Toward the next generation of simulator for intraoperative navigation of scoliotic spine surgeries

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Abstract. Surgical navigation systems are useful for planning pedicle screw positioning and guiding drilling trajectories. However, it is not yet possible to intraoperatively predict the correction of the scoliotic spine resulting from specific screw and rod configuration and instrumentation maneuvers. In this context, the objective of this study is to develop a novel intraoperative simulator for navigated scoliotic spine surgeries. An instrumentation strategy (pedicle screw insertion, rod attachment and rotation, set screw tightening) was computationally simulated on a synthetic model of a scoliotic spine using the preoperative radiographs in the standing position and various parameters recreating the preoperative conditions. The intraoperative decubitus position was then simulated. The resulting geometry was identified using a navigation system and transferred to the simulator, which enabled the updating of the preoperative planning, computing of clinical indices (Cobb angles, etc.) and simulation of instrumentation maneuvers. The Cobb angle decreased from 34° to 24° between the simulated pre- and intraoperative spine (before the instrumentation). Difference in pedicle screw positioning between the preoperative planning and the intraoperative situation was less than 0.5 mm. The intraoperative simulation of the rod attachment and rotation maneuvers resulted in a 12° Cobb angle. In conclusion, this preliminary study is a first step toward developing an integrated simulator for preoperative planning and intraoperative navigation of scoliotic spine surgeries. Once completed, the new intraoperative simulator will enable the surgeon to obtain real-time biomechanical feedback during the navigated surgery of a scoliotic spine, and may contribute to improve the resulting correction and instrumentation parameters (instrumented levels, surgical maneuvers, generated forces, etc.).

Keywords. Scoliotic spine, instrumentation surgery, preoperative planning, intraoperative navigation, intraoperative simulation

1. Introduction

In scoliotic spine surgery, there is no consensus on the best instrumentation strategy for a given patient [1-3]. Recent studies have demonstrated high variability in correction objectives (Cobb angles, balance, etc.) [4] and instrumentation strategies (fusion levels, rotation maneuvers, etc.) [5], even for experienced surgeons.

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In this context, a biomechanical simulator (S3) has been developed for the planning of scoliotic spine surgeries based on the preoperative radiographs of the spine [6]. Using this simulator, surgeons are able to simulate the correction of a given scoliotic spine resulting from different instrumentation strategies (screw positioning, rod attachment and rotation maneuvers) before the intervention.

Intraoperative imaging and navigation systems are useful for planning the positioning of pedicle screws and guiding drilling trajectories [7-11]. However, contrary to the preoperative simulator S3, it is not yet possible to intraoperatively predict the correction of the scoliotic spine resulting from a specific screw pattern, contoured rod configuration and instrumentation maneuvers.

This study aims at demonstrating the feasibility to update the preoperative simulation and instrumentation planning of a given scoliotic spine with respect to intraoperative data from a navigation system.

2. Material and methods

The study was performed on a synthetic model of a scoliotic spine replicating a realistic spinal deformity.

A three-dimensional (3D) geometrical model was constructed using the two-dimensional (2D) X-ray images of the synthetic spine configured in a standing position (Fig. 1a) [12], representing realistic preoperative conditions. Each vertebra of the synthetic spine was before embedded with five spherical steel markers (2-mm diameter) located on the spinous and transverse processes, as well as the laminae. These 3D landmarks were manually identified on the X-ray images for registration purposes.

The geometrical model, generated from the preoperative 3D reconstruction process, was transferred to the simulator S3, and an instrumentation strategy was defined, including pedicle screw insertion, contoured rod attachment and rotation, and set screw tightening (Fig. 1b).

The synthetic spine shape was reconfigured to recreate the patient decubitus positioning during the intervention with the intraoperative correction obtained prior the instrumentation due to the prone positioning and the effect of the anesthesia (Fig. 1c) [6,13]. The steel markers incrusted in each vertebra were manually measured using a surgical navigation system. A rigid registration was computed to transpose the position of each vertebra of the geometrical model in the intraoperative coordinate system using the steel markers (Fig. 1d). The accuracy of this update process was evaluated by comparing the coordinates of the planned pedicle screws (relative to the preoperative spinal shape) to those obtained after the registration process relative to the intraoperative configuration of the spine.

The above-described registration process enabled to update the preoperative planning and simulate the predefined correction maneuvers using the intraoperative decubitus spine geometry. Pre- and post-instrumentation Cobb angles were computed for the simulated pre- and intraoperative spine geometries.

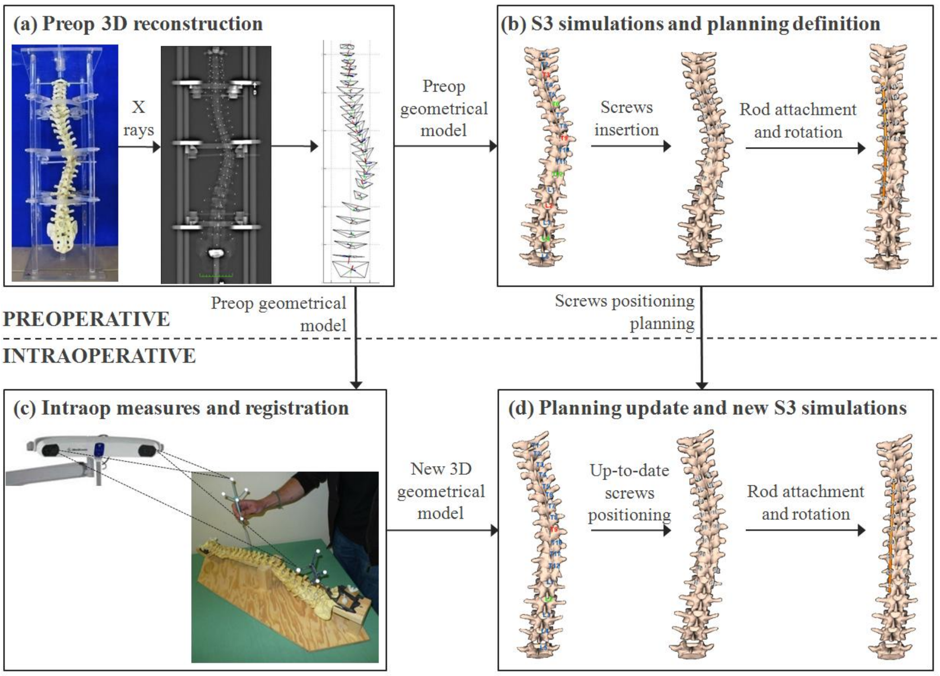

Figure 1. Workflow diagram of the proposed planning update process.

3. Results

After the registration and planning update processes, difference in the positioning of the pedicle screws between the preoperative planning and the intraoperative situation (simulated in S3) was less than 0.5 mm.
The Cobb angle (computed in S3) decreased from 34° to 24° between the simulated pre- and intraoperative spinal shapes before the instrumentation. Then, the intraoperative simulation of the rod attachment and rotation maneuvers resulted in a 12° Cobb angle.

4. Discussion and conclusions

This study demonstrated the feasibility to update the preoperative simulation and instrumentation planning of a given scoliotic spine (made a priori with the simulator S3) with respect to intraoperative data from a navigation system. In this case, the method allowed to represent the intraoperative decubitus spinal shape that is different from the pre-operative standing posture. In the future, this would allow the surgeon to account for any change that occurs in the operative theater, as well as to update the planning or test other instrumentation strategies intraoperatively.

In this preliminary study, the planning update process was performed using manual identification of spherical steel markers embedded in the vertebrae of a moderate scoliosis. This enabled precise measurements of the pre- and intraoperative spinal shapes, respectively in the coordinate systems of the preoperative X-rays 3D reconstruction and the intraoperative navigation system. Next steps include the use of a more severe deformity and the development of (1) new 3D reconstruction and registration processes of pre- and intraoperative spinal shapes by using automatic identification of vertebral anatomical landmarks, and (2) new methods for automatically transferring the up-to-date planning to the navigation system, in order to navigate the screws insertion with respect to the preoperatively planned trajectories.

In conclusion, this preliminary study is a first step toward developing an integrated simulator for preoperative planning and intraoperative navigation of scoliotic spine surgeries. Once completed, the new intraoperative simulator may contribute to (1) obtaining real-time biomechanical feedback during the navigated surgery of a scoliotic spine (Cobb angles, simulations, force analysis, etc.), and (2) optimizing the correction and instrumentation (instrumented levels, surgical maneuvers, generated forces, etc.).

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References

[1] CR. Fischer,Y. Kim. Selective fusion for adolescent idiopathic scoliosis: a review of current operative strategy. *Eur Spine J* **20(7)** (2011), 1048-1057.

[2] JO. Sanders, M. Diab, SB. Richards, LG. Lenke, CE. Johnston, JB. Emans, DJ. Sucato, MA. Erickson, KH. Bridwell, RE. McCarthy, JF. Sarwark, JP. Dormans, Spinal Deformity Study Group. Fixation Points Within the Main Thoracic Curve: Does More Instrumentation Produce Greater Curve Correction and Improved Results? *Spine* **36(21)** (2011), E1402-1406.

[3] M. Imrie, B. Yaszay, TP. Bastrom, DR. Wenger, PO. Newton. Adolescent idiopathic scoliosis: should 100% correction be the goal? *J Pediatr Orthop* **31(Suppl.1)** (2011), S9-13.

[4] Y. Majdouline, CE. Aubin, M. Robitaille, JF. Sarwark, H. Labelle. Scoliosis correction objectives in adolescent idiopathic scoliosis. *J Pediatr Orthop* **27(7)**(2007), 775-781.

[5] M. Robitaille, CE. Aubin, H. Labelle. Intra and interobserver variability of preoperative planning for surgical instrumentation in adolescent idiopathic scoliosis. *Eur Spine J* **16(10)** (2007), 1604-1614.

[6] CE. Aubin, H. Labelle, C. Chevrefils, G. Desroches, J. Clin, A. Boivin. Preoperative planning simulator for spinal deformity surgeries. *Spine* **33(20)** (2008), 2143-2152.

[7] NF. Tian, QS. Huang, P. Zhou, Y. Zhou, RK. Wu, Y. Lou, HZ. Xu. Pedicle screw insertion accuracy with different assisted methods: a systematic review and meta-analysis of comparative studies. *Eur Spine J* **20(6)** (2011), 846-859.

[8] AN. Larson, ER. Santos, DW. Jr Polly, CG. Ledonio, JN. Sembrano, CH. Mielke, KJ. Guidera. Pediatric Pedicle Screw Placement Using Intraoperative CT and 3D Image-Guided Navigation. *Spine* **37(3)** (2012), E188-194.

[9] J. Silbermann, F. Riese, Y. Allam, T. Reichert, H. Koeppert, M. Gutberlet. Computer tomography assessment of pedicle screw placement in lumbar and sacral spine: comparison between free-hand and O-arm based navigation techniques. *Eur Spine J* **20(6)** (2011), 875-881.

[10] KM. Scheufler, J. Franke, A. Eckardt, H. Dohmen. Accuracy of Image-Guided Pedicle Screw Placement using Intraoperative Computed Tomography based Navigation with Automated Referencing. Part II - Thoracolumbar Spine. *Neurosurgery* **69(6)** (2011), 1307-1316.

[11] ID. Gelalis, NK. Paschos, EE. Pakos, AN. Politis, CM. Arnaoutoglou, AC. Karageorgos, A. Ploumis, TA. Xenakis. Accuracy of pedicle screw placement: a systematic review of prospective in vivo studies comparing free hand, fluoroscopy guidance and navigation techniques. *Eur Spine J* **21(2)** (2012), 247-255.

[12] S. Delorme, Y. Petit, JA. de Guise, H. Labelle, CE. Aubin, J. Dansereau. Assessment of the 3-D reconstruction and high-resolution geometrical modeling of the human skeletal trunk from 2-D radiographic images. *IEEE Trans. Biomed. Eng* **50(8)** (2003), 989-998.

[13] S. Delorme, H. Labelle, B. Poitras, CH. Rivard, C. Coillard, J. Dansereau. Pre-, intra-, and postoperative three-dimensional evaluation of adolescent idiopathic scoliosis. *J Spinal Disord* **13** (2000), 93-101.