Accuracy Evaluation of a Novel Spinal Robotic System for Autonomous Laminectomy in Thoracic and Lumbar Vertebrae

A Cadaveric Study

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Background: The main function of robots in spine surgery is to assist with pedicle screw placement. Laminectomy, which is as important as pedicle screw placement, lacks a mature robot-assisted system. The aims of this study were to introduce the first autonomous laminectomy robot, to explore the feasibility of autonomous robotic laminectomy, and to validate its accuracy using a cadaveric model.

Methods: Forty vertebrae from 4 cadavers were included in the study; 7 thoracic and 3 lumbar vertebrae were randomly selected in each cadaver. The surgeon was able to plan the laminectomy path based on computed tomographic (CT) data before the surgical procedure. The robot performed the laminectomy autonomously, and a postoperative CT scan was made. The deviation of each cutting plane from the plan was quantitatively analyzed, and the accuracy and safety were qualitatively evaluated. The time required for the laminectomy was also recorded.

Results: Cuts were performed in 80 laminectomy planes (56 for thoracic vertebrae and 24 for lumbar vertebrae). The mean time for 1-sided laminectomy was 333.59 ± 116.49 seconds, which was shorter for thoracic vertebrae (284.41 ± 66.04 seconds) than lumbar vertebrae (448.33 ± 128.65 seconds) ($p < 0.001$). The mean time for single-level total laminectomy was 814.05 ± 302.23 seconds, which was also shorter for thoracic vertebrae (690.46 ± 165.74 seconds) than lumbar vertebrae (1,102.42 ± 356.13 seconds) ($p = 0.002$). The mean deviation of the cutting plane from the plan was 0.67 ± 0.30 mm for the most superior cutting point and 0.73 ± 0.31 mm for the most inferior point. There were no significant differences in the deviation between thoracic vertebrae (0.66 ± 0.26 mm) and lumbar vertebrae (0.67 ± 0.38 mm) at the superior cutting point ($p = 0.908$) and between thoracic vertebrae (0.72 ± 0.30 mm) and lumbar vertebrae (0.73 ± 0.33 mm) at the inferior cutting point ($p = 0.923$). In the qualitative analysis of the accuracy of the 80 laminectomy planes, 66 (83%) were classified as grade A, 14 (18%) were grade B, and none was grade C. In the safety analysis, 65 planes (81%) were considered safe and the safety of the other 15 planes (19%) was considered uncertain.

Conclusions: The results confirmed the accuracy of this robotic system, supporting its use for laminectomy of thoracolumbar vertebrae.

Level of Evidence: Therapeutic Level V. See Instructions for Authors for a complete description of levels of evidence.

Robotic systems for spinal surgery have evolved rapidly over the past 2 decades, with the U.S. Food and Drug Administration (FDA) approving the first robotic guidance system in 2004[1]. Robots assisting in spinal surgery are mostly designed to improve the accuracy of pedicle screw placement[1,2], and numerous studies have been conducted to assess the accuracy of pedicle screw placement using robotic systems[3-8]. The use of robots in the field of pedicle screw placement has achieved great success. However, there are no mature robots in the field of robot-assisted laminectomy. As with pedicle screw placement, laminectomy carries many risks. Nerve root injury, dural injury, cauda equina syndrome, and even spinal cord injury may occur if the osteotomy is not performed properly[9-11]. In addition, choosing the extent of laminar decompression is a challenge for the surgeon. Insufficient decompression leads to a repeated osteotomy and increases the risk of injury. Excessive decompression leads to

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unnecessary damage to the osseous structure and surrounding tissue, which causes increases in postoperative pain, perioperative blood loss, complications, and length of hospital stay[12-14]. Therefore, a precise robotic system for laminectomy is necessary.

We report the use of the first robotic system designed to perform laminectomy, which represents not only a shift from pedicle screw placement to laminectomy but also an upgrade from robots that provide navigation or actually perform manipulation (in pedicle screw placement) to a robot capable of autonomously performing the surgical procedure (laminectomy). We explored its accuracy using a cadaveric model.

Materials and Methods

Cadaveric Spines

Approval was obtained from the Ethics Committee of our hospital. Four human cadavers were used in this accuracy test. Demographic characteristics of the cadaver donors are described in Table I. There were 2 males and 2 females, with a mean age of 59.5 years (range, 58 to 61 years). Seven thoracic and 3 lumbar spinal levels from each cadaver (a total of 40 vertebrae) were selected at random to undergo laminectomy (Table I).

Spinal Robot Architecture

The robotic system consists of an operating system and a control system. The operating system includes a 6-degrees-of-freedom (DOF) robotic arm (AUBO-i5; AUBO Robotic Technology), a force sensor (SRI; Shanghai Yuli Industrial), a piezoelectric (ultrasonic) osteotome system (XD880A; SMTP Technology), an end effector, and a binocular optical camera (Beijing Zhuzheng Robot). The end effector has 1 DOF in the vertical direction and also includes a force sensor (T1051; Changzhou Allison Technology), which is used to identify the occurrence of cortical penetration during the laminectomy procedure (Fig. 1).

The control terminal of the robotic system is integrated into the trolley-mounted workstation, which includes specially developed preoperative planning software and intraoperative operating software. The preoperative planning software has 2 main functions: (1) to manually plan the cutting path in the laminectomy, and (2) to generate the model used for the 3-dimensional (3D) printing of the registration guide, which is used for rapid registration during the operation (Fig. 2). The intraoperative operating software is used to control the operation of the robotic arm, the end effector, and the piezoelectric osteotome system.

TABLE I Cadaver Donor Information*

Cadaver No.	Age* (yr)	Sex	No. of Vertebrae Used†		BMI‡ (kg/m²)
			Thoracic	Lumbar	
1	60	Female	7	3	23.9
2	61	Female	7	3	22.2
3	59	Male	7	3	23.6
4	58	Male	7	3	20

*The mean age was 59.5 years. †A total of 40 vertebrae were used in the study. ‡The mean body mass index (BMI) was 22.9 kg/m².

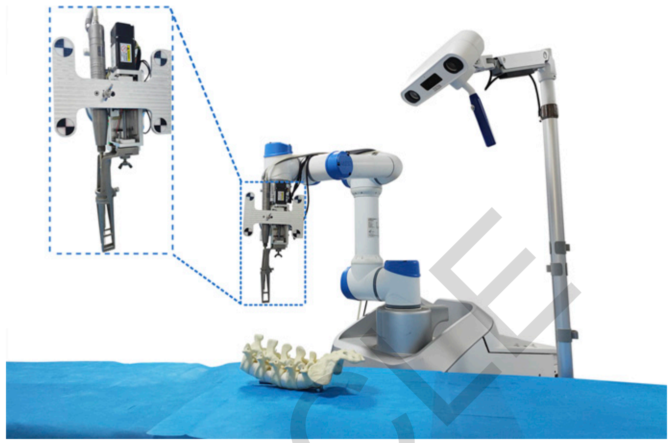

Fig. 1

Diagram of the robotic system. The overview on the right shows all of the components: the robotic arm, binocular camera, and ultrasonic osteotome system. The assembly details of the end effector and the handle of the ultrasonic osteotome are visible in the enlarged view on the left. The end effector includes a tracker representing the position of the tip of ultrasonic bone blade and a sensor measuring force in the vertical direction.

Preoperative Procedure

The first step of the preoperative procedure was planning the cutting path of the laminectomy. All cadavers had a computed tomography (CT) scan (slice thickness of 0.6 mm reconstructed from a standard slice thickness of 3 mm) of the involved spinal area before the surgical procedure, and the resulting DICOM (Digital Imaging and Communications in Medicine) data were imported into the preoperative planning software. By reconstructing the 3D image of the spine, surgeons were able to plan the cutting path of the laminectomy intuitively. The planning of the cutting path on 1 side is described here as an example. To form a line segment, the surgeons first selected a point on the superior side of the lamina and another on the inferior side based on their experience. Then the software generated a plane through the line segment. Surgeons only needed to make a suitable adjustment to the angle of the plane to complete the cutting plane planning, and the software then calculated the cutting path automatically (Figs. 2-A, 2-B, and 2-C).

The second step of the preoperative procedure was to make the 3D-printed registration guide. After the first step, the software would generate the registration guide based on the surface shape of the lamina. Surgeons were able to adjust the placement of the guide appropriately. This guide was composed of 2 parts: the bottom was a mounting part attached to the surface of the lamina, and the top was a tracking part with 3 markers (Fig. 2-D). The crucial function of this guide was to achieve rapid registration during

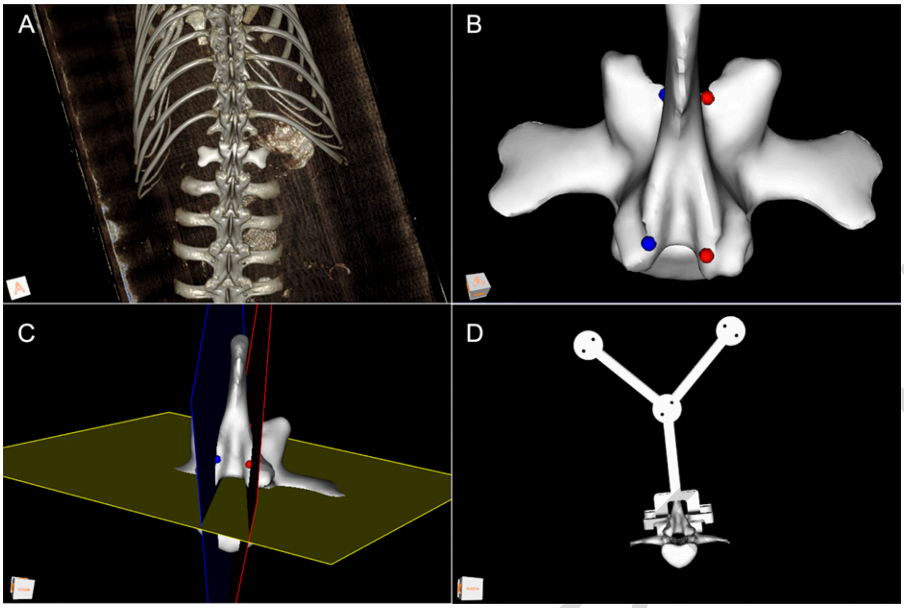

Fig. 2

Figs. 2-A through 2-D The preoperative planning software. **Fig. 2-A** The spinal segments to be planned were selected. **Fig. 2-B** Two points on the left side of the lamina and 2 points on the right side were chosen as benchmarks for defining the 2 cutting planes of the total laminectomy. **Fig. 2-C** The system generated 2 planes (shown in red and blue), each passing through 1 pair of points, and each cutting plane was determined by adjusting its angle appropriately. **Fig. 2-D** The system automatically generated the model of the 3D-printed registration guide, and its placement could be adjusted appropriately.

the operation. The 3D-printed registration guide was sterilized before the surgical procedure.

Intraoperative Procedure

The first step of the intraoperative procedure was to expose the lamina. The initial procedure was the same as in traditional posterior spine surgery. The cadaver was placed in a prone position. All involved vertebrae were exposed via subperiosteal dissection after making a posterior midline skin incision. The soft tissues in the area in which the guide was placed were cleaned carefully without disturbing the facet joint capsule.

The second step was to assemble the robot. The robotic arm was moved to the assistant's side of the operating table and was covered with a sterile sheath. At the same time, the instrument nurse attached the handle and blade of the ultrasonic osteotome system to the end effector of the robotic system and passed it to the surgeon, who installed it onto the robotic arm. There was a sterile sleeve interval between the end effector and the robotic arm. The tip of the ultrasonic bone blade was calibrated.

The third step was registration. The spinous process clamp, on which a tracker was mounted, was fixed to the top of the spinous process of the adjacent level. The 3D-printed guide, with another tracker on its top, was stably placed on the lamina. Then the position data of these 2 trackers were captured by the binocular optical camera, and the system completed the registration automatically. The guide could be moved out after registration.

The fourth step was automatic laminectomy. The robot performed the laminectomy autonomously according to the preplanned cutting path under the supervision of the surgeon, who could push the emergency stop button at any time. The robot adopted a step-by-step vertical cutting method, dividing the cutting plane into several vertical cutting steps that overlapped by 0.5 mm. The planned cutting depth stopped 0.5 mm before reaching the inner edge of the cortex in order to avoid injury caused by the tool penetrating the lamina. The force sensor on the end effector provided a second safeguard during the cutting, as the robot would stop when a force change indicated that penetration was about to occur (Fig. 3). When the robot finished cutting, a surgeon operating on a patient would gently pry the lamina loose and remove it. However, the lamina was not removed in this study in order to permit better evaluation of the cutting results.

Postoperative Analysis

The main outcomes were the number of vertical cuts, the time to perform a 1-sided laminectomy, the time to perform a 1-level total laminectomy, and the accuracy of the laminectomy. The distance between the preplanned cutting line and the actual cutting groove was measured at the most superior and inferior cutting points on the lamina in the axial plane of the CT scan. We also proposed a grading scale for the accuracy of the laminectomy in the coronal and axial planes of the CT scans: grade A indicated that the preplanned cutting line was basically located within the actual cutting groove or the maximum distance between them was <1 mm, grade B indicated that the maximum distance between the preplanned cutting line and the actual cutting groove was 1 to 2 mm (Fig. 4), and grade C indicated that the maximum distance between them was >2 mm. Another evaluated outcome was the safety of the

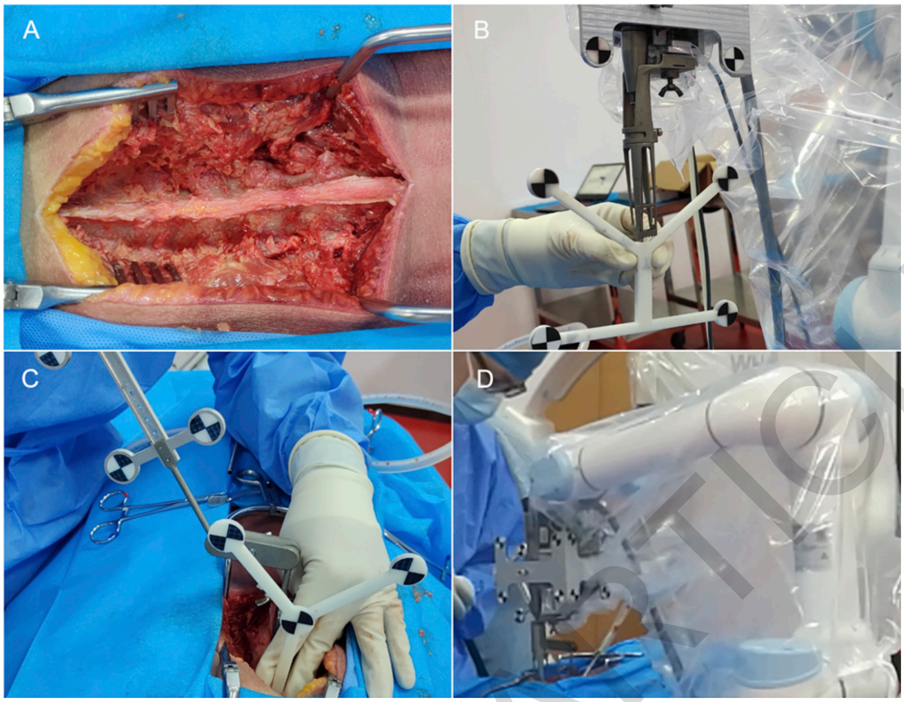

Fig. 3

Figs. 3-A through 3-D Intraoperative procedure. **Fig. 3-A** The lamina was fully exposed. **Fig. 3-B** The robot was assembled, and the position of the tip of the ultrasonic bone blade was calibrated. **Fig. 3-C** The 3D-printed registration guide was used for rapid intraoperative registration. **Fig. 3-D** The robot autonomously performed the laminectomy under the supervision of the surgeon.

laminectomy (Fig. 5). In this study, the spacing between layers in the CT reconstruction was 0.6 mm and the blade width was 3 mm. Thus, a vertical cut was considered to have penetrated the lamina if there was a discontinuity of the inner cortical bone in 5 continuous axial planes (5×0.6 mm = 3 mm). Because we could not judge the depth that this cut extended into the spinal canal on the basis of the CT scan, this condition was considered possibly unsafe, and a grade of B was assigned. Otherwise, the cut was considered safe and a grade of A was assigned.

Statistical Analysis
Continuous variables with a normal distribution were presented as the mean and the standard deviation and were compared between the groups using the unpaired t test. Categorical variables were presented as percentages and were analyzed using the chi-square test. SPSS Statistics version 24.0 (IBM) was used for the data analysis. Significance was set at $p < 0.05$.

Source of Funding
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Results
We performed a total laminectomy on 40 vertebrae, resulting in 80 cutting planes. A total of 1,114 vertical cuts were made, with a mean (and standard deviation) of 13.93 ± 3.63 vertical cuts per cutting plane. The mean time to perform a laminectomy on 1 side was 333.59 ± 116.49 seconds. A single-vertebra total laminectomy took 814.05 ± 302.23 seconds. The mean distance between the actual and preplanned cutting planes was 0.67 ± 0.30 mm (range, 0.09 to 1.53 mm) at the superior cutting point and 0.73 ± 0.31 mm (range, 0.17 to 1.58 mm) at the inferior cutting point. Of the 80 cutting planes, 66 (83%) were rated as grade A, 14 (18%) were grade B, and none was grade C (Table II). In the safety analysis, 65 (81%) were rated as grade A and 15 (19%) were grade B.

A total of 704 vertical cuts were made in the 28 thoracic vertebrae and 410 vertical cuts were made in the 12 lumbar vertebrae, with a mean number of vertical cuts per cutting plane of 12.57 ± 2.66 in the thoracic vertebrae and 17.08 ± 3.67 in the lumbar vertebrae ($p < 0.001$). The mean time to perform 1-sided cutting of a vertebra was 284.41 ± 66.04 seconds for the thoracic vertebrae and 448.33 ± 128.65 seconds for the lumbar vertebrae ($p < 0.001$). Total laminectomy of a vertebra took a mean time of 690.46 ± 165.74 seconds for the thoracic vertebrae and 1,102.42 ± 356.13 seconds for the lumbar vertebrae ($p = 0.002$). The mean deviation from the planned cut was 0.66 ± 0.26 mm for the thoracic vertebrae and 0.67 ± 0.38 mm for the lumbar vertebrae ($p = 0.908$) at the most superior cutting point and 0.72 ± 0.30 mm for the thoracic vertebrae and 0.73 ± 0.33 mm for the lumbar vertebrae ($p = 0.923$) at the most inferior cutting point. In the qualitative assessment of the cutting plane accuracy, 49 (88%) of the 56 thoracic cutting planes were rated as grade A and 7 (13%) were grade B, and 17 (71%) of the 24 lumbar cutting planes were rated as grade A

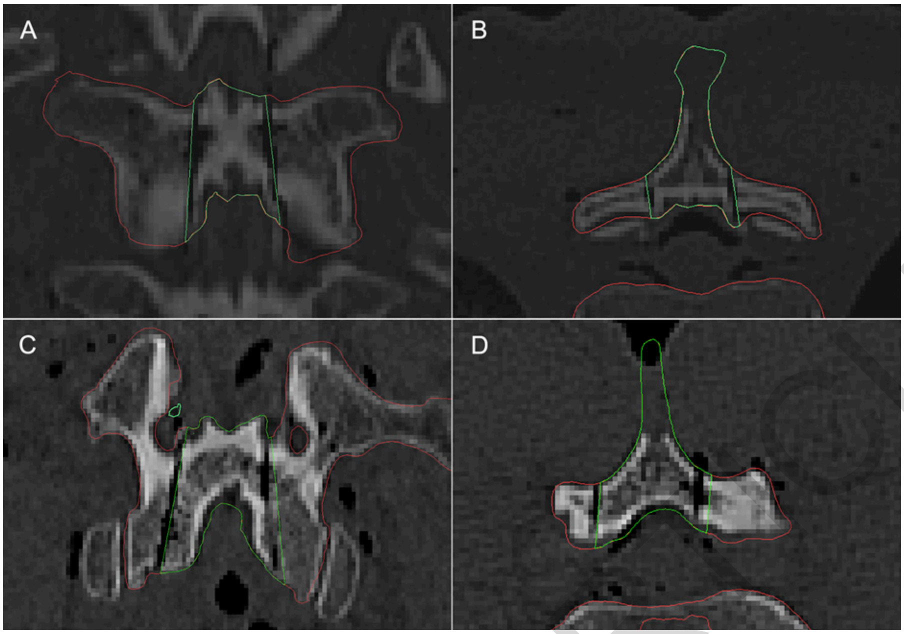

Fig. 4

Annotated postoperative CT scans showing 2 examples of cutting accuracy grades. The green lines represent the preplanned laminectomy. The red line is the reference line. If it matches the contour of the bone, the position of the green line is proved to be correct. In the top row, both preplanned cuts are seen to lie basically within the actual cutting grooves in the coronal plane (**Fig. 4-A**) and the axial plane (**Fig. 4-B**), and the cutting accuracy was classified as grade A. In the bottom row, the preplanned cut on the left side lies between 1 and 2 mm (based on a pixel width of 0.5 mm) from the actual cutting groove in the coronal plane (**Fig. 4-C**) and the axial plane (**Fig. 4-D**), and the cutting accuracy was classified as grade B.

and 7 (29%) were grade B ($p = 0.072$). In the safety analysis, 46 (82%) of the 56 thoracic cutting planes were rated as grade A and 10 (18%) were grade B, and 19 (79%) of the 24 lumbar vertebrae were rated as grade A and 5 (21%) were grade B ($p = 0.755$) (Table II).

Discussion

To our knowledge, this is the first study to explore the efficiency and accuracy of a robotic system for spinal laminectomy using a cadaver model. The mean time for a 1-sided cut was only 333.59 seconds, which was consistent with the 326 seconds in our previous study of porcine vertebrae in vitro[15]. The mean time to complete a total laminectomy was nearly 13.5 minutes (11.5 minutes for the thoracic vertebrae and 18 minutes for the lumbar vertebrae). In our clinical experience, skilled surgeons can use a bone chisel to cut the lamina in about 4 to 6 minutes, but they often need to use a Kerrison rongeur to expand and adjust the amount of decompression, which is often the most time-consuming step. However, because our robotic system preplans the amount of decompression, it can perform the decompression operation in 1 step and reduce the

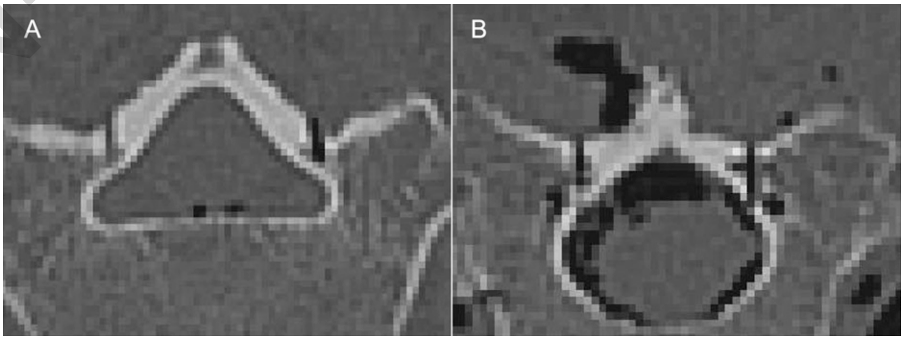

Fig. 5

Figs. 5-A and 5-B Assessment of the safety of the laminectomy. **Fig. 5-A** The inner cortical bone was preserved on both sides of the laminectomy, indicating no penetration. **Fig. 5-B** The cutting line on the right side did not penetrate the inner cortical bone of the lamina, but penetration can be seen at the bottom of the cutting line on the left side.

TABLE II Summary of Robotic Laminectomy Outcomes

	Total (N = 80)	Thoracic Group (N = 56)	Lumbar Group (N = 24)	P Value*
No. of vertical cuts per plane†	13.93 ± 3.63	12.57 ± 2.66	17.08 ± 3.67	<0.001‡
Time for 1-sided laminectomy† *(sec)*	333.59 ± 116.49	284.41 ± 66.04	448.33 ± 128.65	<0.001‡
Time for 1-level laminectomy†§ *(sec)*	814.05 ± 302.23	690.46 ± 165.74	1,102.42 ± 356.13	0.002‡
Accuracy at superior point† *(mm)*	0.67 ± 0.30 (0.09 to 1.53)	0.66 ± 0.26 (0.24 to 1.53)	0.67 ± 0.38 (0.09 to 1.44)	0.908
Accuracy at inferior point† *(mm)*	0.73 ± 0.31 (0.17 to 1.58)	0.72 ± 0.30 (0.17 to 1.58)	0.73 ± 0.33 (0.23 to 1.51)	0.923
Accuracy of cutting plane#				0.072
Grade A	66 (83%)	49 (88%)	17 (71%)	
Grade B	14 (18%)	7 (13%)	7 (29%)	
Grade C	0 (0%)	0 (0%)	0 (0%)	
Safety of cutting plane#				0.755
Grade A	65 (81%)	46 (82%)	19 (79%)	
Grade B	15 (19%)	10 (18%)	5 (21%)	

*Comparison of the thoracic and lumbar groups. †The values are given as the mean and the standard deviation, with or without the range in parentheses. ‡Significant at $p < 0.05$. §One-level laminectomy included both sides of the resection plane, so its total sample was 40 (28 thoracic vertebrae and 12 lumbar vertebrae). #The values are given as the number of cutting planes, with the percentage in parentheses. In the qualitative analysis of safety, grade A indicates that CT was able to confirm the absence of penetration.

subsequent adjustment time. Therefore, the overall time required by this robotic system appears to be in an acceptable range.

Most previous research on the accuracy of robotic laminectomy was performed in vitro on animal vertebrae, and the criterion used for assessment was often the measured residual thickness of the lamina[16-18]. Kanawati et al.[19,20] developed a 3D-printed laminectomy guide, and the cutting plane was also planned before the surgical procedure. Accuracy was also assessed on the basis of the residual thickness of the lamina. However, for a robotic operation, the relationship between the actual cutting plane and the planned plane is the most critical information for evaluating accuracy. Therefore, we measured the distance between the planned and actual positions on the superior and inferior ends of the cutting plane on CT scans. We found an accuracy of approximately 0.7 mm in thoracic or lumbar vertebrae, which is similar to the 0.8-mm difference from the plan in a previous study of robotically assisted pedicle screw placement[21]. It should be pointed out that the 0.7-mm deviation from the plan does not represent the positioning error of the robot, but rather the accumulated errors in the multiple steps involved in the entire process.

We also proposed a scale for overall evaluation of the laminectomy plane by using the Gertzbein-Robbins scale[22], which is widely used in the field of robotically assisted pedicle screw placement[23,24], as the scale design model. Our scale evaluates the relationship between the preplanned cutting plane and the actual cutting groove. The results showed that 83% were grade A, with <1 mm of deviation, and 100% were grades A and B, with <2 mm of deviation, which met our expectations.

The demonstrated safety of the robot reflects the safeguards designed to avoid penetration and to halt the cutting if penetration is about to occur. After the surgeon planned the cutting plane, the robotic system would reserve the final 0.5 mm of the lamina when calculating the depth of the cutting path, and thus plan to stop 0.5 mm before reaching the inner edge of the cortical bone. However, because errors may be introduced by multiple processes such as the CT scanning and the intraoperative registration, that was not enough to ensure safety. Therefore, we added force sensors to the end effector of the robot to allow continuous assessment of the cutting process. When the force information indicated that penetration of the lamina was about to occur, because a change to cortical bone was detected, the robotic arm immediately stopped cutting. The postoperative CT scans showed that 65 planes (81%) were considered safe. It is important to note that the other 19% were not necessarily unsafe, because it was also possible for the robot to have stopped just after penetrating the lamina.

This robotic system has also incorporated some innovations in the registration process. The registration methods commonly used in the past include C-arm or O-arm registration, such as in the Mazor robot[25] and the TianJi robot[26]. However, this approach is cumbersome and requires frequent mobilization of large equipment in the operating room. If the tracker on the bone is accidentally moved in such systems, the registration process needs to be repeated. However, if the tracker on the bone is moved during an operation using the robot in the current study, it is only necessary to place the registration guide again, which greatly simplifies the required process for repeating the registration. This method also eliminates exposure of the patient and the surgeon to ionizing radiation during the registration step.

We use an ultrasonic bone osteotome as a cutting tool not only because it is more suitable for the robotic system, but also because it provides an accurate, rapid, and effective method of bone dissection while reducing the risk of injury to the dural sac and nerve roots[9,27] and reducing bleeding[28-30]. Although the robotic system is still a prototype, we believe that this technique can be used not only for posterior laminectomy, but also for minimally invasive decompression and endoscopic decompression of the spine. Numerous studies have demonstrated the safety and accuracy of robotically assisted percutaneous screw placement[31-33], and recent studies have confirmed the effectiveness of robotically assisted transforaminal lumbar interbody fusion and midline lumbar interbody fusion techniques[34,35]. The robotic system in the current study appears applicable to these techniques as well.

This study had some limitations. First, it was conducted on cadavers, not patients, but that was considered necessary as a first step toward validating the technique. Second, we were unable to simulate the vertical movement of the vertebra with respiration that occurs in a real surgical procedure and would theoretically reduce accuracy. Therefore, we plan to conduct animal experiments to verify that the accuracy of the system is maintained in vivo. Finally, the cadaveric spines that we used had a normal structure, which is different from the situation in clinical patients with pathological changes in the spine. Therefore, additional studies involving pathological vertebrae are needed to validate our robotic system. We believe that robotic-assisted decompression may have broad application in minimally invasive and endoscopic spine surgery.

In conclusion, we developed a novel robotic system for autonomous laminectomy and demonstrated its accuracy in cadavers using CT data. The mean time for 1-level total laminectomy was 13.5 minutes. The mean deviation of the cut from the planned position was 0.67 mm at the most superior cutting point and 0.73 mm at the most inferior point. Of the cutting planes, 83% were rated as grade A with respect to accuracy and 81% were considered safe. These results verify the accuracy of the system and support its use in laminectomy procedures. ■

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