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Using a Force-Controlled Robot for Probing-Based Registration and Automated Bone Drilling in Pedicle Screw Placement Procedures

Saman Vafadar¹, Elie Saghbiny^{1,2}, Antoine Harlé¹, and Guillaume Morel¹

Abstract—Pedicle screw placement is a crucial phase in various spine surgical procedures. In the recent years, robotic solutions have been proposed to assist it. They require intraoperative registration based on CT or fluoroscopic imaging, raising risks for patients and surgeons.

In this study, we investigated registration methods that remove the need for intraoperative imaging. They involve a robot holding a mechanical probe whose tip contacts the bone at sparse locations. This involves either surgeon’s manual guidance, or automatic force-control based probing. Further, once the anatomy is registered, we automate the entire process, including the pedicle preparation and drilling, with the same force controlled robot.

Ten drillings were performed in five lumbar vertebrae of a porcine sample using a custom-designed instrument mounted on the robot’s end-effector. Preoperative and postoperative scans were performed to evaluate the registrations and drillings quantitatively. The mean difference between the planned and postop-measured drilling orientations was 2.2° (Max. 4.4°). The mean distance between the planned entry points and the postop-measured drilling paths was 2.2 mm (Max. 4.1 mm). These results open perspectives for X-ray free robotic operations and pedicle screw placement automation.

I. INTRODUCTION

Spine deformity, also known as scoliosis, can affect patients of different ages. Surgery can correct the deformity and restore the spinal balance [1]. During the procedure, surgeons use pedicle screws and rods to achieve stability [2]. Pedicle screw placement is a challenging procedure as anatomical landmarks are difficult to identify during surgery. The screw is inserted from the posterior column to the vertebral body through the pedicle (Fig. 1). Screw positioning errors may induce neurological or vascular damage that can be irreversible. The conventional free-hand non-assisted pedicle screw placement can lead to a misplacement rate as high as 14% [3].

Surgeons have proposed different ways to increase the precision during the procedure by the use of technological systems. Most of them are based on X-rays, such as fluoroscopy. Although it is the first technique used to insure that the screw is inside the pedicle, it may result in positioning estimation errors, due to the 2D nature of the images [19]. Nowadays, the reference is computer-assisted navigation. The instruments used in the navigation system

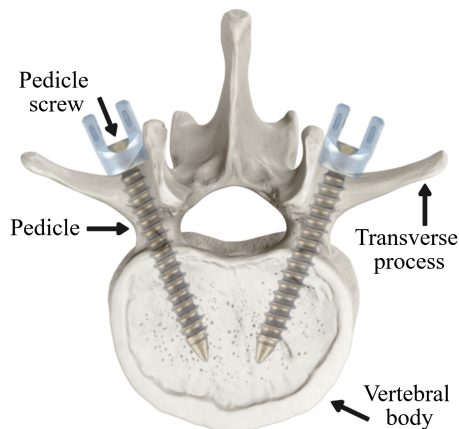


Fig. 1. Schematic of screw [17] placement in a vertebra’s pedicles [18].

have reference points that are recognized by the system’s navigation camera, calibrated prior to intraoperative scanning, and then coupled with anatomic reference pins or clamps. The anatomic references differ between navigation systems. It can be the spinous processes or the iliac crest. The obtained image is automatically registered to the attached software, generating a real-time three-dimensional map for instrumentation guidance [4]. Computer-assisted navigation reduces the exposure to radiation to the patient and the surgeon [7], [6], [5], without removing it completely.

Robotic assistance to spine surgery is a growing field. Similar to computer-assisted navigation, the image is registered to the coordinate system of the robot and the patient, so the robot can access the screw location on the patient, as planned before the surgery. The robot positions a guiding tube in a predefined position and direction. The surgeon will prepare the entry point determined by the robot and the pedicle is then drilled. Spine robotics received the first FDA clearance in 2004. Currently, there are four commercialized robots for spine surgery: MAZOR Renaissance (Medtronic, Dublin, Ireland), MAZOR-X (Medtronic, Dublin, Ireland), ROSA robotic system (Zimmer Biomet, Warsaw, IN), and ExcelsiusGPS (Globus Medical, Inc., Audubon, PA).

All these systems are based on a robotic arm with an optical navigation system. They use fluoroscopy, preoperative CT scans or intraoperative CT scans for registration. Fiducial markers are attached to the patient prior to the scan. The markers can be identified in the scan and the optical navigation system. The robot is registered to the optical navigation system via navigation markers. In this study, we will investigate probing-based surgical registrations

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removing the need for intraoperative imaging.

Probing-based registration is already investigated in different research articles [20], [21], [22], including for orthopedics surgery (total knee replacement) [23]. Also, various registration methods are proposed [24], [25], [26]. Arun et al. [28], [27] proposed a registration method called Sparse Point Registration, which is suited for our application. Compared to the previous methods, it requires less number of points and does not require any prior knowledge of anatomy. We will implement this method for the application of pedicle screw placement. We will also compare it with a baseline, meaning performing the registration using a point set of hand-picked landmarks, probing those points, and a least square method.

Besides, we mentioned that the current commercial systems provide a positioned guiding tube for the surgeon. Herein, we also investigate automating the entire procedure, including pedicle entry point preparation and drilling. Smith et al. [29] explored the similar idea. Meanwhile, they used biomechanical models of vertebrae mounted in a mechanical vise. We move one step forward by accomplishing an ex-vivo experiment.

We summarize the contributions of this study as below:

- Implementation of probing-based registration for spine surgery
- Comparison of the registration method with a baseline
- Automated procedure until pedicle drilling shown through an ex-vivo experiment.

We present the materials and methods in Section II, followed by detailed results and discussion in Section III. This study concludes in Section IV.

II. MATERIALS AND METHODS

A. Experimental Setup

The system, as shown in Fig. 2 consists of four primary elements: (I) a KUKA LBR Med 7 robotic arm, a collaborative robot for medical applications; (II) a custom-designed and developed instrument integrating the drilling system and exchangeable drill bits and probes; (III) a surgical workstation.

The sample was porcine lumbar spine vertebrae purchased at a local butcher shop and fixed on a wooden plate. The vertebral body of each vertebra was drilled, threaded, and screwed using plastic screws. Also, the soft tissues of each side of the vertebrae were screwed. An orthopedic surgeon performed the open surgical approach (Fig. 2).

B. Preoperative Scan and Planning

We performed a CT image of the porcine sample before the ex-vivo experiment. After, we used the *RadiAnt DICOM Viewer* software to 3D reconstruct the vertebrae. The obtained triangular mesh in the previous step was cleaned using the *MeshLab* software. Finally, we did the preoperative plan by importing the reconstructed mesh into *SOLIDWORKS* software. The preoperative plan output was as following:

- 32 landmarks for collaborative probing:

$$P_{Collab.}^{Preop} = \{c_i \in \mathbb{R}^3\}_1^{n=32}$$

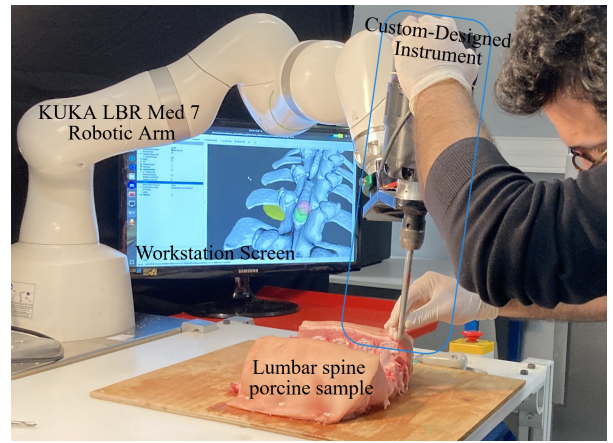


Fig. 2. Collaborative probing

- 152 landmarks for automatic probing and the corresponding orientation:

$$P_{Auto.}^{Preop} = \{a_i \in \mathbb{R}^3\}_1^{n=152}$$

$$O_{Auto.}^{Preop} = \{qa_i \in \mathbb{R}^4\}_1^{n=152}$$

- Ten pedicle entry points and the corresponding drilling orientation:

$$P_{Drill.}^{Preop} = \{d_i \in \mathbb{R}^3\}_1^{n=10}$$

$$O_{Drill.}^{Preop} = \{qd_i \in \mathbb{R}^4\}_1^{n=10}$$

- Vertices of the 3D reconstructed triangular mesh:

$$P_{Mesh}^{Preop} = \{m_i \in \mathbb{R}^3\}_1^{n=5 \times 10^4}$$

C. Probing methods

The probing is conducted in two steps, namely, **collaborative** and **automatic**. In the collaborative step, the robotic arm is in hand-guiding mode, meaning that the surgeon moves the probe's tip to desired points. Meanwhile, in the automatic one, the robot performs the probing automatically without surgeon's intervention.

1) *Collaborative*: The 3D reconstructed mesh of vertebrae is visualized on the workstation screen. Then, a landmark is randomly selected from the landmarks determined in the preoperative plan $P_{Collab.}^{Preop}$, and shown on the vertebrae using a transparent green sphere whose diameter is 5 mm, and its center by a sphere of 0.5 mm. Afterward, the surgeon places the probe's tip on the corresponding point of the sample and the position is registered:

$$P_{Collab.}^{Robot} = \{c'_i \in \mathbb{R}^3\}_1^n$$

This procedure continues until three landmarks are probed. Then, the first transformation for the registration between the two coordinate systems is estimated.

$$c'_i = Collab.T_{Preop}^{Robot}(c_i) + \epsilon_i,$$

$$Collab.T_{Preop}^{Robot}(c_i) = r_{rp} \times c_i + t_{rp}.$$

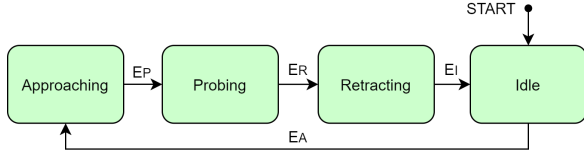


Fig. 3. State machine implemented for automatic probing.

where ${}^{Collab.}T_{Preop}^{Robot}$ is the Euclidean transformation, $r_{rp} \in \mathbb{R}^{3 \times 3}$ is the rotation matrix, $t_{rp} \in \mathbb{R}^3$ is the translation vector, and $\epsilon_i \in \mathbb{R}^3$ is the residual vector.

From the fourth landmark $n = 4$ onward, once the surgeon positions the probe's tip on the desired landmarks, a red sphere is shown, indicating the estimation of the robot for the probe's tip on the 3D mesh. The objective was that the surgeon would be confident of the level of the vertebra. Collaborative probing would continue for $n = 32$ landmarks.

2) *Automatic*: Using the registration obtained in the collaborative probing phase ${}^{Collab.}T_{Preop}^{Robot}$, the points $P_{Auto.}^{Preop}$ which were determined from the preoperative plan are probed automatically. The probed points are:

$$P_{Auto.}^{Robot} = \{a'_i \in \mathbb{R}^3\}_1^n$$

The automatic probing was implemented using a state machine, as shown in Fig. 3, consisting of four primary states: approaching, probing, retracting, and idle. For probing each landmark, first, in the *approaching* state, the probe is positioned 3 cm above the landmark along the probing orientation. Once the desired pose is attained, the event E_P is triggered, changing the state to *probing*. The robot is put into force control mode with the maximum Cartesian velocity of 1 cm/s. When the external measured force reaches 2 N, the position of the probe's tip is recorded, and the event E_I is triggered, changing the state to *retraction*. In *retraction*, the robot goes back to the initial *approach* pose and triggers the E_I event. Now, the operator can reject and remove the probed point in case, during probing, the probe's tip was slid and was not in contact with the vertebrae. This procedure would continue for all the planned landmarks.

D. Registration Algorithms

Two different algorithms are applied to register the points probed collaboratively and automatically from the preoperative space (3D reconstructed vertebrae using CT scan) to the robot space (physical). For registering the landmarks which were collaboratively probed, $P_{Collab.}^{Preop}$ to $P_{Collab.}^{Robot}$, since the correspondences between the points are known, a Least Square Method (LSM) based on singular value decomposition [31] is implemented.

Meanwhile, for registering the landmarks which were automatically probed to the 3D reconstructed mesh vertices, P_{Mesh}^{Preop} to $P_{Auto.}^{Robot}$, the correspondences are not known because of two main reasons. First, the probe's tip may have slid during the probing. Second, ${}^{Collab.}T_{Preop}^{Robot}$ which is the Euclidean transformation between the preoperative plan and the robot, was used for the automatic probing. Thus,

Input:

$$P_{Mesh}^{Preop} = \{m_i \in \mathbb{R}^3\}_1^{n=5 \times 10^4}$$

$$P_{Auto.}^{Robot} = \{a'_i \in \mathbb{R}^3\}_1^{n \leq 152}$$

Initial transformation: ${}^{Collab.}T_{Preop}^{Robot}$

Output:

${}^{Auto.}T_{Preop}^{Robot}$ aligning P_{Mesh}^{Preop} and $P_{Auto.}^{Robot}$.

Pseudocode:

Initialize: $k = 0$, $\epsilon = \inf$, $T = T_0 = {}^{Collab.}T_{Preop}^{Robot}$

while $k < MaxIteration$ OR $\epsilon > Threshold$:

Perturbation:

$$\tilde{T}_j = T_k + \mathcal{N}(0, \Sigma_k)$$

Correspondence and Evaluation:

$$m'_i = FindClosestPoint(\tilde{T}_j(m_i), a'_i \in P_{Auto.}^{Robot})$$

$$c_j = \sqrt{\sum_{i=1}^n \|m'_i - a'_i\|^2 / n}$$

Locally optimal estimate:

$$\hat{T}_k = argmin_{\tilde{T}_j}(c_j)$$

Iterative Closest Point (ICP):

$$T_k = ICP(P_{Mesh}^{Preop}, P_{Auto.}^{Robot}, \hat{T}_k)$$

$$\epsilon_k = \text{Correspondence and Evaluation (above)}$$

if $\epsilon_k < \epsilon$:

$$T = T_k, \epsilon = \epsilon_k$$

$$k = k + 1$$

Fig. 4. Sparse Point Registration (SPR) method

considering the known correspondences would propagate the existing errors of the collaborative probing into the automatic one.

A Sparse Point Registration (SPR) method [27] was implemented based on the Iterative Closest Point (ICP) method. SPR is an iterative algorithm that perturbs the current best estimate and generates several transformations. The generated transformations are evaluated, and the best one is fed into the ICP method as an initial seed. The current best estimate would be replaced by the transformation obtained from the ICP if provided a better estimate. The pseudocode is shown in Fig 4.

E. Pedicle Drilling

For pedicle drilling, entry points and corresponding drilling orientations, determined in the preoperative planning, are transformed to the robot's frame using transformation ${}^{Auto.}T_{Preop}^{Robot}$ obtained from the SPR method.

The pedicles are drilled in two steps: entry point preparation and pedicle drilling. For entry point preparation, a 6 mm nonthreaded drill bit (Fig. 5) is mounted to the drilling instrument. The drill bit is posed 15 mm above the entry point along the drilling orientation for each pedicle. Then, the robot is put in the force control mode, applying a force of 1 N, a maximum Cartesian velocity of 0.2 mm/sec along



Fig. 5. Drill bits used for pedicle drilling

the drilling orientation, and a drilling rotational velocity of 1000 *rpm*. The depth of the drilled hole is approximately 5 *mm*.

A 3 *mm* threaded drill bit (Fig. 5) is used in pedicle drilling. The drill bit reaches 2 *cm* above the entry point along the drilling orientation. Then, the robot is put in the force control mode, applying a force of 10 *N*, a maximum Cartesian velocity of 1 *cm/sec*, and a drilling rotational velocity of 30 *rpm*. The prepared entry points helped engage the threaded drill bit easily in the bone.

F. Postoperative Scan and Assessment

We also performed a CT scan of the porcine sample after the ex-vivo experiment. We followed the same procedure described in Section II-B to 3D reconstruct the vertebrae and perform the postoperative analysis.

For assessment, we registered the 3D reconstructed vertebrae obtained from preoperative and postoperative CT scans. We used two different techniques. One, we used the registration algorithms, as explained in Section II-D, by using the LSM algorithm followed by the SPR algorithm where the results of the LSM was used as an initial estimate for the SPR. Two, using *SOLIDWORKS* software, we manually registered the two meshes.

An axis was fitted to every drilled pedicle of the postoperative 3D reconstructed vertebrae. Then, we measured the angles between the preoperative and postoperative drilling axes. We also measured the Euclidean distance between the preoperatively planned pedicle entry points and the postoperatively drilling axes.

III. RESULTS AND DISCUSSION

A. Comparison Between Registration Methods

The probed points – collaboratively and automatically – are shown in Fig. 6. A summary of the registration methods is provided in Table I. For collaborative probing and registration using LSM algorithm, the mean difference between the target point cloud and the transformed source cloud is less than 0.2 *mm*, showing no bias. Also, 2SD (two standard deviation) is less than 1.4 *mm*. On the other hand, for automatic probing and registration using SPR algorithm,

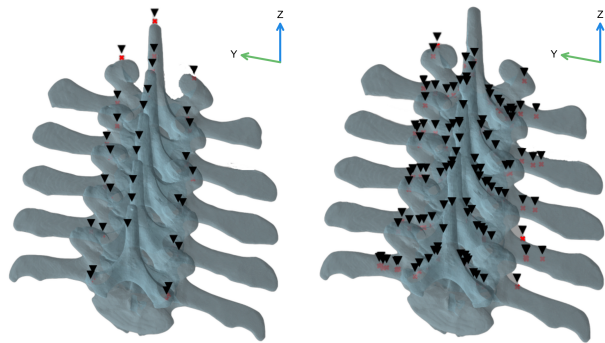


Fig. 6. **Left:** Collaboratively probed points displayed on the preoperatively 3D reconstructed vertebrae using transformation $^{Collab.}T_{Preop}^{Robot}$. **Right:** Automatically probed points displayed on the preoperatively 3D reconstructed vertebrae using transformation $^{Auto.}T_{Preop}^{Robot}$.

TABLE I

SUMMARY OF THE REGISTRATION PARAMETERS AND RESULTS

Reg. Method	Collaborative			Automatic		
Source point cloud	$P_{Collab.}^{Preop}$			$P_{Auto.}^{Mesh}$		
Target point cloud	$P_{Collab.}^{Robot}$			$P_{Auto.}^{Robot}$		
Transformation	$^{Collab.}T_{Preop}^{Robot}$			$^{Auto.}T_{Preop}^{Robot}$		
Reg. algorithm	LSM			SPR		
RMS Diff. (<i>mm</i>)	2.3			0.6		
Mean Diff. (<i>mm</i>)	<i>X</i>	<i>Y</i>	<i>Z</i>	<i>X</i>	<i>Y</i>	<i>Z</i>
	0.1	-0.2	0.0	0.0	0.0	0.1
2SD Diff. (<i>mm</i>)	<i>X</i>	<i>Y</i>	<i>Z</i>	<i>X</i>	<i>Y</i>	<i>Z</i>
	0.8	1.4	0.8	0.4	0.8	0.6

the mean difference is less than 0.1 *mm*, indicating no bias. 2SD is less than 0.8 *mm*.

These findings should be interpreted with caution. We registered to the robot space (physical space) a set of fiducial landmarks defined preoperatively in the preoperative space (3D reconstructed vertebrae using CT scan) and reported the corresponding error. This is known as fiducial registration. Meanwhile, true registration, also known as target registration, is used for pedicle entry points and drilling paths from the preoperative space to the robot space. This will be referred to as target registration. Fiducial registration error and target registration error are uncorrelated, as shown in [30]. Thus, while the fiducial registration error appears to be promising, the target registration error should be evaluated independently.

The difference between the two transformations is summarized in Table II. The difference between their origin is less than 1 *mm*. The unit translation vector shows the main difference is along the *Z*-axis. Also, the difference between the orientation of the transformations is less than 1° and mainly around the *X*-axis. More intuitive to understand, the differences between the transformations applied on the drilling paths (drilling orientation and pedicle entry points) are shown in Table III.

B. Preoperative-Postoperative Evaluation

Ten drillings were performed in ten pedicles of five lumbar vertebrae (L1-L5). The right pedicle of the first lumbar ver-

TABLE II

DIFFERENCE BETWEEN THE RESULTS OF THE REGISTRATION METHODS

Translation XYZ	Norm. mm	Unit Trans. Vector		
	0.6	-0.02	0.37	-0.93
Rotation XYZ	Norm. °	Unit Rot. Vector		
	0.8	0.45	-0.89	0.01

TABLE III

DIFFERENCE BETWEEN THE REGISTRATION METHODS AT THE DRILLING PATHS

Diff. drilling paths	Angle (°) Norm	Entry point (mm)			
		Norm	X	Y	Z
L5R	0.8	1.5	0.2	-0.2	-1.4
L5L		1.5	-0.1	-0.3	-1.5
L4R		1.0	0.3	0.0	-0.9
L4L		1.0	0.0	0.0	-1.0
L3L		0.6	0.0	0.2	-0.5
L3R		0.6	-0.2	0.2	-0.5
L2R		0.5	0.2	0.5	0.0
L2L		0.5	-0.1	0.5	0.0
L1R		0.8	0.0	0.7	0.4
L1L		0.8	-0.2	0.7	0.4

tebra is represented by L1R. Table IV shows the difference between the preoperative drilling and postoperative drilled orientations, as well as the distance between preoperatively defined pedicle entry points and postoperatively measured drilled paths. L4L was removed as an outlier because, due to some errors, the drilled path was outside of the pedicle and could not be fitted with an axis.

Registration Reg. 1 and Reg. 2 in Table IV refer respectively to the numerical and manual registration methods described in Section II-F for registering the preoperative to postoperative space.

The mean difference between the two registration methods for angles is -0.2° , indicating a slight bias. In the meantime, 2SD is less than 0.2° . We would consider the difference acceptable because it is normally distributed and has a 95% confidence interval $[-0.4 \ 0.0]$. As a result, we can conclude that the reported errors are valid. For further analysis, we take into account the errors obtained by using Reg. 1 registration.

The mean angle difference between the preoperative and postoperative drilling axis is 2.2° , and the max is 4.4° . Also, the mean distance between the preoperative entry points and postoperative drilling axes is 2.3 mm . The correlation between the angle differences and the distances is weak (Pearson's $r < 0.25$).

C. Sources of Error

The interpretation of errors is challenging because there are different sources: (I) vertebrae 3D reconstruction errors, (II) registration errors, (III) the vertebrae flexibility mounted on a wooden plate, (IV) the robotic arm flexibility, (V) and tool calibration (center point and principal axes).

The 3D reconstruction of vertebrae was accomplished using an experimentally tuned thresholding. Hence, preoperative and postoperative 3D reconstruction errors could propagate into registrations methods. On the other hand, one of the primary sources of error is the flexibility of the

TABLE IV

PREOPERATIVE-POSTOPERATIVE COMPARISON

Pedicle	Angle (°)		Dist. (mm)	
	Reg. 1	Reg. 2	Reg. 1	Reg. 2
L5R	1.7	1.8	4.4	4.1
L5L	1.3	1.5	1.0	0.9
L4R	3.7	3.8	3.5	3.3
L3R	1.7	1.9	0.7	1.0
L3L	1.6	1.7	3.6	3.1
L2R	2.7	3.0	3.7	3.6
L2L	1.8	2.0	0.2	0.4
L1R	4.4	4.7	1.8	1.9
L1L	0.8	1.0	1.8	1.2

vertebrae. If we consider each vertebra as a rigid object, there are two types of flexibility. One is induced by the relative movement of each vertebra in relation to the adjacent ones, while the other is from the fixation of the entire lumbar spine to the wooden plate. The former is especially relevant to the first and last vertebrae (L1 and L5), connected to the spine via a single vertebral disc, whereas the others (L2 to L4) are connected via two discs. The latter is concerned with the entire spine, especially when there are torques about the X -axis (Fig. 6), and the whole spine can be rotated about it.

During the experiment, on one hand, we observed that while automatically probing the left and right transverse process, the flexibility of the entire spine was different. When applying force on the right side, the spine showed more flexibility than the left side. To confirm this observation, we probed a set of points manually and automatically. The difference between these points, probed using two different methods, along Z -axis is shown in Table V. On the other hand, we visualized the preoperative and postoperative drilling paths. We observed that in the YZ plane (Fig. 6), the difference between drilling orientations is about the $+X$ -axis. We believe these findings are consistent and can be explained using Fig 7.

As shown in Fig. 7, we believe that the transformation matrix found in automatic probing is tilted erroneously about the X -axis. This error was introduced because of more significant flexibility of right side of the entire spine. Thus, the drilling orientations were tilted about the X -axis.

Another source of error was the robot's flexibility. For drilling, the robot was force controlled. Since the force controller was based on impedance control [32], the robotic arm was flexible. The drill advancement for preparation of the pedicle entry point is shown in Fig. 8. The drill bit deviates from the planned path once it becomes in contact with the vertebra.

TABLE V

DIFFERENCE BETWEEN PROBED POINTS COLLABORATIVELY AND AUTOMATICALLY ALONG Z -AXIS

Left side		Right side	
Mean	2SD	Mean	2SD
0.6 mm	2.6 mm	-3.2 mm	3.4 mm

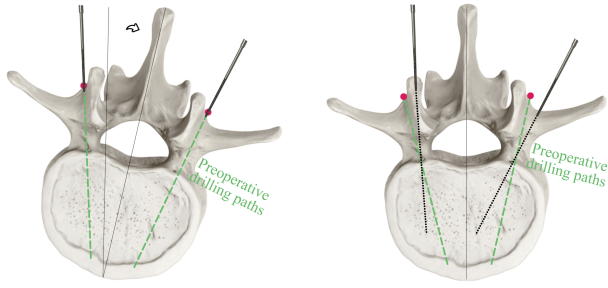


Fig. 7. **Left:** registration in which the vertebra is tilted erroneously. **Right:** errors in drilling orientations.

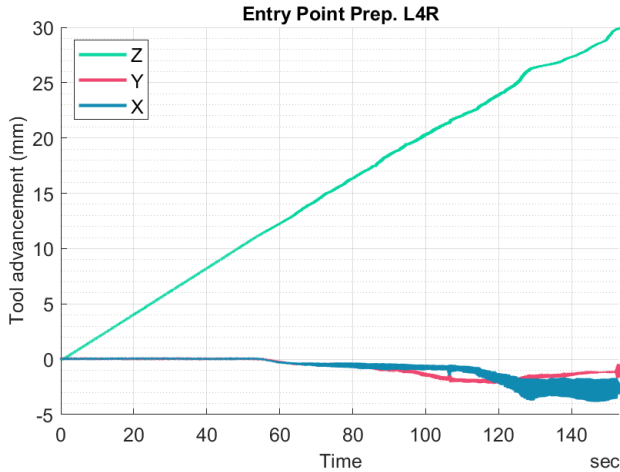


Fig. 8. Tool advancement with respect to its initial position while drilling for preparation of the L4R pedicle entry point. The Z -axis is defined along the drill bit axis.

D. Sensitivity analysis

In this study, we probed 32 points collaboratively and 152 points automatically (we rejected several points during probing). Herein, we analyze what would have happened if we had performed the registration using fewer probed points. Different subsets of the farthest points from the entire set of the probed points, collaboratively and automatically, are selected, and the registration is performed using every subset. Then, the distance between the computed transformation and the one calculated using the entire set (referred to as the 'final' transformation) is measured.

The results for collaboratively probed points are shown in Fig. 9. Furthermore, in this figure, the results of a Monte-Carlo simulation from 20×10^3 times by adding a Gaussian noise ($\mu = 0$, $2SD = 1$ mm, similar to Table I) on every axis of probed points are shown. The maximum distance is always above 4 mm. The mean distance does not change considerably by adding the number of points. Meanwhile, for experimental data, the subsets containing more than 23 points yields distances less than 1 mm.

For registration using the automatically probed points, since the initial guess is obtained using collaborative approach, the trends are shown for different subsets of both sets. The results are shown in Fig. 10. After 45 automatically probed points, increasing the number of points does not

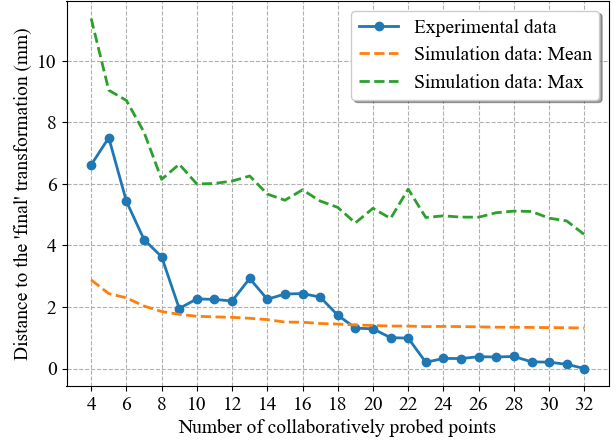


Fig. 9. Distance between the transformation computed using a subset of collaboratively probed points, and the 'final' transformation, using the entire point set.

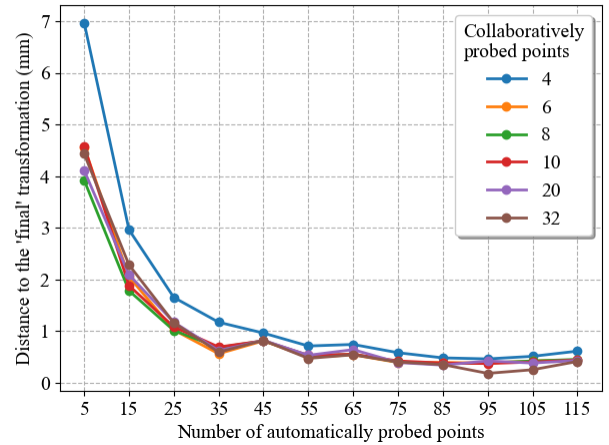


Fig. 10. Distance between the transformation computed using a subset of automatically probed points, and the 'final' transformation, using the entire point set.

change significantly (less than 1 mm) and is robust to the initial guess.

IV. CONCLUSIONS AND FUTURE WORKS

This study investigated the potential of probing-based surgical registrations for PSP. Moreover, it showed that the entire PSP process could be automated. There were, in fact, several limitations. The porcine vertebrae were installed statically with respect to the robot. However, breathing causes a small amount of movement. Work is in progress, and the wooden plate will be installed on a moving platform to simulate breathing motion for the upcoming ex-vivo studies. The pedicle entry points were prepared using a drill bit, but because it could not easily remove the bones, the drill tip slid and diverged from the entry points. Work is ongoing, and we will employ a tree-shaped carbide burr in the following experiments.

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