebra (L5) and a line joining the latter with the highest vertebra (C7 or T1).

Table (4.2) Comparison of the three models tested.

	Feature Extraction	Concatenate with	Loss Function		
P2P-NET [137]	PointNet++	Noise	Geometric	Regular	Density
Proposed PDNet	F-CNNs	Noise	Geometric	-	-
Proposed CPDNet	F-CNNs	Noise + Metadata	Geometric	-	Rigid Transformation

Figure 4.3 presents the averaged results for all models tested. We report the root mean square of the differences (RMSE) for each model and each clinical index. Clearly, adding noise gives more flexibility to the networks to distinguish between nearby points in terms of their predicted displacements. The patient metadata allows the networks to learn similarity of the scoliotic deformity (and its correction) between similar patients. However, comparing the results between PDNet and CPDNet reveals that the rigid transformation loss contributes the most to improving the performance. As shown in Figure 4.3, CPDNet achieved the lowest RMSE for all three clinical indices, reaching values of 1.5° , 7.6° , and 4.9° for Coronal Balance, Cobb LAT, and Cobb PA respectively. These values confirm that by exploiting the addition of both noise and metadata, CPDNet is able to preserve the topology of the global spine shape better than the other models.

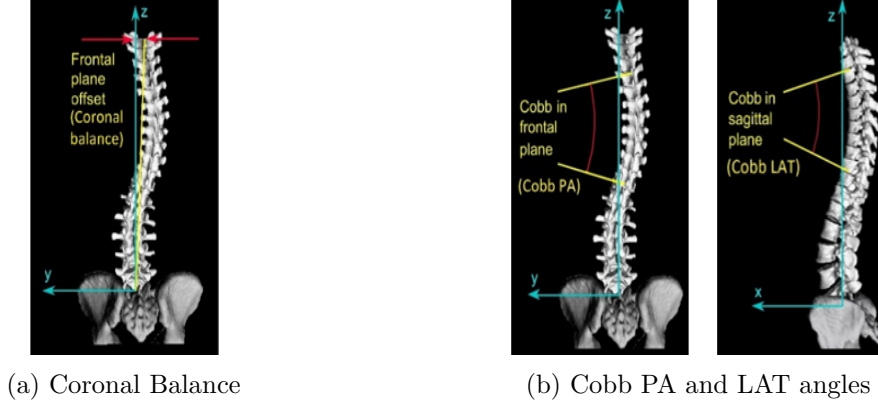


Figure (4.2) Clinical indices: (a) Coronal Balance, (b) Cobb PA and LAT angles.

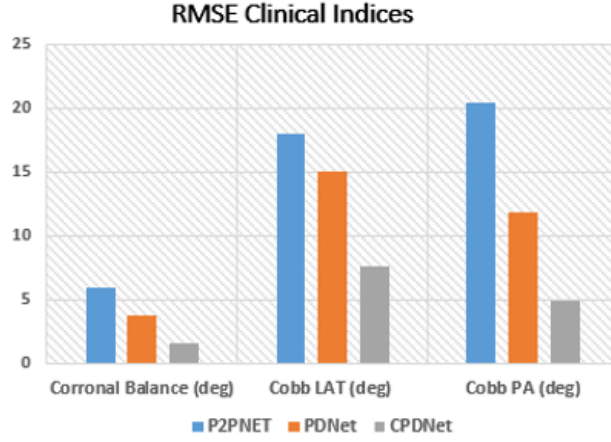


Figure (4.3) RMSE errors by the three models.

Figure 4.4 shows the qualitative results obtained for two patients from the test set: P1 (sex=girl, age=13, height=162.4 cm, weight=41 kg, BMI=15.5, and surgical technique=S1) and P2 (sex=boy, age=16, height=166 cm, weight=58.6 kg, BMI=21.3, and surgical technique=S2), as predicted by the different models. Postop spine predictions are presented in different colors: P2P-NET in cyan, PDNet in purple, CPDNet without metadata in yellow, CPDNet with metadata in red, and real shapes in green. Going from left to right in the figure for both patients, the results show gradual improvements of the predicted postoperative spine shape by using the models presented in Table 4.2.

The first column shows that P2P-NET does not learn the deformation of the postoperative spine shapes due to the structure of its PointNET++ feature extraction modules [135], which cannot learn the relation between similar (i.e. neighboring) points that have small local deformities between them. This is the case between landmarks from consecutive vertebrae.

Even though P2P-NET introduces point-wise noise to allow for differences in the feature vectors of similar points, nevertheless the network’s tendency is to always extract similar features for neighboring points. Hence, significant differences are observed in the frontal plane for the predicted postoperative spine shapes by P2P-NET for P1 and P2, and in the sagittal plane for P1.

In the second column, the PDNet results confirm that our simple fully convolutional neural networks can learn transformations between points better than PointNET++. This could be due to the fact that with a limited number of points in the shapes (in our case, $n=108$), the 1D F-CNNs can be trained more efficiently. But the PDNet model still has difficulty learning the large scoliotic deformities in the main thoracic area. When the rigid transformation loss is introduced in the CPDNet_noMeta model, we observe a small improvement in the frontal plane for both patients. With the enhanced loss function, CPDNet_noMeta can learn the translations and rotations between consecutive vertebrae. The predicted postop spine shape by CPDNet_noMeta is closer to the ground truth than PDNet’s for patient P2 in the sagittal plane. Contributing to this outcome is the presence of 23 patients in the training set who underwent surgery with technique S2, like P2. However, the network still needs to learn adequate preop-to-postop deformations based on a smaller number of similar cases in the dataset. The full CPDNet model reaches this goal, as can be seen by the improvement in the thoracolumbar area in the sagittal plane for P1. Despite the small number of patients (seven) who underwent surgery with S1, like P1, exploiting the patient metadata allows the network to learn the surgical correction from those few samples.

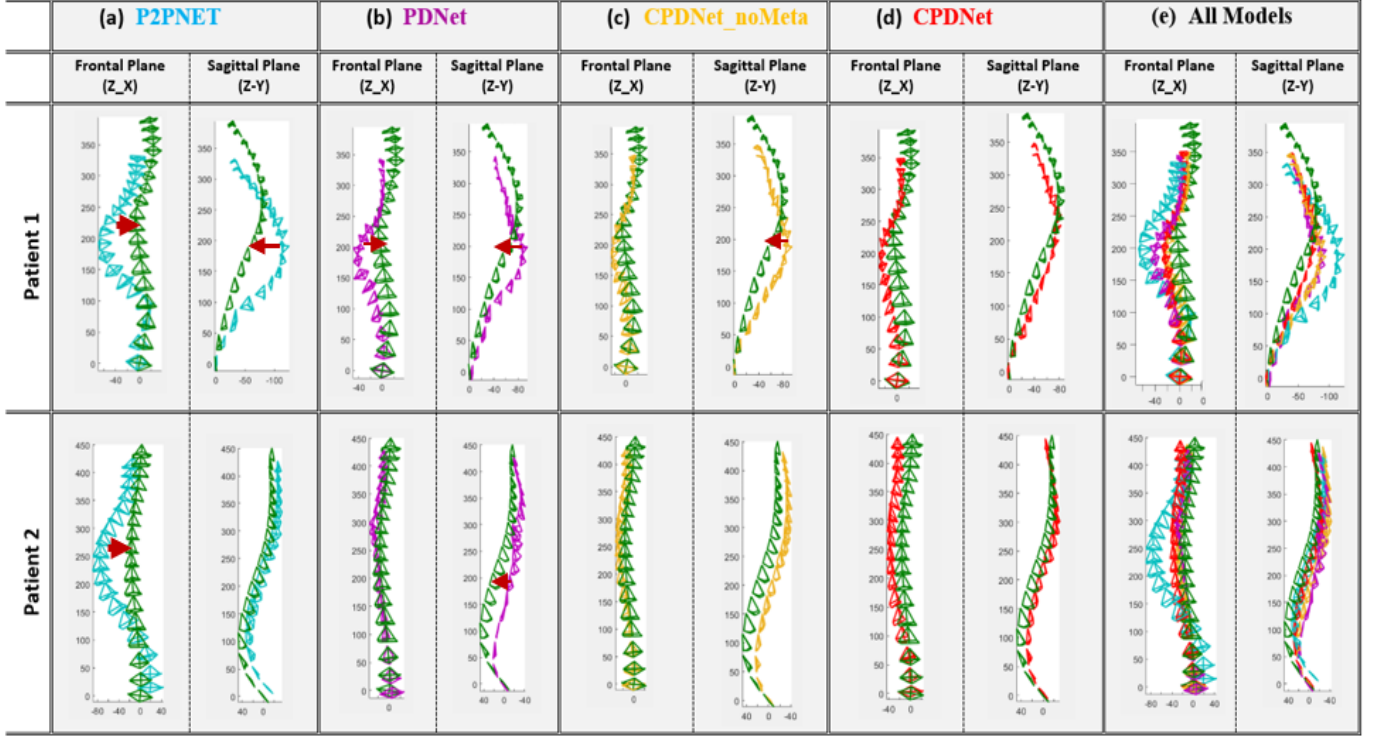


Figure (4.4) Comparison of 3D postoperative spine shapes predicted by the different models, for two patients from the test set. In all cases, the real postop spine shape is shown in green, and each predicted-real pair is displayed in the frontal and sagittal planes. Columns show predictions by (a) P2P-NET; (b) PDNet; (c) proposed CPDNet with no patient metadata; (d) CPDNet with patient metadata. The last column superimposes all the spine models. The red arrows indicate large discrepancies between the predicted and real postop spine shapes for each network.

4.6 Conclusion

We have presented a Controlled Point Deformation Network (CPDNet) as a supervised neural network to predict a patient's spine shape after scoliosis surgery. Our network (CPDNet) leverages intrinsic shape properties in the form of neighborhood constraints between consecutive vertebrae along the spine, to control the deformation of a source configuration toward a target one. We apply this approach to predicting the output spine shape of scoliosis patients undergoing corrective spine surgery. Experimentally, CPDNet predicts the postoperative shapes of previously operated patients in our test set with average accuracies of 1.5° , 7.6° , and 4.9° for the clinical indices of coronal balance and Cobb angle in the sagittal and frontal planes, respectively. Clinically, CPDNet could serve as the basis for developing a surgical planning tool for scoliosis, allowing the surgeon and patient to visualize projected postoperative outcomes based on different surgical techniques.

4.7 Acknowledgments

This work has not been submitted for publication or presentation elsewhere. This work has been funded by the Canadian Institutes of Health Research (CIHR) and the TransMedTech Institute.

CHAPTER 5 ARTICLE 2: AUTOMATIC ASSESSMENT of SCOLIOSIS SURGERY OUTCOME ON TRUNK SHAPE USING LEFT-RIGHT TRUNK ASYMMETRY

Maryam Khani^a, Philippe Debanné^{a, b}, François Guibault^a, Hubert Labelle^b, Stefan Parent^b, Farida Cheriet^{a, b}

^aPolytechnique Montréal, Department of Computer and Software Engineering, P.O. Box 6079, Montréal, H3C 3A7, Québec, Canada

^bSainte Justine Hospital Research Center, 3175, Chemin de la Côte-Sainte-Catherine, Montréal, H3T 1C5, Québec, Canada

Presentation This work was submitted to the journal “European Spine Journal” on July 27, 2023.

5.1 Abstract

Purpose: To present a novel set of Left-Right Trunk Asymmetry (LRTA) indices, and use them to assess the postoperative appearance of the trunk in Adolescent Idiopathic Scoliosis (AIS) patients.

Methods: We hypothesize that LRTA measurements provide complementary information to existing trunk asymmetry indices when documenting the outcome of scoliosis surgery. Forty-nine AIS patients with thoracic curves who underwent posterior spinal fusion were included. All had surface topography scans taken preoperatively and at least six months postoperatively. We documented spinal curvature using radiographic Cobb angles, scoliometer readings and coronal balance. To evaluate Global Trunk Asymmetry (GTA), we used the standard measures of Back Surface Rotation (BSR) and Trunk Lateral Shift (TLS). To measure LRTA, we identified asymmetry areas as regions of significant deviation between the left and right sides of the 3D back surface. New parameters called Deformation Rate (DR) and Maximum Asymmetry (MA) were measured in different regions based on the asymmetry areas. We compared the GTA and LRTA changes with those in spinal curvature before and after surgery.

Results: The GTA indices, mainly TLS, showed improvement for more than 75% of patients.

There was significant improvement of LRTA in the shoulder blades and waist regions (95% and 80% of patients respectively).

Conclusion: We report positive outcomes for LRTA in the majority of patients, specifically in the shoulder blades and waist, even when no reduction of BSR is observed. The proposed indices can evaluate local trunk asymmetries and the degree to which they are improved or worsened after scoliosis surgery.

Keywords: Adolescent Idiopathic Scoliosis (AIS). Global Trunk Asymmetry (GTA). Left-Right Trunk Asymmetry (LRTA). Scoliosis Surgery Outcome. Trunk Shape.

Statements and Declarations: The authors have no competing interests to declare that are relevant to the content of this article.

5.2 Introduction

Adolescent Idiopathic Scoliosis (AIS) is a three-dimensional deformation of the spine leading to asymmetry of external trunk shape [29]. AIS is diagnosed in adolescents aged 10-18 years and can progress rapidly. The external deformations involve trunk imbalance and asymmetries in the shoulders, scapulae, waist, hips, and chest. Severe scoliosis can cause functional problems, e.g. cardiac and pulmonary dysfunction, and backaches [20]. Therefore, a surgical correction becomes necessary to stop progression and improve patients' quality of life [147]. However, persistence of residual trunk asymmetry is frequent and difficult to predict by clinicians, even though correcting the apparent deformity is a major concern for patients [148].

Many studies measured trunk asymmetry at the global level (Global Trunk Asymmetry or GTA) to evaluate trunk deformity [14, 30, 31, 90, 91, 149–151]. Research using surface topography scans documented the deformity in the coronal plane by assessing the back valley line [90] and trunk cross-sections centroid line [91]. Score and index-based methods [149, 150] were proposed, but most of them suffer from poor reproducibility as they require manual identification of landmarks on the back. Also, these works reduce the entire measurement profiles to single values, often the maxima, to indicate deformation severity. To capture local surface deformations, it is important to consider the whole measurement profiles.

Various approaches computed functional asymmetry indices from trunk cross-sections [30, 32, 151]. Multi-level indices were computed in [32] from the Back Surface Rotation (BSR), Trunk Rotation (TR), and coronal and sagittal trunk deviation to assess global changes between two acquisitions. To evaluate Left-Right Trunk Asymmetry (LRTA), [152] reflected a set of fixed surface points around the sagittal plane. As an adaptation to the scoliotic trunk,

[153, 154] first computed a plane of symmetry, then evaluated LRTA by reflecting the 3D back surface points around the plane. This markerless approach visualizes the asymmetry on the whole torso instead of using 2D indices limited to specific areas, although it only provides a qualitative assessment. To analyse surgery outcome, both GTA and LRTA measurements are needed to accurately compare preoperative and postoperative trunk surfaces [140].

The objective of this study is to quantitatively assess the postoperative appearance of the trunk by using a novel set of LRTA indices combined with GTA indices, in a retrospective cohort of surgical AIS patients. We first describe the measurements used, then apply them to trunk surface data to document the outcomes in terms of trunk asymmetry.

5.3 Materials and Methods

Patient Data

We included a total of 49 patients who underwent posterior spinal fusion from 2009 to 2018 at our hospital by one of three orthopaedic surgeons. Inclusion criteria were: Lenke 1A main thoracic curve type, full pre-operative and post-operative trunk acquisitions taken at most 6 months before and at least 6 months after surgery. We also included 26 non-scoliotic subjects to determine a threshold value for the LRTA measurements. Our study protocol was approved by the hospital's Research Ethics Committee. The two groups are summarized in Table 5.1.

Table (5.1) Demographic and radiological information of AIS and non-scoliotic cohorts.

	Scoliotic patients (Number = 49)		Controls (N=26)	
N = 49	Mean $\pm$ Std	Min, Max	Mean $\pm$ Std	Min, Max
Age (years)	15.51 $\pm$ 2.06	11, 19	14.6 $\pm$ 2.01	10.8, 18.0
Height (cm)	161.13 $\pm$ 8.13	143, 178	161.2 $\pm$ 10.8	126.4, 177.4
Weight (kg)	52.12 $\pm$ 7.91	32, 66	52.4 $\pm$ 11.0	21.6, 71.5
Preop thoracic Cobb angle (°)	58.18 $\pm$ 10.37	40, 96	2.9 $\pm$ 4.2	0, 10

Each patient was scanned using a non-invasive optical system with an accuracy of 1.1 mm [84].

Patient-specific trunk geometric models were then reconstructed using an automated method in three steps: pre-processing, registering, and merging the acquired data (Figure 5.1) [155].



(a) System of four 3D optical digitizer to scan the patient. (b) Registering and merging of partial trunk surfaces.

Figure (5.1) 3D reconstruction process to obtain whole trunk shape.

2D Spinal Measurements

We obtained 2D spinal measurements including Cobb angles for the proximal thoracic (Cobb PT), main thoracic (Cobb MT), and thoracolumbar/lumbar (Cobb TLL) spine regions in the frontal plane from each patient's X-rays. In addition, scoliometer values in the thoracic and lumbar regions (Scoliometer_T and Scoliometer_L) and coronal balance (CB) were collected.

Global Trunk Asymmetry Measurements

From each trunk surface model, 300 horizontal cross-sections are extracted between the L5/S1 and C7/T1 levels. Then, GTA measurements, namely BSR, TR and Trunk Lateral Shift (TLS), are computed as in [32]. To provide continuous smooth representations, cubic B-splines are fitted to these measurements.

Left-Right Trunk Asymmetry Measurements

To perform left-right asymmetry analysis, we first identify the best symmetry plane. The latter is defined as the plane that minimizes the distance between the points of the 3D trunk shape (called *original trunk shape*) and its *reflection* [153,154] (see Figure 5.2). Principal Component Analysis is applied to estimate the principal directions of the shape, then compute the symmetry plane. All points of the original shape are reflected to create a new surface on top of the original one.

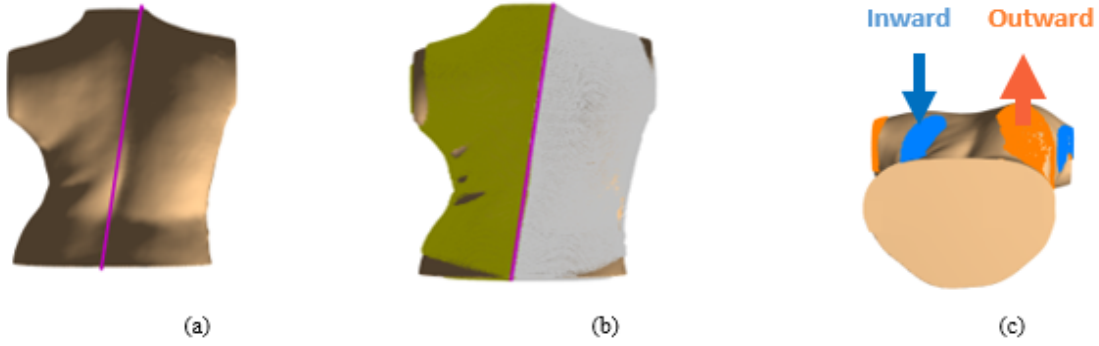


Figure (5.2) Illustration of steps to obtain the distance map, using a depth threshold of 9 mm.

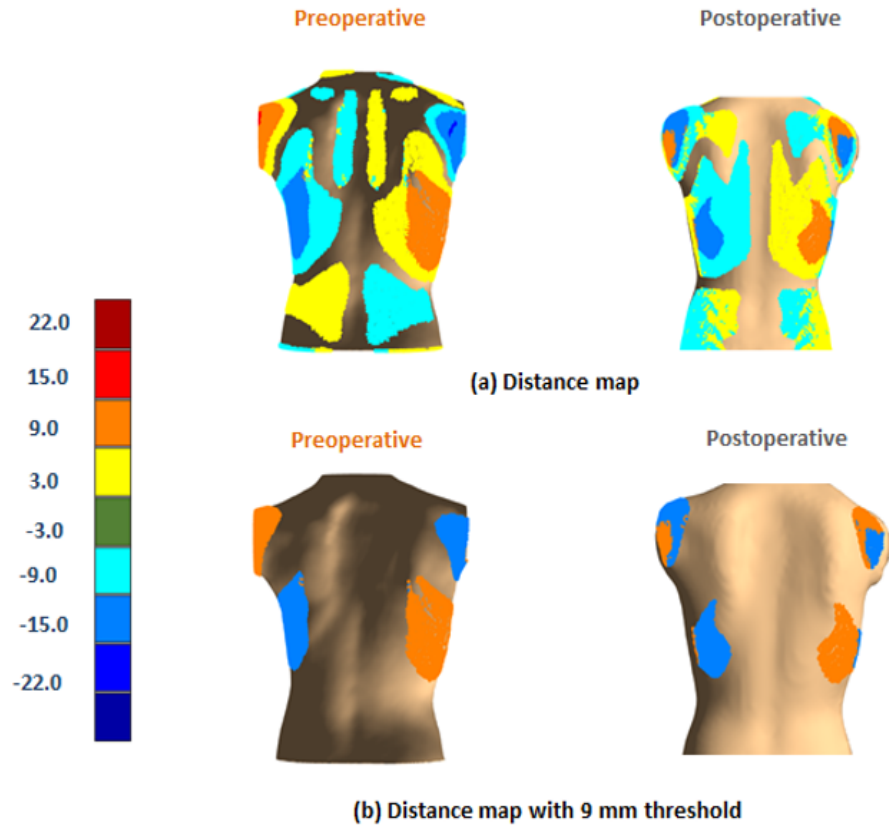


Figure (5.3) Sample of pre- and post-operative distance maps computed for a patient. (a) full distance map with area colours corresponding to depth index at left; (b) LRTA areas when applying depth threshold.

A Computing distance map

To encode the gap between the original trunk shape (O) and its reflection (R), a distance

map is calculated as a set of local deviations. To this end, the k-d tree algorithm is used to find the nearest neighbour to each point from O on R . The deviation between the two points $P_O = (x_O, y_O, z_O)$ and $P_R = (x_R, y_R, z_R)$ is simply the Euclidean distance: $\sqrt{(x_O - x_R)^2 + (y_O - y_R)^2 + (z_O - z_R)^2}$; the value is signed to indicate which surface (O or R) lies outward at that location. Different deviation ranges are visualized using a colourmap to show LRTA areas (see Figure 5.3 (a)).

B Threshold for deviation maps

Because the resolution of the acquisition system is high and the acquired surfaces are noisy, and because non-scoliotic controls can also exhibit some asymmetry, we need to filter the distance maps by setting a significance threshold for the asymmetry data. We examined the range of absolute deviation values for the 26 controls at their initial and six-month monitoring visits. These were compared to thresholds value in the range 3 mm (≤ -3 mm inward and ≥ 3 mm outward) to 15 mm (≤ -15 mm inward and ≥ 15 mm outward) (see Figure 5.4). We selected a distance of 9 mm such that the majority of controls are considered non-scoliotic, while not being too high, thereby providing an adequate compromise between sensitivity and specificity.

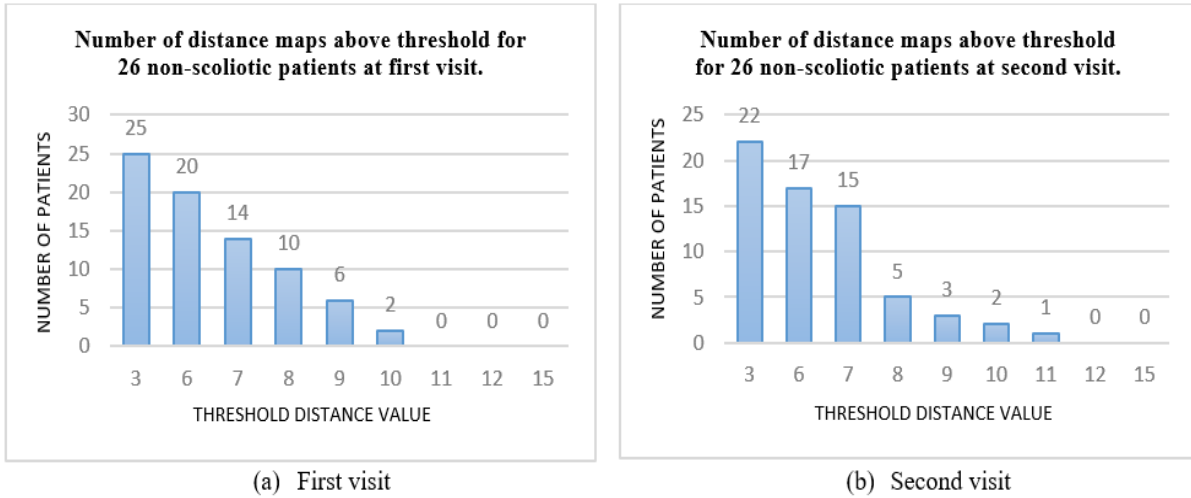


Figure (5.4) Comparison of distance maps of a set of non-scoliotic patients against threshold values in the range [3,15] mm.

C Deformation rate

Asymmetry regions are defined as regions of the back surface where the deviation (outward or inward) between left and right sides is greater than the threshold. In

Figure 5.3 (b), left-right pairs of asymmetry regions are apparent (areas in orange or blue).

We divide the back surface into a set of *slices* delimited by consecutive cross-sections along the trunk. (Note that the density of slices is lower than for computing the GTA measures, as explained below.) We then define the Deformation Rate (DR) **for each slice** as the proportion of 3D surface points belonging to asymmetry regions:

$$\text{Deformation Rate} = \frac{\text{Number of outward and inward 3D points}}{\text{Total number of 3D points}} \quad (5.1)$$

D Quantitative measurement of LRTA

We compute LRTA measurements that reveal the deformity of different areas of the back, from cervical level C6 down to lumbar level L4. This area is divided into 48 consecutive cross-sections, thus 47 slices. This number was determined experimentally to yield surgical outcome results in terms of LRTA most coherent with those from spinal measurements.

We propose the following definitions for specific regions which are of interest to researchers and clinicians. These regions correspond to the different anatomical segments seen in Figure 5.5.

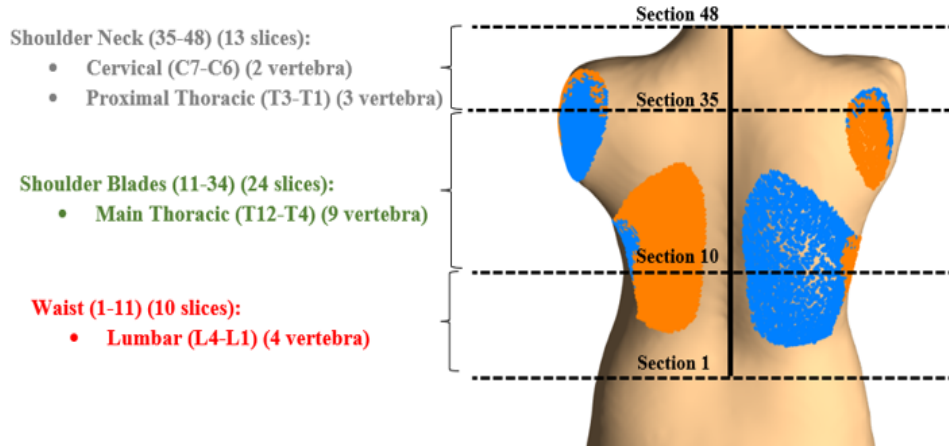


Figure (5.5) Definition of measurement regions spanning the back surface for LRTA indices.

Region Definitions:

- **Waist / Lumbar:** sections 1 to 11, corresponding to vertebral levels L4 to L1;
- **Shoulder Blades / Main Thoracic:** sections 11 to 35 (T12 to T4);

- **Shoulder-Neck / Cervical & Proximal Thoracic (PT):** sections 35s to 48, (T3 to C6).

We now propose the following LRTA measurements for each region:

- **Deformation Rate (DR):**
 - 1) The DR is computed for all slices in the region.
 - 2) The average DR value is also kept.
- **Maximum Deformity (MD):**
 - 1) Defined as the maximum of the DR values over all slices.
- **Maximum Asymmetry (MA):**
 - 1) For each pair of points (P_O , P_R) from O and R with deviation greater than the threshold, three asymmetry measures are computed: **Offset** = $|x_O| - |x_R|$, **Height** = $|y_O| - |y_R|$, and **Depth** = $|z_O| - |z_R|$.
 - 2) The maximum values of Offset, Height, and Depth over all slices are computed as **MA of Offset**, **MA of Height**, and **MA of Depth**.

5.4 Results

A AIS surgical outcome with respect to GTA and LRTA measurements

We compared 2D spinal deformity measurements with 3D trunk deformity measurements by computing GTA and LRTA indices at the preoperative and postoperative visits. To quantify changes in GTA and LRTA, we used the correction rate (CR) proposed by Seoud et al. [29]:

$$CR_{indice}(\%) = 100 \times \frac{\sum |f_{pre}^{index}(t)| - \sum |f_{post}^{index}(t)|}{\sum |f_{pre}^{index}(t)|} \quad (5.2)$$

where f_{pre}^{index} and f_{post}^{index} refer to the preoperative and postoperative functional measurements of a given index. The latter can be the BSR, TR, TLS, or any of the LRTA measurements computed on individual slices. Similarly, a correction rate is defined for single measurements (Cobb angle, scoliometer, and coronal balance):

$$CR_{Cobb}(\%) = 100 \times \frac{Cobb_{pre} - Cobb_{post}}{Cobb_{pre}} \quad (5.3)$$

A positive (resp. negative) value of CR indicates an improvement (resp. worsening) of the deformity after surgery.

In Table 5.2, three clusters are identified: (1) Decreased; (2) Stable; (3) Increased deformity. At the 6-month follow-up, the Cobb MT of all 49 patients has decreased. For a majority of patients, the Cobb PT and TLL also decreased. The GTA parameters likewise decreased for most patients, but increased for several patients. For the LRTA, for most patients the DR increased in shoulder-neck, but decreased for most patients in the shoulder blades and waist.

Figure 5.6 displays violin plots for spinal, GTA and LRTA corrections. The distributions of all Cobb angles decreased significantly. Among the GTA and LRTA corrections, TLS, DR waist and DR shoulder blades decreased, while DR shoulder-neck increased slightly.

Table (5.2) Numbers of patients for each outcome based on Cobb angles, GTA and LRTA measurements.

Measurements	Decreased (CR>0)	Stable (CR 0)	Increased (CR<0)
Radiographic Cobb			
Cobb PT	34	15	0
Cobb MT	49	0	0
Cobb TLL	41	8	0
Global Trunk Asymmetry (GTA)			
BSR	37	1	11
TR	39	1	9
TLS	43	0	6
Left-Right Trunk Asymmetry (LRTA)			
DR in Shoulder-Neck (DRSN)	19	0	30
DR in Shoulder Blades (DRSB)	47	0	2
DR in Waist (DRW)	39	9	1

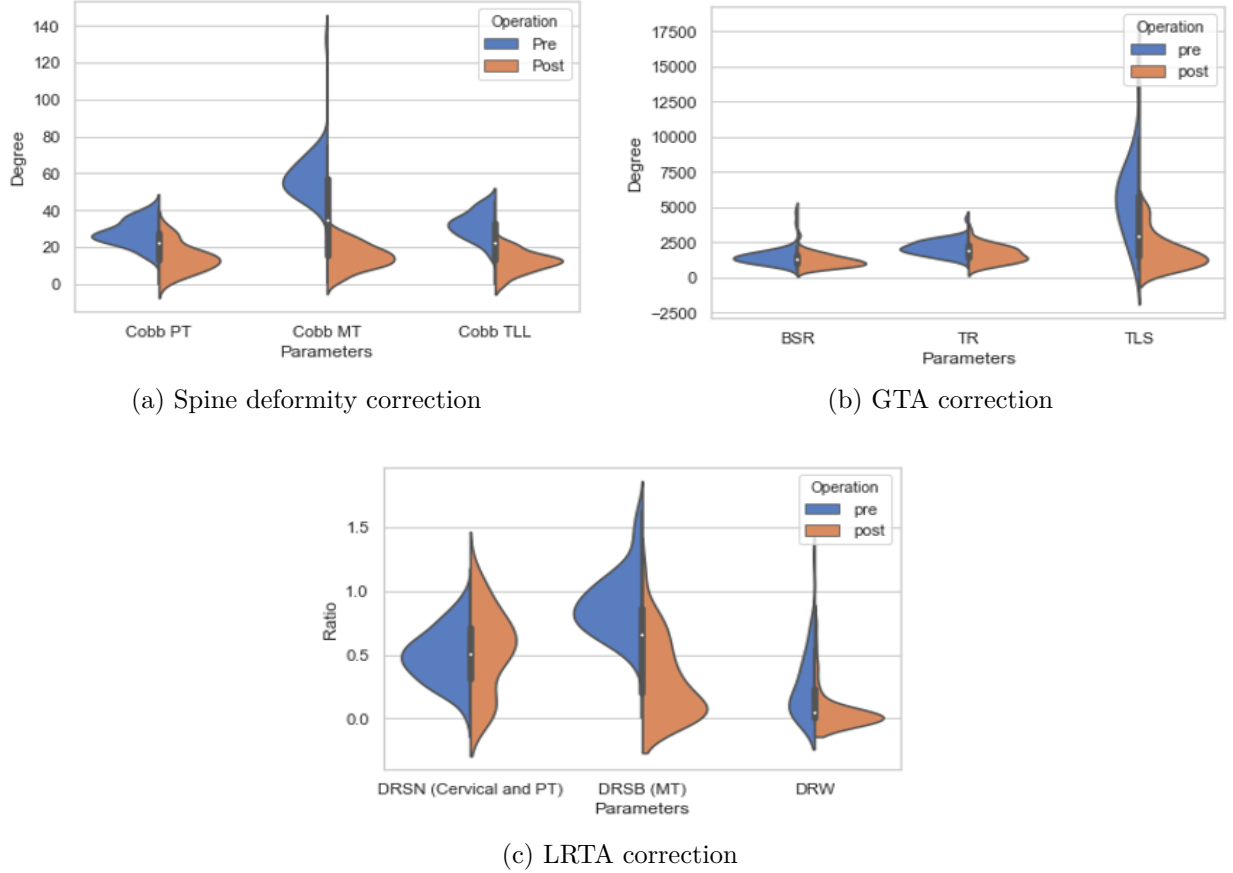


Figure (5.6) Violin plots showing spinal, GTA, and LRTA corrections preoperatively (blue) and postoperatively (orange).

B GTA and LRTA: two example cases

We selected two patients to evaluate changes in their GTA and LRTA measurements. Figure 5.7 and Figure 5.8 show the surgery outcome for the two exemplars. The first patient exhibits good trunk correction. The 3D trunk surface illustrates an improvement of more than 50% in CR of DR for shoulder blades and waist. Moreover, the BSR and TR curves decrease substantially (see functional plots and angular ranges at bottom of Figure 5.7). By contrast, the second patient reveals poor GTA correction. In this case, the BSR and TR functional curves both increase in postop. The 3D trunk surface shows an improvement of less than 50% of DR in all regions.

The LRTA corrections are illustrated in Figure 5.8 as superimposed deformation maps from the preop (light grey) and postop (dark grey) trunk shapes for the three regions. These plots display a decrease in size of the asymmetry areas from pre- to post-operative in all regions

and for both cases. Thus, although the 2nd patient exhibits poor asymmetry correction in terms of GTA, the LRTA assessment indicates satisfactory surgical outcome.

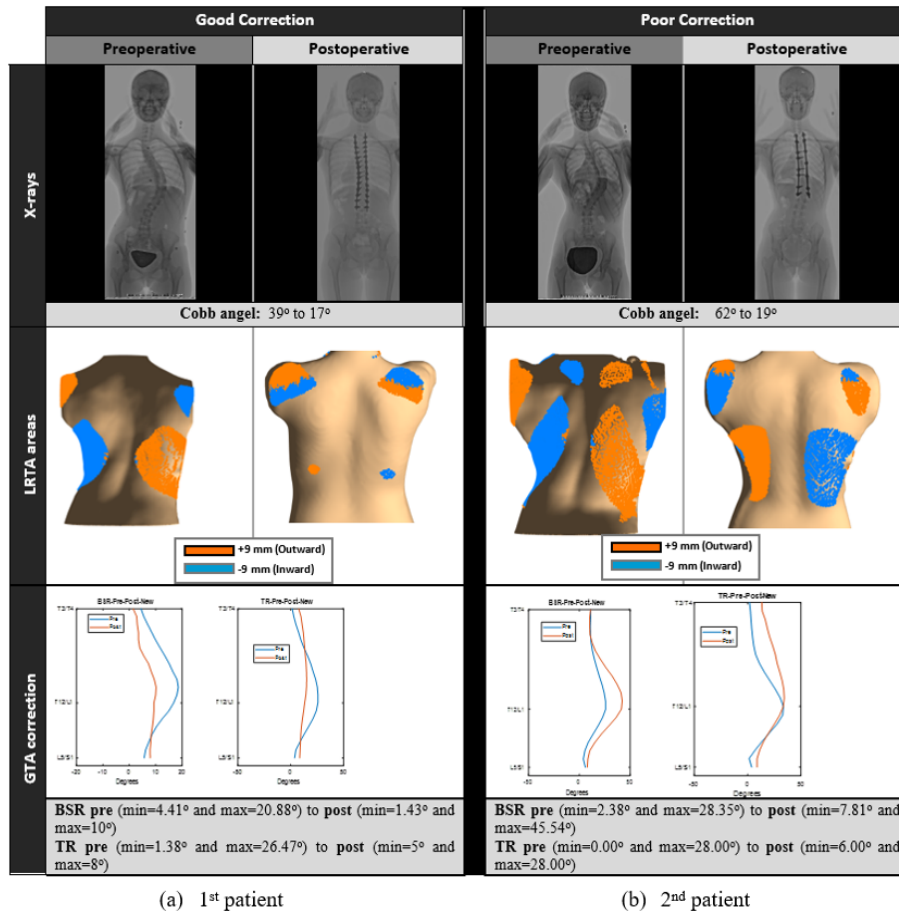


Figure (5.7) X-rays, depth maps, and GTA measurements (BSR and TR) of two selected patients: (a) good correction for GTA; (b) poor correction for GTA.

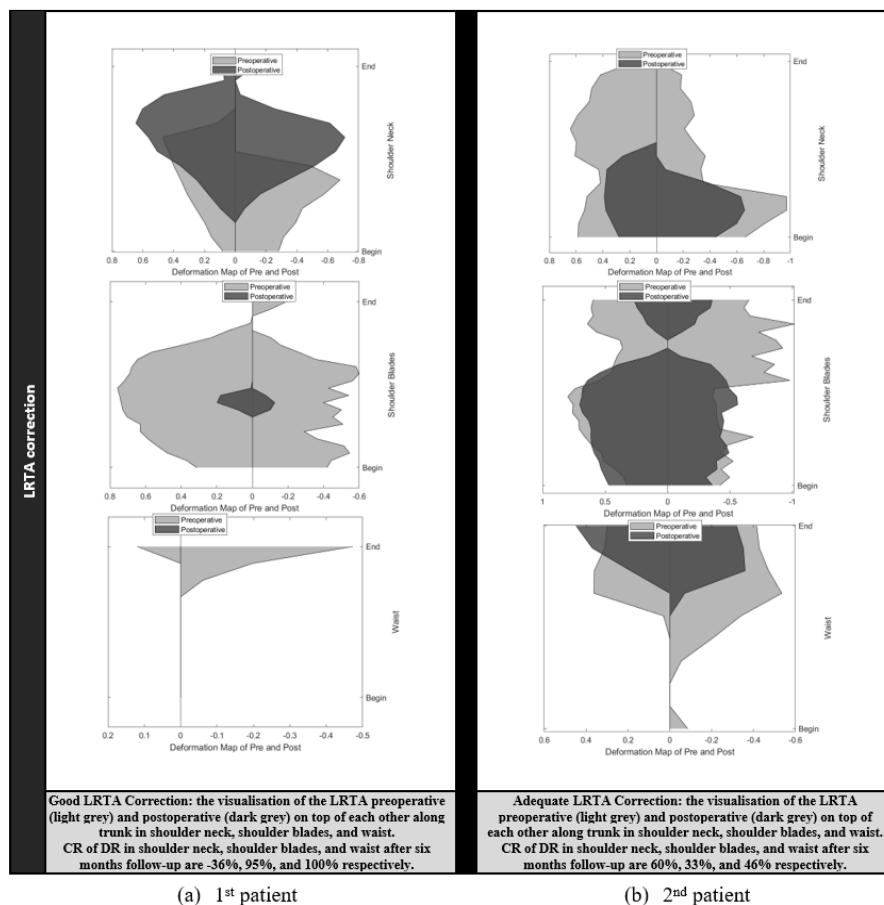


Figure (5.8) LRTA corrections (DR) of two selected patients: (a) good correction for LRTA; (b) satisfactory for LRTA.

5.5 Discussion

Standard spinal deformity measurements indicate good surgical correction in the MT region, while the PT and TLL Cobb angles improved for most patients but remained stable in some cases. This is as expected given that the main focus of surgery is to correct spinal deformity, and the main thoracic curvatures in our Lenke 1A cohort were all well corrected.

By contrast, the outcomes in terms of trunk deformity are mixed. Indeed, all three GTA indices increased (deteriorated) for significant subsets of the patients (22%, 16% and 12% of patients for BSR, TR and TLS respectively). However, the LRTA measurements provide a more nuanced picture. In the shoulder-neck region, the DR increased for 61% of patients, but in the other two regions, the DR decreased for the vast majority (at least 80%). Thus, existing trunk asymmetry indices (BSR, TR and TLS) don't offer a complete assessment of surgical outcome. The proposed LRTA measurements allow clinicians to document more

precisely the locations where external asymmetries were corrected (or not), and to what extent.

This is illustrated by the two exemplars. For the first patient, the GTA and LRTA measures are largely in agreement. But for the second patient, despite the worsening of GTA implied by the BSR and TR functional curves, the depth maps show that in fact the asymmetry areas have diminished in the shoulders-neck and waist, and diminished somewhat in the shoulder blades.

Our findings are generally consistent with the previous study in [29]. In a similar cohort of Lenke 1A AIS patients, the authors also found that despite good spinal curvature reduction evidenced by radiographic measures and TLS, reduction of BSR was much less pronounced. This emphasizes both the difficulty in achieving good asymmetry correction in the transverse plane, and the importance of documenting treatment outcome with regard to external asymmetry.

5.6 Conclusion

We have proposed a novel set of left-right trunk asymmetry (LRTA) measurements and employed them to document the outcome of spinal surgery in a retrospective cohort of scoliosis patients. We report positive outcomes for LRTA in the majority of patients, specifically in the shoulder blades and waist regions, even when no reduction of back surface rotation is observed. The proposed method is useful to measure the effect of scoliosis surgery on local regions of the trunk. As future work, we will analyse patient self-assessment questionnaires using the LRTA measurements. This will allow surgeons to quantify the aspects of trunk appearance of most concern to patients and how the actual surgical results compare with patients' perceptions and expectations.

5.7 Acknowledgments

This work was funded by the Canadian Institutes of Health Research (CIHR) and the Trans-MedTech Institute. The authors thank the personnel of the Orthopaedics Research Clinical Unit (URCO, CHU Sainte-Justine) for their help with collecting clinical data. The authors have no competing interests to declare that are relevant to the content of this article.

CHAPTER 6 ANALYSING THE RELATIONSHIP BETWEEN 3D TRUNK MEASUREMENTS AND SATISFACTION AND EXPECTATION OF THE SCOLIOTIC PATIENTS

6.1 Introduction

The Spinal Appearance Questionnaire (SAQ) and the Scoliosis Research Society (SRS) questionnaires are two frequently utilized patient-reported outcome measures. These questionnaires are often used to assess patients' perceptions and experiences related to their spinal appearance and scoliosis, respectively. The SAQ questionnaire requires patients to choose from a set of drawings that depict various aspects of their body image, such as rib prominence, body curve, and shoulder asymmetry. Additionally, it includes supplementary questions regarding self-image satisfaction and expectations. On the other hand, the SRS questionnaire involves questions about the patient's pain levels, physical activity, and mental health. A total score is calculated based on the patient's responses, which serve as an indicator of their overall quality of life.

Due to the significance of patient-reported outcomes, many efforts have been made to develop objective measures that can assess the health-related quality of life of patients [156]. It is important for clinicians to evaluate the satisfaction of patients and parents regarding the appearance of the patient's trunk, pain levels, self-image, functionality, and mental health following scoliosis surgery. This assessment is an essential part of ensuring the success of the surgery and the overall health and well-being of the patient. Considering the preoperative mental health, pain, and expectations of both patients and their parents would be beneficial in enhancing the outcome of Adolescent Idiopathic Scoliosis (AIS) surgery and optimizing their satisfaction. This approach can potentially improve the overall experience of the surgery for the patients and their parents, leading to better outcomes and overall well-being. Therefore, evaluating postoperative trunk asymmetry deformities using questionnaires is used to document the surgical outcome based on the perception of the patients and their parents.

It is important to document the level of satisfaction and expectation of both patients and their parents about the outcome of the surgery. Based on our knowledge, there is no study revealing the level of satisfaction and expectation of the patients and their parents through determining the association between each question in both SAQ and SRS with the spine and 3D trunk measurements including metrics that can detect local deformities. In order to establish the association between each item in the SAQ and SRS questionnaires with these measurements, a more comprehensive set of 3D trunk measurements is required. These measurements should

be able of calculating global trunk asymmetries (like back surface rotation) and the left right trunk asymmetries in specific areas (such as the shoulders). Therefore, detecting left-right trunk asymmetry would be beneficial to evaluate the patient and parent's satisfaction and expectation from SAQ and SRS questionnaires as well as to assess the outcome of the scoliosis surgery automatically using reliable indices. This motivated us to conduct an analysis of both patient and parent self-assessment questionnaires (SAQ) and Scoliosis Research Society (SRS) scores, along with 3D trunk measurements which compute both global deformities and left-right trunk asymmetries in local regions.

The objective of this study is to analyze the existing questionnaires SAQ and SRS using spine and 3D trunk measurements to highlight which aspects of trunk appearance are more important for patients and their parents. This analysis can be used as a diagnostic tool in support to provide better treatment for new patients. If a patient underestimates the deformity of their back surface, it means that she/he is more concerned about her/his trunk appearance in a specific region, so clinicians should try to address this specific concern in the treatment.

6.1.1 Questionnaires

1. SAQ

Sanders *et al.* [92] have proposed SAQ based on the Walter Read Visual Assessment Scale. The SAQ reflects the expectation of the patients and their parents including two sections with a total of 19 and 20 questions to be answered by patients and their parents respectively: 1) drawing questions showing the severity levels of different components of the spinal deformity; 2) texting questions scoring the dissatisfaction with other spinal deformity components. The SAQ is more related to the self-perceived images domain by asking questions about general (three questions), curve (two questions), prominence (two questions), trunk shift (two questions), waist (three questions), shoulders (two questions), kyphosis (one questions), and chest (two questions). Figure 6.1 illustrates the first section of the questionnaire of SAQ including the drawing questions from questions 1 to 7 which will be analyzed in this chapter. In addition, Figure 6.2 illustrates the second section of the questionnaire of SAQ including one drawing question and 11 text questions from questions 9 to 17.

STATUSSM OUTCOMES ASSESSMENT SYSTEM Spinal Appearance Questionnaire V1.1 WRSVA used with permission of David Polly, MD. <i>Patient's Evaluation of Body Shape</i> Directions: Answer questions by filling in the correct circle or writing in the information. If you need to change an answer, completely erase the incorrect mark and fill in the correct information. Mark only one answer for each question. Please do not mark outside of the circle or make stray marks on the form. Today's Date (MM/DD/YY) Shade circles like this: Not like this: <table style="border-collapse: collapse; text-align: center;"> <tr><td style="border: 1px solid black; width: 20px;">3</td><td style="border: 1px solid black; width: 20px;">5</td><td style="border: 1px solid black; width: 20px;">7</td></tr> <tr><td style="border: 1px solid black; width: 20px;">3</td><td style="border: 1px solid black; width: 20px;">5</td><td style="border: 1px solid black; width: 20px;">7</td></tr> </table> For best results, please avoid contact with the outline of boxes.	3	5	7	3	5	7	(For Internal Use Only) Identification Number Event
3	5	7					
3	5	7					

Please look carefully at the following statements and pictures. Please shade the circle that best describes your condition.

01. Body curve (Mark only one)

02. Rib prominence (bump) (Mark only one)

03. Flank prominence (bump) (Mark only one)

04. Head chest hips (Mark only one)

05. Position of head over hips (Mark only one)

06. Shoulder level (Mark only one)

07. Spine prominence (bump) (Mark only one)

Please continue on next page

© 2006 Medtronic Sofamor Danek
All Rights Reserved

0725 -

Draft

-1 of 2-

Figure (6.1) SAQ: section one

PhDx ID: _____

08. Please pick one category that bothers you the most out of these 5 categories of images.

Rib prominence

Flank prominence

Head chest hips

Shoulder level

Spine prominence











Not true

A little true

Somewhat true

Fairly true

Very true

09. I want to be more even.

☐

☐

☐

☐

☐

10. I want to look better in clothes.

☐

☐

☐

☐

☐

11. I want to have more even hips.

☐

☐

☐

☐

☐

12. I want to have a more even waist.

☐

☐

☐

☐

☐

13. I want to have more even leg length.

☐

☐

☐

☐

☐

14. I want to have more even breasts.

☐

☐

☐

☐

☐

15. I want to have a more even chest in the front.

☐

☐

☐

☐

☐

16. I want to have more even shoulders.

☐

☐

☐

☐

☐

17. I am self conscious about my spine surgery scar.
(Answer this only if you have had spine surgery)

☐

☐

☐

☐

☐

Very bad

Bad

Fair

Good

Very good

18. How would you rate your self image?

☐

☐

☐

☐

☐

19. What would you most like to change about your body's shape and why?

0725 -

Draft



-2 of 2-

Figure (6.2) SAQ: section two

2. SRS

Haider *et al.* [93] have proposed SRS questionnaire as a practical instrument to assess the outcome of spinal surgery and health-related quality of life for AIS patients. The SRS questionnaire reflects the patient's perspective about his or her spinal surgery and satisfaction covering five domains including Pain (five questions), Self-perceived images (five questions), Function (five questions), Mental Health (five questions), and Satisfaction with Management (two questions). Figure 6.3 and Figure 6.4 show the questions of SRS including questions about pain, self-perceived, function, mental health, and satisfaction with management before surgery by questions from 1 to 23 and after surgery from 24 to 30.

Scoliosis Patient Questionnaire:
Version 30 (Encompasses Versions 22 and 24)

Modified 11/12/03

Patient Name: _____		Age: _____		Date: _____	
Medical Record # _____		SS: _____			
Exam:	Pre-treatment	3 mos.	6 mos.	1 year	_____ years

Your doctors are carefully evaluating the condition of your back before and after your treatment. Please circle the one best answer to each question unless otherwise indicated. If you already have had surgery, please complete sections 1 and 2. Otherwise, just complete section 1.

All results will be kept confidential.

Section 1: All patients

1. Which one of the following best describes the amount of pain you have experienced during the past 6 months? ☐ None ☐ Moderate to severe ☐ Mild ☐ Severe ☐ Moderate 2. Which one of the following best describes the amount of pain you have experienced over the last month? ☐ None ☐ Moderate to severe ☐ Mild ☐ Severe ☐ Moderate 3. During the past 6 months have you been a very nervous person? ☐ None of the time ☐ Most of the time ☐ A little of the time ☐ All of the time ☐ Some of the time 4. If you had to spend the rest of your life with your back shape as it is right now, how would you feel about it? ☐ Very happy ☐ Somewhat unhappy ☐ Somewhat happy ☐ Very unhappy ☐ Neither happy nor unhappy 5. What is your current level of activity? ☐ Bedridden/wheelchair ☐ Primarily no activity ☐ Light labor, such as household chores ☐ Moderate manual labor and moderate sports, such as walking and biking ☐ Full activities without restriction 6. How do you look in clothes? ☐ Very good ☐ Good ☐ Fair ☐ Bad ☐ Very bad	7. In the past 6 months have you felt so down in the dumps that nothing could cheer you up? ☐ Very often ☐ Rarely ☐ Often ☐ Never ☐ Sometimes 8. Do you experience back pain when at rest? ☐ Very often ☐ Rarely ☐ Often ☐ Never ☐ Sometimes 9. What is your current level of work/school activity? ☐ 100% normal ☐ 25% normal ☐ 75% normal ☐ 0% normal ☐ 50% normal 10. Which of the following best describes the appearance of your trunk; defined as the human body except for the head and extremities? ☐ Very good ☐ Poor ☐ Good ☐ Very poor ☐ Fair 11. Which one of the following best describes your medication usage for your back? ☐ None ☐ Non-narcotics weekly or less (e.g., Tylenol, Ibuprofen) ☐ Non-narcotics daily ☐ Narcotics weekly or less (e.g., Percocet, Lorcet, Codeine, Darvocet) ☐ Narcotics daily ☐ Other (please specify below) Medication: _____ Usage (weekly or less or daily): _____
--	--

Figure (6.3) SRS: section one

12. Does your back limit your ability to do things around the house?
☐ Never ☐ Often
☐ Rarely ☐ Very often
☐ Sometimes
13. Have you felt calm and peaceful during the past 6 months?
☐ All of the time ☐ A little of the time
☐ Most of the time ☐ None of the time
☐ Some of the time
14. Do you feel that your back condition affects your personal relationships?
☐ None ☐ Moderately
☐ Slightly ☐ Severely
☐ Mildly
15. Are you and/or your family experiencing financial difficulties because of your back?
☐ Severely ☐ Slightly
☐ Moderately ☐ None
☐ Mildly
16. In the past 6 months have you felt down-hearted and blue?
☐ Never ☐ Often
☐ Rarely ☐ Very often
☐ Sometimes
17. In the last 3 months have you taken any sick days from work/school due to back pain and, if so, how many?
☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 or more
18. Do you go out more or less than your friends?
☐ Much more ☐ Less
☐ More ☐ Much less
☐ Same
19. Do you feel attractive with your current back condition?
☐ Yes, very ☐ No, not very much
☐ Yes, somewhat ☐ No, not at all
☐ Neither attractive nor unattractive
20. Have you been a happy person during the past 6 months?
☐ None of the time ☐ Most of the time
☐ A little of the time ☐ All of the time
☐ Some of the time
21. Are you satisfied with the results of your back management?
☐ Very satisfied ☐ Unsatisfied
☐ Satisfied ☐ Very unsatisfied
☐ Neither satisfied nor unsatisfied
22. Would you have the same management again if you had the same condition?
☐ Definitely yes ☐ Probably not
☐ Probably yes ☐ Definitely not
☐ Not sure
23. On a scale of 1 to 9, with 1 being very low and 9 being extremely high, how would you rate your self-image?
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9

Section 2: Post-surgery patients only

24. Compared with before treatment, how do you feel you now look?
☐ Much better ☐ Worse
☐ Better ☐ Much worse
☐ Same
25. Has your back treatment changed your function and daily activity?
☐ Increased ☐ Not changed ☐ Decreased
26. Has your back treatment changed your ability to enjoy sports/hobbies?
☐ Increased ☐ Not changed ☐ Decreased
27. Has your back treatment _____ your back pain?
☐ Increased ☐ Not changed ☐ Decreased
28. Has your treatment changed your confidence in personal relationships with others?
☐ Increased ☐ Not changed ☐ Decreased
29. Has your treatment changed the way others view you?
☐ Much better ☐ Worse
☐ Better ☐ Much worse
☐ Same
30. Has your treatment changed your self-image?
☐ Increased ☐ Not changed ☐ Decreased

Figure (6.4) SRS: section two

6.1.2 Patient Data

We collected the results of questionnaires of 100 AIS adolescent patients with Lenke 1A curve who underwent a posterior spinal fusion (PSF) from 2009 to 2018 at Sainte-Justine University Hospital Center, Montreal, Canada, by one of three orthopedic surgeons. These data have been collected under the approved study protocol by the hospital's Research Ethics Committee. We collected the existing questionnaires of SAQ, and SRS of the patients and their parents. In addition of the questionnaires, we collected clinical data of patients. A total of 55 patients of the 100 patients, who satisfied the criteria including a Lenke 1A main thoracic curve type, full pre-operative and post-operative trunk acquisition taken respectively at least two years after surgery, were included in this study.

A mesh of the whole trunk surfaces is built by obtaining pre-operative and post-operative trunk acquisitions and reconstructed by using a non-invasive optical system (Four Inspeck digitizers described in the chapter 2 in the section of assessment of the trunk shape (see Figure 2.11)). We analyzed the medical records, 3D trunk acquisition and spinal radiographs, and 3D trunk measurements of the AIS cases with spinal surgery. The selected cohort were females in the range of 10 to 21 years with a range Cobb angles 24° to 86° before surgery which has decreased to the range of 0° to 31° after surgery. Demographic and radiological characteristics of the selected cohort are summarized in Table 6.1.

Table (6.1) Demographic and Radiological Information of Selected Cohort

Number=55	Mean $\pm$Std	Range of Values
Age (year)	14 ± 2.4	10 to 21
Height (cm)	155.6 ± 16.7	49.7 to 173.9
Weight (kg)	53.27 ± 19.80	30 to 165.7
Pre-op Cobb (deg)	51.67 ± 11.67	24 to 86
Post-op Cobb (deg)	14.32 ± 7.8	0 to 31
BMI	20.0 ± 3.8	14.06 to 34.2

6.1.3 3D Trunk Measurements

In this study, we computed the 3D trunk measurements BSR, Coronal Lateral Shift, and Coronal Balance based on the proposed method in [29] and we computed the LRTA measurements to assess deformities in local regions such as deformities in shoulders based on the proposed new indices in the previous objective. Also, we computed the Cobb angle as the

spinal measurement using the radiographic images. Moreover, we computed the correlation between the Correction Rates (CRs) of 3D measurements and 2D clinical measurements between preoperative and postoperative values for our cohort to confirm that these 3D indices are related to the 2D clinical measurements (see Table 6.2).

Table (6.2) The correlation between the Correction Rates (CRs) of 3D trunk measurements (BSR, Coronal Lateral Shift, Coronal Balance, and Shoulder Level) and 2D spine measurements (Scoliometer T, Scoliometer L, Cobb PT, Cobb MT, Cobb TLL) are computed. The correlation values bigger than 0.20 are highlighted.

	$CR_{Scoliometer\ T}$	$CR_{Scoliometer\ L}$	$CR_{Cobb\ PT}$	$CR_{Cobb\ MT}$	$CR_{Cobb\ TLL}$
$CR_{BSR(Lumbar)}$	0.03	0.20	0.29	0.20	0.30
$CR_{Coronal\ Lateral\ Shift}$	-0.05	0.27	0.28	0.50	0.35
$CR_{Coronal\ Balance}$	-0.08	0.27	-0.08	-0.05	-0.03
$CR_{Shoulder\ Level}$	-0.22	0.18	0.24	0.17	0.28

6.1.4 Finding Association Between Questionnaires and Trunk Measurements

Before analyzing questionnaires, the relation between each question of questionnaires and each measurement should be found. Table 6.3 and Figure 6.6 show the result of the agreement with an expert in public health domain about the relation between each question of SAQ and SRS with spine and 3D trunk measurements. As the Table 6.3 shows, each question of SAQ is associated with one trunk measurement and questions of each domain of SRS is associated with a group of trunk measurements including Cobb angle, Coronal Lateral Shift (CLS), Coronal Balance (CB), Shoulder Level (ShL), and BSR (thoracic, thoracic lumbar and lumbar).

The association between questions of each questionnaire and those measurements are described bellow:

1. Association between SAQ and Spine and Trunk Measurements

- **Association between Cobb angle and Q1:**

Q1 draws the body curve in the coronal plane which can be associated with the Cobb angle showing the degree of curvature in the coronal plane [15,16].

- **Association among BSR (Thoracic), BSR (Thoracic Lumbar), and BSR (Thoracic, Thoracic Lumbar, lumbar) with Q2, Q3, and Q7 respectively.**

Q2, Q3, and Q7 draw the rib prominence in the thoracic region, flank prominence in the thoracic lumbar region, and spine prominence along the trunk respectively which can be associated with the BSR curve in the different regions along the trunk based on the definition of BSR [29]. Figure 6.5 illustrates calculating the BSR for one cross-section along the trunk. Therefore, the curve of BSR (Back Surface Rotation) can reflect the spine prominence along the trunk. The sub-curve of BSR calculated from a group of sub-sections in the thoracic region of the trunk can be considered as rib prominence and the thoracic lumbar region of the trunk can reflect the flank prominence.

- **Association between Coronal Lateral Shift and Q4**

Q4 draws the deviation along the head, chest, and hips which can be associated with Coronal Lateral Shift based on the definition of Trunk Lateral Deviation in the coronal plane [29]. Figure 6.5 illustrates calculating the TLS for one cross-section which in the coronal plane along the trunk shows the Coronal Lateral Shift. Since the Coronal Lateral Shift curve is calculated from the cross-section centers along the trunk, it can reflect the deviation between the head, chest, and hips.

- **Association between Coronal Balance and Q5**

Q5 draws the position of the head over the hips which can be associated with Coronal Balance. Based on the definition of Coronal Balance, it measures the positioning of the upper spine with respect to the midline, determining if it is correctly aligned or shifted to one side. Therefore, Coronal Balance can reflect the alignment of the head over the hips.

- **Association between Shoulder Level and Q6**

Q6 draws the shoulder level showing one shoulder being higher than the other shoulder which can be associated with our proposed Maximum Asymmetry of Height in shoulder-neck. Height of Asymmetry is computed for cross-sections in the local region of shoulder-neck then the maximum height over all those cross-sections is computed (see Chapter 5) which can reflect the shoulder level.

2. Association between SRS and Spine and Trunk Measurements

- **Association between Cobb angle, CLS, CB, ShL, BSR and Function Activity**

The first subgroup of questions ask about the level of patient's activities such as work/sport activities and how their back limit affect their daily activities such as

going out, enjoying sports and hobbies. Function Activity Domain includes questions 5, 9, 12, 18, 25, and 26 which each question could be associated with Cobb angle, CLS, CB, ShL, and BSR. Therefore, we analyzed all those measurements.

- **Association between Cobb angle, CLS, CB, ShL, BSR and Pain Domain**

The second subgroup of questions ask about the amount of pain that patients have experienced during last month, three-months and last six-months even during the rest time. Also, questions regarding the medication usage which can reflect the amount of pain. The Pain Domain comprises questions 1, 2, 8, 11, 17, and 27. Each of these questions can be associated to measurements such as Cobb angle, CLS, CB, ShL, and BSR. As a result, we examined all of these measurements.

- **Association between Cobb angle, CLS, CB, ShL, BSR and Self-image Domain**

The third subgroup of questions ask about the feeling of patients about their back shape such as looking in cloths, living with this situation. Also, asking about how the patients describe the appearance of their trunk and it's effect on their personal relationships. Then, they are asked about how their treatment changed their confidence, self-image and the way others view them. The set of questions in the Self-image Domain includes items 4, 6, 10, 14, 15, 19, 23, 28, 29, and 30. The same as other domains, each of these questions can be associated with measurements like Cobb angle, CLS, CB, ShL, and BSR. Consequently, we conducted an analysis of all these measurements.

- **Association between Cobb angle, CLS, CB, ShL, BSR and Mental Health Domain**

The fourth subgroup of questions ask about their feeling about the life, their happiest or have felt down hearted, have felt calm during last six-months. Mental Health Domain comprises questions 3, 7, 13, 16, and 20. Each of these questions can be associated with measurements such as Cobb angle, CLS, CB, ShL, and BSR. As a result, we performed an analysis of these measurements.

- **Association between Cobb angle, CLS, CB, ShL, BSR and Satisfaction Domain**

The fifth subgroup of questions ask the level of satisfaction of the patients about the results of back management. Also, what is their feeling about their post back shape comparing with pre back shape. Satisfaction Domain includes questions 21, 22, and 24 which each question again could be associated with Cobb angle, CLS, CB, ShL, and BSR and we analyzed all those measurements.

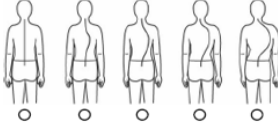
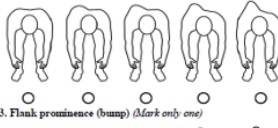
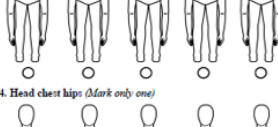
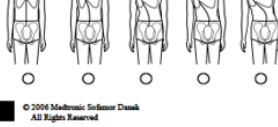
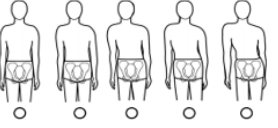
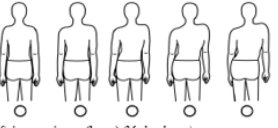
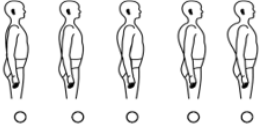
STATUS™ OUTCOMES ASSESSMENT SYSTEM
Spinal Appearance Questionnaire V1.1
WISPA used with permission of David Polly, MD.

Patient's Evaluation of Body Shape

Directions: Answer questions by filling in the correct circle or writing in the information. If you need to change an answer, completely erase the incorrect mark and fill in the correct information. Mark only one answer for each question. Please do not mark outside of the circle or make stray marks on the form.

Today's Date (MM/DD/YY) / / Shade circles like this: ☒ ☐ ☐ ☐ ☐ For best results, please avoid contact with the outline of boxes. Not like this: ☐ ☐ ☐ ☐ ☐

Please look carefully at the following statements and pictures. Please shade the circle that best describes your condition.

Cobb angle → 01. Body curve (Mark only one)  02. Rib prominence (bump) (Mark only one)  03. Flank prominence (bump) (Mark only one)  04. Head chest hips (Mark only one) 	05. Position of head over hips (Mark only one)  06. Shoulder level (Mark only one)  07. Spine prominence (bump) (Mark only one) 	→ Coronal Balance → Shoulder Level → BSR (Thoracic, Thoracic Lumber, Lumber)
---	---	--

Please continue on next page

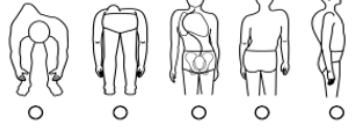
© 2004 Medtronic Sofamor Danek
All Rights Reserved

0725 Draft

-1 of 2-

3D Trunk Shape with Local Trunk Asymmetry Areas → 08. Please pick one category that bothers you the most out of these 5 categories of images.

Rib prominence Flank prominence Head chest hips Shoulder level Spine prominence



Sentences can be Changed

	Not true	A little true	Somewhat true	Fairly true	Very true
09. I want to be more even.	☐	☐	☐	☐	☐
10. I want to look better in clothes.	☐	☐	☐	☐	☐
11. I want to have more even hips.	☐	☐	☐	☐	☐
12. I want to have a more even waist.	☐	☐	☐	☐	☐
13. I want to have more even leg length.	☐	☐	☐	☐	☐
14. I want to have more even breasts.	☐	☐	☐	☐	☐
15. I want to have a more even chest in the front.	☐	☐	☐	☐	☐
16. I want to have more even shoulders.	☐	☐	☐	☐	☐
17. I am self-conscious about my spine surgery scar. (Answer this only if you have had spine surgery)	☐	☐	☐	☐	☐
18. How would you rate your self image?	Very bad	Bad	Fair	Good	Very good
19. What would you most like to change about your body's shape and why?					

Figure (6.6) Association between questions of SAQ and Spine and Trunk Measurements

6.1.5 SAQ Analysis using 3D Measurements

Referring to SAQ, they are two sections. The first section includes 7 questions that ask patients about different aspects of their bodies by using figures. To analyze the existing SAQ, the following steps have been done:

Step 1: As Figure 6.1 shows, there are five answers for each question describing different severity for the related question that is from 1 to 5. First, we did a mapping between these five answers and 2D/3D measurements computed for our cohort. To find this mapping, we calculated the 2D/3D indices for patients using the 3D trunk shape of each patient then we extracted the maximum values of those computed 2D/3D indices among our patients. Each maximum value is divided by five to get the *Expectation Values* for each question which is associated with each 2D/3D indices. Then, to find the *Expected Answer*, we compared the computed 2D/3D indices with the *Expectation Values*. For example, the maximum value of BSR for our cohort (55 patients) is 57. Then, it is divided into five and rounded (11) to get *Expectation Values* for question 2 (e.g., the ranges of BSR are ($<11^\circ$), (11° to 22°), (22° to 33°), (33° to 44°), ($>44^\circ$)). Then, the BSR computed from the 3D trunk shape of each patient is compared with the *Expectation Values* to find the *Expected Answer*. For example, the computed BSR value of the *Patient A* is 15° falling into the range (11° to 22°) which shows the *Expected Answer* for question 2 associated with BSR for *Patient A* is 2.

Step 2: Second, the *Evaluation Error* for both preoperative and postoperative SAQ is computed by finding the difference between the *Selected Answers* (1 to 5) by the patients and the *Expected Answers* which reflected the value of our computed indices from the 3D shape of patients. For example, one patient selected the answer of 2 for his or her Rib prominence while the value of the BSR (Thoracic) computed from his or her 3D shape is 25° which falls into the range the answer 3; therefore, the *Evaluation Error* is -1 meaning that patient did one under evaluation about his or her Rib prominence. The *Evaluation Error* for parents is computed in the same way. It should be noted that we used the same *Expectation Values* for answers 1 to 5 in both preoperative and postoperative evaluations to highlight the improvement.

Step 3: Then, the average value and standard deviation of associated indices with each question are computed for each answer from 1 to 5 based on the answers of patients and their parents which are called *Perception Values*. The *Perception Chart* based on the *Perception Values* is a kind of supportive for *Expectation Chart* based on the *Expectation Values*. It helps us by identifying the percentages of patients who are not evaluating preoperative and postoperative trunk appearance as *Expectation Values*. It could be useful to analyze the *Expectation Chart*. Moreover, it should be noted that we have the same strategy to compute

Perception Values. Therefore, we have a different range of *Perception Values* for answers 1 to 5 in preoperative and postoperative evaluations since the answers of patients and their parents from preoperative to postoperative evaluations are changed.

Step 4: We analyzed both *Expectation and Perception Charts* for both patients and their parents.

6.1.6 SRS Analysing using 3D Measurements

Referring to SRS, the existing SRS covers 5 domains including function activity, pain, self-image, mental health, and satisfaction management. To analyze the existing Questionnaire SRS, we applied the following steps:

Step 1: We focused on the first 22 questions from SRS questionnaire as can be seen in Figure 6.3 and 6.4. These questions cover 5 domains (function activity, pain, self-image, mental health, and satisfaction management). Therefore, each domain is scored by a few questions. Also, each question has five answers that reflect the answer of patients in a range of the best (Scored with 5) to the worst (Scored with 1).

Step 2: We calculated a *Score Domain* for each domain per patient. Since there is more than one question for each domain to score, we used mean scores of those related questions. Indeed, we used the sub-score instead of the individual score for each domain. It is important that before computing the sub-score, some items needed to be inverted because some of the question scores are in a negative sense (from the worse to the best) and some others in a positive sense (from the best to the worst). We needed to make sure that those scores already are inverted. Figure 6.7 shows a sample of different scoring for questions 8 and 9 in the positive and negative senses respectively. Question 9 which is related to the function activity domain is scored in the positive sense from the best (100% normal) to the worst (0% normal). On the opposite, question 8 which is related to the pain domain is scored in the negative sense from the worst (very often) to the best (never). Therefore, we scored question 9 from 5 to 1 means from the best to the worst and we did inverting scores for question 8 from 1 to 5 means from the worst to the best.

8. **Do you experience back pain when at rest?**
- | | | | |
|-------------------------------------|---|---------------------------------|---|
| ☐ Very often | 1 | ☐ Rarely | 4 |
| ☐ Often | 2 | ☐ Never | 5 |
| ☐ Sometimes | 3 | | |
9. **What is your current level of work/school activity?**
- | | | | |
|--------------------------------------|---|-------------------------------------|---|
| ☐ 100% normal | 5 | ☐ 25% normal | 2 |
| ☐ 75% normal | 4 | ☐ 0% normal | 1 |
| ☐ 50% normal | 3 | | |

Figure (6.7) A sample of scoring the answers of questions 8 and 9 from SRS

Step 3: To analyze each domain, first we computed the *Score Domain* for each patient. Second, we used the same *Expected Answer* for each 2D/3D indices as explained in the previous steps of analyzing the SAQ since each question of SRS has five answers which is the same range of answering for the questions of SAQ. Third, the computed *Score Domain* is compared with the *Expected Answer* for all patients to compute the percentage of patients. For example, figure 6.24 shows analysis of the function domain in our cohort. It shows that a maximum of 32% of patients with a BSR of mild (scored 2) reported that they have often (scored 2) functional activities in their daily life. We analyzed the association of each domain with all computed 2D/3D indices including Cobb, BSR, Coronal Lateral Shift, Coronal Balance, and Shoulder Level.

Step 4: Patients answer the questions from 24 to 30 after surgery which generally show the satisfaction of the management and how the surgery improved their condition. In this step, we computed individual scores for each question because these questions are separated. Also, question 23 is treated independently. It was added into the initial version of SRS 22 and usually, it is not considered for computing sub-scores domain.

6.2 Results

In this section, we illustrated the results of analyzing the existing SAQ and SRS completed by both patients and parents in our cohort. Figures 6.8 and 6.9 present the general results of comparing the answering of the patients and their parents to SAQ questions from 1 to 7 before and after surgery with our computed 3D indices. However, we described the results of analyzing each question separately in the following.

Questions SAQ	Operation	Expectation					Patients/ Parents	Observation				
		Answer 1	Answer 2	Answer 3	Answer 4	Answer 5		Answer 1	Answer 2	Answer 3	Answer 4	Answer 5
Q1-Cobb angle	Pre	< 17°	[17° -34°]	[34° -51°]	[51° -68°]	> 68°	Patients	-	[38° -56°]	[46° -60°]	[52° -64°]	54°
							Parents	-	[35° -47°]	[47° -61°]	[50° -62°]	[50° -62°]
	Post	< 17°	[17° -34°]	[34° -51°]	[51° -68°]	> 68°	Patients	[5° -15°]	[8° -26°]	-	-	-
							Parents	[2° -16°]	[10° -26°]	29°	-	-
Q2-BSR (Thoracic)	Pre	<11°	[11° -22°]	[22° -33°]	[33° -44°]	> 44°	Patients	[8° -10°]	[7° -29°]	[4° -30°]	7°	
							Parents	-	[23° -29°]	[6° -22°]	[11° -51°]	-
	Post	<11°	[11° -22°]	[22° -33°]	[33° -44°]	> 44°	Patients	[3° -23°]	[5° -25°]	-	-	-
							Parents	[5° -21°]	[4° -28°]	10°	-	-
Q3-BSR (Thoracic Lumber)	Pre	<5°	[5° -11°]	[11° -16°]	[16° -22°]	>22°	Patients	[5° -15°]	[6° -16°]	[8° -18°]	[10° -22°]	[11° -13°]
							Parents	[1° -15°]	[7° -19°]	[7° -13°]	[11° -19°]	13°
	Post	<5°	[5° -11°]	[11° -16°]	[16° -22°]	>22°	Patients	[5° -11°]	[6° -18°]	[10° -18°]	12°	-
							Parents	[5° -11°]	[7° -17°]	[6° -28°]	15°	-
Q4-Coronal Lateral Shift	Pre	<14°	[14° -28°]	[28° -42°]	[42° -56°]	>56°	Patients	23°	[18° -38°]	[71° -39°]	[22° -46°]	[27° -55°]
							Parents	23°	[20° -34°]	[19° -37°]	[21° -47°]	[17° -45°]
	Post	<14°	[14° -28°]	[28° -42°]	[42° -56°]	>56°	Patients	[8° -24°]	[8° -26°]	[4° -26°]	-	-
							Parents	[9-21]	[9-31]	15	-	-
Q5-Coronal Balance	Pre	<2°	[2° -4°]	[4° -6°]	[6° -8°]	>8°	Patients	[0.5° -2.5°]	[-0.2° -3.7°]	[-0.1° -3.8°]	[0.5° -2.8°]	[-0.7° -7.2°]
							Parents	3.1°	[-0.1° -3.6°]	[0° -3.9°]	[0.8° -2.8°]	[1.4° -3.4°]
	Post	<2°	[2° -4°]	[4° -6°]	[6° -8°]	>8°	Patients	[-0.7° -1.22°]	[-0.2° -1.7°]	-	-	-
							Parents	[-0.6° -1.3°]	[-0.1° -1.8°]	1.5°	-	-
Q6-Shoulder Level	Pre	<5°	[5° -11°]	[11° -17°]	[17° -23°]	>23°	Patients	12°	[3° -17°]	[9° -21°]	[4° -28°]	[2° -18°]
							Parents	-	[5° -19°]	[8° -18°]	[7° -27°]	-
	Post	<5°	[5° -11°]	[11° -17°]	[17° -23°]	>23°	Patients	[1° -9°]	[1° -9°]	[3° -7°]	-	-
							Parents	[2° -10°]	[0° -10°]	[5° -11°]	4°	-
Q7-BSR (T, TL, L)	Pre	<14°	[14° -28°]	[28° -42°]	[42° -56°]	>56°	Patients	[8° -28°]	[15° -25°]	[6° -38°]	[12° -14°]	-
							Parents	[17° -27°]	[16° -30°]	[6° -38°]	[10° -18°]	-
	Post	<14°	[14° -28°]	[28° -42°]	[42° -56°]	>56°	Patients	[7° -17°]	[6° -32°]	[9° -13°]	18°	-
							Parents	[6° -20°]	[5° -31°]	[7° -43°]	9°	-

Figure (6.8) The *Expectation and Perception Values* for each measurement related to SAQ questions

Questions SAQ		Patients				Parents			
		Numbers of answered	Under evaluation	Fit with evaluation	Over evaluation	Numbers of answered	Under evaluation	Fit with evaluation	Over evaluation
Q1	Pre	39	54%	41%	5%	33	45%	39%	15%
	Post	49	8%	71%	20%	38	11%	68%	21%
Q2	Pre	39	10%	51%	34%	50	9%	39%	45%
	Post	33	22%	58%	14%	40	28%	50%	13%
Q3	Pre	38	37%	32%	31%	50	15%	45%	39%
	Post	33	58%	38%	4%	39	58%	29%	14%
Q4	Pre	38	37%	39%	24%	50	16%	38%	64%
	Post	32	16%	48%	36%	38	16%	47%	37%
Q5	Pre	35	14%	26%	60%	49	34%	19%	69%
	Post	32	4%	63%	33%	39	8%	58%	34%
Q6	Pre	34	38%	21%	41%	46	39%	23%	39%
	Post	31	22%	48%	30%	39	27%	38%	35%
Q7	Pre	38	18%	39%	42%	51	30%	43%	70%
	Post	23	25%	45%	27%	38	16%	63%	18%

Figure (6.9) The evaluation of patients and parents 'expectations (under, fit, or over-evaluation)

6.2.1 Patients and Parents' Expectations

Question 1: *Body Curve* associated with *Cobb angle*

In the preoperative evaluation, the view of 41% patients and 39% parents about the body curve is in agreement with our computed Cobb angle in the range of $[34^{\circ}; 68^{\circ}]$ (answers 3 and 4). In the postoperative evaluation, the view of 71% patients and 68% parents about the body curve is in agreement with our computed Cobb angle which has decreased from the range $[34^{\circ}; 68^{\circ}]$ (answers of 3 and 4) preoperative to $34^{\circ} <$ (answers 1 and 2) postoperative. Figures 6.10 and 6.11 show the preoperative and postoperative evaluation charts respectively for the body curve. As can be shown from the difference between the preoperative evaluation chart and the postoperative evaluation chart, the answering of both patients and parents are moved from answers 3 and 4 (they can see the moderate deformity of their back) preoperative to 1 and 2 (they can see small deformity of their back) postoperative. This proves the satisfaction of the patients and parents with the result of the surgery related to the body curve. Both patients and parents can see body curves less than 34° after scoliosis surgery. It reveals that the body curve showing the deformity of the spine has improved significantly.

Figure 6.10 shows the results of evaluating the patients' and parents' expectations in answering question 1 (Body curve) of SAQ preoperatively. The right column shows the *Expectation Value* of the Cobb angle computed from the preoperative SAQ and the left column shows the *Perception Value* of the Cobb angle computed from preoperative SAQ. The first-row charts present the results of analyzing the patients' answers and the second-row charts show the results of analyzing parents' answers.

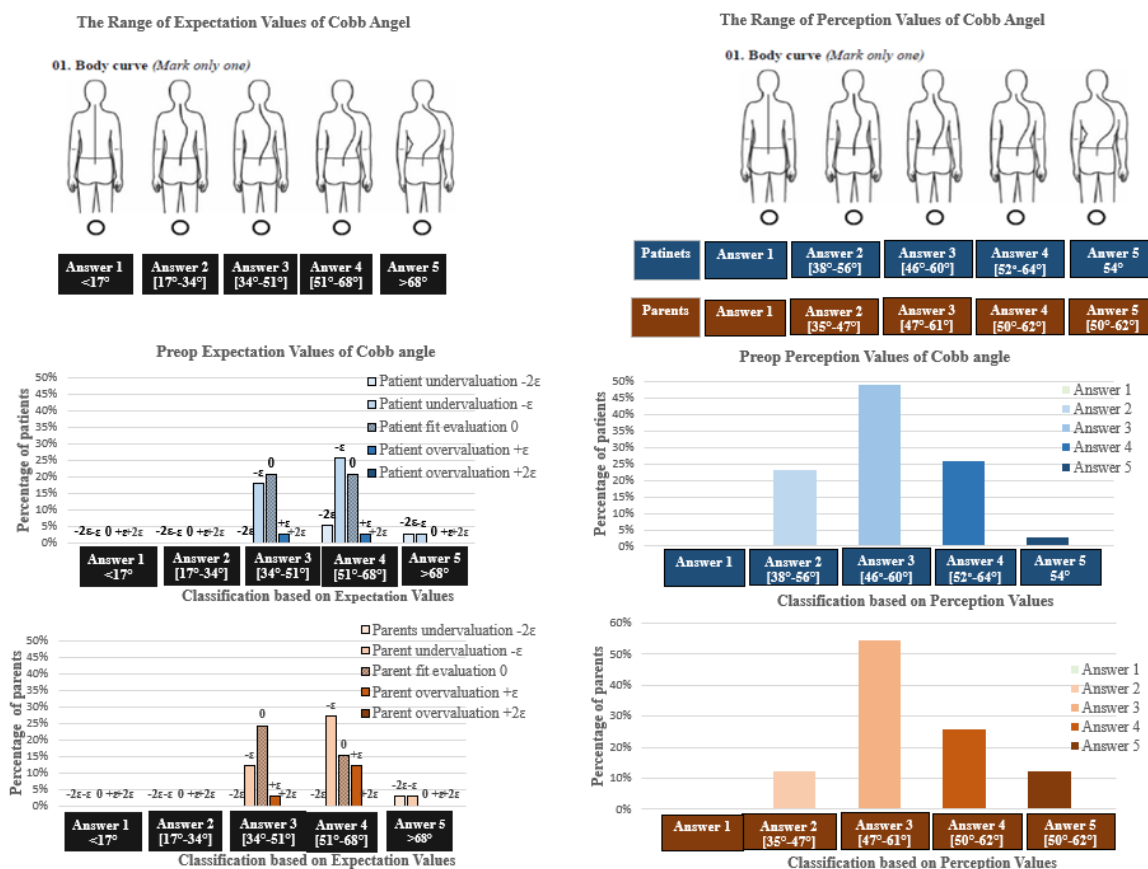


Figure (6.10) Evaluation question 1 (body curve associated with Cobb angle) of preoperative SAQ.

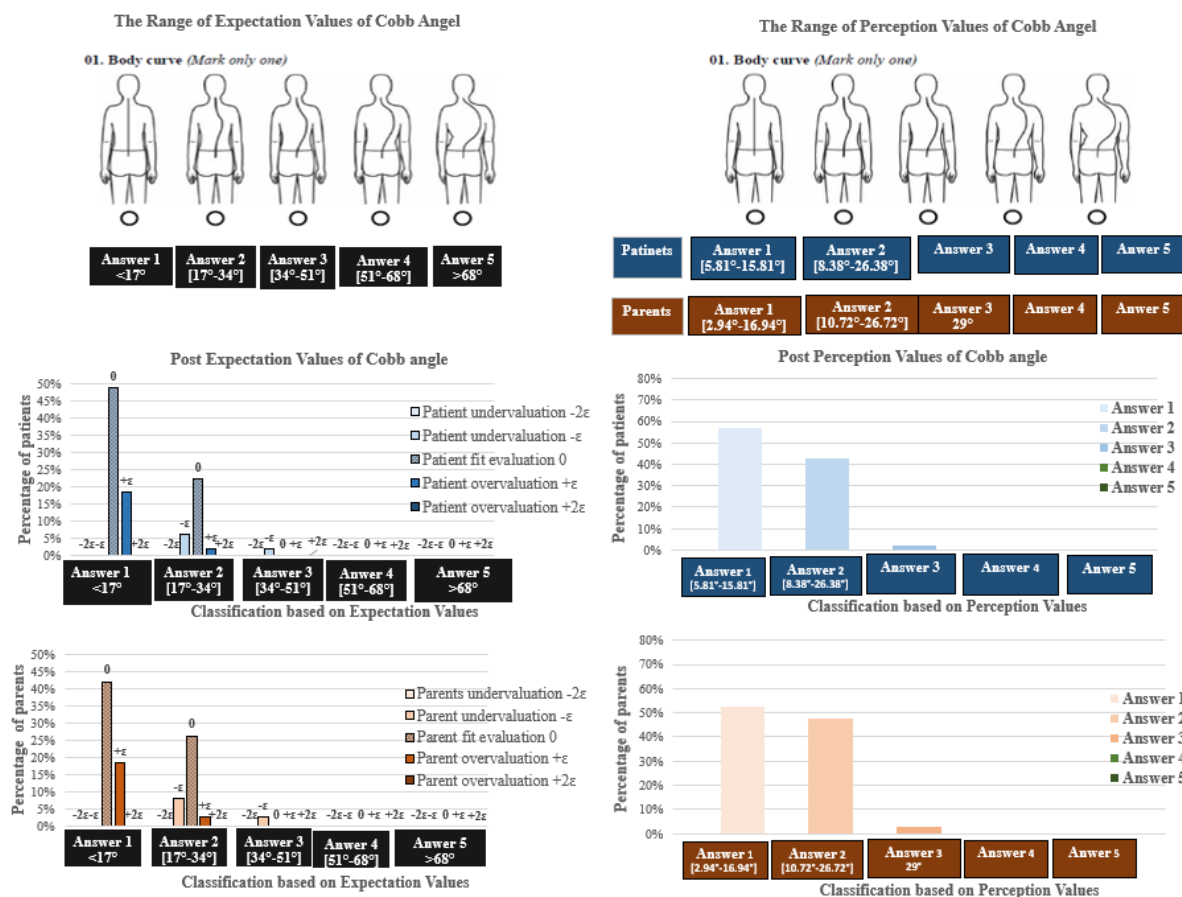


Figure (6.11) Evaluation question 1 (body curve associated with Cobb angle) of postoperative SAQ.

Question 2: *Rib Prominence* (bump) associated with *BSR (Thoracic)*

Figures 6.12 and 6.13 display the preoperative and postoperative evaluation charts respectively for the rib prominence. In the preoperative evaluation, when the rib prominence is $[11^\circ; 33^\circ]$ (answers 2 and 3), the view of patients and parents is in agreement with our computed BSR (Thoracic). For less or more severe cases with rib prominence in the range $<11^\circ$ (answers 1) or $>33^\circ$ (answers 4 and 5), the view of the patients and their parents are more or less, comparable with our computed BSR (Thoracic). It reveals that when the rib prominence is in the range $[11^\circ; 33^\circ]$, patients and parents can see the real deformity. In the postoperative evaluation, both patients and parents tend to see the rib prominence in agreement or close to agreement with our computed BSR (Thoracic) which has decreased mostly from group 2 ($[11^\circ; 22^\circ]$) to group 1 ($<11^\circ$). It shows that they are satisfied with the result of the surgery related to decreasing the rib prominence. The difference between the preoperative evaluation chart and the postoperative evaluation chart indicates that the

patients and parents can see the improvement of the rib prominence after surgery and they are satisfied with the result of the surgery on the curve of the rib prominence.

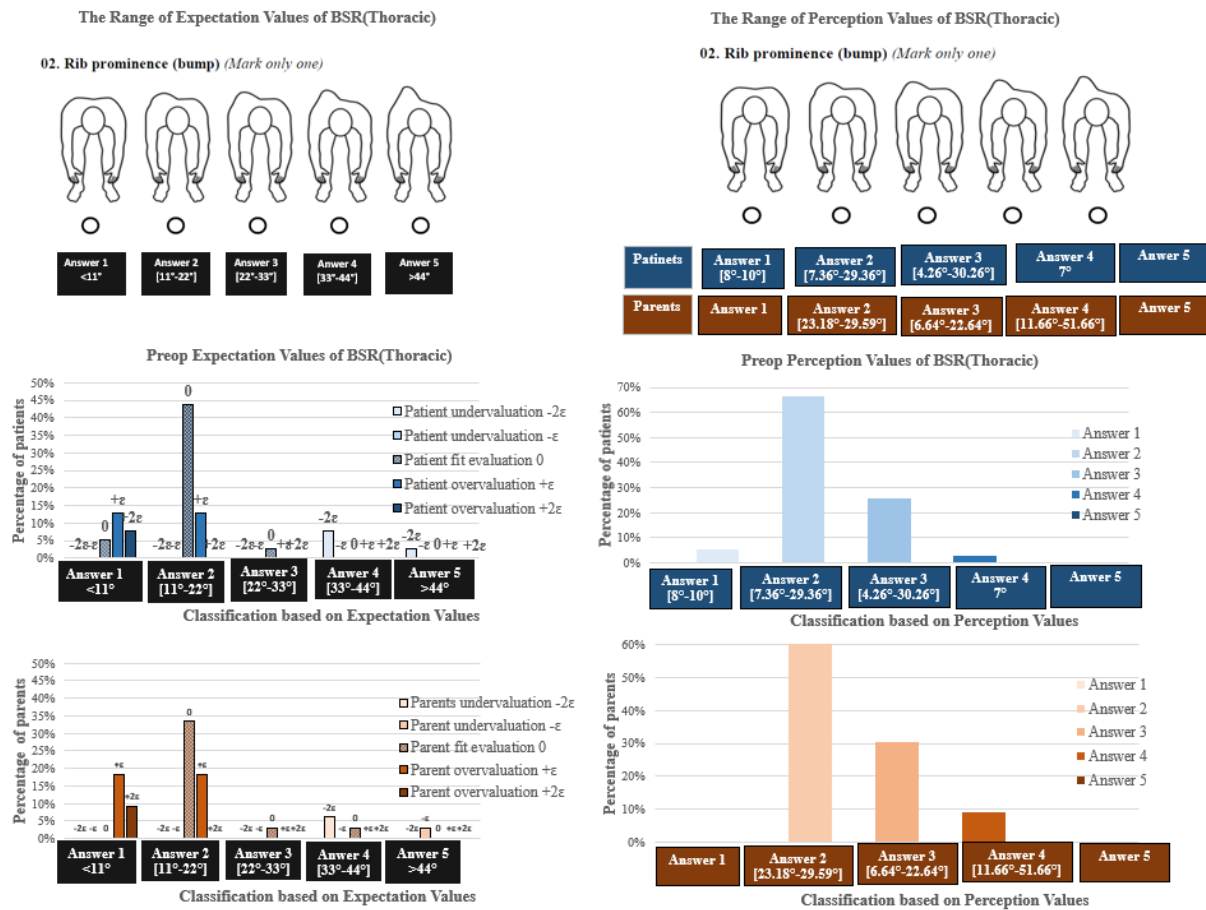


Figure (6.12) Evaluation question 2 (Rib Prominence associated with BSR (Thoracic)) of preoperative SAQ.

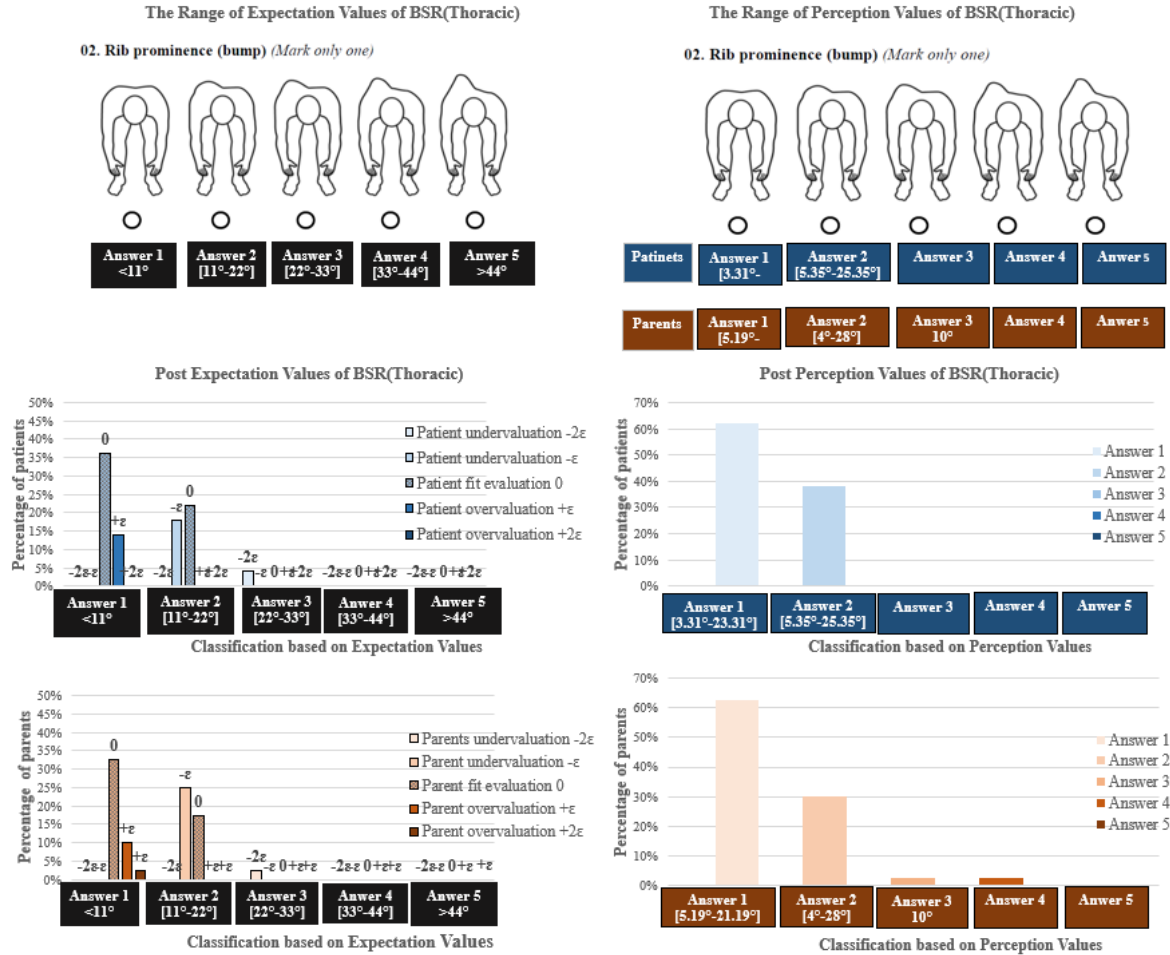


Figure (6.13) Evaluation question 2 (Rib Prominence associated with BSR (Thoracic)) of postoperative SAQ.

Question 3: *Flank Prominence* (bump) associated with *BSR (Thoracic Lumbar)*

Figures 6.14 and 6.15 show the preoperative and postoperative evaluation charts respectively for the flank prominence. In the preoperative evaluation, the view of 37% patients and 45% parents about the flank prominence is close to agreement and in agreement respectively with our computed BSR (Thoracic-Lumbar) in the range $[5^\circ; 20^\circ]$ (group 2, 3, and 4). The result shows that patients see their flank prominence less than its real deformity, but parents see the real deformity of the flank prominence of their children. In the postoperative evaluation, the view of 58% patients and 58% parents about the flank prominence is close in agreement (less) with our computed BSR (Thoracic-Lumbar). The difference between the preoperative evaluation chart and postoperative evaluation chart shows the satisfaction of both patients and parents with the results of the surgery related to the flank prominence. They see less

deformity than real deformity. However, both patients and parents did not answer this question very accurately, and they see the deformity less than its real value. It can be because this sketch of the body can not be evaluated by them. This measurement is difficult to evaluate, and it is difficult for children to imagine how it looks like. However, it is easier for parents to see this deformity. The comparison of the preoperative and postoperative results also shows that the correction of Thoracic-Lumbar (Flank prominence) is not as good as other aspects. However, both patients and parents see less deformity than the real deformity.

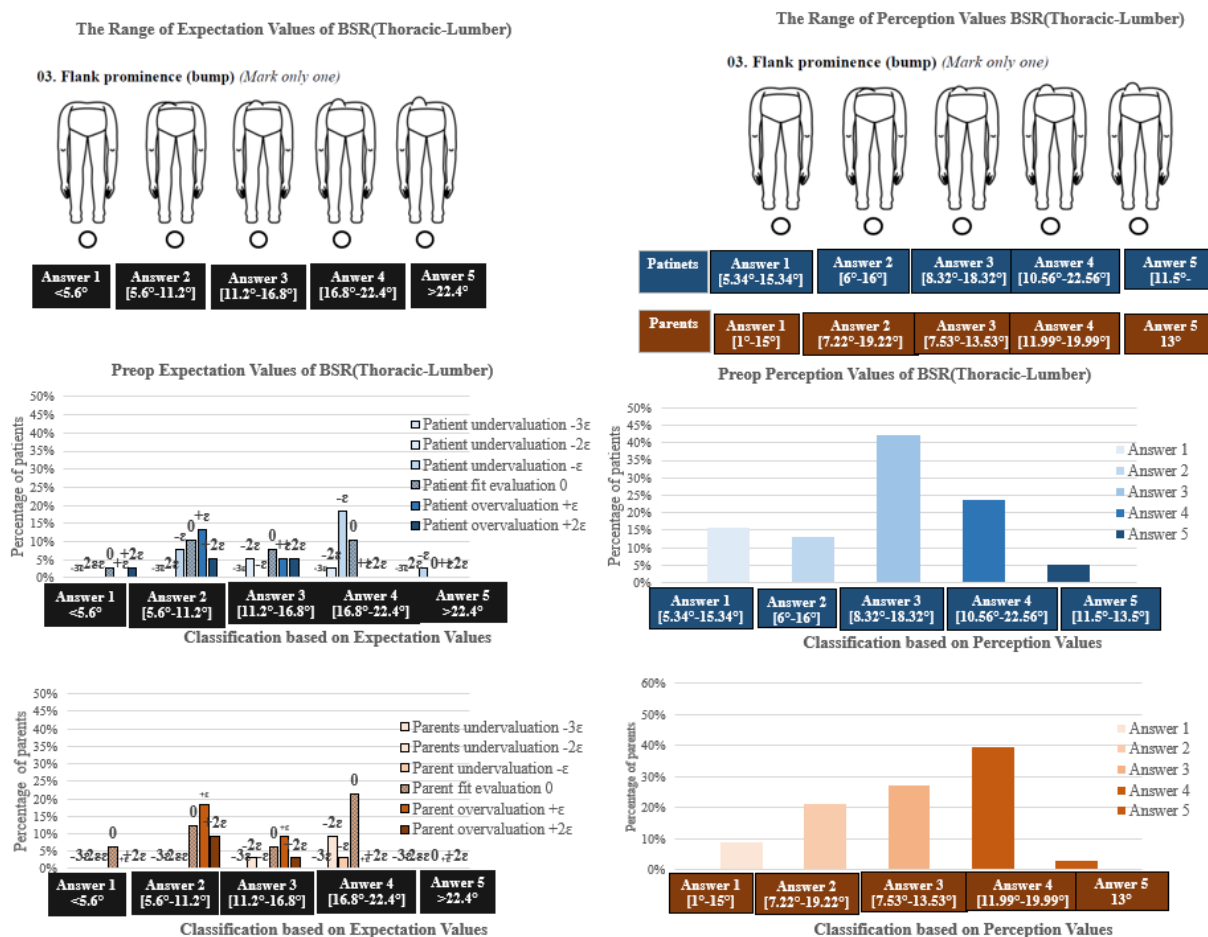


Figure (6.14) Evaluation question 3 (Flank Prominence associated with BSR (Thoracic Lumbar)) of preoperative SAQ.

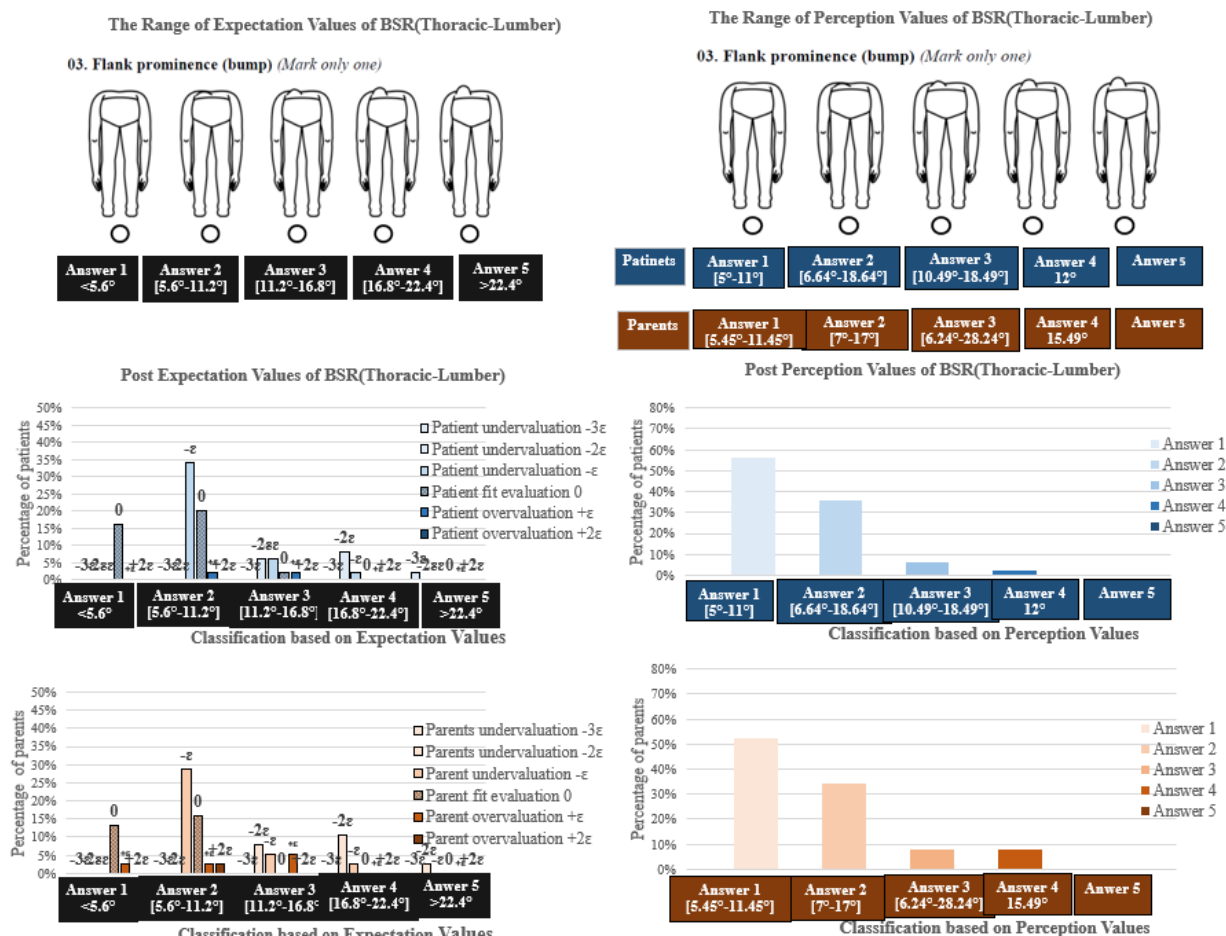


Figure (6.15) Evaluation question 3 (Flank Prominence associated with BSR (Thoracic Lumbar)) of postoperative SAQ.

Question 4: *Head Chest Hips* associated with *Coronal Lateral Shift*

Figures 6.16 and 6.17 show the preoperative and postoperative evaluation charts respectively for the head chest hips. In the preoperative evaluation, the view of 39% patients and 38% parents about the relation between their head-chest-hips is in agreement with our computed coronal lateral shift in the range $>14^\circ$ (answers 2 to 5). In the postoperative evaluation, the view of 48% patients and 47% parents about the relation between their head-chest-hips matches our computed coronal lateral shift which is shifted to the range $<56^\circ$ (answers 1 to 4). The difference between the preoperative evaluation chart and the postoperative evaluation chart indicates the satisfaction of both patients and parents with the results of the surgery related to the relation between their head-chest-hips. They selected the sketches with less deformity to answer this question of SAQ postoperatively. However, for the range $[14^\circ; 56^\circ]$

of coronal lateral shift (answers 2 to 4), both patients and parents see a bigger deformity than the real deformity and for small values of coronal lateral shift of $< 14^\circ$ (answer of 1), they can see the real deformity of coronal lateral shift. It can reveal that they have more concerns about the relation between their head-chest-hips and they want to see more improvement in general. Concerning the preoperative evaluation chart, the perception of parents about this deformity is exaggerated (e.g., parents mostly answer 4 while the expectation value reveals that they should answer 2). However, the perception of patients is closer to the real deformity.

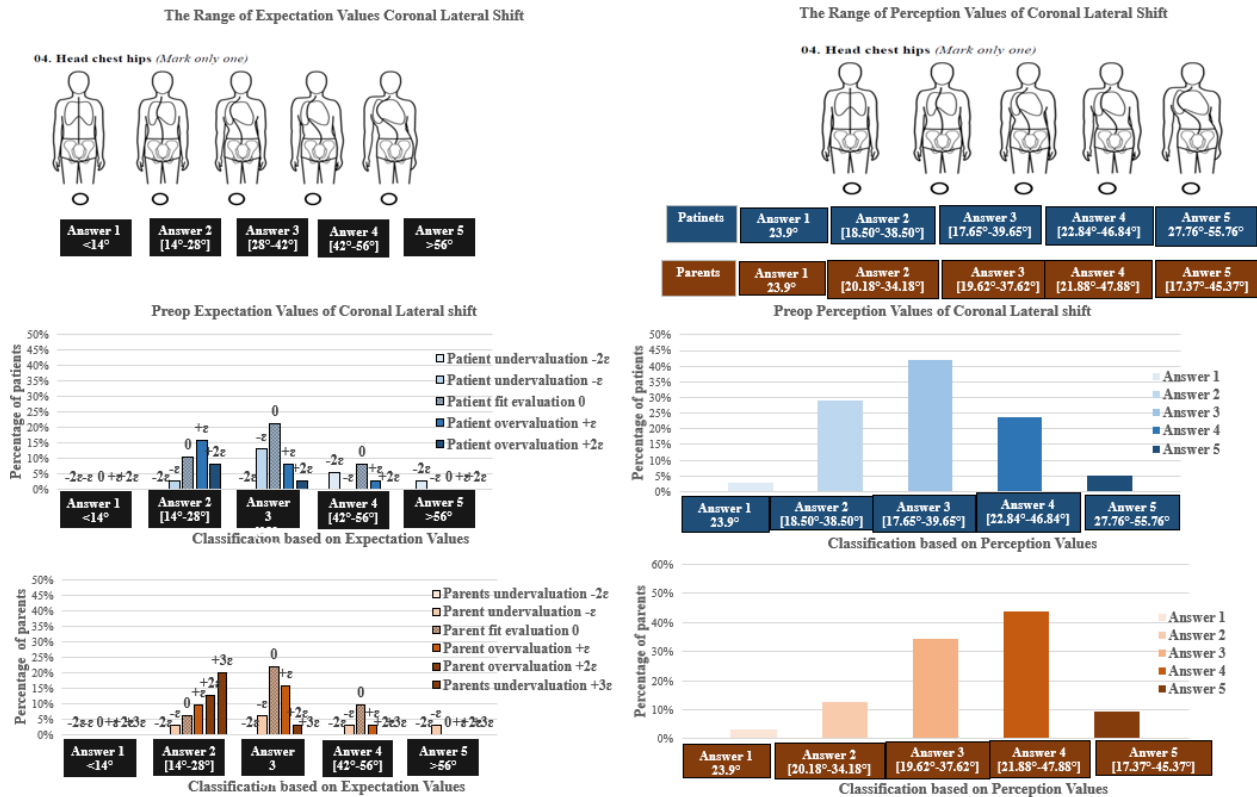


Figure (6.16) Evaluation question 4 (Head Chest Hips associated with Coronal Lateral Shift) of preoperative SAQ.

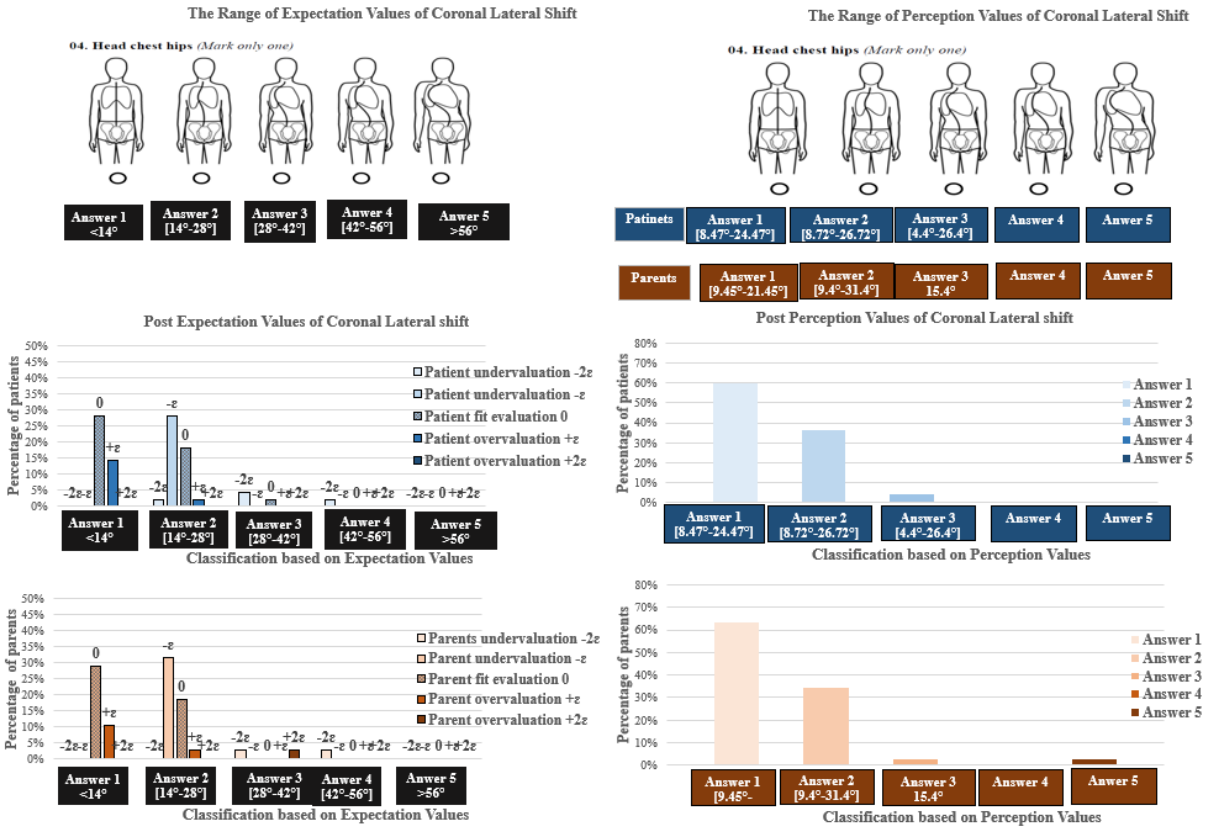


Figure (6.17) Evaluation question 4 (Head Chest Hips associated with Coronal Lateral Shift) of postoperative SAQ.

Question 5: *Position of head over hips associated with Coronal Balance*

Figures 6.18 and 6.19 show the preoperative and postoperative evaluation charts respectively for the position of head over hips. In the preoperative evaluation, when the Coronal Balance is <2°, the view of both patients and parents about the position of head over hips is larger than our computed Coronal Balance. However, the view of both patients and parents about the position of head over hips when the Coronal Balance is less than 8°, is a combination of in the agreement or close to the agreement (over, fit, and less) with our computed Coronal Balance. It reveals that when the Coronal Balance is less than 6°, both patients and parents tend to see more deformity than its real value. In the postoperative evaluation, both patients and parents tend to see the position of head over hips in agreement with our computed Coronal Balance which has decreased mostly from answers 1 to 4 (8°) to answer 1 ([<2°]). It signifies their satisfaction with the result of surgery to decrease the deformity related to the position of the head over the hips. The difference between the preoperative evaluation chart and postoperative evaluation chart shows the patients and parents can see the improvement

of deformity related to the position of head over hips after surgery and they are satisfied with the result of surgery on the position of head over hips.

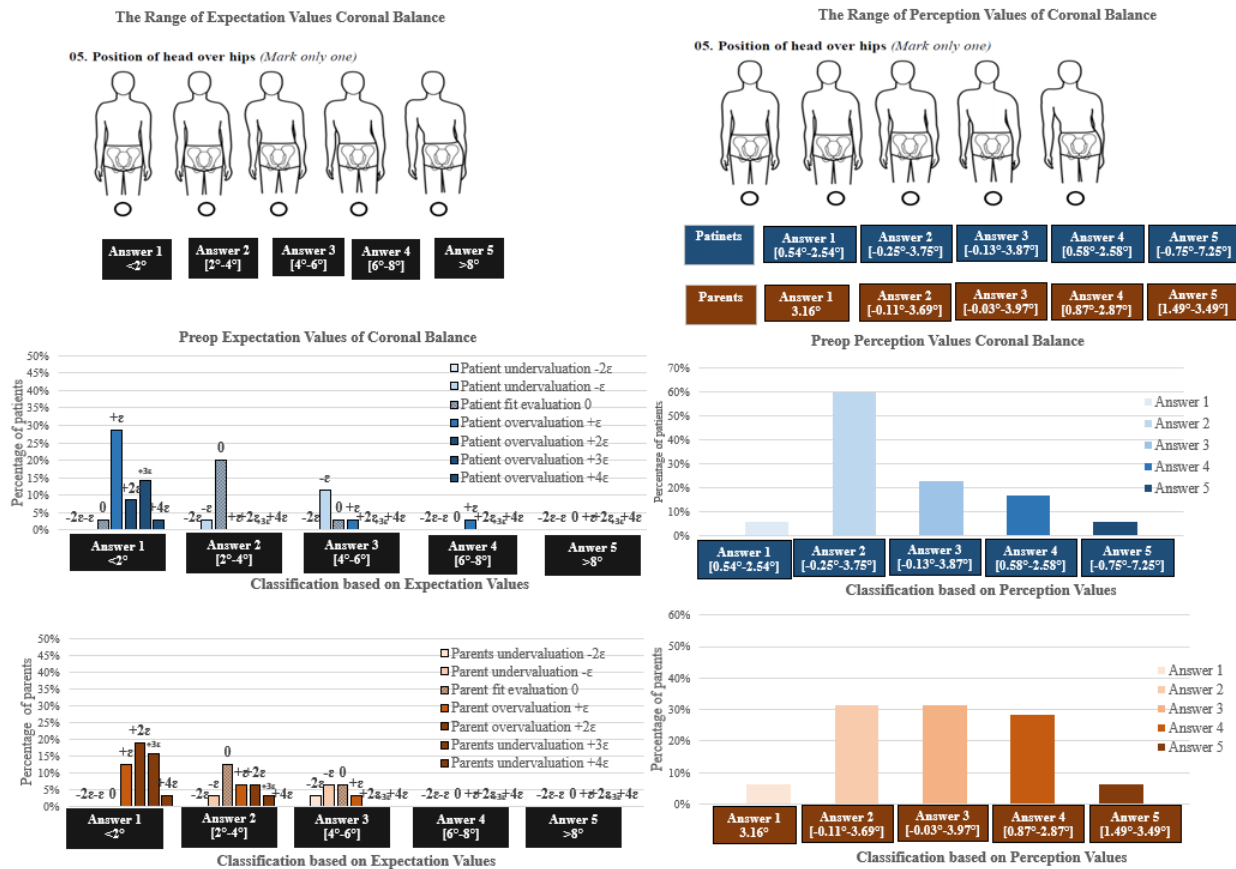


Figure (6.18) Evaluation question 5 (Position of head over hips associated with Coronal Balance) of preoperative SAQ.

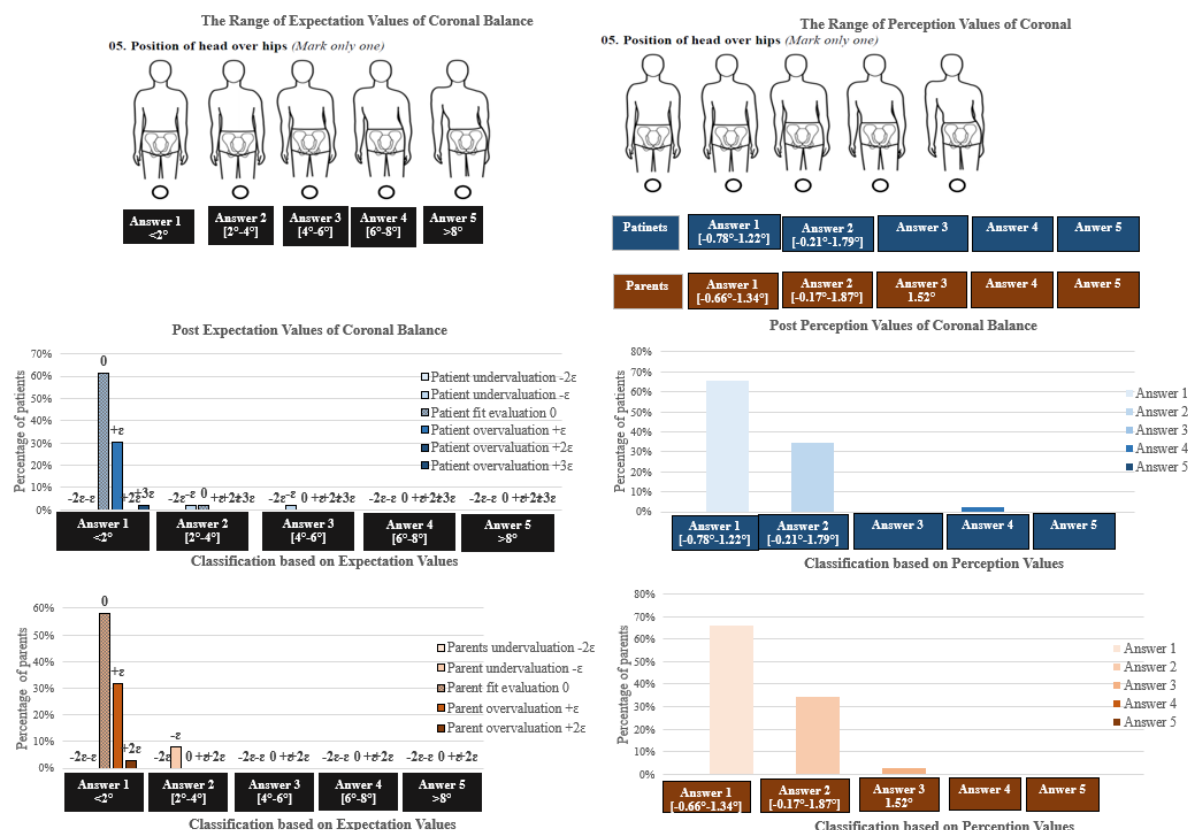


Figure (6.19) Evaluation question 5 (Position of head over hips associated with Coronal Balance) of postoperative SAQ.

Question 6: *Shoulder Level* associated with *Maximum Asymmetry of Height in Shoulder-Neck*

Figures 6.20 and 6.21 show the preoperative and postoperative evaluation charts respectively for the shoulder level. In the preoperative evaluation, when the shoulder level is in the range $[5.8^\circ$ to more than $23^\circ]$, the view of both patients and parents about the shoulder level is a combination of in the agreement or close to the agreement (over, fit, and less) with our computed Shoulder Level. In the postoperative evaluation, both patients and parents tend to see the shoulder level in agreement with our computed shoulder level which has decreased mostly from answers 1 to 5 ($<5.88^\circ$; $>23^\circ$) to answers 1 and 2 ($<5.88^\circ$; $>11.6^\circ$). It indicates that they are satisfied with the result of surgery to decrease the deformity related to the shoulder level. The difference between the preoperative evaluation chart and postoperative evaluation chart shows the patients and parents can see the improvement of deformity related to the shoulder level after surgery and they are satisfied with the result of surgery on the shoulder level. However, still, some patients and parents see bigger deformities at the shoulder

level. The previous studies showed that the achievement of shoulder balance is an important factor for the satisfaction of patients and parents and it is important for the evaluation of clinical outcomes. Many studies have been done to identify factors affecting the postoperative shoulder level which is important in surgical decision making.

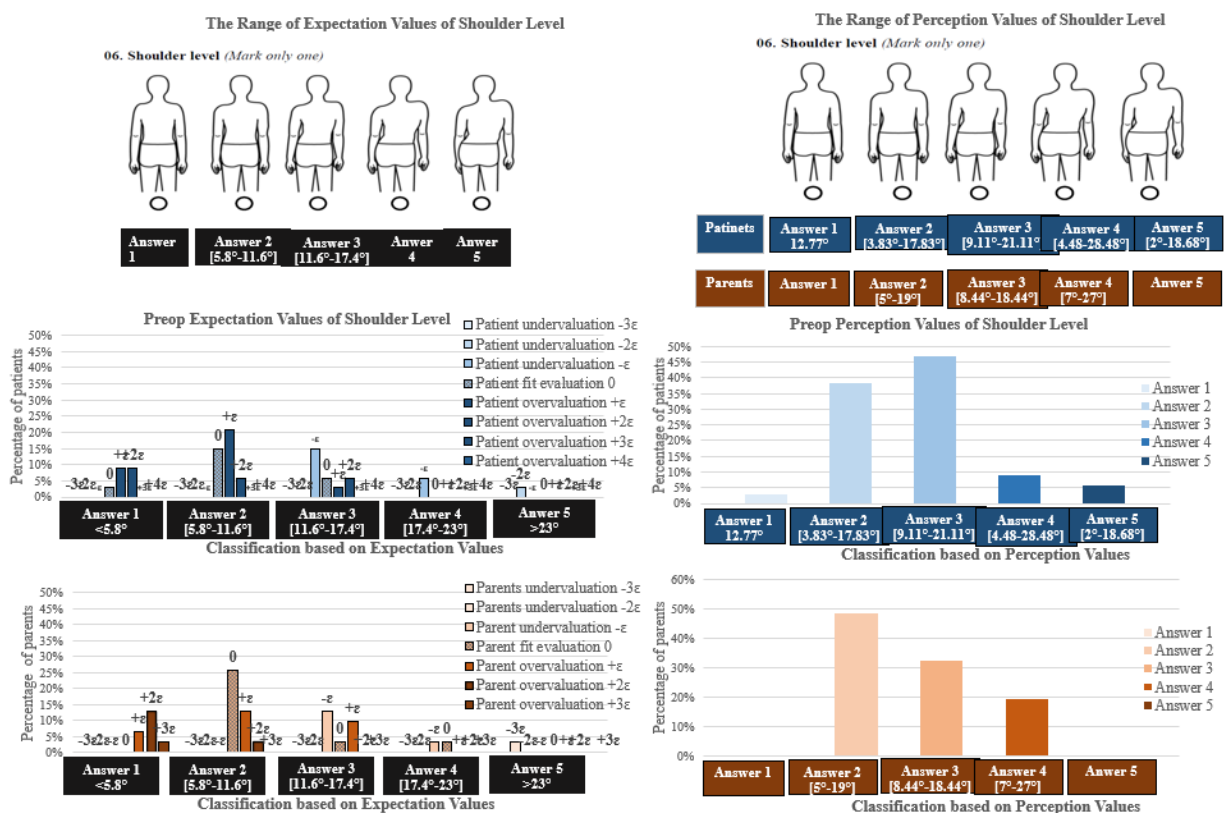


Figure (6.20) Evaluation question 6 (Shoulder Level associated with Maximum Asymmetry of Height in Shoulder-Neck) of preoperative SAQ.

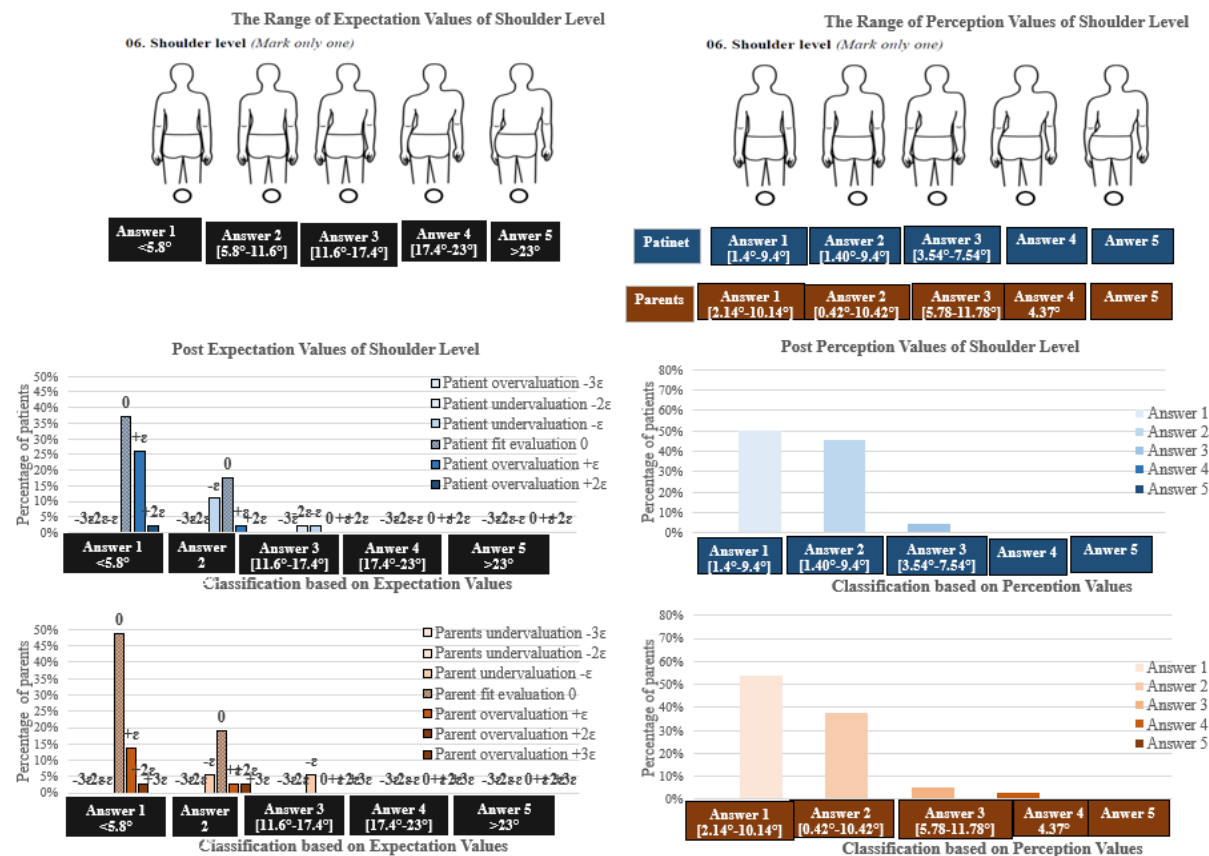


Figure (6.21) Evaluation question 6 (Shoulder Level associated with Maximum Asymmetry of Height in Shoulder-Neck) of postoperative SAQ.

Question 7: *Spine Prominence* (bump) associated with *BSR* (*Thoracic, Thoracic Lumbar, lumbar*)

Figures 6.22 and 6.23 present the preoperative and postoperative evaluation charts respectively for the spine prominence. In the preoperative evaluation, patients and parents tend to see the whole prominence of the spine bigger than its actual deformity when the BSR deformity (Thoracic, thoracic lumbar, and lumbar) is less than 14° and in agreement with its actual deformity when it is more than 14° . 42% of patients and 70% of parents evaluated the spine prominence as bigger than its actual value. In the postoperative evaluation, both patients and parents tend to see the prominence of the spine in the agreement or close to the agreement with the computed BSR after surgery. 45% of patients and 63% of parents evaluated the prominence of spine to fit its actual value after surgery. The difference between the preoperative evaluation chart and the postoperative evaluation chart demonstrates that the satisfaction of both patients and parents with the results of surgery related to the spine

prominence.

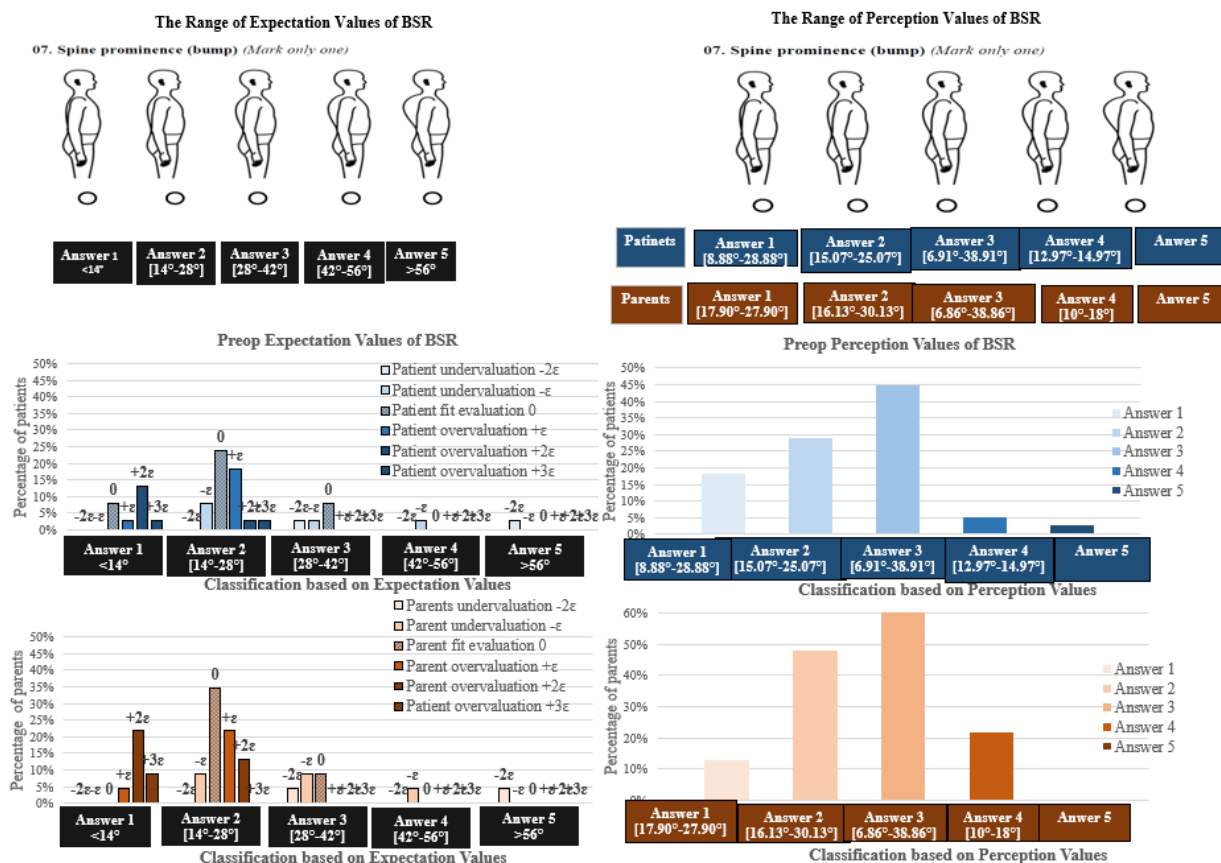


Figure (6.22) Evaluation question 7 (Spine Prominence associated with BSR (Thoracic, Thoracic Lumbar, lumbar)) of preoperative SAQ.

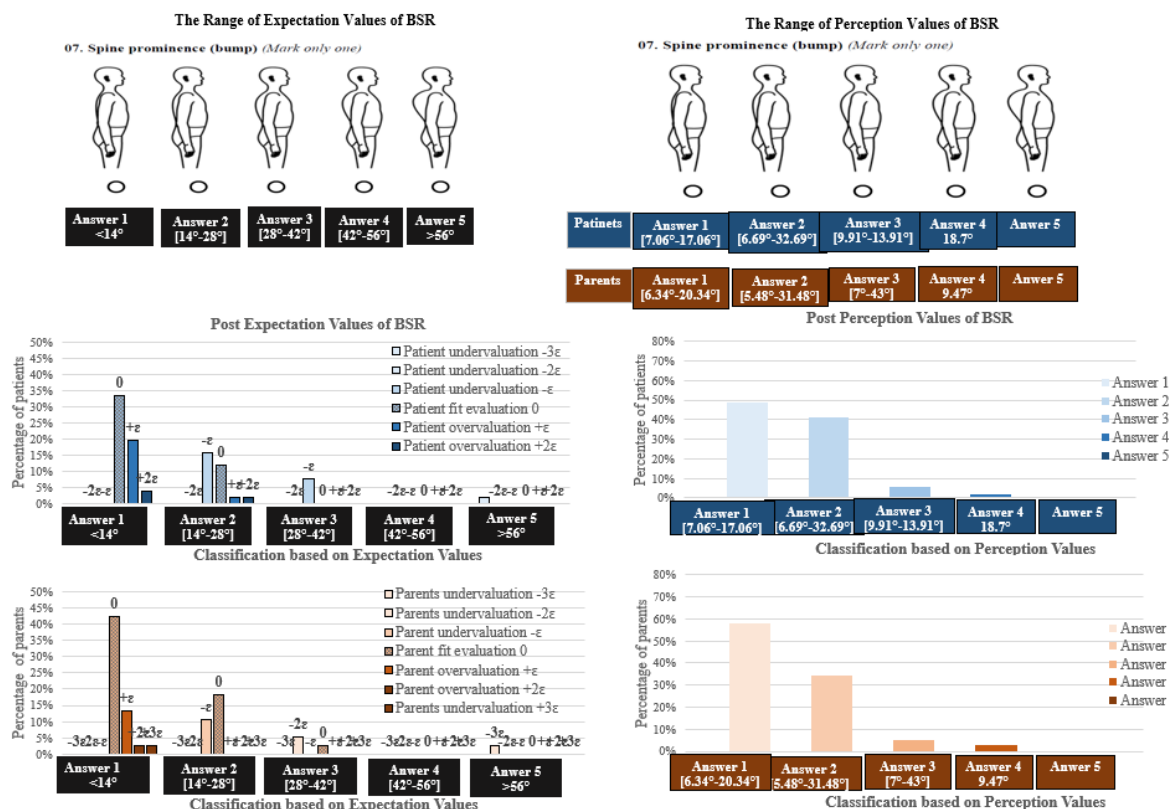


Figure (6.23) Evaluation question 7 (Spine Prominence associated with BSR (Thoracic, Thoracic Lumbar, lumbar)) of postoperative SAQ.

6.2.2 Patient's Satisfaction

Function Activity Domain (Questions 5, 9, 12, 15, 18, 25, 26)

Figure 6.24 displays the results of comparing the answering of the patients to the questions of function activity domain before and after surgery with our computed 3D indices from right to left. The difference between the preoperative evaluation chart and the postoperative evaluation chart shows that even, though the body curve, spine prominence, head chest hips, position of head over hips, and shoulder level have improved but patients still have moderate function activity in their daily life.

Pain Domain (Questions 1, 2, 8, 11, 17, 27)

Figure 6.25 provides the results of comparing the answering of the patients to the questions of pain domain preoperative and postoperative with our computed 3D indices from right to left. To make the range scoring meaningful for the pain domain from the best to the worst, we used 100% for the worst and 0% for the best. The difference between the preoperative evaluation

chart and the postoperative evaluation chart shows that by improving the deformities of the body curve, spine prominence, head chest hips, the position of head over hips, and shoulder level, patients have a noun or less amount of pain which they have experienced recently.

Self-Image Domain (Questions 4, 6, 10, 14, 19, 23, 28, 29, 30)

Figure 6.26 shows the results of comparing the answering of patients to the questions of self-image domain preoperative and postoperative with our computed 3D indices from right to left. The difference between the preoperative evaluation chart and the postoperative evaluation chart shows that patients' ideas about their self-image (such as their feeling about their back shape as it is right now) have changed mostly from neither happy nor unhappy and somewhat happy to very happy preoperative to postoperative as a result of improvement in the deformities of body curve, spine prominence, head chest hips, the position of head over hips, and shoulder level.

	% Of patients		Cobb					BSR					Coronal Lateral Shift					Coronal Balance					Shoulder Level					
			Best.....Worst					Best.....Worst					Best.....Worst					Best.....Worst					Best.....Worst					
Function	Preoperative	Best.....Worst	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	
			0%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			25%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			50%	0	0	0	8	2	2	4	4	0	0	0	0	4	0	0	0	2	4	0	0	0	2	0	2	0
			75%	0	0	22	24	4	12	32	4	0	2	0	16	22	4	2	26	16	4	2	0	8	14	12	6	2
			100%	0	0	10	22	8	6	24	8	2	0	0	10	8	8	0	18	4	6	0	0	4	4	6	4	6
	Postoperative	Best.....Worst	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	
			0%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
			25%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
			50%	9	2	0	0	0	4	7	0	0	0	4	0	2	2	0	9	2	0	0	0	7	4	0	0	0
			75%	53	20	2	0	0	49	22	4	0	2	38	13	11	0	0	65	5	0	0	0	40	18	5	2	0
			100%	7	5	0	0	0	7	2	4	0	0	4	7	0	0	0	9	0	2	0	0	5	0	2	2	0

Figure (6.24) Evaluation of patients' satisfaction in Function Domain

			% Of patients					Cobb					BSR					Coronal Lateral Shift					Coronal Balance					Shoulder Level				
			Best.....Worst					Best.....Worst					Best.....Worst					Best.....Worst					Best.....Worst									
Pain	Preoperative			1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5				
		Best.....Worst	100%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
			75%	0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0				
			50%	0	0	6	2	6	8	6	0	0	0	0	0	2	6	2	0	4	4	4	0	0	0	4	0	2				
			25%	0	0	14	40	4	8	38	8	2	2	0	14	22	8	0	24	14	4	2	0	10	10	10	6	6				
			0%	0	0	12	10	4	4	16	6	0	0	0	10	6	2	2	16	4	4	0	0	2	6	8	4	0				
	Postoperative			1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5				
		Best.....Worst	100%	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0				
			75%	2	2	0	0	0	2	2	0	0	0	2	0	2	0	0	4	0	0	0	0	4	0	0	0	0				
			50%	5	0	0	0	0	4	2	0	0	0	2	2	0	0	0	4	2	0	0	0	4	2	0	0	0				
			25%	29	11	2	0	0	25	13	4	0	0	18	9	2	2	0	33	2	2	0	0	18	9	5	0	0				
			0%	31	15	0	0	0	27	15	4	0	2	24	9	9	0	0	42	4	0	0	0	27	9	2	4	0				

Figure (6.25) Evaluation of patients' satisfaction in Pain Domain

			% Of patients					Cobb					BSR					Coronal Lateral Shift					Coronal Balance					Shoulder Level				
			Best.....Worst					Best.....Worst					Best.....Worst					Best.....Worst					Best.....Worst									
Self-Image	Preoperative		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5					
		Worst	0%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
		25%	0	0	2	8	2	4	2	6	0	0	0	0	8	0	0	0	4	6	0	0	0	6	0	2	0					
		50%	0	0	18	26	4	8	28	8	2	2	0	14	16	6	0	2	4	8	2	2	0	10	8	8	8	2				
		75%	0	0	8	18	8	6	26	2	0	0	0	8	10	6	0	8	8	4	0	0	2	2	8	2	6					
		100%	0	0	4	0	0	2	2	0	0	0	0	4	0	0	0	2	2	0	0	0	0	2	2	0	0					
	Postoperative		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5					
		Worst	0%	0	2	0	0	0	2	0	0	0	0	2	0	0	0	0	2	0	0	0	0	2	0	0	0	0				
		25%	2	0	0	0	0	0	2	0	0	0	0	0	2	0	0	2	0	0	0	0	2	0	0	0	0					
		50%	9	4	0	0	0	5	4	2	0	2	4	2	0	2	0	1	1	0	0	0	7	4	0	0	0					
		75%	40	15	2	0	0	36	20	2	0	0	35	13	5	0	0	4	9	5	0	0	31	11	5	4	0					
		100%	18	7	0	0	0	16	5	4	0	0	5	5	5	0	0	2	0	2	2	0	11	7	2	0	0					

Figure (6.26) Evaluation of patients' satisfaction in Self-Image Domain

Mental Health Domain (Questions 3, 7, 13, 16, 20)

Figure 6.27 shows the results of comparing the answers of patients to the questions of mental health domain preoperative and postoperative with our computed 3D indices from right to left. The difference between the preoperative evaluation chart and the postoperative evaluation chart shows that patients' ideas about their mental health (such as being very nervous) have changed mostly from some of the time and a little of the time to none of the time preoperative to postoperative as a result of improvement in the deformities of body curve, spine prominence, head chest hips, the position of head over hips, and shoulder level.

Satisfaction Domain (Questions 21, 22, 24)

Figure 6.28 displays the results of comparing the answers of patients to the questions of satisfaction domain preoperative and postoperative with our computed 3D indices from right to left. The difference between the preoperative evaluation chart and the postoperative evaluation chart shows that patients' satisfaction with the result of surgery has changed from very unsatisfied, unsatisfied, and neither satisfied nor unsatisfied to satisfied and very satisfied preoperative to postoperative by improving the deformities of different parts.

		% Of patients	Cobb					BSR					Coronal Lateral Shift					Coronal Balance					Shoulder Level				
			Best.....Worst					Best.....Worst					Best.....Worst					Best.....Worst					Best.....Worst				
Mental Health	Preoperative	Best.....Worst	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
		0%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		25%	0	0	2	2	0	2	0	2	0	0	0	2	0	0	0	2	0	2	0	0	0	0	2	0	0
		50%	0	0	4	12	2	4	14	0	0	0	0	4	6	2	0	2	8	2	0	0	2	6	0	0	0
		75%	0	0	16	30	8	10	32	8	2	2	0	12	22	8	2	32	10	8	0	0	10	8	8	0	0
		100%	0	0	10	10	4	4	14	6	8	0	0	8	6	2	0	8	4	2	2	0	0	6	8	2	0
	Postoperative	Best.....Worst	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
		0%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		25%	2	0	0	0	0	0	2	0	0	0	0	0	2	0	0	2	0	0	0	0	2	0	0	0	0
		50%	11	2	0	0	0	5	7	0	0	0	2	2	0	2	0	7	4	0	0	0	7	2	0	0	0
		75%	35	11	2	0	0	31	11	4	0	2	25	11	4	0	0	42	0	2	0	0	27	9	4	0	0
		100%	22	15	0	0	0	24	11	4	5	0	18	7	7	0	0	33	4	0	0	0	16	11	4	0	0

Figure (6.27) Evaluation of patients' satisfaction in Mental-Health Domain

		% Of patients	Cobb					BSR					Coronal Lateral Shift					Coronal Balance					Shoulder Level				
			Best.....Worst					Best.....Worst					Best.....Worst					Best.....Worst					Best.....Worst				
Satisfaction	Preoperative	Best.....Worst	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
		0%	0	0	3	0	0	3	0	0	0	0	0	3	0	0	0	3	0	0	0	0	0	0	3	0	0
		25%	0	0	5	0	3	0	5	3	0	0	0	5	0	0	0	3	3	0	0	0	0	0	3	3	0
		50%	0	0	3	16	0	0	11	8	0	0	0	0	11	3	0	3	8	5	0	0	3	3	3	5	0
		75%	0	0	11	24	11	14	32	0	0	0	0	8	19	5	3	24	5	8	0	0	0	14	5	3	8
		100%	0	0	8	8	3	5	8	3	3	0	0	11	3	3	0	5	8	5	0	0	8	5	3	0	0
	Postoperative	Best.....Worst	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
		0%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		25%	0	2	0	0	0	0	2	0	0	0	2	0	0	0	0	2	0	0	0	0	0	0	2	0	0
		50%	4	2	0	0	0	4	2	0	0	0	2	0	2	0	0	5	0	0	0	0	5	0	0	0	0
		75%	22	9	2	0	0	20	9	2	0	2	18	7	2	2	0	29	2	0	0	0	18	11	2	0	0
		100%	44	15	0	0	0	36	18	5	0	0	24	13	9	0	0	47	5	2	0	0	29	11	4	4	0

Figure (6.28) Evaluation of patients' satisfaction in Satisfaction Domain

6.3 Discussion

Regarding spinal correction, the Cobb angle is decreased in all cohorts which is an indication of a good spine correction achieved after scoliosis surgery making both patients and parents satisfied. However, there is trunk deformity in the back surface such as rib prominence, flank prominence, shoulders, and hips which are the major factors of patients' satisfaction [20]. Based on the previous study of our team [29,32], it shows that the realigning of the trunk is performed well, however, the deformity of back surface rotation is more challenging. Based on the results of this study, we can highlight that despite the challenge in the correction of the back surface rotation postoperatively, both parents and patients are satisfied with the results of the surgery regarding the rib prominence.

By analyzing the questionnaire of SAQ, we concluded that those patients and parents are satisfied with the results of the surgery related to body curve, rib prominence, the position of head over hips, and spinal prominence. In most cases, the flank prominence is not the concern of the patients and their parents. Furthermore, the perception of parents about head-chest hip is exaggerated. However, the perception of the patients is close to real deformity. Regarding deformity in the shoulder level, some patients and parents still can see a bigger deformity. In conclusion, it shows that parents see the deformities of the back surface of their children more than the real deformity before surgery, however, they are satisfied with the result of surgery. Patients are more satisfied with the results of surgery and their view is closer to the computed value in comparison with their parents. Generally, both patients and parents tend to see less deformity in postoperative. In postoperative evaluation, most of them selected answer 1 while the deformity was not that much corrected by interpreting. The correction of thoracic lumbar is not as good as the correction of other aspects. All aspects which are in the coronal view such as the head chest hips, the position of head over hips, and shoulder level are more important for both patients and parents.

In future work, patients could be asked to fill out the questionnaires by using an interface to visualize trunk and then answer questionnaires more precisely because more deformities can be seen even for the back surface. The future analysis of questionnaires using the new techniques can be compared with the results of this thesis to show the difference in answers of patients with and without using interface which visualizes the 3D trunk shape.

CHAPTER 7 ARTICLE 3: CHANGES IN TRUNK APPEARANCE AFTER SCOLIOSIS SPINE SURGERY: TWO-YEARS FOLLOW-UP STUDY

Maryam Khani^{a,b}, Farida Cheriet^{a,b}, Lama Seoud^{a,b}, Philippe Debanné^{a,b}, Stefan Parent^b, Hubert Labelle^b

^a Polytechnique Montréal, Department of Computer and Software Engineering, P.O. Box 6079, Montréal, H3C 3A7, Québec, Canada

^b Sainte Justine Hospital Research Center, 3175, Chemin de la Côte-Sainte-Catherine, Montréal, H3T 1C5, Québec, Canada

Presentation This work was submitted to the journal “Spine Deformity Journal” on August 7, 2023.

7.1 Abstract

Purpose: To assess the postoperative appearance of the trunk in surgically treated scoliosis patients after two-years follow-up using reliable indices and compare the results with six-months follow-up.

Methods: Forty-six Adolescent Idiopathic Scoliosis (AIS) patients (female; preop mean age 14.4 ± 2.4 y) who underwent a posterior spinal fusion from 2009 to 2018 were included in this study. All of them had Lenke 1A thoracic curves, with surface topography taken preoperatively, at six-months and two-years postoperatively. To assess the spinal deformity, we measured Cobb angles from spinal X-rays. To assess the trunk deformity, the Back Surface Rotation (BSR) and Trunk Lateral Shift (TLS) were computed along the trunk. We analysed the effect of age, height, weight, Cobb angle, length of follow-up, and surgical technique. We also compared correction rates of the spinal and trunk measurements after-six months and two-years follow-up.

Results: Regarding the spinal correction, the Cobb angle decreased in the whole cohort, which shows that good spinal correction was achieved after scoliosis surgery. Regarding the trunk correction, the correction rates for the TLS and BSR are positive (i.e. improved) for 76% and 48% of the patients respectively after two-years follow-up. In comparison with six-months follow-up, the mean TLS correction rate increases while there is no improvement for

the BSR on average.

Conclusion: Although there is a correction of more than 55% of the TLS after two-years follow-up, the BSR remains the same over time and the persistence of rib hump on the back surface can be observed after two-years follow-up.

Level of evidence: III.

Keywords: Adolescent Idiopathic Scoliosis (AIS); Trunk Deformity; Two years Follow-up; Scoliosis Surgery Outcome.

Statements and Declarations: The authors have no competing interests to declare that are relevant to the content of this article.

7.2 Introduction

Adolescent Idiopathic Scoliosis (AIS) is a three-dimensional deformation of the spine leading to asymmetry of the external shape of the trunk [29]. AIS is commonly diagnosed in adolescents aged between 10-18 years progressing rapidly during the adolescent growth. A severe scoliosis can cause functional problems in addition to trunk shape deformations, e.g., cardiac, pulmonary dysfunction, backaches [20]. Therefore, a surgical correction becomes necessary for these patients to stop scoliosis progression and to improve their quality of life by improving their external appearance [147]. After surgical treatment, persistence of external trunk asymmetry is frequent and difficult to predict by clinicians. This is a significant problem considering that correction of the apparent deformity is a major factor of satisfaction for the patients [148]. In light of this, evaluating residual postoperative deformity is important to document the effect of surgery on the external shape of the trunk.

To assess trunk deformity, clinicians commonly apply a standard screening procedure including the Adam forward bending test [14]. The latter is a multi-segmental assessment of the trunk deformity consisting in measuring the angle of the back surface inclination using a scoliometer (with the patient in forward bending position) between C7 and S1 at 10 levels [90].

To assess the trunk appearance, cross-sectional based methods [30, 32, 151] computing functional asymmetry indices were developed. In [32], several indices were used including Back Surface Rotation (BSR), Trunk Lateral shift (TLS), and coronal and sagittal trunk deviations computed from horizontal cross-sections of the trunk shape. A novel representation of the trunk was thereby used to assess global changes of the trunk deformity between two acquisitions.

While [29] analysed the changes in trunk appearance six months after scoliosis spinal surgery, a previous study [141] reported the importance of having a minimum follow-up period of two years to ensure vertebral stability and minimal loss of correction over time.

The objective of this study is to use reliable 3D trunk measurements proposed in a previous study [29] to assess the postoperative appearance of the trunk after two years follow-up and compare the results with those obtained after six months follow-up.

7.3 Materials and Methods

A Patient Data

For this study, we gathered retrospective data considering the following inclusion criteria: a Lenke 1A main thoracic curve type, full pre-operative and post-operative trunk acquisitions taken respectively at most six months before, and at least two years after surgery. Based on those criteria, we found 46 patients who underwent a posterior spinal fusion (PSF) from 2009 to 2018 at our hospital, by one of three orthopaedic surgeons. Each surgeon had a preferred surgical technique: The first surgeon (O1) performed a procedure that involves rotating a rod by 90 degrees, focusing mainly on the concave rod. This surgeon contoured the sagittal rod on the convex side and applied compression at the apex. The second surgeon (O2) included a direct vertebral derotation in addition to the rod rotation at all the instrument levels. The third surgeon (O3) performed a reduction through spine translation. These data have been collected under a study protocol approved by the hospital’s Research Ethics Committee. Demographic and radiological characteristics of the selected cohort are summarized in Table 7.1.

Table (7.1) Demographic and Radiological Information of Selected Cohort

Number=46	Mean $\pm$ Std	Range
Age (years)	14.5 $\pm$ 2.03	11 to 19
Height (cm)	159 $\pm$ 9.26	139 to 178
Weight (kg)	50.25 $\pm$ 9.84	30 to 79
Pre-op Cobb (deg)	54 $\pm$ 10.40	32 to 75

B Patient-Specific Trunk Geometric Model

To acquire and reconstruct a mesh of the whole trunk at the pre-operative and post-operative visits, a non-invasive optical system was used to capture the surface of the trunk in less than 5 seconds with an accuracy of 1.1 mm [84]. The 3D reconstruction of the surface of the trunk is transposed into a patient-specific 3D reference frame that

is equivalent to the whole-body coordinate system of the Scoliosis Research Society (SRS) [157]. The definition sets the origin as the midpoint of the PSIS, the y-axis upwards vertically, the x-axis horizontally parallel to the ASIS line, oriented towards the right, and the z-axis oriented toward the back.

C Trunk Measurements

300 horizontal, equally spaced cross-sections are extracted from L5/S1 to C7/T1 vertebral levels along the trunk height (Y-axis). Trunk asymmetry measurements including the BSR and TLS are subsequently computed for each cross-section. To quantify changes in BSR and TLS before and after surgery, we used the relative correction rate (CR) proposed in 7.1:

$$CR_{BSR}(\%) = 100 \times \frac{\sum |f_{pre}^{BSR}(t)| - \sum |f_{post}^{BSR}(t)|}{\sum |f_{pre}^{BSR}(t)|} \quad (7.1)$$

$$CR_{TLS}(\%) = 100 \times \frac{\sum |f_{pre}^{TLS}(t)| - \sum |f_{post}^{TLS}(t)|}{\sum |f_{pre}^{TLS}(t)|} \quad (7.2)$$

where f_{pre}^{BSR} and f_{pre}^{TLS} refer to the preoperative functional measurements of BSR and TLS and f_{post}^{BSR} and f_{post}^{TLS} refer to the postoperative functional measurements of BSR and TLS. To compute the functional measurements, the sum of absolute values of the measurement is computed along the trunk shape. Positive and negative values of CR indicate respectively an improvement and a worsening of the deformity after surgery.

D Spinal Measurements

We collected the 3D spine shape reconstructions obtained from calibrated biplanar radiographs for each patient at the preoperative, six months and two years postoperative visits. Then, 2D spinal measurements including the proximal thoracic (PT), main thoracic (MT), and thoracolumbar/lumbar (TLL) Cobb angles were computed in the frontal plane. In addition, we obtained the scoliometer measurements in the thoracic and lumbar regions. Similarly to the trunk measurements, a CR can be defined for a given spine measurement:

$$CR_{Meas}(\%) = 100 \times \frac{Meas_{pre} - Meas_{post}}{Meas_{pre}} \quad (7.3)$$

where Meas is a Cobb angle or scoliometer reading.

Furthermore, we performed a correlation analysis between the CRs of the trunk measurements and those of the 2D spinal measurements.

7.4 Results

A Correction rates after two years follow-up

Table 7.2 illustrates the BSR, TLS, and Cobb angle CRs for all the cohort and per surgeon. On average, the TLS is reduced (median of 55%) after two years. The TLS has decreased for 76% (35/46) of the patients, with a CR reaching up to 88%. For 24% (11/46) of the patients, the TLS has increased after two years.

The results present a negligible correction of the BSR (median of -1%). The BSR has improved for 48% (22/46) of the patients, but the CR never exceeds 56%. The BSR remained stable for 7% (3/46) of the patients and has worsened for 45% (21/46) of the patients two years after surgery.

To compare with spinal correction, the MT Cobb angle shows an average CR of 74%, revealing a good correction of the scoliotic spine curvature in the frontal plane.

We conducted analyses of variance (regression model and ANOVA) to evaluate the association between the changes in the trunk shape and clinical variables as well as surgical techniques. Table 7.3 shows that there is no significant association between clinical measurements (age, height, weight, and preoperative Cobb angle) and CRs after two years for the BSR or the TLS ($p > 0.05$ in all cases). Seoud et al. [29] reported that the surgical technique has significant impact on the CRs of the BSR after six months. We also implemented a one-way ANOVA model with the three surgical techniques as the categorical variable and BSR or TLS as the continuous variable. Our own results show that surgical technique has no significant impact on the CRs of the BSR ($F(2,43) = 0.26$, $p = 0.76$) or TLS ($F(2,43) = 0.79$, $p = 0.45$).

Table 7.4 shows the Pearson correlation coefficients obtained between the Cobb angle and scoliometer CRs, on one hand, and the BSR and TLS CRs, on the other hand, at two years follow-up. The result shows that there are significant correlations between the CR of the TLS and the main thoracic Cobb angle ($R=0.35$), and between the CR of the BSR and the thoracic scoliometer reading ($R=0.24$).

Table (7.2) BSR, TLS, and MT Cobb angle CRs, overall and per surgeon (two years follow-up).

CR (%)	Mean	Median	Standard Deviation	Minimum	Maximum
Overall CR_{BSR}	-5	-1	36	-109	56
O1 (n = 19)	7	4	33	-70	31
O2 (n = 23)	-2	-1	41	-109	56
O3 (n = 4)	-16	-23	33	-48	28
Overall CR_{TLS}	32	55	57	-152	88
O1 (n = 19)	39	59	54	-73	88
O2 (n = 23)	23	53	63	-152	82
O3 (n = 4)	56	57	6	50	61
Overall Cobb_{MT}	74	74	18	22	100
O1 (n = 19)	77	75	12	52	100
O2 (n = 23)	69	69	21	22	100
O3 (n = 4)	84	86	18	62	100

Table (7.3) Association of CRs with clinical variables (regression model, two-year follow-up).

	CR_{TLS}			CR_{BSR}		
N = 46	R²	F	P	R²	F	P
Age	0.0009	0.038	0.844	0.024	1.034	0.314
Height	0.008	0.372	0.544	0.006	0.259	0.613
Weight	0.001	0.048	0.827	0.014	0.624	0.433
Pre-op Cobb	0.009	0.410	0.525	0.017	0.754	0.390
Follow-up length	0.007	0.328	0.569	0.056	2.520	0.119

Table (7.4) Correlation between spine and trunk CRs (n=46) after two-years follow-up. (*: $p < 0.05$)

Length of follow-up	Two years	
CR	CR _{BSR}	CR _{TLS}
CR _{Cobb PT}	0.03	0.06
CR _{Cobb MT}	0.03	0.35 *
CR _{Cobb TLL}	0.02	0.08
CR _{Scoliometer T}	0.24 *	0.11
CR _{Scoliometer L}	0.001	0.18

B Postoperative Evolution of the Trunk Shape

Figure 7.1 presents box plots of the absolute values of the MT Cobb angles and scoliometer readings, the sum of absolute values of the BSR, and the sum of absolute values of the TLS according to patient visit: preoperatively, after six months and after two years. A Student's t test analysis for the values in Figure 7.1 shows that there are statistically significant improvements for scoliometer, Cobb angle, and TLS from preop to six months and preop to two years postop. The only significant improvements from six months to two years are for Cobb angle and TLS. However, we didn't find any significant differences between preop, six month, and two-year postop for BSR.

Figure 7.2 visualises the average evolution of BSR and TLS per surgeon from preop to postop six months and postop two years. The sum of absolute values of BSR and TLS for surgeons O1, O2, and O3 are in the same range, with no change on average after two years follow-up.

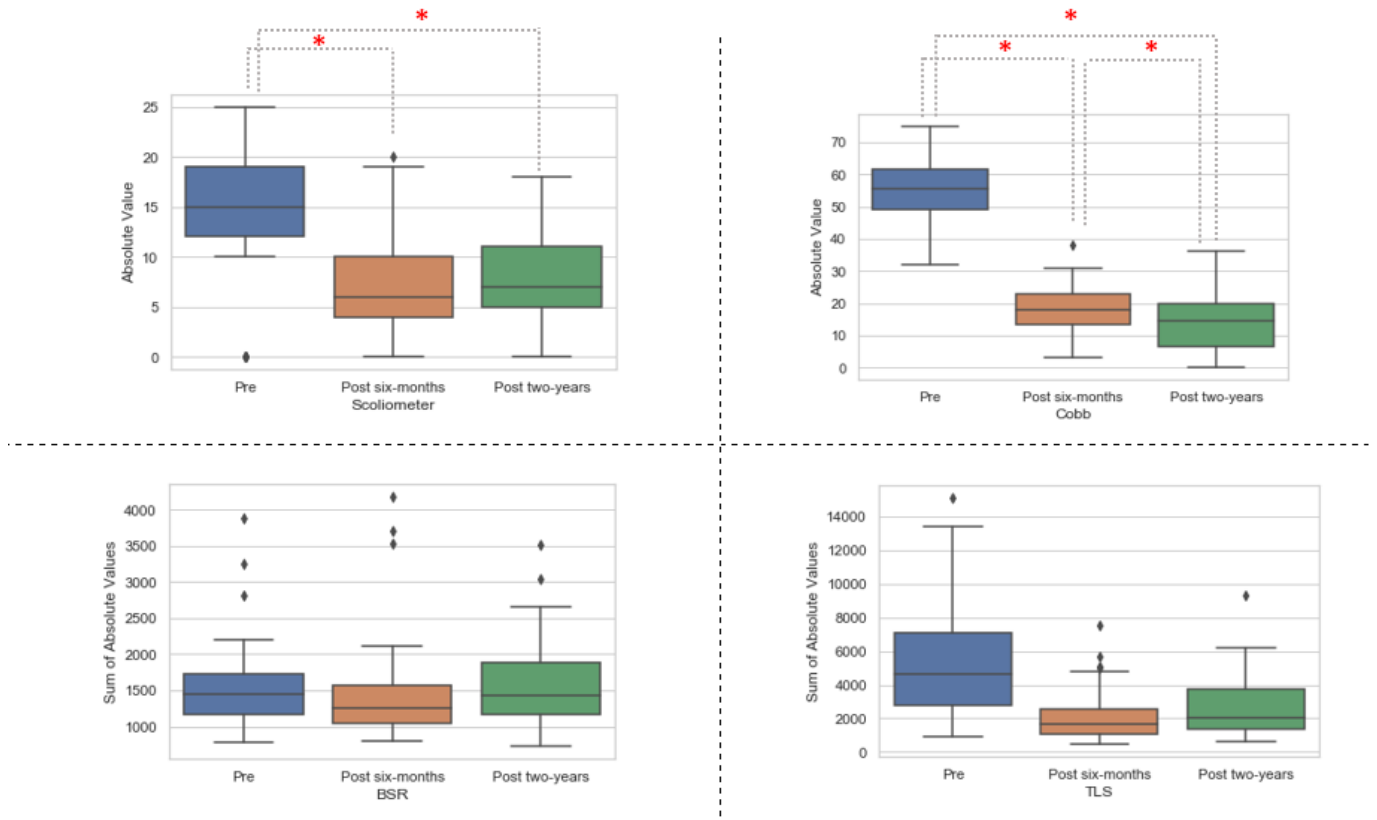
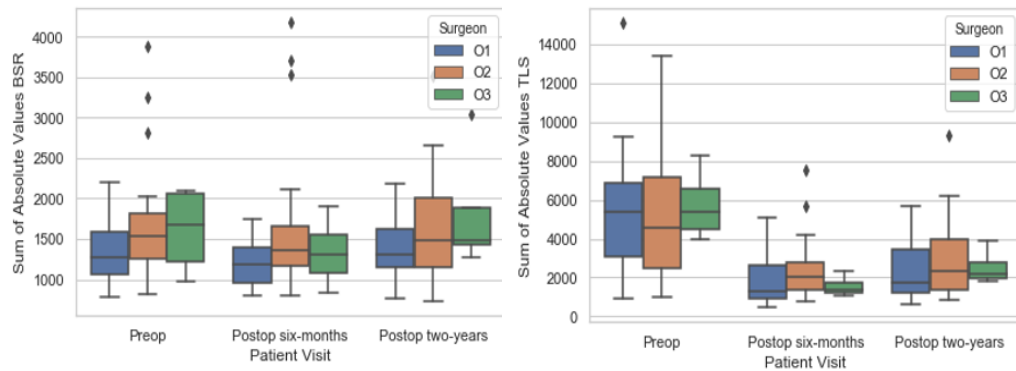


Figure (7.1) Box plots for thoracic scolioter, MT Cobb, BSR and TLS: preop (blue), postop six months (orange) and postop two years (green). Individual black diamonds are outliers. Red asterisks “*” at the top indicate significant improvements between patient visits.



(a) Sum of absolute values of BSR per surgeon (b) Sum of absolute values of TLS per surgeon

Figure (7.2) Box plots and distributions for BSR (a) and TLS (b) per surgeon: O1 (blue), O2 (orange), and O3 (green) are shown for preop, six months, and two years follow-up. Outliers are individual black diamonds.

7.5 Discussion

According to Benli et al. [141], it is important to have a minimum of two years follow-up to document vertebral stability and ensure that spinal correction is maintained. Since patients and their parents are concerned about their appearance, rib hump and curve of the spine after surgery [148], we reported the correction rates of these indices after two years and then compared the results with those obtained after six months. To the best of our knowledge, this is the first study with two years clinical follow-up documenting the surgical outcome in terms of trunk shape using surface topography (as opposed to rib hump measurements by scoliometer like in [158, 159]). It represents a continuation of the six months follow-up study on trunk shape in [29]. Previous studies using trunk asymmetry indices extracted the maximum values of BSR and TLS along the trunk [30, 31, 90, 91, 149–151]. By contrast, our measurements are multilevel and computed all along the trunk height.

The hypothesis regarding correlation between spine and trunk deformity is supported by the significant correlation found between the TLS CR and the MT Cobb angle, with p -value = 0.01 and $R=0.35$ (see Table 7.4). This shows that a better correction of the thoracic region can result in a better realignment of the trunk. In regard to the spinal correction, the Cobb angle decreased in the whole cohort, thus a good spine correction was achieved after scoliosis surgery. Since the Cobb angle is correlated to the TLS, the correction of more than 50% of the TLS after spine surgery (see Table 7.2) is as expected. Some patients showed deterioration of TLS; in particular, an extreme value of $CR_{TLS} (< -150\%)$ for one patient means there was a very mild TLS before surgery that more than doubled two years after surgery. Generally, though, a good trunk realignment in the coronal plane was achieved. In comparison with [29], the most significant correction in the trunk deformity measurements is for the TLS.

Referring to the correction of the BSR, the study in [29] reported a mean correction of 18% of BSR in 49 patients, while we document a mean CR of -5% in the cohort of 46 patients after two years, meaning that the 6-months post-operative correction of the rib hump is lost after two years. This finding corroborates the rib-hump reassertion phenomenon reported by Pratt et al. [158].

Newton et al. [159] documented a mean reduction of 7° in scoliometer measurements for patients having undergone PSF, corresponding to a CR of 44%. In our cohort, we instead found mean increases of 3.5° and 4.8° in maximal BSR value after six months and two years, corresponding to mean CRs of -69% and -74%. This quantifies a worsening of the rib hump over time, and again confirms the rib reassertion phenomenon documented in long-term

follow-up [158, 160].

The contrasting findings between scoliometer and BSR in terms of correction rates could be explained by the fact that the scoliometer measurement is performed at the apex of the thoracic curve in forward bending, while we consider the sum of BSR values along the spine in the upright position. In fact, a decrease in scoliometer measurement does not necessarily mean that the rib hump has been corrected. Rather, the hump could have spread to a wider region, in which case a lower maximal deformity is concomitant with an increased cumulative measurement.

No statistically significant relationships between clinical indices such as age, height, and weight were observed with the BSR and TLS measures (see Table 7.3). Neither do the surgical techniques have an impact on the BSR and TLS CRs after six months or two years. This finding is contrasted with the one in [29] where a statistically significant difference between surgical techniques was noted in terms of BSR CR. This difference could be explained by different number of patients in the two cohorts (49 patients in [29] vs. 46 in our cohort, of which 27 patients were in common), and/or by the comparatively small number of patients who underwent treatment by surgeon O3 ($n=4$).

This study shows that the effect of the surgery on the Cobb angle is stable and can even improve with time, while its effect on the BSR and TLS risks changing, even deteriorating, in the long term (when patients are monitored for two years or more post-operatively). This finding highlights the need for surgical approaches to focus on achieving a better correction of the trunk shape, in particular the rib hump.

Our study has a number of limitations. First, we computed only two 3D trunk shape indices, namely the BSR (which evaluates the extent of posterior rib hump) and TLS in the frontal plane. These two indices reflect major concerns of the patients and their parents. They are computed along the trunk height and analysing multilevel functional measurements allows us to evaluate global trunk deformity in the coronal and axial planes. However, new indices to assess local deformities in specific areas such as the upper shoulders, shoulder blades, waist, and the PT, MT and TLL regions, would be needed. Indeed, these local asymmetries could express trunk asymmetry more precisely. Second, our study cohort only included AIS patients of class Lenke 1A, which is the most frequent curve type among AIS patients. However, it would be helpful to evaluate the surgical outcome for all types of spinal curves.

As future work, we are interested in investigating how surgical outcome in terms of BSR and TLS correlates with the outcome in terms of patient satisfaction. This knowledge could help surgeons to know how much of a correction in the trunk shape is needed to be considered as satisfactory for the patients and their parents.

7.6 Acknowledgments

This work was funded by the Canadian Institutes of Health Research (CIHR) and the Trans-MedTech Institute. The authors thank the personnel of the Orthopaedics Research Clinical Unit (URCO, CHU Sainte-Justine) for their help with collecting clinical data. The authors have no competing interests to declare that are relevant to the content of this article.

CHAPTER 8 GENERAL DISCUSSION

This thesis project has the general objective of developing a surgical planning tool related to patients with Adolescent Idiopathic Scoliosis (AIS). Through this tool, both surgeons and patients will be able to visualize the expected outcomes of spinal surgery. Additionally, the goal is to facilitate the automatic assessment and documentation of the results obtained from scoliotic surgical procedures. Therefore, we applied deep learning algorithms to predict the postoperative shape of the spine as well as proposed mathematical metrics to develop the automatic assessment of the appearance of the trunk after spinal surgery. The development of these methods will assist surgeons and AIS patients.

The following sections discuss our contributions and their limitations.

8.1 Prediction of Postoperative Shape Of the Spine using Deep Learning Approaches

Our main contribution is the prediction of the postoperative spine shape after scoliosis spinal surgery that can be used in the existing trunk simulator. Therefore, the trunk simulator can visualize the trunk shape after surgery by propagating the spine correction toward the external shape of the trunk. Although there are spinal simulators [3, 52–55], they come with the limitation of necessitating the definition of the spine’s mechanical properties and the properties of its individual components. Furthermore, they are not validated for general population since only limit cohort of patients are considered while this is essential to predict the postoperative spine shape for general population. We have shown that state-of-art deep learning models have the capability of predicting the personalized surgery outcome.

In the literature, the P2P network [137] which is developed as a base model works well for shapes with large displacement such as deforming from one type of chair to another type but for our project, we are looking to find displacement between the preoperative shape of the spine and postoperative shape of the spine, even if there is a small displacement between the consecutive vertebra. We have shown that our proposed model can learn small deformations including translation and rotation between consecutive vertebrae. The proposed model with a simple structure of FCCN could fit with the structure of our data and it has shown that the network is sensitive to the small displacement.

8.1.1 Limitations

While our proposed approach has brought several contributions to the prediction of spinal surgery, the work is still far from complete. The most important shortcoming of our proposed method is that it can not preserve the topology of each vertebra even though the proposed model can preserve the global topology of the spine. Therefore, it needs to consider the constraint for points of each vertebra. A potential approach is to add a loss function to learn the point displacement of the vertebra. The integration of such an additional network, however, should increase the preservation of both global topology and local topology of each vertebra.

Also, there is a limitation regarding the model's utilization of clinical metadata which is restricted to a few variables, and there has been no investigation into the potential of incorporating additional clinical information into the model.

Another drawback is that the model is only trained for small number of patients who underwent the surgery with 6-month follow-up data. However, it is important to consider sufficient data for training a deep learning-based model. In our case, to predict the postoperative spine shape for different surgical strategies, it is crucial to collect enough data for each type of scoliosis surgery.

8.2 Automatic Assessment of Scoliosis Surgery Outcome

LRTA Measurements

Evaluating the accuracy of the AIS surgical tool in predicting the postoperative trunk shape is crucial to ensure its reliability. However, the existing approaches used to assess trunk appearance after surgery by computing GTA measurements which can not identify local deformities of trunk surface. The second contribution of this study involves introducing a novel set of LRTA indices which combined with GTA indices provide valuable insights on the outcomes of surgical procedures. They provide quantitative evaluation of postoperative trunk appearance in a retrospective cohort of surgical AIS patients. The introduced indices have demonstrated their ability to assess specific trunk asymmetries and to quantify improvement or deterioration following scoliosis surgery.

Evaluate the patient and parent's expectations and satisfaction

The clinician's assessment of patients' and their parents' expectation and satisfaction with the appearance of patients' trunks after scoliosis surgery is important. Therefore, we are motivated to analyze SAQ and SRS of both patients and parents with 3D surface topogra-

phy measurements. Although the previous studies analyzed the SRS questionnaires using volumetric asymmetry metrics, they did not assess both patients' and parents' reported questionnaires SAQ and SRS with spine and 3D trunk deformity measurements. Also, more comprehensive 3D trunk measurements are needed that can compute both global deformities and left-right trunk asymmetries in local regions which can highlight the expectation and satisfaction of the patients and their parents. The third contribution of this research study is finding the association of the SAQ and SRS scores with the 3D trunk deformity measurements to evaluate the patient's expectation and satisfaction from those correlated scores. By finding the association between the 3D trunk measurements and questionnaires of SAQ and SRS, we could analyze the satisfaction and expectation of both patients and their parents about the results of surgery which can help clinicians.

8.2.1 Limitations

Despite several mentioned contributions of our proposed LRTA indices and the results of analysing questionnaires, there are still certain limitations in our approach.

Firstly, the introduced indices only applied on data of 49 patients who underwent posterior spinal fusion with 6 months follow-up after surgery. More data should be considered. Also, instead of criteria of at least six-months follow up to select the patients, it is better to have a cohort with constant duration of follow up such as six-months $\pm$ two-months.

To determine more precisely which proposed measurements are really able to measure, a validity/reliability study would be useful. Also, designing an interface to visualize trunk shape could help patient in filling out the questionnaires. This could lead to more accurate questionnaire responses due to the enhanced visibility of deformities, especially those on the back surface. Therefore, future assessments of the questionnaires using this interface can be compared with the results of this thesis. This comparison aims to highlight variations in responses between patients who utilized the visual interface for 3D trunk shape visualization and those who didn't. Moreover, the ordinal logistic regression model which is a more complex statistical model could be used to explore the the relationship between questionnaire items and 3D trunk measurements more profoundly. The model could set the questionnaire items as the dependent variable and the 3D trunk measurements as the independent variable. Also, a research study to compare the findings in terms of LRTA measurements with what the questionnaires show, would be valuable for clinicians.

8.3 Two-Years Follow-up Study of Scoliosis Surgery Outcome

It is crucial to have a two-years follow-up study as prior studies have highlighted its significance in maintaining vertebral stability and observing spinal correction without any deterioration [109]. Existing research studies have recorded scoliosis surgical outcomes up to a six-month follow-up, but currently, there is no documentation available on evaluating the impact of spinal surgery on overall trunk surface deformities after a two-year follow-up. Another contribution of this study is documenting the changes in trunk appearance after scoliosis spine surgery in two-year follow-up study. We assessed the postoperative appearance of the trunk in scoliosis patients who underwent surgery in two-years follow-up and compared these findings with the results from the six-month follow-up. Our finding could be valuable in documenting the long-term surgical outcomes, taking into account the perception of both the patients and their parents.

8.3.1 Limitations

Although our documentation provided some contributions, there are few limitations which need to be addressed in the future work.

A larger cohort would provide more statistically significant findings, and maybe more significant correlations (higher R values) with the underlying spine correction. Also, it is better to have patient cohort with different curve types.

In the current cohort, surgeon O3 only operated 4 patients. More balanced in cohorts of patients operated by the participating surgeons would be needed to get better conclusion.

Also, to assess the spinal deformity, we only measured Cobb angles from spinal X-rays and to assess the trunk deformity, we only computed the Back Surface Rotation (BSR) and Trunk Lateral Shift (TLS) along the trunk. There are more clinical measurements to assess spine and trunk deformities which should be considered.

CHAPTER 9 CONCLUSION

Summary of Works

This thesis has addressed the automatic analysis of the scoliotic trunk for surgery planning and outcome assessment.

Firstly, we proposed a new tool to assist in surgical planning, enabling accurate prediction of the effect of scoliosis surgery on the appearance of the trunk shape. We introduced a supervised neural network called Controlled Point Deformation Network (CPDNet) to predict the postoperative spine shape of scoliosis patients. The predicted postoperative shape of the spine can be fed into the existing simulator of the external shape of the trunk to simulate the propagation of the spine correction toward the external shape of the trunk. Our CPDNet utilizes the inherent properties of shape, such as neighborhood constraints between consecutive vertebrae along the spine, to effectively regulate the deformation of a source configuration towards a desired target. The application of this proposed approach is directed toward predicting the postoperative spinal shape in scoliosis patients who are undergoing corrective spine surgery. CPDNet has the clinical potential to serve as the basis for developing a surgical planning tool in scoliosis cases. This tool would enable surgeons and patients to visualize and evaluate the projected postoperative outcomes based on different surgical techniques, thereby enhancing the decision-making process.

Secondly, we proposed a novel set of quantitative metrics to assess the postoperative appearance of the trunk shape in AIS patients after their surgery and during clinical follow-ups. It could work effectively to assess the accuracy and reliability of the AIS surgical tool in predicting the external shape of the trunk. Also, they could be used for detecting left-right trunk asymmetry measurements in local regions such as shoulders and waist.

Following the proposed metrics, we extended the research by documenting the level of satisfaction and expectation of both patients and their parents about the outcome of the scoliosis surgery. We investigated how surgical outcomes in terms of global and left-right trunk deformities in asymmetry areas are associated with the outcome in terms of patient satisfaction and expectations. This knowledge could help surgeons to know how much of a correction in the trunk shape is needed to be considered as satisfactory for the patients and their parents.

Another contribution of this thesis is documenting the changes in trunk appearance after two-years follow-up in scoliosis spine surgery. A two-year follow-up study is important due to the previous studies highlighting its importance in ensuring vertebral stability and observing

the preservation of spinal correction without any loss. The findings of this study show that the impact of surgery on the Cobb angle will be stable and can even improve over time. However, the effects on BSR and TLS can vary and potentially worsen in the long term, specifically when patients are observed for a period of two years or more after the operation. These results highlight the importance of surgical approaches prioritizing a more effective correction of the trunk shape, particularly addressing the rib hump.

Future Work

We believe the developed methods and documentation will contribute to the design of a surgical planning tool specifically for the treatment of AIS patients, with the purpose of enabling surgeons and patients to visualize the predicted outcome of spinal surgery. It can help both the clinicians and the patient to see the potential results of the surgery. Then, the patient can make a decision to accept or refuse surgery. Additionally, these contributions aim to automate the assessment and documentation of scoliotic surgical results.

The limitations discussed in chapter 8 provide opportunities for new developments and innovations to emerge. It would be very helpful to add more constraints to have the same displacements for points of each vertebra which helps to preserve the topology of each vertebra not only the global topology of the spine. Moreover, more meta-data such as preoperative patient-specific factors and surgical factors could be added as feature vectors. This might enhance the performance of the network and the accuracy of the predicted postoperative spine shape. After developing the proposed model of CPDNet, it would be interesting to provide the predicted postoperative spine shape as input for the existing trunk simulator [27, 28]. This existing developed physical model is based on optimizing the energy deformation associated with the preop-postop displacement of the spine propagated to each element in an incompressible tetrahedral mass system. Although the results obtained in this manner are promising, more effort needs to be deployed in the calibration of the rigidity constants of the physical model. Then, this tool can be used as a scoliotic surgery planning tool which helps to visualize the outcome of spine surgery to see the potential results of the surgery.

Another interesting research topic could be evaluating the surgical outcome in both terms of global deformities and LRTA deformities in local regions of the back surface of the trunk shape for all types of spinal curves and not only the specific types such as class Lenke 1A.

REFERENCES

- [1] W. Wang *et al.*, “Top theories for the etiopathogenesis of adolescent idiopathic scoliosis,” p. S14–S27, 2011.
- [2] S. Weinstein *et al.*, “Adolescent idiopathic scoliosis.” *Lancet*, vol. 371, no. 9623, p. 1527–1537, 2008.
- [3] M. Aebi, “The adult scoliosis,” *Eur. Spine J.*, vol. 14, no. 10, p. 925–948, 2005.
- [4] M. Konieczny, H. Senyurt, and R. Krauspe, “Epidemiology of adolescent idiopathic scoliosis,” *J Child Orthop*, pp. 3–9, 2013.
- [5] H. Lombaert *et al.*, “Focusr: Feature oriented correspondence using spectral regularization-a method for precise surface matching,” *IEEE Transactions on Pattern Analysis and Machine Intelligence.*, pp. 2143–2160, 2013.
- [6] P. Deacon, B. Flood, and R. Dickson, “Idiopathic scoliosis in three dimensions. a radiographic and morphometric analysis,” *J. Bone Joint Surg. Brit.*, vol. 66, no. 4, p. 509–512, 1984.
- [7] D. Fong *et al.*, “A meta-analysis of the clinical effectiveness of school scoliosis screening,” *Spine*, p. 1061–1071, 2010.
- [8] J. Sabirin *et al.*, “School scoliosis screening programme-a systematic review,” *Med J Malays*, p. 261–267, 2010.
- [9] H. Sox *et al.*, “Screening for adolescent idiopathic scoliosis: review article.” *JAMA*, p. 2667–2672, 1993.
- [10] W. Bunnell, “An objective criterion for scoliosis screening.” *J Bone Joint Surg*, p. 1381–1387, 1984.
- [11] N. Scutt, P. Dangerfield, and J. Dorgan, “The relationship between surface and radiological deformity in adolescent idiopathic scoliosis: effect of change in body position,” *Eur Spine J.*, pp. 85–90, 1996.
- [12] G. Murrell *et al.*, “An assessment of the reliability of the scoliometer,” *Spine*, vol. 18, pp. 709–712, 1993.

- [13] L. Amendt *et al.*, “Validity and reliability testing of the scoliometer,” *Phys Ther*, vol. 70, p. 108–117, 1990.
- [14] P. Patias *et al.*, “A review of the trunk surface metrics used as scoliosis and other deformities evaluation indices,” *Scoliosis*, vol. 5, no. 1, 2010.
- [15] R. Buchanan *et al.*, “Do you see what i see? looking at scoliosis surgical outcomes through orthopedists’ eyes,” *Spine*, vol. 28, no. 24, p. 2700–2704, 2003.
- [16] A. K. Malfair, D. Flemming1 *et al.*, “Radiographic evaluation of scoliosis: review,” *Amer. J. Roentgenol.*, vol. 194, no. 3, p. S8–S22, 2010.
- [17] S. Roy *et al.*, “A noninvasive 3D body scanner and software tool towards analysis of scoliosis,” *Biomed. Res. Int.*, pp. 1–15, 2019.
- [18] K. Pehrsson, O. A. Larsson, S., and A. Nachemson, “Long-term followup of patients with untreated scoliosis. a study of mortality, causes of death, and symptoms,” *Spine*, vol. 9, no. 17, p. 1091–1096, 1992.
- [19] T. N. Theologis *et al.*, “Quantifying the cosmetic defect of adolescent idiopathic scoliosis,” *Spine*, vol. 18, no. 7, p. 909–912, 1993.
- [20] M. Hawes, “Impact of spine surgery on signs and symptoms of spinal deformity,” *Pediatric Rehabil.*, vol. 9, no. 4, p. 318–339, 2006.
- [21] L. Hackenberg *et al.*, “Rasterstereographic back shape analysis in idiopathic scoliosis after posterior correction and fusion,” *J. Bone Joint Surg. Brit.*, vol. 18, no. 10, p. 883–889, 2003.
- [22] C. Wise *et al.*, “The cartilage matrisome in adolescent idiopathic scoliosis. bone research,” vol. 8, no. 13, 2020.
- [23] C. Aubin, H. Labelle, and O. Ciolofan, “Variability of spinal instrumentation configurations in adolescent idiopathic scoliosis,” *Eur Spine J*, p. 57–64, 2007.
- [24] Y. Majdouline *et al.*, “Scoliosis correction objectives in adolescent idiopathic scoliosis,” *J Pediatr Orthop*, p. 775–781, 2007.
- [25] M. Robitaille, C. Aubin, and H. Labelle, “Intra and interobserver variability of pre-operative planning for surgical instrumentation in adolescent idiopathic scoliosis,” *Eur Spine J*, p. 1604–1614, 2007.

- [26] Y. Majdouline *et al.*, “Preoperative assessment and evaluation of instrumentation strategies for the treatment of adolescent idiopathic scoliosis: computer simulation and optimization,” *Scoliosis*, vol. 7, no. 21, 2012.
- [27] K. Assi *et al.*, “Physically based trunk soft tissue modeling for scoliosis surgery planning systems,” *Computerized Medical Imaging and Graphics : the Official Journal of the Computerized Medical Imaging Society.*, vol. 40, pp. 217–228, 2015.
- [28] O. Dionne *et al.*, “Simulation of the postoperative trunk appearance in scoliotic surgery,” *ISBI 2012.*, pp. 1208–1211, 2012.
- [29] L. Seoud *et al.*, “Changes in trunk appearance after scoliosis spinal surgery and their relation to changes in spinal measurements,” *Spine Deformity*, vol. 3, 2015.
- [30] P. O. Ajemba, N. Durdle, and V. J. Raso, “Characterizing torso shape deformity in scoliosissing structured splines models,” *IEEE Trans. Biomed. Eng.*, vol. 56, no. 6, p. 1652–1662, 2009.
- [31] V. Pazos *et al.*, “Reliability of trunk shape measurements based on 3D surface reconstructions,” *Eur Spine J.*, vol. 16, no. 11, p. 1882–1891, 2007.
- [32] L. Seoud *et al.*, “Multilevel analysis of trunk surface measurements for noninvasive assessment of scoliosis deformities,” *Spine.*, 2012.
- [33] L. Seoud *et al.*, “Noninvasive clinical assessment of trunk deformities associated with scoliosis,” *IEEE Journal of Biomedical and Health Informatics.*, vol. 17, pp. 392–401, 2013.
- [34] A. Jalalian, I. Gibson, and E. Tay, “Computational biomechanical modeling of scoliotic spine: Challenges and opportunities,” *Epub*, 2013.
- [35] C. Aubin, “Scoliosis study using finite element models.” *Stud Health Technol Inform*, vol. 91, pp. 309–313, 2002.
- [36] I. Stokes and M. Gardner-Morse, “Three-dimensional simulation of harrington distraction instrumentation for surgical correction of scoliosis,” *Spine.*, pp. 2457–2464, 1993.
- [37] I. Stokes and M. Gardner-Morse, “Simulation of surgical maneuvers with CD instrumentation,” *Three dimensional analysis of spinal deformities*, pp. 377 – 380, 1995.
- [38] V. Lafage *et al.*, “3D finite element simulation of cotrel-dubousset correction,” *Comput Aided Surg.*, pp. 17–25, 2004.

- [39] P. Le Borgne *et al.*, “Finite element model of scoliotic spine: Mechanical personalization,” *International Research Society of Spinal Deformities*, pp. 130 – 133, 1998.
- [40] C. Aubin, V. Goussev, and Y. Petit, “Biomechanical modelling of segmental instrumentation for surgical correction of 3D spinal deformities using euler- bernoulli thin-beam elastic deformation equations,” *Med Biol Eng Comput*, pp. 216–221, 2004.
- [41] K. Duke *et al.*, “Computer simulation for the optimization of patient positioning in spinal deformity instrumentation surgery,” *Med Biol Eng Comput.*, vol. 46, no. 1, pp. 33–41, 2008.
- [42] J. Henao *et al.*, “Patient-specific finite element model of the spine and spinal cord to assess the neurological impact of scoliosis correction: preliminary application on two cases with and without intraoperative neurological complications,” *Comput Methods Biomech Biomed Engin.*, vol. 19, no. 8, pp. 901–910, 2016.
- [43] I. Stokes *et al.*, “Biomechanical simulations for the planning of scoliosis surgery,” *Stud Health Technol Inform*, vol. 59, pp. 343–346, 1999.
- [44] F. Poulin *et al.*, “Biomechanical modeling of instrumentation for the scoliotic spine using flexible elements: a feasibility study,” *Ann Chir.*, p. 761–767, 1998.
- [45] C. Aubin *et al.*, “Biomechanical modeling of posterior instrumentation of the scoliotic spine,” *Engin*, pp. 27–32, 2003.
- [46] G. Desroches *et al.*, “Simulation of an anterior spine instrumentation in adolescent idiopathic scoliosis using a flexible multi-body model,” *Med Biol Eng Comput*, pp. 759–768, 2007.
- [47] C. Aubin *et al.*, “Preoperative planning simulator for spinal deformity surgeries,” *Spine.*, vol. 33, pp. 2143–52, 2008.
- [48] M. Robitaille, C. Aubin, and H. Labelle, “Effects of alternative instrumentation strategies in adolescent idiopathic scoliosis: a biomechanical analysis,” *Orthop. Res.*, vol. 27, p. 104–113, 2009.
- [49] Y. Majdouline *et al.*, “Computer simulation for the optimization of instrumentation strategies in adolescent idiopathic scoliosis,” *Medical biological engineering computing.*, vol. 47, pp. 1143–54, 2009.

- [50] Y. Petit, C. Aubin, and H. Labelle, "Patient-specific mechanical properties of a flexible multi-body model of the scoliotic spine." *Med Biol Eng Comput.*, vol. 42, no. 1, pp. 55–60, 2004.
- [51] S. Pasha and J. Flynn, "Data-driven classification of the 3D spinal curve in adolescent idiopathic scoliosis with an applications in surgical outcome prediction." *Global geometric torsion estimation*, vol. 8, no. 1, 2018.
- [52] S. Pasha *et al.*, "Discovering the association between the pre- and post-operative 3D spinal curve patterns in adolescent idiopathic scoliosis," *Spine Deformity*, vol. 9, no. 4, 2020.
- [53] S. Pasha *et al.*, "Machine learning predicts the 3D outcomes of adolescent idiopathic scoliosis surgery using patient–surgeon specific parameters," *Spine*, vol. 46, no. 9, 2021.
- [54] G. Picinbono, H. Delingette, and N. Ayache, "Real-time large displacement elasticity for surgery simulation: non-linear tensor-mass model," *Proceedings of the third international conference on medical image computing and computer-assisted intervention*, pp. 643–652, 2000.
- [55] S. Cotin, H. Delingette, and N. Ayache, "Real-time elastic deformations of soft tissues for surgery simulation," *IEEE Trans Visual Comput Graph*, vol. 59, p. 62–73, 1999.
- [56] J. Dansereau *et al.*, "Three dimensional reconstruction of the spine and the rib cage from stereoradiographic and imaging techniques," *16th Conf Can Soc-Mech Eng*, p. 61–64, 1990.
- [57] F. Cheriet and J. Meunier, "Self-calibration of a biplane x-ray imaging system for an optimal three dimensional reconstruction. comput med imaging graph," p. 133–141, 1999.
- [58] S. Kadoury *et al.*, "A versatile 3D reconstruction system of the spine and pelvis for clinical assessment of spinal deformities," *Med Biol Eng Comput*, p. 591–602, 2007.
- [59] S. Pasha *et al.*, "Characterizing the differences between the 2D and 3D measurements of spine in adolescent idiopathic scoliosis," *Eur Spine J*, p. 3137–3145, 2016.
- [60] H. Labelle *et al.*, "Seeing the spine in 3D: how will it change what we do?" *J Pediatr Orthop*, pp. S37–S45, 2011.

- [61] J. Boisvert *et al.*, “Articulated spine models for 3D reconstruction from partial radiographic data,” *IEEE Transactions on Biomedical Engineering*, vol. 55, no. 11, pp. 2565–2574, 2008.
- [62] J. Boisvert *et al.*, “3D reconstruction of the human spine from radiograph(s) using a multi-body statistical model,” *Proc. SPIE Medical Imaging: Visualization, Image-Guided Procedures, and Modeling*, vol. 7261, no. 11, pp. 754–761, 2009.
- [63] C. Vidal *et al.*, “Reliability of cervical lordosis and global sagittal spinal balance measurements in adolescent idiopathic scoliosis,” *Eur Spine J.*, pp. 1362–1367, 2013.
- [64] C. R. Fischer and Y. Kim, “Selective fusion for adolescent idiopathic scoliosis: A review of current operative strategy,” *European spine journal*, vol. 20, pp. 1048–1057, 2011.
- [65] J. Cobb, “Outline for the study of scoliosis,” *Instructional Course Lectures, American Academy of Orthopaedic Surgeons*, vol. 5, pp. 261–275, 1948.
- [66] I. Stokes, L. Bigalow, and M. Moreland, “Measurement of axial rotation of vertebrae in scoliosis,” *Spine*, vol. 11, pp. 213–218, 1986.
- [67] C. Nash and J. Moe, “A study of vertebral rotation,” *Journal of Bone and Joint Surgery*, vol. 51, pp. 223–229, 1969.
- [68] B. Drerup, “Principles of measurement of vertebral rotation from the frontal projection of the pedicles. journal of biomechanics,” *J Bone Joint Surg Br*, vol. 17, pp. 923–935, 1984.
- [69] M. Mehta, “Radiographic estimation of vertebral rotation in scoliosis,” *J Bone Joint Surg Br*, vol. 55, pp. 513–520, 1973.
- [70] M. Karami, A. Maleki, and K. Mazda, “Assessment of coronal radiographic parameters of the spine in the treatment of adolescent idiopathic scoliosis,” *Arch Bone Jt Surg.*, vol. 4, pp. 376–380, 2016.
- [71] Q. Ma *et al.*, “Coronal balance vs. sagittal profile in adolescent idiopathic scoliosis, are they correlated?” *European spine journal*, vol. 20, pp. 1048–1057, 2020.
- [72] S. Pasha and K. Baldwin, “Surgical outcome differences between the 3D subtypes of right thoracic adolescent idiopathic scoliosis,” *Eur Spine J*, p. 3076–3084, 2019.
- [73] P. Newton *et al.*, “What factors are associated with kyphosis restoration in lordotic adolescent idiopathic scoliosis patients?” *Spine Deform.*, p. 596–601, 2019.

- [74] I. Stokes, A. Sangole, and C. Aubin, "Classification of scoliosis deformity three-dimensional spinal shape by cluster analysis," *Spine*, p. 584–590, 2009.
- [75] P. Poncet, J. Dansereau, and H. Labelle, "Geometric torsion in idiopathic scoliosis: three-dimensional analysis and proposal for a new classification," *Spine*, p. 2235–2243, 2001.
- [76] S. Somoskeoy *et al.*, "Clinical validation of coronal and sagittal spinal curve measurements based on three-dimensional vertebra vector parameters," *Spine*, p. 960–968, 2012.
- [77] S. Pasha, J. Shen, and S. Kadoury, "True 3D parameters of the spinal deformity in adolescent idiopathic scoliosis," *Spine Deform.*, pp. 703–710, 2021.
- [78] T. Arginteanu, D. DeTurck, and S. Pasha, "Application of călugăreanu–white–fuller theorem in classification of pediatric spinal deformity," *Med Biol Eng Comput.*, vol. 58, no. 12, pp. 2963–2969, 2020.
- [79] S. Kadoury, J. Shen, and S. Parent, "Global geometric torsion estimation in adolescent idiopathic scoliosis," *Med Biol Eng Comput*, p. 309–319, 2014.
- [80] J. White, "Self-linking and the gauss integral in higher dimensions," *Am J Math*, p. 693–728, 1969.
- [81] J. Shen *et al.*, "Geometric torsion in adolescent idiopathic scoliosis: a surgical outcomes study of lenke type 1 patients," *Spine Phila Pa 1976*, vol. 41, p. 1903–1907, 2016.
- [82] X. Liu *et al.*, "Effects of trunk position on back surface-contour measured by raster stereophotography," *American journal of orthopedics (Belle Mead, N.J.)*, vol. 31, pp. 402–6, 2002.
- [83] P. Poncet *et al.*, "Reconstruction of laser-scanned 3D torso topography and stereoradiographical spine and rib-cage geometry in scoliosis," *Comput. Methods Biomech Biomed Engin.*, pp. 59–75, 2000.
- [84] V. Pazos *et al.*, "Accuracy assessment of human trunk surface 3D reconstructions from an optical digitising system," *Med Biol Eng Comput.*, pp. 11–5, 2005.
- [85] O. Ahmad *et al.*, "Torso shape extraction from 3D body scanning data using automatic segmentation tool," *3DBODY.TECH Conference Expo - 8th International Conference and Exhibition on 3D Body Scanning and Processing Technologies*, pp. 192–199, 2017.

- [86] K. Assi, H. Labelle, and F. Cheriet, "Statistical model based 3D shape prediction of postoperative trunks for non-invasive scoliosis surgery planning," *Computers in biology and medicine.*, vol. 48C, pp. 85–93, 03 2014.
- [87] C. Fortin *et al.*, "Reliability of a quantitative clinical posture assessment tool among persons with idiopathic scoliosis," *Physiotherapy.*, vol. 98, pp. 64–75, 2012.
- [88] C. Fortin *et al.*, "Validity of a quantitative clinical measurement tool of trunk posture in idiopathic scoliosis," *Spine.*, vol. 35, pp. E988–94, 2010.
- [89] C. Fortin *et al.*, "Differences in standing and sitting postures of youth with idiopathic scoliosis from quantitative analysis of digital photographs," *Physical occupational therapy in pediatrics*, pp. 313–26, 2013.
- [90] I. Stokes, J. Armstrong, and M. Moreland, "Spinal deformity and back surface asymmetry in idiopathic scoliosis," *J Orthop Res.*, pp. 129–37, 1988.
- [91] J. Jaremko *et al.*, "Estimation of spinal deformity in scoliosis from torso surface cross sections," *Spine.*, vol. 26, no. 14, pp. 1583–1591, 2001.
- [92] J. Sanders *et al.*, "the spinal appearance questionnaire: results of reliability, validity, and responsiveness testing in patients with idiopathic scoliosis," *Journal of Spine.*, p. 2719–22, 2007.
- [93] T. Haher *et al.*, "Results of the scoliosis research society instrument for evaluation of surgical outcome in adolescent idiopathic scoliosis: a multicenter study of 244 patients," *Journal of Spine.*, p. 1435–40, 1999.
- [94] J. Guo *et al.*, "A validation study on the traditional chinese version of spinal appearance questionnaire for adolescent idiopathic scoliosis," *J Pediatr Orthop*, vol. 25, no. 10, pp. 3186–3193, 2016.
- [95] S. Bae *et al.*, "Validation of the korean version of the body image disturbance questionnaire-scoliosis," *Spine*, vol. 25, no. 10, pp. E582–E586, 2020.
- [96] A. Alanay *et al.*, "Reliability and validity of adapted turkish version of scoliosis research society-22 (SRS-22) questionnaire," *Spine*, vol. 30, no. 21, p. 2464–2468, 2005.
- [97] A. Yapar *et al.*, "Reliability and validity of the adapted turkish version of the spinal appearance questionnaire," *Spine Deform.*, vol. 9, p. 57–66, 2020.

- [98] M. Roy-Beaudry *et al.*, “Validation and clinical relevance of a french-canadian version of the spinal appearance questionnaire in adolescent patients,” *Journal of Spine.*, vol. 36, no. 9, pp. 746–51, 2011.
- [99] M. Beauséjour *et al.*, “Reliability and validity of adapted french canadian version of scoliosis research society outcomes questionnaire (SRS-22) in quebec,” *Journal of Spine.*, vol. 34, no. 6, pp. 623–8, 2009.
- [100] A. Danielsson, “What impact does spinal deformity correction for adolescent idiopathic scoliosis make on quality of life?” *Spine.*, p. S101–S108, 2007.
- [101] L. D’Andrea *et al.*, “Do radiographic parameters correlate with clinical outcomes in adolescent idiopathic scoliosis?” *Spine.*, vol. 25, no. 14, p. 1795–1802, 2000.
- [102] P. Smith *et al.*, “Parents’ and patients’ perceptions of postoperative appearance in adolescent idiopathic scoliosis,” *Spine.*, vol. 31, no. 20, p. 2367–2374, 2006.
- [103] J. Cheshire *et al.*, “Do the SRS-22 self-image and mental health domain scores reflect the degree of asymmetry of the back in adolescent idiopathic scoliosis?” *Scoliosis Spinal Disord.*, vol. 12, no. 37, 2017.
- [104] P. Brewer *et al.*, “Influence of cobb angle and isis2 surface topography volumetric asymmetry on scoliosis research society-22 outcome scores in scoliosis,” *Spine Deform.*, vol. 1, no. 6, p. 452–457, 2013.
- [105] C. Sieberg *et al.*, “Predicting postsurgical satisfaction in adolescents with idiopathic scoliosis: The role of presurgical functioning and expectations,” *J Pediatr Orthop.*, vol. 37, no. 8, pp. e548–e551, 2017.
- [106] A. Charalampidis, H. Möller, and P. Gerdhem, “Predictors of persistent postoperative pain after surgery for idiopathic scoliosis,” *J Child Orthop.*, vol. 15, no. 5, 2021.
- [107] P. Brewer *et al.*, “Influence of cobb angle and isis2 surface topography volumetric asymmetry on scoliosis research society-22 outcome scores in scoliosis,” *Spine Deform.*, vol. 1, no. 6, p. 452–7, 2013.
- [108] J. Yang *et al.*, “Safety and effectiveness of minimally invasive scoliosis surgery for adolescent idiopathic scoliosis: a retrospective case series of 84 patients,” *Eur Spine J.*, vol. 29, no. 4, pp. 761–769, 2020.

- [109] M. Uehara *et al.*, “Long-term surgical results of skip pedicle screw fixation for patients with adolescent idiopathic scoliosis: A minimum-ten-year follow-up study,” *J Clin Med.*, vol. 9, no. 12, 2020.
- [110] P. Newton *et al.*, “Prospective 10-year follow-up assessment of spinal fusions for thoracic ais: radiographic and clinical outcomes.” *Spine Deform.*, vol. 8, no. 1, pp. 57–66, 2020.
- [111] W. Chau and B. Kin-Wah Ng, “Longitudinal changes of spinal appearance questionnaire and SRS-22 questionnaire domain scores on surgical adolescent idiopathic scoliosis patients before and after 2 years of operation,” *Journal of Orthopedics and Joint Surgery*, vol. 3, no. 1, pp. 31–35, 2021.
- [112] W. Chau and B. Kin-Wah Ng, “What kinds of cosmetic appearances were improved after scoliosis surgery in adolescent idiopathic patients? a longitudinal long-term post-operative 7-year study using spinal appearance questionnaire,” *Journal of Orthopedics and Joint surgery*, vol. 4, no. 1, pp. 1–7, 2022.
- [113] J. Li *et al.*, “Grass: Generative recursive autoencoders for shape structures,” *ACM Trans. Graph.*, vol. 36, no. 4, 2017.
- [114] C. Nash and C. K. Williams, “The shape variational autoencoder: A deep generative model of part-segmented 3D objects,” *Computer Graphics Forum.*, vol. 36, no. 5, p. 1–12, 2017.
- [115] Q. Tan *et al.*, “Variational autoencoders for deforming 3D mesh models,” *In IEEE Conf. on Computer Vision and Pattern Recognition (CVPR).*, pp. 5841–5850, 2018.
- [116] O. Litany *et al.*, “Deformable shape completion with graph convolutional autoencoders,” *CVPR (arXiv:1712.00268)*, 2018.
- [117] Q. Tan *et al.*, “Mesh-based autoencoders for localized deformation component analysis,” *Computer Science, Graphics (arXiv:1709.04304)*, 2018.
- [118] L. Gao *et al.*, “Automatic unpaired shape deformation transfer,” *ACM Trans. Graph.*, vol. 37, no. 6, 2018.
- [119] A. Ranjan *et al.*, “Generating 3D faces using convolutional mesh autoencoders,” *In European Conference on Computer Vision (ECCV).*, p. 725–741, 2018.
- [120] Y. Yuan *et al.*, “Mesh variational autoencoders with edge contraction pooling,” *Computer Science, Graphics (arXiv:1908.02507)*, 2019.

- [121] Q. Ma, J. Yang, and A. Ranjan, “Learning to dress 3D people in generative clothing,” *CVPR (arXiv:1907.13615)*, 2020.
- [122] Q. Ma *et al.*, “Dressing 3D humans using a conditional mesh-vae-gan,” *ArXiv.*, vol. abs/1907.13615, 2019.
- [123] L. Gao *et al.*, “SDM-NET: Deep generative network for structured deformable mesh,” *ACM Trans. Graph.*, vol. 38, no. 6, p. 1–15, 2019.
- [124] A. Chang *et al.*, “Shapenet: An information-rich 3D model repository,” *Computer Science, Graphics (arXiv:1512.03012)*, 2015.
- [125] A. Dai *et al.*, “ScanNet: Richly-annotated 3D reconstructions of indoor scenes.” In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, 2017.
- [126] A. Dai *et al.*, “Scancomplete: Largescale scene completion and semantic segmentation for 3D scans,” In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, p. 4578–4587, 2018.
- [127] S. Song *et al.*, “Semantic scene completion from a single depth image,” In *Proc. IEEE Conf. on Computer Vision and Pattern Recognition (CVPR) IEEE*, 2017.
- [128] T. Groueix *et al.*, “A papier-mache approach to learning 3D surface generation,” In *The IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 2018.
- [129] L. Escheder *et al.*, “Occupancy networks: Learning 3D reconstruction in function space,” In *Proceedings IEEE Conf. on Computer*, 2019.
- [130] J. Park *et al.*, “DeepSDF: Learning continuous signed distance functions for shape representation,” In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, p. 165–174, 2019.
- [131] Q. Xu *et al.*, “Disn: Deep implicit surface network for high-quality single-view 3D reconstruction,” *Advances in Neural Information Processing Systems 32*, p. 492–502, 2019.
- [132] X. Zhu *et al.*, “ResSNet: Learning geometric information for point cloud processing,” *Sensors (Basel)*, vol. 21, no. 9, 2021.
- [133] C. Qi *et al.*, “Pointnet: Deep learning on point sets for 3D classification and segmentation.” In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, p. 652–660, 2017.

- [134] I. Goodfellow, Y. Bengio, and A. Courville, “Deep learning; adaptive computation and machine learning,” 2016.
- [135] C. R. Qi *et al.*, “Pointnet++: Deep hierarchical feature learning on point sets in a metric space,” *NeurIPS*, p. 5105–5114, 2017.
- [136] W. Liu *et al.*, “Deep learning on point clouds and its application: A survey,” *Sensors*, vol. 19, no. 19, 2019.
- [137] K. Yin *et al.*, “P2P-NET: Bidirectional point displacement net for shape transform,” *ACM Transactions on Graphics*, vol. 37, no. 4, 2018.
- [138] B. Yang *et al.*, “P2MAT-NET: Learning medial axis transform from sparse point clouds,” *Computer Aided Geometric Design*, vol. 37, no. 4, 2020.
- [139] H. Blum, “A transformation for extracting new descriptors of shape,” *Models for the Preception of Speech Visual Form*, vol. 19, pp. 362–380, 1967.
- [140] O. Ahmad *et al.*, “Spectral shape analysis of human torsos: Application to the evaluation of scoliosis surgery outcome,” *IEEE Journal of Biomedical and Health Informatics*, vol. 22, no. 5, pp. 1552 – 1560, 2018.
- [141] I. Benli *et al.*, “Minimum 10 years follow-up surgical results of adolescent idiopathic scoliosis patients treated with tsrh instrumentation,” *Eur Spine J.*, vol. 16, no. 3, pp. 381–391, 2007.
- [142] M. Khani *et al.*, “Prediction of postoperative 3D spine shape using controlled point deformation network (cpdnet),” *Medical Imaging 2023: Image Processing*, vol. 12464, 2023.
- [143] L. Lenke *et al.*, “Adolescent idiopathic scoliosis: a new classification to determine extent of spinal arthrodesis,” *J Bone Joint Surg Am.*, vol. 83, no. 8, pp. 1169–1181, 2001.
- [144] J. Challis., “A procedure for determining rigid body transformation parameters,” *Journal of Biomechanics*, vol. 28, no. 6, pp. 733–737, 1995.
- [145] X. Pennec and J. Thirion, “A framework for uncertainty and validation of 3D registration methods based on points and frames,” *International Journal of Computer Vision*, vol. 25, pp. 1573–1405, 1997.
- [146] M. O’Brien *et al.*, “Spinal deformity study group: Radiographic measurement manual,” *Scoliosis Research Society*, 2023. [Online]. Available: <http://www.srs.org/professionals/online-education-and-resources/radiographic-measurement-manual>

- [147] M. Tones, N. Moss, and J. Polly, DW., “A review of quality of life and psychosocial issues in scoliosis,” *Spine*, vol. 31, no. 26, pp. 3027–3038, 2006.
- [148] R. Pratt *et al.*, “Patient and parental perception of adolescent idiopathic scoliosis before and after surgery in comparison with surface and radiographic measurements,” *Spine*, vol. 27, no. 14, pp. 1543–1550, 2002.
- [149] M. Minguez *et al.*, “Quantifier variables of the back surface deformity obtained with a noninvasive structured light method: evaluation of their usefulness in idiopathic scoliosis diagnosis.” *Eur Spine J*, vol. 16, p. 73–82, 2007.
- [150] N. Suzuki *et al.*, “Analysis of posterior trunk symmetry index (potsi) in scoliosis,” *Stud Health Technol Inform*, p. 81–84, 1999.
- [151] J. Jaremko *et al.*, “Indices of torso asymmetry related to spinal deformity in scoliosis,” *Clinical Biomechanics*, pp. 559–568, 2002.
- [152] C. Goldberg *et al.*, “Surface topography and vectors: a new measure for the three-dimensional quantification of scoliotic deformity.” *Stud Health Technol Inform*, vol. 123, pp. 449–455, 2006.
- [153] A. Komeili and et al., “Surface topography asymmetry maps categorizing external deformity in scoliosis.” *The Spine Journal: official journal of the North American Spine Society.*, vol. 14, pp. 973–983, 2014.
- [154] A. Komeili and et al., “Monitoring for idiopathic scoliosis curve progression using surface topography asymmetry analysis of the torso in adolescents.” *Spine Journal*, vol. 15, pp. 743–751, 2015.
- [155] M. Adankon *et al.*, “Scoliosis follow-up using noninvasive trunk surface acquisition,” *IEEE Transactions on Biomedical Engineering.*, vol. 60, no. 8, pp. 2262–2270, 2013.
- [156] J. Cheshire *et al.*, “Do the SRS-22 self-image and mental health domain scores reflect the degree of asymmetry of the back in adolescent idiopathic scoliosis?” *Scoliosis Spinal Disord*, vol. 12, no. 37, 2017.
- [157] I. Stokes, “Three-dimensional terminology of spinal deformity. a report presented to the scoliosis research society by the scoliosis research society working group on 3D terminology of spinal deformity,” *Spine*, vol. 19, pp. 236–248, 1994.

- [158] R. Pratt *et al.*, “Changes in surface and radiographic deformity after universal spine system for right thoracic adolescent idiopathic scoliosis: is rib-hump reassertion a mechanical problem of the thoracic cage rather than an effect of relative anterior spinal overgrowth?” *Spine Br*, vol. 26, pp. 1778–1787, 2001.
- [159] P. Newton *et al.*, “Surgical treatment of lenke 1 main thoracic idiopathic scoliosis: results of a prospective, multicentre study.” *Spine*, vol. 26, pp. 328–338, 2013.
- [160] C. Weatherley *et al.*, “The rib deformity in adolescent idiopathic scoliosis. a prospective study to evaluate changes after harrington distraction and posterior fusion.” *TJ Bone Joint Surg Br*, vol. 69, pp. 179–182, 1987.
- [161] W. Chen, L. Le, and E. H. Lou, “Ultrasound imaging of spinal vertebrae to study scoliosis,” *Open Journal of Acoustics*, vol. 2, no. 3, 2012.

APPENDIX A SCOLIOSIS

Scoliosis

To know about scoliosis, it is better to know about the anatomy of normal spine. The spine contains four regions including (see Figure A.1):

1. **Cervical spine:** The neck beginning at the base of skull which is labeled C1 to C7 (the "C" means cervical).
2. **Thoracic spine:** The mid-back including 12 vertebrae which are labeled T1 to T12 (the "T" means thoracic).
3. **Lumbar spine:** The low back with five vertebrae which are labeled L1 to L5 (the "L" means lumbar).
4. **Sacrum and coccyx:** Sacrum with five vertebrae which fuse to form one bone and the coccyx (known as tail bone) has four vertebrae.

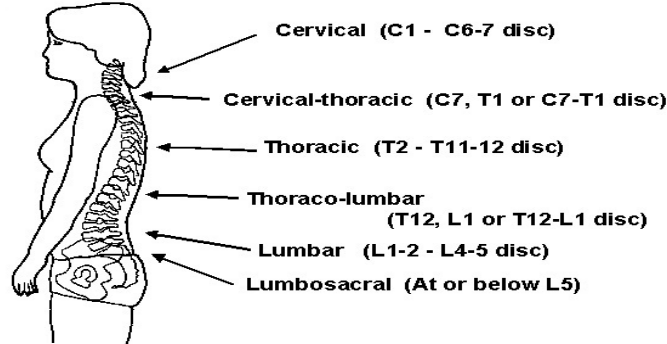


Figure (A.1) Three area of interest (used under licence CC BY) [14]

Also, normal spinal includes two inward (Lordosis) and outward (Kyphosis) curves which help the back carry our weight as well as they are significant for flexibility.

There are different types of spinal disorder including *Lordosis*, *Kyphosis*, *Flat Back*, *Sway Back*, and *Scoliosis* [14]. The goal of this project is studding on the trunk deformities associated with scoliosis disorder. Scoliosis type can be fall in the one of the following group: *Thoracic Scoliosis*, *Lumbar Scoliosis*, *Thoraco-Lumbar Scoliosis*, *Combined Scoliosis*.

Scoliosis is a three-dimensional lateral curvature of the spine usually in a S or C-shaped deformation and different scoliosis types are reported. Scoliosis patients with Cobb angle 10

or more are two to three percent of the population [161] and most of the scoliosis patients are adolescent girls [17, 30].

Scoliosis Types:

Scoliosis types can be classified based on *Severity Levels* or *Etiology*.

1. Based on Severity Level [30]

(I) mild, including a cobb angle 10-20 degree with a small spinal deformity; **(II) moderate**, including a cobb angle between 20-40 degree; **(III) severe**, including a cobb angle exceeded 40 degree. The treatment for these types of scoliosis includes physiotherapy, using a brace, and surgical intervention respectively.

2. Based on the Etiology [17]

(2.1) Idiopathic Scoliosis: It happens when an etiology can not be detected and there is a unknown causes. X-ray of these group shows a rotation of the vertebral body. The shape of idiopathic scoliosis is S-shaped curve. These group is classified base on the age of diagnosing including (1) infantile, before the age of three; (2) juvenile, between three and ten years; (3) adolescent, beyond the age of ten. The 80% of the cases are classified in the group 3 and the rest into group 1 and 2.

(2.2) Neurogenic Scoliosis: It happens when its etiology includes several neuromuscular conditions including cerebral palsy (CP) and it also includes muscular imbalances. Patients with CP have a neurogenic scoliosis at an early age. There is a strong correlation between the severity level and the rate of progression in this group. The shape of neurogenic scoliosis is a large-bowed C-shape curve. Sever neurogenic scoliosis can lead to the rib pain, back pain, cardiac, lung complications due to the balance and sitting abilities.

(2.3) Congenital Scoliosis: This type maybe starts before birth. Vertebrae maybe fused and are not formed well.

(2.4) Early Onset Scoliosis: It happens before 10 years of age.

(2.5) Degenerative Scoliosis: It happens because of wear on the joints and discs of spine in lumbar spine of older adults.

Scoliosis Indices:

There is a multivariate correlation between the torso shape and spinal shape. However, torso deformity can not be used to describe the spinal deformity. Abnormal torso shape should

be viewed related to the spinal shape but maybe separate of spinal deformity [30]. However, there are a few of metrics which are used to evaluate the scoliosis. These metrics specially are computed in three areas of interest along the trunk including: *Upper Thoracic* ($T3-T4$), *Main Thoracic* ($T5-T12$), and *Thoraco-Lumbar* ($T12-L1$ or $L2-L3$) (see Figure A.1). Metrics are measured along the three perpendicular reference planes including *Coronal*, *Sagittal*, and *Transverse* planes. These metrics are categorized as two groups: 1) metrics are dependent to the measurement techniques; 2) metrics are independent to the measurement techniques. The later metrics are more useful such as Trunk Rotation index.

To compare the measured indices computed in different time, they should be coordinate free (such as areas and volumes) or they should be in the same coordinate system (such as angles, distance and link). Referring to the later case, a stable coordinate system for different follow-ups or screening sessions is needed. There is two solutions to have stable coordinate system: (1) Building a constant system using points on the background but this method makes technical problem; (2) Defining the “body specific” coordinate system based on the anatomical landmarks in different systems. The late one is selected as best method. The general body coordinate system is shown in the Figure A.2. However, different “**body specific**” coordinate systems have been proposed including: SOSORT system; ISIS (Integrated Shape imaging system); QSI (Quantec Spinal Image System); POTSI (Posterior Trunk Symmetry Index); SHS (Suzuki Hump Sum); DAPI (Deformation of the Axial Plane Index) systems [14].

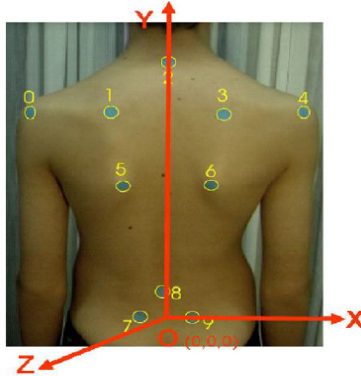


Figure (A.2) General Body Coordinate System (used under licence CC BY) [14]

APPENDIX B COMPLEMENTARY EXPERIMENTS

Complementary Experiments

A Automatic Assessment of Scoliosis Surgery Outcome

Correlation between the changes in LRTA trunk deformity and GTA and spine deformity

We conducted a correlation analysis between the different LRTA parameters, on one hand, and the spinal measurements and GTA indices, on the other. Figure B.1 shows the Pearson correlation coefficients obtained when comparing the Correction Rates (CRs) between these different measurements across the cohort. Results reveal several significant correlations ($p < 0.05$) between LRTA parameters and GTA or spinal measurements. Regression analysis was done for those relationships, as summarised in Figure B.2. The two strongest correlations are between MA of Depth in the shoulder-neck region and Cobb MT and between MA of Offset in the shoulder blades region and CB.

CR	CR _{Scoliometer T}	CR _{Scoliometer L}	CR Cobb PT	CR Cobb MT	CR Cobb TLL	CR _{CB}	CR _{BSR}	CR _{TR}	CR _{TLs}
Waist									
CR _{DR}	0.33*	0.01	0.08	0.33	0.09	0.28*	-0.04	0.10	0.07
CR _{MD}	0.33*	-0.05	-0.15	0.16	0.03	0.18	-0.06	0.12	0.23
CR _{MA}									
Height	0.32*	-0.09	-0.11	0.05	0.07	0.10	-0.07	0.00	0.29
Offset	0.26	-0.15	-0.15	0.02	0.03	0.05	-0.09	0.04	0.35
Depth	0.33*	-0.05	-0.11	0.29	0.04	0.20	0.00	0.29	0.11
Shoulder-Neck (Cervical and PT)									
CR _{DR}	-0.11	0.02	-0.26	0.06	-0.11	-0.10	-0.06	-0.02	-0.03
CR _{MD}	0.06	-0.06	-0.22	0.12	-0.15	0.02	-0.02	-0.01	0.02
CR _{MA}									
Height	0.22	-0.07	0.12	-0.16	0.13	0.14	-0.10	-0.11	0.15
Offset	0.06	-0.02	-0.15	0.21	-0.10	0.33*	0.01	0.25	-0.04
Depth	0.16	0.04	-0.10	0.39*	-0.04	0.00	0.07	0.28*	0.00
Shoulder Blades (MT)									
CR _{DR}	0.07	0.11	0.00	0.25	-0.21	-0.09	-0.01	0.20	-0.16
CR _{MD}	0.00	0.01	0.18	0.11	-0.06	-0.16	0.06	-0.03	0.02
CR _{MA}									
Height	0.15	-0.06	0.15	-0.17	0.05	0.10	-0.10	-0.13	0.14
Offset	0.03	0.03	-0.03	0.14	-0.13	0.35*	0.03	0.21	0.00
Depth	0.10	-0.05	-0.01	0.28	0.14	-0.11	0.06	0.17	0.08

Figure (B.1) Correlations between CRs of spinal and GTA measurements and those of LRTA indices (n=49). Highlighted numbers indicate significant correlations; asterisks indicate that regression analysis was applied for two measurements (results in Figure B.2). Red asterisks indicate the highest correlation values in this figure.

	Significant correlations between CRs	Spinal / Global Trunk Deformity	P-Value	R
Local Trunk Deformity	Waist			
	Deformation Rate	Scoliometer T	0.02	0.32
	Maximum Deformity	Scoliometer T	0.02	0.32
	Maximum Asymmetry (Height)	Scoliometer T	0.02	0.32
	Maximum Asymmetry (Depth)	Scoliometer T	0.02	0.32
	Deformation Rate	Coronal Balance	0.04	0.29
	Shoulder-Neck			
	Maximum Asymmetry (Offset)	Coronal Balance	0.02	0.32
	Maximum Asymmetry (Depth)	Cobb MT	0.006	0.38
	Maximum Asymmetry (Depth)	Trunk Rotation	0.05	0.27
	Shoulder Blades			
	Maximum Asymmetry (Offset)	Coronal Balance	0.01	0.35

Figure (B.2) Regression analysis for the significant correlations found between spinal clinical measurements or GTA corrections and LRTA corrections

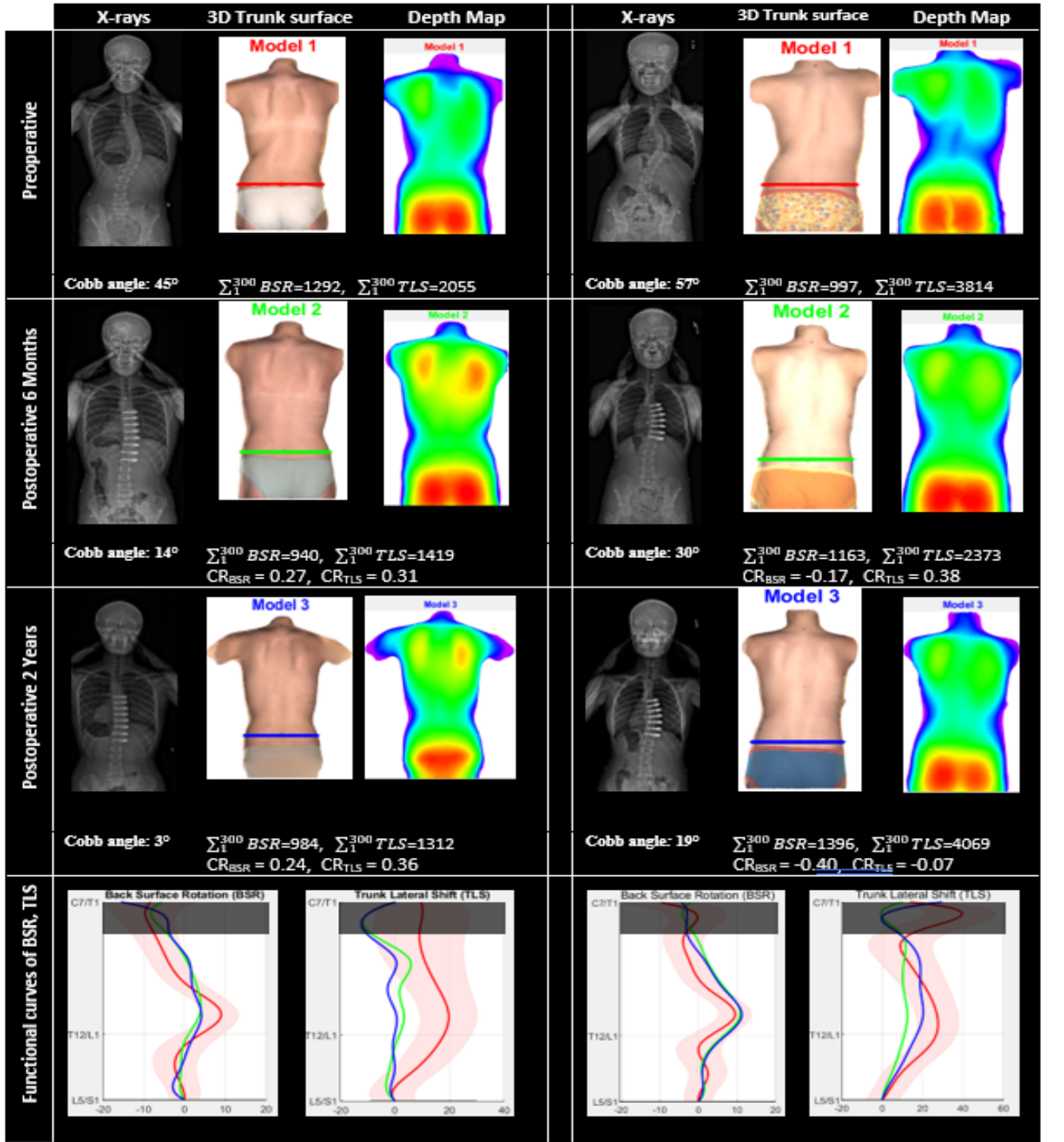
The correlation analysis found some significant relationships between proposed LRTA measurements and spinal indices used in clinical practice (Cobb angles, coronal balance, and scoliometer readings). Although the R values are low (between 0.3 and 0.4), the related quantities (MA of Depth in Shoulder-Neck and MA of Offset in Shoulder Blades versus Cobb MT and CB) suggest that LRTA measures (obtained non-invasively) can point toward underlying spine shape.

B Two Years follow-up study

Exemplar Cases

We selected two patients from our cohort to illustrate how their trunk deformities changed postoperatively, at six months and two years (Figure B.3). For each case, we used X-rays to visualize the spinal correction and the 3D trunk surface and the colour-depth map to have a better visualization of local deformities of the trunk. The functional curves of the BSR and TLS before surgery (in red), at six-months (in green), and at two-years follow-up (in blue) are plotted, together with the 95% confidence intervals for both indices (pink shaded areas around red curves). When the postoperative curves are outside the confidence interval, it means that there is a statistically signifi-

cant difference between pre and six-months or between pre and two-years postoperative follow-up.



a) Case one, showing good correction based on Cobb, BSR and TLS after two-years follow-up.

b) Case two, showing good correction based on Cobb, but poor correction based on BSR and TLS after two-years follow-up.

Figure (B.3) Spinal measurement (Cobb angle), trunk measurements (BSR and TLS), and visualization of the 3D trunk shape of two selected patients from our cohort: a) good correction of trunk indices; b) poor correction of trunk indices.

Note that the top regions of the curve plots, corresponding to the shoulders and neck, have high variability depending on how much of the arms are cut in the pre-processing of 3D trunk shape. Also, the functional curves are also less reliable in that region due to the heightened impact of patient posture variability. Thus, our analysis excludes the shaded areas in those plots. Figure B.3 (a) illustrates the case of a good correction in terms of Cobb angle, BSR, and TLS. For this patient, the X-rays show the Cobb angle decreasing from 45° preop to 14° and 3° after six months and two years postop. The correction ratios for BSR are $CR_{BSR} = 0.27$ pre to post six-months and $CR_{BSR} = 0.24$ pre to post two-years. The maximum values of BSR preoperative, six-month and two years follow-up (excluding the shoulders) are 9.42, 4.02, and 4.19 respectively. There is a significant correction of the TLS from pre to post six-months follow-up ($CR_{TLS} = 0.31$) also pre to post two-years follow-up ($CR_{TLS} = 0.36$). Also, the maximum values of TLS preoperative, six-month, and two years follow-up are 19.76, -7.84, and -8.59 respectively. Despite a good realignment of the trunk, a rib hump appears in the proximal thoracic region at six months follow-up. However, the rib hump becomes less visible at two years follow-up.

B.3 (b) shows a case of a poorer correction based on the values of the BSR and the TLS after surgery. It shows negative corrections of the BSR with $CR_{BSR} = -0.17$ and $CR_{BSR} = -0.40$ after six months and two years follow-up respectively, signifying a worsening of BSR. Also, the maximum values of BSR preoperative, six-month and two years follow-up are 9.71, 10.85, and 11.27 respectively. However, there is a significant correction of the TLS with $CR_{TLS} = 0.38$ after six months but the curve of the TLS after two years reveals a deterioration over time with $CR_{TLS} = -0.07$. Moreover, the maximum values of TLS at the three time points are 27.69, 12.46, and 20.34 respectively. Although there is no improvement after two years follow-up in terms of trunk indices (BSR and TLS), the depth maps show that the realignment of the patient's back surface has improved significantly from preop to postop at six months and two years. Moreover, there is a stable spinal correction of the Cobb angle from 57° preop to 30° and 19° postoperatively after six months and two years follow-up. Furthermore, the post-op depth maps show that the symmetry has improved in the shoulders even though the BSR increases during the follow-up. Generally, our results confirm the persistence of rib hump manifested on the patients' backs after surgical intervention, which can become more accentuated in some patients which can be seen in case two in Figure B.3 (b).