RESEARCH ARTICLE

Prediction of Post-operative Clinical Indices in Scoliosis Correction Surgery Using an Adaptive Neuro-fuzzy Interface System

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Abstract

Objectives: Accurate estimation of post-operative clinical parameters in scoliosis correction surgery is crucial. Different studies have been carried out to investigate scoliosis surgery results, which were costly, time-consuming, and with limited application. This study aims to estimate post-operative main thoracic cobb and thoracic kyphosis angles in adolescent idiopathic scoliosis patients using an adaptive neuro-fuzzy interface system.

Methods: Distinct pre-operative clinical indices of fifty-five patients (e.g., thoracic cobb, kyphosis, lordosis, and pelvic incidence) were taken as the inputs of the adaptive neuro-fuzzy interface system in four categorized groups, and post-operative thoracic cobb and kyphosis angles were taken as the outputs. To evaluate the robustness of this adaptive system, the predicted values of post-operative angles were compared with the measured indices after the surgery by calculating the root mean square errors and clinical corrective deviation indices, including the relative deviation of post-operative angle prediction from the actual angle after the surgery.

Results: The group with inputs for main thoracic cobb, pelvic incidence, thoracic kyphosis, and T1 spinopelvic inclination angles had the lowest root mean square error among the four groups. The error values were 3.0° and 6.3° for the post-operative cobb and thoracic kyphosis angles, respectively. Moreover, the values of clinical corrective deviation indices were calculated for four sample cases, including 0.0086 and 0.0641 for the cobb angles of two cases and 0.0534 and 0.2879 for thoracic kyphosis of the other two cases.

Conclusion: In all scoliotic cases, the post-operative cobb angles were lesser than the pre-operative ones; however, the post-operative thoracic kyphosis might be lesser or higher than the pre-operative ones. Therefore, the cobb angle correction is in a more regular pattern and is more straightforward to predict cobb angles. Consequently, their root-mean-squared errors become lesser values than thoracic kyphosis.

Level of evidence: IV

Keywords: Cobb angle, Pelvic incidence, Posterior surgery, Spine, Thoracic kyphosis

Introduction

Scoliosis is a sort of 3D spinal deformity disorder that mainly affects the thoracic or lumbar areas in the frontal plane. [1] Investigation of adolescent idiopathic scoliosis (AIS) is a trending research topic. [2, 3] Scoliosis involves 2-4% of adolescents and is ten times more prevalent in females than males. [4] Generally, a patient needs surgical correction when the frontal cobb angle is more than 40°-50°. [5-7] To determine post-operative indices in scoliosis correction surgery, various experimental and modeling studies have been undertaken [8,9] The experimental studies use *in vitro* or *in vivo* methods. [10, 11] the *in vitro* studies attempt to evaluate the effect of surgical instruments and techniques on spinal fusion biomechanics on cadavers. [10, 12] the *in vivo* studies investigate the

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biomechanics of scoliosis fusion with their force and moment behaviors, using force sensors throughout the surgery. Both *in vitro* and *in vivo* studies are limited and costly. [11, 13, 14]

The modeling studies are divided into two groups, i.e., finite element modeling (FEM) and multibody modeling (MBM) approaches. The FEM methods have regularly applied anatomical models of vertebrae, discs, and other soft tissues with different material properties. [9, 15] Additionally, they have used the geometrical models of rods and screws to simulate scoliosis correction surgery by applying corrective loads. [8,16,17] In MBM methods, separate vertebral bodies and mathematical calculations are used in a functional model while considering soft tissue effects as spring elements. The multibody models for the scoliotic spine investigate their mechanical behavior and chain mechanism kinematics. [18-20] The modeling methods are time-consuming and limited due to case numbers for developing more general and practical methods.

Artificial intelligence studies use machine learning algorithms, such as neural networks to investigate spine modeling. [21-23] Neural network techniques have been applied for different purposes, including scoliosis detection or estimating the cobb angles from upper body clinical indices [24,25] and determining spinal fusion patterns of different Lenke types. [26] In addition, some studies were performed to estimate the amount of Cobb angle correction or post-operative kyphosis angles in posterior scoliosis surgery using statistical analysis. [27, 28] these methods have the advantage of considering many cases to estimate clinical parameters. The problem, however, remains in the minimization of estimation errors.

Therefore, previous studies did not use a forthright approach to predict post-operative Cobb or kyphosis angles in scoliosis surgery based on a substantial number of patients. Moreover, these studies were costly, time-consuming, and limited to be performed on many scoliotic patients. As a result, the present study aims to predict the post-operative angles in AIS patients using an adaptive neuro-fuzzy interface system (ANFIS). The objective of the current manuscript is to predict the main thoracic Cobb (MTC) and thoracic kyphosis (TK) angles in AIS patients who have undergone posterior scoliosis surgery. Therefore, four different arrangements of pre-operative clinical parameters have been examined and applied as the inputs of the ANFIS. Afterward, the post-operative clinical indices, were used to train and test an ANFIS that estimates these values in new scoliotic cases. Our approach is hypothesized to provide a more accurate yet easier tool to estimate post-operative angles. The detailed acronyms and definitions used in this study are listed in [Table 1].

Table 1. Definition of acronyms used in the study

Acronym	Definition
ANFIS	Adaptive Neuro-Fuzzy Interface System
PTC	Proximal Thoracic Cobb
MTC	Main Thoracic Cobb
TLC	Thoracolumbar Cobb
PI	Pelvic Incidence
TK	Thoracic Kyphosis
LL	Lumbar Lordosis
T1 SPi	T1-SpinoPelvic Inclination
RMSE	Root Mean Square Error
CCDI	Clinical Corrective Deviation Index

Materials and Methods

Collection of AIS Patient Radiographs

The EOS imaging system with the capability of low-dose biplanar radiography was used for imaging and collecting frontal and sagittal views of pre- and post-operative radiographs of 55 AIS patients (i.e., 49 females and 6 males) in Shafa Yahyaian Hospital. [29] The patients were 15 ± 3 years old in different Lenke types and took the posterior rod surgery; 34 were the Lenke type A. This research is a retrospective study. The ethical approval was obtained from the Ethics Committee of the Iran University of Medical Sciences (IUMS) for obtaining and analyzing EOS radiographs of the AIS patients under letter no. IR.IUMS.REC.1398.1162, dated 02/22/2020. Hence, the ethical standards laid down in the Declaration of Helsinki in 1964 have been adhered to in the present study. Informed consent was obtained from all patients in Shafa Yahyaian Hospital.

Measurement of Clinical Parameters

Surgimap (v2.3.2.1, A Nemaris Inc. Product, New York, USA) image processing commercial software was used to determine pre-operative main thoracic cobb (MTC), proximal thoracic cobb (PTC), thoracolumbar cobb (TLC), Thoracic kyphosis (TK), lumbar lordosis (LL), pelvic incidence (PI), and T1 spinopelvic inclination (T1 SPi) angles [Figure 1]. Post-operative MTC and TK angles were also measured as important guides for estimating post-operative spine curvatures.

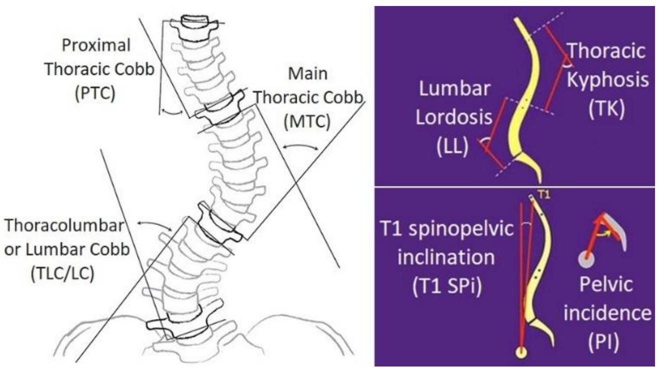

Figure 1. Clinical indices of the scoliotic spine calculated in the frontal and sagittal planes

Prediction with Adaptive Neuro-Fuzzy Interface System

The ANFIS with the combination of fuzzy-logic-based and neural network learning methods, was developed to be trained using pre-operative and post-operative clinical parameters. As indicated in the ANFIS algorithm flowchart, different combinations of pre-operative parameters were used as ANFIS inputs to compare their training outcomes [Figure 2]. The first layer of the ANFIS structure took pre-operative indices as inputs of fuzzy logic to divide them into several membership functions (MFs) in the next layer. To minimize the root-mean-squared error (RMSE) in post-operative MTC and TK estimations, the number of MFs was adjusted through trial and error. In the fuzzy interface system employing the Sugeno model and Gaussian-type MFs, the subtractive clustering technique was employed.

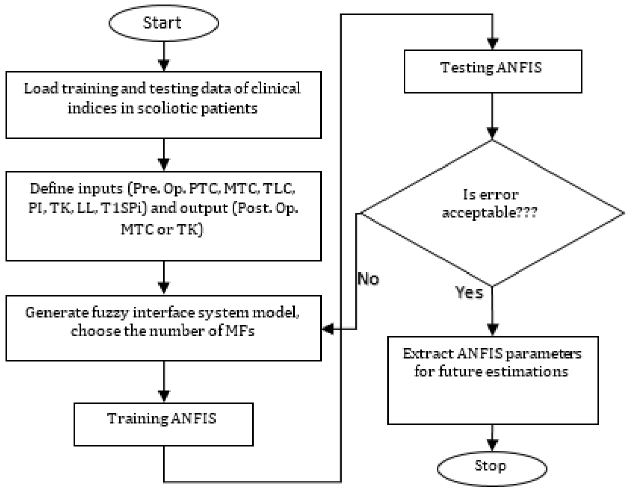

Figure 2. Adaptive neuro-fuzzy interface system (ANFIS) flowchart and structure for estimating post-operative main thoracic Cobb (MTC) and thoracic kyphosis (TK) angles

Four groups of pre-operative angles were determined as ANFIS inputs to calculate RMSE values of post-operative MTC and TK angles for each group in categories [Table 2]. This procedure assisted in finding the most appropriate input selections to predict post-operative MTC and TK angles with the least possible errors.

Table 2. Classification of pre-operative clinical indices as adaptive neuro-fuzzy interface system inputs in four groups

Group number	ANFIS inputs (pre-operative clinical indices)
Group 1	MTC, PI, TK
Group 2	MTC, PI, TK, T1 SPi
Group 3	PTC, MTC, TLC, PI, TK, LL
Group 4	PTC, MTC, TLC, PI, TK, LL, T1 SPi

The selected inputs were examined in two scoliosis types: all cases with all Lenke types (55 patients) and those with Lenke A type (34 patients). Furthermore, the ANFIS analysis was performed by three different numbers of MFs for each input to investigate their effects, i.e., 35, 40, and 45 for all Lenke-type cases and 15, 20, and 25 for Lenke type A cases for all four groups. Additionally, the number of rules is identical to the number of MFs in all groups.

Definition and Calculation of Estimation Errors and Deviation Index

Around 70% of AIS patients' clinical data were used for training, 15% for validation, and 15% for testing in all ANFIS stages. The testing process error was the difference between post-operative angles actually achieved and those predicted (i.e., post-operative MTC and TK). Also, the clinical corrective deviation index (CCDI) was defined as the relative deviation in the ANFIS prediction of post-operative MTC and TK from their actual values. The terms RMSE and CCDI were defined and calculated as follows:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Pred\_idx_i - Op\_idx_i)^2}$$

$$CCDI = \frac{1}{N}\sum_{i=1}^{N}\frac{|Pred\_idx_i - Op\_idx_i|}{|PreOp\_idx_i - Op\_idx_i|}$$

Op_idx, Pred_idx, and PreOp_idx represent the actual post-operative output, ANFIS prediction for output, and the pre-operative input of the tested data, respectively (all in degrees). According to Table 2, the tested data in four groups of inputs were used to validate ANFIS and calculate RMSE and CCDI values in two modes, including eight cases from 55 patients of all Lenke types and five cases from 34 patients of Lenke A type patients.

Results

Root-mean-squared error (RMSE) and clinical corrective deviation index (CCDI) values

Group 2 (MTC, PI, TK, and T1 SPi angles as inputs of ANFIS) typically had the lowest RMSE and CCDI values. Figure 3 depicts these results for four groups of 55 (all Lenke types) and 34 (Lenke A type) AIS patients. Generally, group 2 had reduced RMSE and CCDI values than other groups. The validation errors were considerably lower than the test errors. As an example, for all 55 cases in group 2 with 40 MFs, the RMSE values of the validation and test data were 0.70 and 3.00 for post-op MTC and 1.24 and 6.32 for post-op TK, respectively.

In addition, the CCDI values for post-operative MTC were much less than those for post-operative TK. In certain circumstances, such as group 1, the RMSE values of post-operative MTC decreased when the number of MFs was increased, whereas they grew in group 3; hence, increasing the number of MFs did not always reduce or raise the values of RMSE and CCDI.

Comparison between post-operative MTC and TK indicated that the RMSE values of TK were usually higher than those in MTC. Moreover, the CCDI values of TK were mostly and considerably higher than MTC. The RMSE values for Lenke A type cases were higher than all Lenke types in group 1, while they were lower in group 4. The CCDI values were higher for TK of Lenke a type than in all Lenke types in group 1, while they were considerably lower in groups 3 and 4.

Although the number of MFs affected the RMSE or CCDI parameters, their effect was not in a regular pattern and depended on the number of cases and ANFIS inputs. However, the RMSE and CCDI values increased with increasing or decreasing the numbers of MFs, excessively. Therefore, an appropriate number of MFs should have been selected to reduce these values. The difference between post-operative MTC and TK estimations was more evident in CCDI than in RMSE, and the CCDI values for MTC were considerably lower than those for TK [Figure 3].

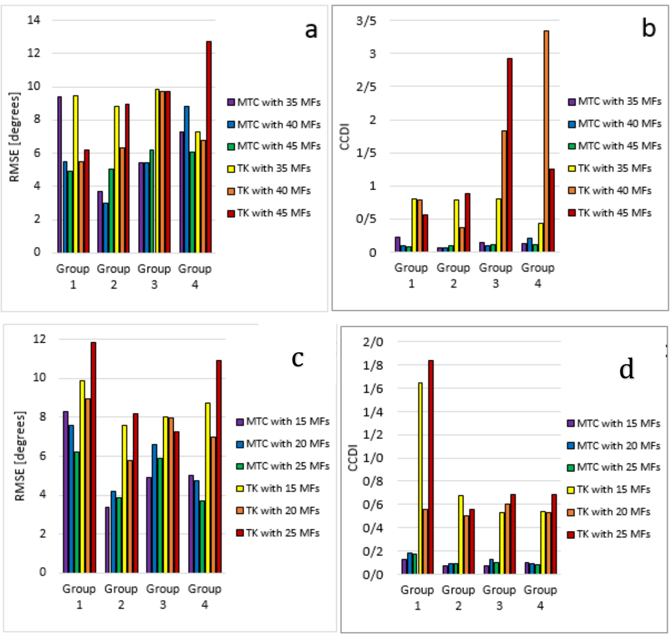

Figure 3. Root-mean-squared error (RMSE) and clinical corrective deviation index (CCDI) parameters for four groups of ANFIS inputs in different numbers of membership functions (MFs), a. RMSE for all Lenke types (55 cases), b. CCDI for all Lenke types, c. RMSE for Lenke A type (34 cases), d. CCDI for Lenke A type

Post-operative main thoracic Cobb and thoracic kyphosis prediction

Since group 2 possesses lower RMSE and CCDI values, the results of this group were investigated in more detail. The sample results of operated and predicted values for post-operative MTC and TK in test data of group 2 (8 cases) were investigated, and 40 MFs were used in ANFIS for all Lenke types [Figure 4]. Moreover, the convergence of RMSE for group 2 (with 40 MFs) is illustrated in Figure 4.

To visualize the results, four samples of operated and predicted results of group 2 were selected randomly (2 cases for MTC and 2 cases for TK estimation), and the pre-operative (PreOp) and post-operative (PostOp) MTC and TK were calculated and illustrated [Figure 5].

Cases A and D had the minimum and maximum CCDI values, respectively [Figure 5]. In cases A and C, the differences between the operated and predicted results of post-operative MTC were equal to 0.8 and 2.7°, respectively. In cases B and D, these differences were equal to 0.7 and 5.7 degrees, respectively. Therefore, the error values were higher in estimating TK compared to MTC. Moreover, the difference between pre-operative and post-operative values was higher in MTC compared to TK.

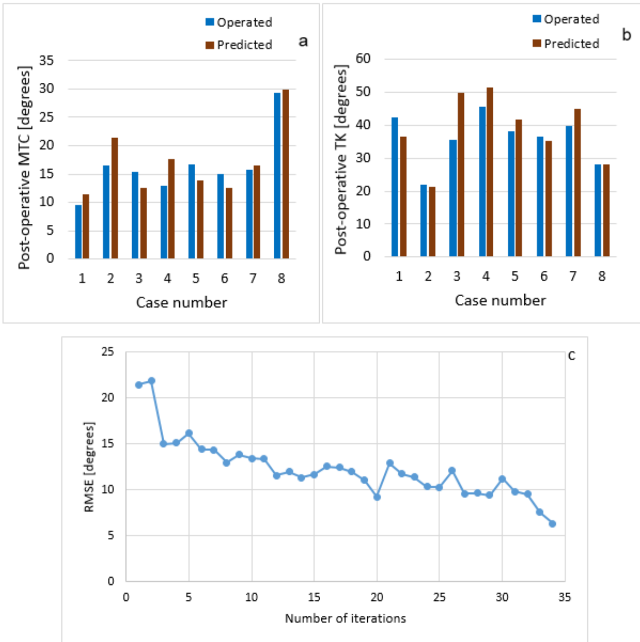

Figure 4. Comparison of Operated (actual) and Predicted (with ANFIS) values for post-operative MTC (RMSE=3.00 degrees) and TK (RMSE=6.32 degrees) in test data of eight scoliotic cases in group 2 with 40 membership functions, and the convergence of RMSE in TK during 34 iterations

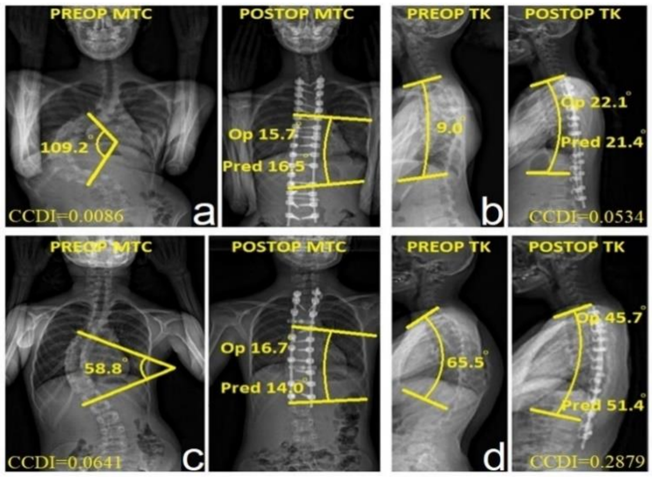

Figure 5. Illustration of results in four scoliotic cases of group 2, pre-operative, operated (Op), and predicted (Pred) post-operative values for MTC (a and c) and TK (b and d) angles

Discussion

The ANFIS algorithm was an advantageous method for accelerating the prediction of post-operative clinical parameters and assisting surgeon performance. The ANFIS uses the fuzzy method in combination with the neural network. In other words, it integrates neural networks and Fuzzy Logic principles and can take advantage of both within a single framework. The fuzzy rules can categorize inputs and create MFs. Thus, its training error becomes considerably lower, even with the limited number of cases (55 cases).

Post-operative MTC and TK are the most critical clinical indices influencing biomechanical characteristics of the spine and its stability. Therefore, the accurate assessment and prediction of them are of utmost importance.

Limitations and disadvantages

There was a limited number of AIS cases in this research, and it is evident that a larger sample size would allow for a more accurate prediction of post-operative clinical indices. Also, the surgical treatments for scoliosis correction, such as de-rotation techniques at different spinal levels, alter the scoliotic curve during the correction, which is not taken into account in this study because it is extremely difficult to implement in ANFIS.

Because of the two-dimensional radiographs, the measurement of clinical scoliosis indices, such as Cobb angle, was performed in two-dimensional analysis. In contrast, the three-dimensional measurements may differ from two-dimensional ones, particularly in the three-dimensional correction of scoliosis [30,31].

Spinal stiffness (due to the intervertebral discs and ligaments) influences its curvature during scoliosis correction; however, there are no data on actual stiffness values in AIS cases, and its effect is neglected in this study.

The ANFIS algorithm includes only one output; hence, it is impossible to estimate multiple post-operative angles simultaneously. Therefore, there is a separate ANFIS for each of the post-operative MTC and TK, which lacks the interrelation between them to estimate simultaneously.

Analysis of Results

Surgeons always attempt to reduce the Cobb angle to the lowest possible value to make the reduction of MTC evident after the operation. However, it is not the case for post-operative TK since, in some cases, the TK increases after scoliosis correction surgery. This explains why RMSE values of post-operative TK are usually higher than those of MTC (especially in group 2). Therefore, it is easier for the ANFIS algorithm to predict the Cobb angle, leading to the lower values of RMSE. According to the CCDI definition, higher CCDI in TK angles is generally due to the lower difference between pre-and post-operative TK values than in MTC in almost all groups [Figure 3].

Group 2 has the lowest RMSE and CCDI values for all Lenke types and Lenke A cases, representing that the arrangement of ANFIS inputs in this group is more appropriate for this investigation. Group 2 clinical parameters include MTC, PI, TK, and T1 SPi, where the MTC is a highly efficient angle of the scoliosis curve in the frontal plane, as the PI and TK angles are in the sagittal plane. In addition, the T1 SPi angle influences the sagittal spinal curve and sagittal balance. [32] Hence, these clinical parameters can assist as adequate training parameters for ANFIS. As T1 SPi is not included in group 1, the errors in this group increase. In addition, the number of inputs is greater in groups 3 and 4. (i.e., 6 and 7 inputs, respectively), while the number of AIS cases is limited. Consequently, their RMSE and CCDI values became greater than those in group 2 [Figure 3].

The difference between the predicted and operated results, as well as RMSE values, are higher in estimating post-operative TK. Because in the majority of cases, the MTC angles have been reduced considerably from their pre-operative values since the surgeon attempts to reduce the Cobb angle as much as possible. However, the variation of TK angles does not follow a regular pattern between pre- and post-operative values in different cases. For instance, four sample cases are investigated [Figure 5], which indicates that the post-operative TK can be higher or lower than its pre-operative value. Thus, it is more difficult for the ANFIS algorithm to predict accurate post-operative TK than post-operative MTC [Figure 4].

Conclusion

The application of the ANFIS algorithm is beneficial for predicting post-operative clinical indices, especially when there are enough AIS cases. Furthermore, this method can assist the surgeon in estimating post-operative clinical parameters in scoliosis correction surgery (before the actual operation) and improve the surgery.

The prediction of post-operative Cobb and kyphosis angles became possible based on a trained network that used the dataset of professional surgeons. Consequently, this trained network can be used to predict post-operative angles (and other post-op clinical parameters in future work) to lead other amateur surgeons to what is expected from post-op results. Furthermore, predicting post-op Cobb and kyphosis angles helps the surgeon estimate the curvature angle of fusion rods before the surgery. Since the rod curvature is regulated based on the preferred post-op angles such as thoracic kyphosis, which the surgeon wants to achieve. Therefore, this training method could be used for rod curvature estimation for future work.

The results indicate that the estimation errors are often lower in post-operative MTC than TK since the pattern of pre-and post-operative MTC is more regular than TK; hence, it would be more straightforward for ANFIS to train data based on MTC angles, which some studies confirmed that network training or statistical analysis could be used to predict Cobb angles. [24, 27]

Lastly, future studies could explore some other concerns. It is suggested to increase the number of AIS cases to improve the prediction accuracy of post-operative clinical parameters and reduce estimation errors. In addition, simulating the spine by incorporating the effect of soft tissue stiffness on scoliosis curvature improves the overall simulation process during scoliosis surgery. In addition, it will be crucial to examine the rod curvatures in posterior corrective surgery for AIS patients using machine learning algorithms with pre-operative inputs.

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REFERENCES

1. Schlösser TP, Colo D, Castelein RM. Etiology and pathogenesis of adolescent idiopathic scoliosis. Elsevier; 2015:2-8. doi:https://doi.org/10.1053/j.semss.2015.01.003
2. Zhao T, Li Y, Dai Z, et al. Bibliometric Analysis of the Scientific Literature on Adolescent Idiopathic Scoliosis. World Neurosurgery. 2021/04/16/ 2021; 151:e265-e277. doi:https://doi.org/10.1016/j.wneu.2021.04.020
3. Mohamed M, Trivedi J, Davidson N, Munigangaiah S. Adolescent idiopathic scoliosis: a review of current concepts. Orthopaedics and Trauma. 2020/12/01/ 2020; 34(6):338-345. doi:https://doi.org/10.1016/j.mporth.2020.09.003
4. Sharifmoradi K, Naderi A, Saljoghiyan P. The Effect of Boston Brace on Lower Limb and L5-S1 Joint Contact Forces during Walking in Patients with Idiopathic Scoliosis. Scientific journal of Ilam University of medical sciences. 2017; 25(3):90-99. doi: http://dx.doi.org/10.29252/sjimu.25.3.90
5. Chung N, Cheng Y-H, Po H-L, et al. Spinal phantom comparability study of Cobb angle measurement of scoliosis using digital radiographic imaging. Journal of orthopaedic translation. 2018; 15:81-90. doi: https://doi.org/10.1016/j.jot.2018.09.005
6. Li Y, Kakar RS, Fu Y-C, et al. Postural control of individuals with spinal fusion for adolescent idiopathic scoliosis. Clinical Biomechanics. 2019; 61:46-51. doi: https://doi.org/10.1016/j.clinbiomech.2018.11.001
7. Luković V, Ćuković S, Milošević D, Devedžić G. An ontology-based module of the information system ScolioMedIS for 3D digital diagnosis of adolescent scoliosis. Computer Methods and Programs in Biomedicine. 2019/09/01/ 2019;178:247-263. doi:https://doi.org/10.1016/j.cmpb.2019.06.027
8. Salmingo RA, Tadano S, Fujisaki K, Abe Y, Ito M. Relationship of forces acting on implant rods and degree of scoliosis correction. Clinical biomechanics. 2013; 28(2):122-128. doi: https://doi.org/10.1016/j.clinbiomech.2012.12.001
9. Wang W, Baran GR, Betz RR, Samdani AF, Pahys JM, Cahill PJ. The use of finite element models to assist understanding and treatment for scoliosis: a review paper. Spine Deformity. 2014; 2(1):10-27. doi: https://doi.org/10.1016/j.jspd.2013.09.007
10. Cho SK, Caridi J, Kim JS, Cheung ZB, Gandhi A, Inzana J. Attenuation of Proximal Junctional Kyphosis Using Sublaminar Polyester Tension Bands: A Biomechanical Study. World neurosurgery. 2018; 120:e1136-e1142. doi: https://doi.org/10.1016/j.wneu.2018.08.244
11. Le Navéaux F, Aubin C-E, Parent S, Newton PO, Labelle H. 3D rod shape changes in adolescent idiopathic scoliosis instrumentation: how much does it impact correction? European Spine Journal. 2017; 26(6):1676-1683. doi: https://doi.org/10.1007/s00586-017-4958-1
12. Lavelle WF, Moldavsky M, Cai Y, Ordway NR, Bucklen BS. An initial biomechanical investigation of fusionless anterior tether constructs for controlled scoliosis correction. The Spine Journal. 2016; 16(3):408-413. doi: https://doi.org/10.1016/j.spinee.2015.11.004
13. Fairhurst H, Little JP, Adam CJ. Intra-operative measurement of applied forces during anterior scoliosis correction. Clinical Biomechanics. 2016; 40:68-73. doi: https://doi.org/10.1016/j.clinbiomech.2016.10.014
14. Reutlinger C, Hasler C, Scheffler K, Büchler P. Intraoperative determination of the load–displacement behavior of scoliotic spinal motion segments: preliminary clinical results. European spine journal. 2012; 21(6):860-867. doi: https://doi.org/10.1007/s00586-012-2164-8
15. Roth AK, Beheshtiha AS, van der Meer R, et al. Validation of a finite element model of the thoracolumbar spine to study instrumentation level variations in early onset scoliosis correction. Journal of the Mechanical Behavior of Biomedical Materials. 2021/05/01/ 2021; 117:104360. doi:https://doi.org/10.1016/j.jmbbm.2021.104360
16. Clin J, Le Navéaux F, Driscoll M, et al. Biomechanical Comparison of the Load-Sharing Capacity of High and Low Implant Density Constructs With Three Types of Pedicle Screws for the Instrumentation of Adolescent Idiopathic Scoliosis. Spine deformity. 2019; 7(1):2-10. doi: https://doi.org/10.1016/j.jspd.2018.06.007
17. Wang X, Boyer L, Le Naveaux F, Schwend RM, Aubin C-E. How does differential rod contouring contribute to 3-dimensional correction and affect the bone-screw forces in adolescent idiopathic scoliosis instrumentation? Clinical Biomechanics. 2016; 39:115-121. doi:

https://doi.org/10.1016/j.clinbiomech.2016.10.002

18. Jalalian A, Tay FE, Arastehfar S, Liu G. A patient-specific multibody kinematic model for representation of the scoliotic spine movement in frontal plane of the human body. Multibody system dynamics. 2017; 39(3):197-220. doi: https://link.springer.com/article/10.1007/s11044-016-9556-1
19. Petit Y, Aubin C-É, Labelle H. Patient-specific mechanical properties of a flexible multi-body model of the scoliotic spine. Medical and Biological Engineering and Computing. 2004; 42(1):55-60. doi: https://doi.org/10.1007/bf02351011
20 Koutras C, Pérez J, Kardash K, Otaduy MA. A study of the sensitivity of biomechanical models of the spine for scoliosis brace design. Computer Methods and Programs in Biomedicine. 2021/08/01/ 2021; 207:106125. doi:https://doi.org/10.1016/j.cmpb.2021.106125.
21. Jaremko JL, Poncet P, Ronsky J, et al. Comparison of Cobb angles measured manually, calculated from 3-D spinal reconstruction, and estimated from torso asymmetry. Computer methods in biomechanics and biomedical engineering. 2002; 5(4):277-281. doi: https://doi.org/10.1080/10255840290032649
22. Zhang J, Lou E, Le LH, Hill DL, Raso JV, Wang Y. Automatic Cobb measurement of scoliosis based on fuzzy Hough transform with vertebral shape prior. Journal of digital imaging. 2009; 22(5):463. doi: https://doi.org/10.1007/s10278-008-9127-y
23. Rak M, Steffen J, Meyer A, Hansen C, Tönnies KD. Combining convolutional neural networks and star convex cuts for fast whole spine vertebra segmentation in MRI. Computer Methods and Programs in Biomedicine. 2019/08/01/ 2019; 177:47-56. doi:https://doi.org/10.1016/j.cmpb.2019.05.003
24. Jaremko JL, Poncet P, Ronsky J, et al. Genetic Algorithm–Neural Network Estimation of Cobb Angle from Torso Asymmetry in Scoliosis. Journal of biomechanical engineering. 2002; 124(5):496-503. doi: https://doi.org/10.1115/1.1503375
25. Kokabu T, Kanai S, Kawakami N, et al. An algorithm for using deep learning convolutional neural networks with three dimensional depth sensor imaging in scoliosis detection. The Spine Journal. 2021; 21(6):980-987. doi: https://doi.org/10.1016/j.spinee.2021.01.022
26. Phan P, Mezghani N, Wai EK, de Guise J, Labelle H. Artificial neural networks assessing adolescent idiopathic scoliosis: comparison with Lenke classification. The Spine Journal. 2013; 13(11):1527-1533. doi: https://doi.org/10.1016/j.spinee.2013.07.449
27. Tokala DP, Nelson IW, Mehta JS, Powell R, Grannum S, Hutchinson MJ. Prediction of scoliosis curve correction using pedicle screw constructs in AIS: A comparison of fulcrum bend radiographs and traction radiographs under general anesthesia. Global Spine Journal. 2018; 8(7):676-682. doi: https://doi.org/10.1177/2192568218763147
28. Hu B, Wang L, Song Y, Yang X, Liu L, Zhou C. Postoperative proximal junctional kyphosis correlated with thoracic inlet angle in Lenke 5c adolescent idiopathic scoliosis patients following posterior surgery. BMC Musculoskeletal Disorders. 2022; 23(1):1-11. doi:https://doi.org/10.1186/s12891-022-05868-8
29. Garg B, Mehta N, Bansal T, Malhotra R. EOS® imaging: Concept and current applications in spinal disorders. Journal of Clinical Orthopaedics and Trauma. 2020/09/01/ 2020; 11(5):786-793. doi:https://doi.org/10.1016/j.jcot.2020.06.012
30. Lechner R, Putzer D, Dammerer D, Liebensteiner M, Bach C, Thaler M. Comparison of two-and three-dimensional measurement of the Cobb angle in scoliosis. International Orthopaedics. 2017; 41(5):957-962. doi:https://doi.org/10.1007/s00264-016-3359-0
31. Skov ST, Li H, Hansen ES, et al. New growth rod concept provides three dimensional correction, spinal growth, and preserved pulmonary function in early-onset scoliosis. International Orthopaedics. 2020; 44(9):1773-1783. doi:https://doi.org/10.1007/s00264-020-04604-y
32 Ghandhari H, Mahabadi MA, Nikouei F, et al. The role of spinopelvic parameters in clinical outcomes of spinal osteotomies in patients with sagittal imbalance. Archives of Bone and Joint Surgery. 2018; 6(4):324. doi:http://dx.doi.org/10.22038/abjs.2017.26676.1705.