Tracked ultrasound snapshots in percutaneous pedicle screw placement navigation: a feasibility study

Tamas Ungi, MD, PhD[a], Eric Moult[a], Joseph H. Schwab, MD[b], Gabor Fichtinger, PhD[a]

[a] Laboratory for Percutaneous Surgery, School of Computing, Queen's University, Kingston, ON, Canada

[b] Department of Orthopedic Surgery, Massachusetts General Hospital, Boston, MA, USA.

Abstract

Background. Computerized navigation improves the clinical outcome of pedicle screw placement surgery. Navigation requires spatial registration of preoperative images to the intraoperative tracking coordinate system. This registration may be accomplished using tracked ultrasound snapshots, allowing for accurate pedicle screw placement without ionizing radiation. **Questions.** Are there reliable ultrasound landmarks that can be identified in each vertebra? Do tracked ultrasound snapshots provide accurate registration of pedicle screw plans in an intraoperative setting? **Methods.** Ultrasound visibility of registration landmarks were checked on volunteers and phantoms. Two artificial lumbar spine phantoms were used to evaluate registration accuracy of pedicle screw plans using tracked ultrasound snapshots. An ultrasound machine with integrated electromagnetic tracking was used for tracked ultrasound acquisition. Registration was performed using the 3D Slicer open-source software[1]. **Results.** The four articular processes proved to be reliable ultrasound registration landmarks. Pedicle screw plans were registered to the intraoperative coordinate system using landmarks at sufficient accuracy. The registered plans did not intersect the pedicle walls. Registered plan positions had an error less than 1.28 ± 1.37 mm (average ± SD) in each direction, and angle difference less than 1.92 ± 1.95 degrees around each axis relative to the ground truth plan positions. **Conclusions.** Landmarks on tracked ultrasound snapshots provide accurate pedicle screw plan registration in computer navigated surgery. **Clinical Relevance.** Tracked ultrasound may allow accurate, computer navigated pedicle screw placement without ionizing radiation.

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[1] www.slicer.org

Introduction

Few surgical procedures motivate computerized navigation technologies more than pedicle screw placement. Being the standard of care in many spinal deformation diseases, improvement of this procedure has an impact on a large patient population, which includes children and seniors. Vertebrae and surgical tools can be equipped with position tracking devices, enabling accurate and real-time virtual reality visualization. Various intraoperative navigation methods have been developed and published over the past decades. In this paper, we evaluate tracked ultrasound snapshots (TUSS) [20] for intraoperative localization of planned screw positions in pedicle screw navigation.

Although pedicle screw placement is considered a low-risk procedure [4], intraoperative 3-D navigation by continuous tracking of the instruments can prevent adverse outcomes and decrease intraoperative ionizing radiation. In particular, real-time 3-D navigation is associated with significantly less operation time and blood loss compared to fluoroscopic guidance [24], while also reducing the radiation burden on operating staff [3, 1]. Furthermore, having access to 3-D guidance during navigation results in fewer screw removals and reduces the number of potentially unsafe screws [19]. In fact, a recent meta-analysis of published literature revealed that the risk of pedicle perforation drops from 15% to 6% with computer navigation in pedicle screw placement [17]. These favorable effects motivate research into an optimal navigation technology that is simple, low-cost and accurate, as well as safe for patients and operating staff.

Registration of a preoperative computed tomography (CT) with an intraoperative stereotactic guidance system can completely eliminate ionizing radiation during pedicle screw placement, while maintaining highly accurate screw placement [8]. This registration method requires landmark localization in both the CT and the intraoperative tracking coordinate systems. These landmarks determine the transformation that fuses the preoperative CT with the intraoperative virtual reality navigation scene. In this study, TUSS is used to find these landmarks through non-invasive ultrasound (US) imaging. The resulting registration transformation is used to place the pedicle screw plans in the surgical navigation coordinate system.

Automatic CT to US image registration methods are promising alternatives to manual landmarking of US images and have been subject to intensive research for spine images; however, are yet to find a method to compute a reliable registration transform on all reported experimental test cases with satisfactory accuracy. Since intraoperative conditions could further reduce the success rate of these automatic methods, we chose manually defined landmarks as the most accurate available CT registration method for this procedure. It should still be noted, however, the implications will be applicable to automatic registration methods in the future when they become as reliable as manually selected landmarks.

In our evaluation, pedicle screw positions were planned using a preoperative CT scan. The plans were later registered to the surgical navigation coordinate system using TUSS landmarks. We evaluated the registration based on clinical safety parameters of the registered pedicle screw plans in two patient-based phantom models. The presented method is open-source and conveniently available for the research community an extension for the 3D Slicer application.

Materials and Methods

Plan registration workflow

Our proposed surgical workflow is shown in Figure 1. A preoperative CT scan was used to define pedicle screw positions and registration landmarks were defined on the CT scans of vertebrae. In the intraoperative phase, corresponding landmarks were localized using TUSS. After landmark registration, we transformed the CT-based pedicle screw plans to the intraoperative navigation coordinate system for evaluation.

Landmark-based registration transformation is computed using the Fiducial Registration module of the 3D Slicer application.

Tracked US and navigation system

The design of the intraoperative navigation system is shown in Figure 4. We used a Sonix Tablet (Ultrasonix, Richmond, BC, Canada) US machine, with an integrated GPS extension for electromagnetic position tracking. This tracker hardware extension is comprised of a DriveBay electromagnetic tracker (Ascension, Burlington, VT, USA) and an adjustable arm that holds the EM transmitter. The 3-D navigation software was implemented as an extension (PerkNav) for the 3D Slicer application [20]. The navigation software ran on a dedicated computer, getting real-time tracking and US image data through a network connection from the US machine, using the OpenIGTLink data communication protocol [18].

Pedicle screw plans used for evaluation

We used two rapid prototyped spine segments of L2-L5 for the evaluation of the presented TUSS-based pedicle screw plan registration. The spine models were generated by manually contouring one healthy and one degenerative spine CT scans. Planning of the pedicle screws was done using four points in the CT image of each pedicle (Figure 2). Optimal positions and orientations of the screws were determined by manually placing these points on the left and right edge of the pedicles on coronal CT slices in an anterior and a posterior section of the pedicles. Corresponding predefined points on the screw models were registered to these CT points to obtain optimal positions of the screws for each pedicle.

Planned positions of the screws in the healthy and the degenerative models are shown in Figure 3. All planned screws are 4 mm in diameter and 50 mm in length.

Anatomical landmarks for CT and US images

Registration from the CT image to the surgical navigation scene was done using anatomical landmark points on the vertebrae. For this, we identified landmarks that are visible on both CT and intraoperative US images. Previous studies show that the articular processes of the vertebrae are reliable landmarks in both imaging modalities [22].

Lumbar spine images of 10 human subjects were examined to verify visibility of anatomical landmarks on US images. The study protocol was approved by the Health Sciences Research Ethics Board at Queen's University. Written informed consent was obtained from subjects prior to participation in the study. The clinical parameters of the examined population are shown in Table 1. Registration landmarks were defined as the most posterior points of the four articular processes of each vertebra.

Finding the articular processes with US imaging can be a difficult task. Therefore, an axial tracked US snapshot was taken to help find the intersecting sagittal US planes that correspond to the facet joint regions, as shown in Figure 4. US landmark points were defined on sagittal tracked US snapshots.

Evaluation of registration accuracy

The proposed registration workflow was executed in two patient-based lumbar spine models. One model was derived from healthy anatomy, while the other from degenerative spine disease anatomy. The tests involved L2-L5 segments in each spine model, with two pedicle screw plans in each vertebra.

We reported translational and orientation errors between US-based screw positions and the CT-based screw positions. Translational error was measured at the center of the screw plan, which was positioned near the center of the pedicles during the planning phase. Orientation errors were decomposed into three Euler angles using the left-right, posterior-anterior, and inferior-superior anatomical axes.

Breaches of the pedicle wall or vertebral body were also examined.

Results

The selected four registration landmarks were visible in all 10 human subjects, and in all patient-based simulation phantoms.

All vertebrae in the two phantom models were successfully registered using US landmark points. Figure 5 shows an overview of positions of the US-based pedicle screw plans (in red) compared to the ground truth positions of the plans (in blue), along with semi-transparent vertebrae in the healthy and degenerative models.

Position and orientation differences between CT-based and US-based pedicle screw plans, for all anatomical directions and axes, are summarized in Table 2.

We plotted the translational error in the coronal plane of individual screw centers (Figure 6), because projection of the error data onto this plane is most relevant from the perspective of clinical complications. The maximum translation error (3.51 mm) occurred in the superior direction in the degenerative model.

Perforation of the pedicle wall by the TUSS-based screw plans were not detected in any of the pedicles.

Discussion

We found that TUSS may be a useful tool in pedicle screw navigation, potentially improving safety and reducing ionizing radiation in spinal fusion surgeries. Landmarks on TUSS images provide sufficient information to register the preoperative screw plans with the surgical navigation system. The translational errors found in our evaluation study were not uniform in different directions. In particular, the deviation of positions was largest in the inferior-superior anatomical direction. Because facet joints were used as landmarks for US-CT registration, this may be attributed to the elongated shape of the facet joints in the inferior-superior direction.

Navigation improves the clinical outcome of spine fusion surgery, although some studies fail to show significant improvement over traditional [15]. Evaluation of the surgical plan is performed in different ways in the literature. Liang *et al*. measured position and orientation error compared to a ground truth surgical plan [11]. Kawaguchi et al.

determined critical breaches of the screws using postoperative CT [9]. Zhang et al. used perforation of the pedicle wall and deviation from the lateral pedicle wall [25]. Following evaluation methods described in these earlier works, we reported both position and orientation accuracy of the screw plans registered using TUSS, and we examined the registered plans for pedicle wall perforation.

The past decades have brought many innovations that have greatly assisted spinal surgery navigation. A simple and robust method to control the movement of surgical tools is to provide artificial mechanical constraints. Some groups have developed rapid prototyped templates for the lamina based on a preoperative CT scan of the spine [9, 13]. This method requires direct contact with a relatively large bone surface and is therefore is unsuitable in minimally invasive procedures. The most advanced mechanical apparatus designed for this operation is the SpineAssist (MAZOR Surgical Technologies, Caesarea, Israel) miniature robot, mounted on a T-frame fixed rigidly to the spine [12]. Although this robot provides excellent clinical outcomes [7], its cost and complexity may impose limitations on its applicability as the standard of care. Liang et al. used the intersection of two laser planes to guide the pedicle probe to position the guide-wires for screws [11]. Von Jako et al. used EM tracking in minimally invasive percutaneous pedicle screw placement [21]. These two technologies successfully reduced, but did not eliminate, fluoroscopy from the procedure. Intraoperative CT imaging also makes pedicle screw placement safe and accurate in adult and pediatric surgery [14, 10]; however, little advantage was found compared to navigation using preoperative CT [2]. Moreover, this technology requires investment into expensive instrumentation and does not eliminate ionizing radiation. Our presented system is based on EM tracking and US imaging, two technologies that are low-cost and safe for patients and operating staff. Furthermore, as our method is implemented as free, open-source software, we expect it to disseminate easily among researchers and eventually clinicians performing pedicle screw placements.

The presented study, however, has a number of limitations. The two CT scans—along with the rapid prototyped bone models from which they are derived—does not give a representative sample of the patient population undergoing spinal fusion surgery. A larger sample size with various deformations is not yet available for us, but the presented results seem promising enough to suggest that this method may have significant clinical benefit in the future. Another issue is that translation errors of the screw placement are somewhat biased in the superior direction (Figure 6), which indicates a systematic error in our method. If the source of this bias is discovered in the future, accuracy is likely to further increase.

As mentioned previously, landmark registration may be replaced in the future by automatic CT to US registration methods. This would eliminate the need for training operators for landmark recognition, and would also shorten the procedure time. Some promising automatic registration methods have been already proposed. These methods are either based on image-to-image registration [23], or require prior segmentation of the vertebrae [6]. Biomechanical constraints can also be applied in the registration algorithm to account for the characteristic deformation of the spinal column between CT and US scan. However, registration still fails in a significant number of trials even under experimental conditions when used in image-based [5] or surface-based algorithms [16]. Since success rates are reportedly below 90%, and surgical cases would probably result in a lower success rate than experimental cases, we have chosen not to use these otherwise promising automatic registration methods. Consequently, our results may be close to the highest accuracy that is achievable using intraoperative US for registration of the screw plans.

Our findings also suggest that TUSS can be used in the navigation of other minimally invasive spinal interventions, such as vertebroplasty. The invasiveness of the proposed navigation method in different procedures could be further reduced by using skin-mounted or table-mounted reference sensors. The presented software is suitable for customization of the procedure workflow and the tracked surgical tools. We help dissemination of the software and use-cases through a freely available multiplatform extension to the 3D Slicer application. Further instructions for users and developers can be found on the project website.

In conclusion, tracked US technology may effectively contribute to navigated spinal fusion surgery. In particular, tracked US snapshots of vertebral landmarks can be used to localize planned pedicle screw positions in the intraoperative surgical navigation scene without ionizing radiation.

References

1. Bandela JR, Jacob RP, Arreola M, Griglock TM, Bova F, Yang M. Use of CT-Based Intraoperative Spinal Navigation: Management of Radiation Exposure to Operator, Staff, and Patients. *World Neurosurg*. 2011 Nov 7.
2. Costa F, Cardia A, Ortolina A, Fabio G, Zerbi A, Fornari M. Spinal navigation: standard preoperative versus intraoperative computed tomography data set acquisition for computer-guidance system: radiological and clinical study in 100 consecutive patients. *Spine (Phila Pa 1976).* 2011;36:2094-8.
3. Cui G, Wang Y, Kao TH, Zhang Y, Liu Z, Liu B, Li J, Zhang X, Zhu S, Lu N, Mao K, Wang Z, Zhang X, Yuan X, Dong T, Xiao S. Application of intraoperative computed tomography with or without navigation system in surgical correction of spinal deformity: a preliminary result of 59 consecutive human cases. *Spine (Phila Pa 1976)*. 2012;37:891-900.
4. Gautschi OP, Schatlo B, Schaller K, Tessitore E. Clinically relevant complications related to pedicle screw placement in thoracolumbar surgery and their management: a literature review of 35,630 pedicle screws. *Neurosurg Focus.* 2011;31:E8.
5. Gill S, Abolmaesumi P, Fichtinger G, Boisvert J, Pichora D, Borshneck D, Mousavi P. Biomechanically constrained groupwise ultrasound to CT registration of the lumbar spine. *Med Image Anal*. 2012;16:662-74.
6. Herring JL, Dawant BM, Maurer CR Jr, Muratore DM, Galloway RL, Fitzpatrick JM. Surface-based registration of CT images to physical space for image-guided surgery of the spine: a sensitivity study. *IEEE Trans Med Imaging*. 1998;17:743-52.

7. Hu X, Ohnmeiss DD, Lieberman IH. Robotic-assisted pedicle screw placement: lessons learned from the first 102 patients. *Eur Spine J*. 2012 Sep 14.
8. Kalfas IH, Kormos DW, Murphy MA, McKenzie RL, Barnett GH, Bell GR, Steiner CP, Trimble MB, Weisenberger JP. Application of frameless stereotaxy to pedicle screw fixation of the spine. *J Neurosurg*. 1995;83:641-7.
9. Kawaguchi Y, Nakano M, Yasuda T, Seki S, Hori T, Kimura T. Development of a new technique for pedicle screw and magerl screw insertion using a 3-dimensional image guide. *Spine (Phila Pa 1976).* 2012;37:1983-8.
10. Larson AN, Polly DW Jr, Guidera KJ, Mielke CH, Santos ER, Ledonio CG, Sembrano JN. The accuracy of navigation and 3D image-guided placement for the placement of pedicle screws in congenital spine deformity. *J Pediatr Orthop*. 2012;32:e23-9.
11. Liang JT, Doke T, Onogi S, Ohashi S, Ohnishi I, Sakuma I, Nakajima Y. A fluorolaser navigation system to guide linear surgical tool insertion. *Int J Comput Assist Radiol Surg*. 2012;7:931-9.
12. Lieberman IH, Togawa D, Kayanja MM, Reinhardt MK, Friedlander A, Knoller N, Benzel EC. Bone-mounted miniature robotic guidance for pedicle screw and translaminar facet screw placement: Part I--Technical development and a test case result. *Neurosurgery*. 2006;59:641-50.
13. Lu S, Zhang YZ, Wang Z, Shi JH, Chen YB, Xu XM, Xu YQ. Accuracy and efficacy of thoracic pedicle screws in scoliosis with patient-specific drill template. *Med Biol Eng Comput*. 2012;50:751-8.

14. Park P, Foley KT, Cowan JA, Marca FL. Minimally invasive pedicle screw fixation utilizing O-arm fluoroscopy with computer-assisted navigation: Feasibility, technique, and preliminary results. *Surg Neurol Int*. 2010;1:44.
15. Patil S, Lindley EM, Burger EL, Yoshihara H, Patel VV. Pedicle screw placement with O-arm and stealth navigation. *Orthopedics*. 2012;35:e61-5.
16. Rasoulian A, Abolmaesumi P, Mousavi P. Feature-based multibody rigid registration of CT and ultrasound images of lumbar spine. *Med Phys*. 2012;39:3154-66.
17. Shin BJ, James AR, Njoku IU, Härtl R. Pedicle screw navigation: a systematic review and meta-analysis of perforation risk for computer-navigated versus freehand insertion. *J Neurosurg Spine.* 2012;17:113-22.
18. Tokuda J, Fischer GS, Papademetris X, Yaniv Z, Ibanez L, Cheng P, Liu H, Blevins J, Arata J, Golby AJ, Kapur T, Pieper S, Burdette EC, Fichtinger G, Tempany CM, Hata N. OpenIGTLink: an open network protocol for image-guided therapy environment. *Int J Med Robot*. 2009;5:423-34.
19. Ughwanogho E, Patel NM, Baldwin KD, Sampson NR, Flynn JM. Computed tomography-guided navigation of thoracic pedicle screws for adolescent idiopathic scoliosis results in more accurate placement and less screw removal. *Spine (Phila Pa 1976).* 2012;37:E473-8.
20. Ungi T, Abolmaesumi P, Jalal R, Welch M, Ayukawa I, Nagpal S, Lasso A, Jaeger M, Borschneck DP, Fichtinger G, Mousavi P. Spinal needle navigation by tracked ultrasound snapshots. *IEEE Trans Biomed Eng.* 2012;59:2766-72.
21. von Jako R, Finn MA, Yonemura KS, Araghi A, Khoo LT, Carrino JA, Perez-Cruet M. Minimally invasive percutaneous transpedicular screw fixation: increased

accuracy and reduced radiation exposure by means of a novel electromagnetic navigation system. *Acta Neurochir (Wien)*. 2011;153:589-96.

22. Winter S, Pechlivanis I, Dekomien C, Igel C, Schmieder K. Toward registration of 3D ultrasound and CT images of the spine in clinical praxis: design and evaluation of a data acquisition protocol. *Ultrasound Med Biol.* 2009;35:1773-82.
23. Yan CX, Goulet B, Tampieri D, Collins DL. Ultrasound-CT registration of vertebrae without reconstruction. *Int J Comput Assist Radiol Surg.* 2012;7:901-9.
24. Yang YL, Zhou DS, He JL. Comparison of Isocentric C-Arm 3-Dimensional Navigation and Conventional Fluoroscopy for C1 Lateral Mass and C2 Pedicle Screw Placement for Atlantoaxial Instability. *J Spinal Disord Tech*. 2011 Nov 18.
25. Zhang HL, Zhou DS, Jiang ZS. Analysis of accuracy of computer-assisted navigation in cervical pedicle screw installation. *Orthop Surg*. 2011;3:52-6.

Legends

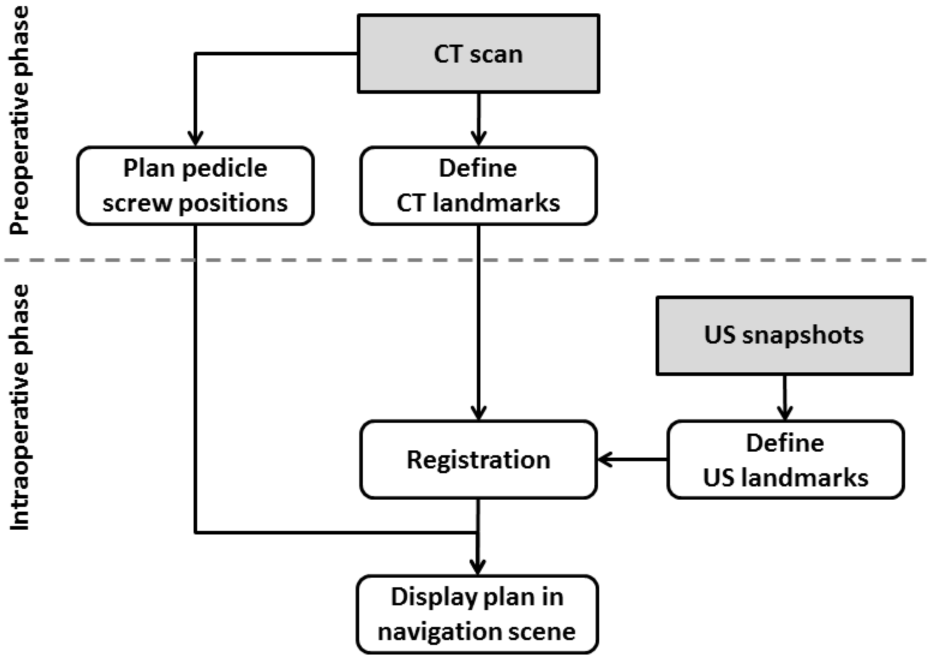

Figure 1. Proposed surgical workflow with US-based registration.

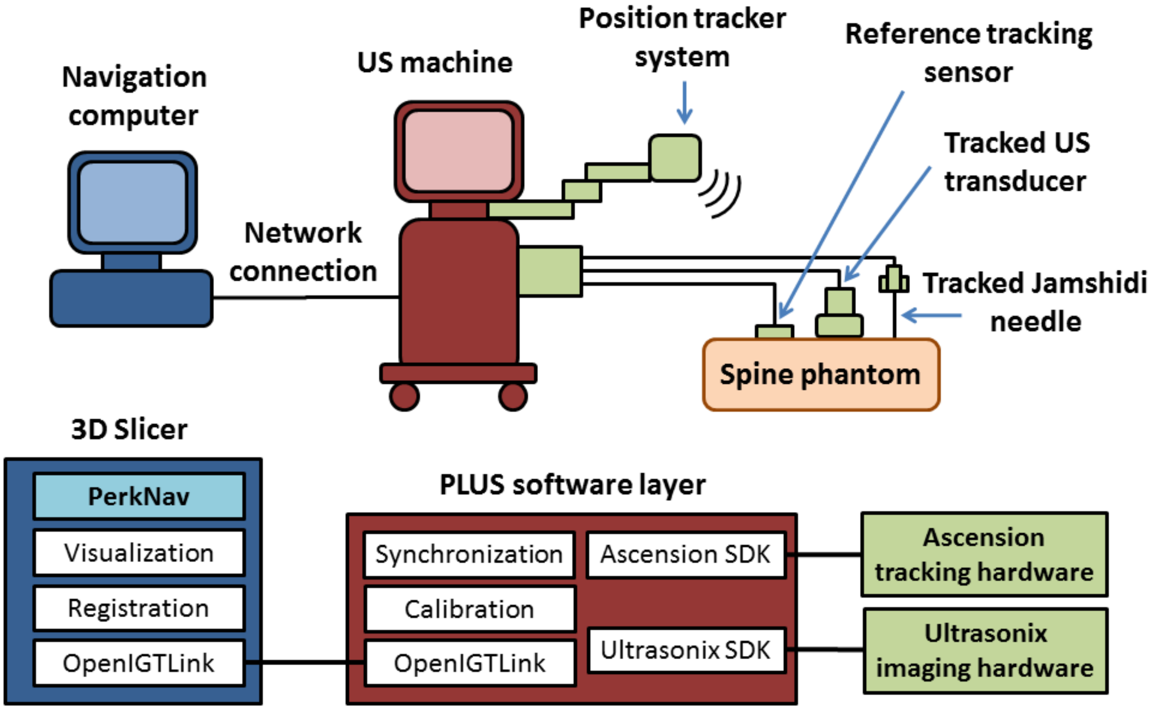

Figure 2. Schematic system overview of the intraoperative navigation hardware and software system.

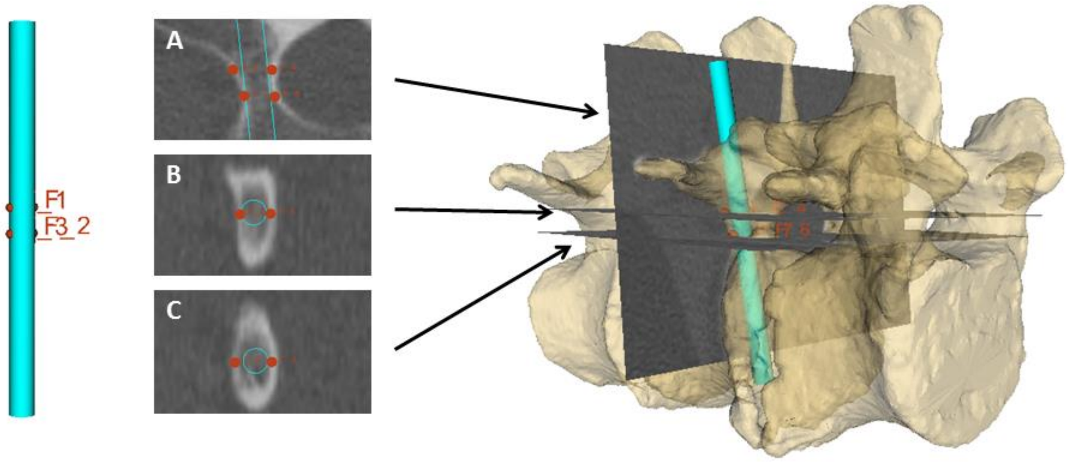

Figure 3. Planning of pedicle screws is facilitated using landmark points (red dots) on the CT image and the screw plan.

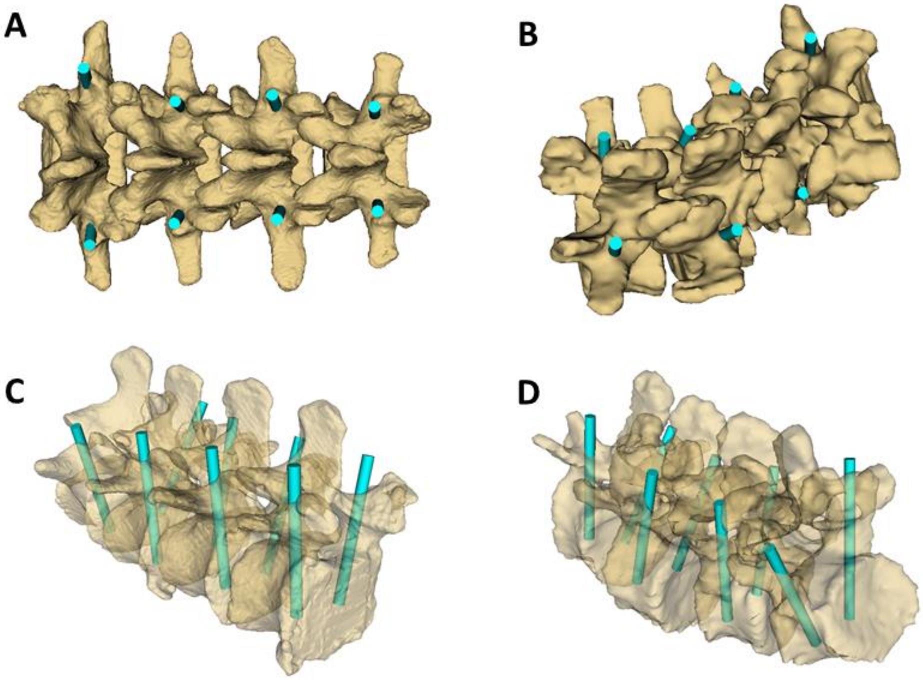

Figure 4. Planned screw positions are shown on the healthy spine model (A and C views) and the degenerative spine model (B and D views). Posterior views are shown in the top row (A and B) and right oblique view with semi-transparent bone models in the bottom row (C and D).

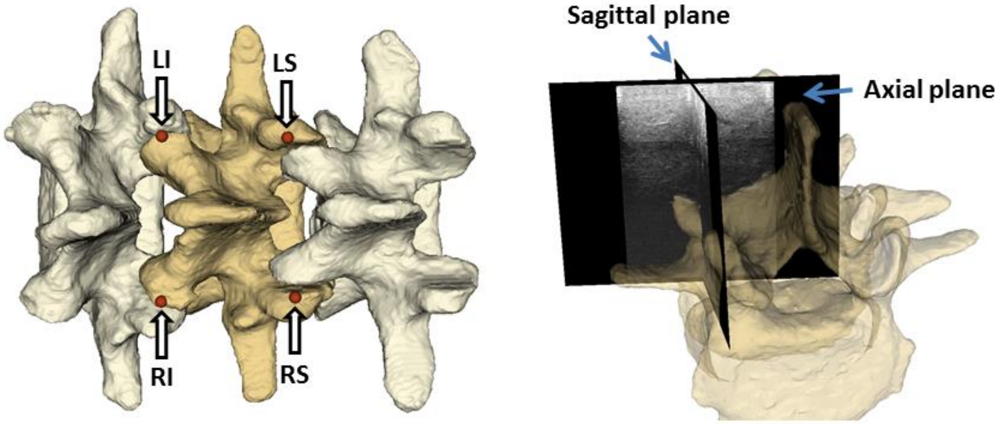

Figure 5. Four selected landmarks for vertebra registration (left panel). US snapshots (right panel) illustrate how to guide the sagittal plane to the facet joint area. The semi-transparent vertebra overlaid on US snapshots is only for illustration, and is not visible during actual landmark definition.

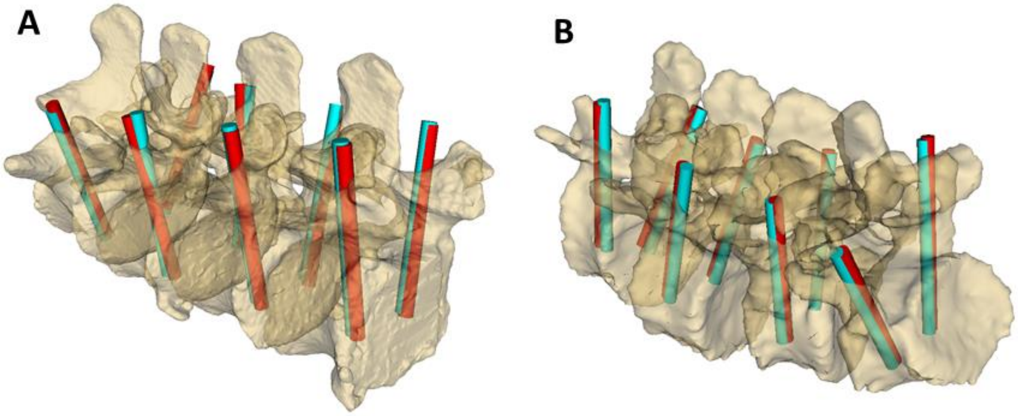

Figure 6. Overview of pedicle screw plan positions as defined in the CT image (blue rods) and as registered using US snapshots (red rods) in the healthy spine model (A) and the degenerative model (B).

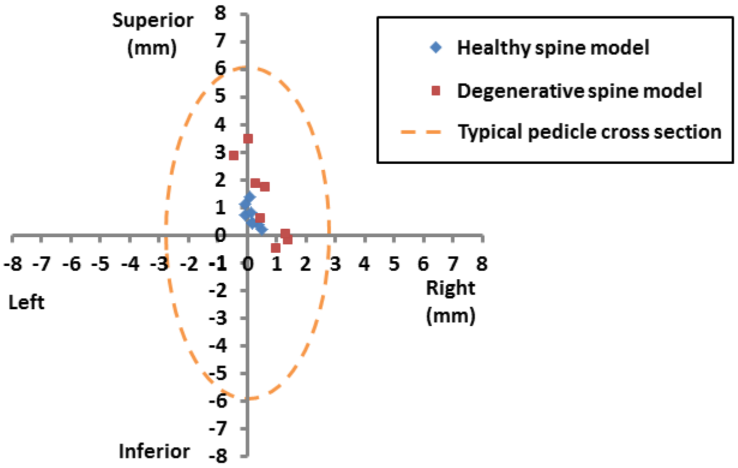

Figure 7. Scatter plot of translation errors of individual TUSS-based screw positions relative to the CT-based screw positions in the left-right, inferior-superior anatomical plane.

Table 1. Clinical parameters of human subjects.

Parameter	**Value**
Height (m) ± SD	171.2 ±8.1
Weight (kg) ± SD	75.9 ± 20.0
Body mass index (BMI) ± SD	25.7 ± 6.2
Age (years) ± SD	29.1 ± 8.2
Sex (male/female)	5/5

Table 2. Translation (position) and orientation error of the US-based pedicle screw center relative to the CT-based pedicle screw center. R: right, A: anterior, S: superior directions. L-R: left-right, P-A: posterior-anterior, I-S: inferior-superior rotation axes. SD: standard deviation.

Error Type	**Healthy Model**	**Degenerative Model**
	Mean ± SD	**Mean ± SD**
Translation R (mm)	0.16 ± 0.19	0.55 ± 0.59
Translation A (mm)	-0.01 ± 1.22	-0.35 ± 0.40
Translation S (mm)	0.68 ± 0.38	1.28 ± 1.37
Rotation L-R (deg)	1.92 ± 1.95	1.60 ± 1.56
Rotation P-A (deg)	-0.05 ± 0.42	0.81 ± 1.15
Rotation I-S (deg)	0.40 ± 0.99	-0.79 ± 0.46