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ORIGINAL RESEARCH

The Role of Robot-Assisted Technique in Treating Adult Degenerative Scoliosis with Circumferential Minimal Invasive Correction Surgery – A Retrospective Analysis of 51 Consecutive Cases

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Study Design: Retrospective chart review.

Objective: This study aims to investigate the application of robots in treating adult degenerative scoliosis (ADS) with circumferential minimal invasive surgery (cMIS).

Background: The cMIS is useful but faces a lot of challenges in correcting ADS. One of the most important challenges is the difficulty in screw placement. Robot-assisted technique demonstrates lots of advantages but the data about its application in treating ADS is limited in literatures.

Methods: A total of 51 cases diagnosed with ADS were retrospectively analyzed. All patients underwent cMIS technique with staged surgeries (OLIF and PPS fixation). Group A enrolled 21 patients and performed robot-assisted technique. Group B enrolled 30 patients and performed fluoroscopy guided technique. Clinical outcomes like the operation time, radiation exposure, pressure curve and post-operation VAS score were recorded. 3D-CT scan was also performed to evaluate the accuracy of the screws.

Results: The average preparation time were much higher in group A (23.4 ± 2.8 vs 3.1 ± 1.0 min, $p < 0.0001$). But the total operation time was similar (62.7 ± 12.5 vs 55.7 ± 20.6 min, $p = 0.174$). The average fluoroscopic scan number were 9.4 ± 1.7 in group A, much lower than that of group A (27.7 ±5.9, $p < 0.001$). No statistical difference was found with the VAS scale between the groups ($p = 0.631$). No matter considers only screws of grade A as perfect screws (81.5% vs 73.8%) or considers both grade A and B as acceptable screws (93.8% vs 87.7%), group A demonstrated significant higher screw accuracy ($p = 0.038$, $p = 0.018$, respectively). Also, the robots demonstrated significant less facet joint violence ($p < 0.0001$), larger inward tilt angle ($p < 0.0001$), and longer screw length ($p = 0.0008$).

Conclusion: The robot-assisted technique demonstrated significant advantages like higher pedicle screw accuracy, better trajectory, less radiation exposure, but similar operation time compared with fluoroscopy guided technique in treating ADS with CMIS.

Keywords: adult degenerative scoliosis, circumferential minimal invasive surgery, robotics, OrthBot, pressure curve

Introduction

Adult degenerative scoliosis (ADS) is a complex three-dimensional deformity of the spine characterized by an abnormal sideways curvature of the spine that develops in adulthood. In the population aged 60 and above, the prevalence rate is 9%, while among women aged 80 and above, the prevalence can be as high as 40%. Among asymptomatic elderly individuals aged 65 and above, the detection rate of ADS can reach 32%-68%, suggesting that the actual prevalence may be underestimated. ADS is always due to the asymmetric degeneration of the discs/facet joints and sometimes asymmetric vertebral body height loss because of vertebral compression fractures.[1,2] In ADS, asymmetric loading on the discs

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or facet joints leads to coronal/sagittal deformity and axial rotation, which further causes the asymmetric degenerative changes, and therefore worsening of the deformity in a cyclical manner. Patients with ADS often suffer from significant pain and weakness of the back, and/or leg pain and weakness due to nerve root compressions. The ADS always requires surgical treatment with long-level pedicle screw instrumentation, together with procedures like osteotomy, decompression, and interbody fusion. Previous operation strategies always use posterior approach with a long incision, the damage to the muscle may cause significant chronic pain, weakness, and adjacent segment degeneration. Nowadays, the circumferential minimal invasive surgery (cMIS) with lateral lumbar interbody fusion (LLIF)/ oblique lateral interbody fusion (OLIF) and percutaneous pedicle screw (PPS) application is more and more popular with less invasion but comparable results against open techniques for class I–III types of ADS according to modifies MISDEF classification.[3,4] Also, in a lot studies, the ADS cases were treated with modified cMIS technique via staged surgeries, namely, first stage OLIF and second stage PPS fixation. As the staged surgery was shown able to reduce the operation time and surgical trauma for single surgery, and most importantly to reduce the instrumented vertebras.[5,6]

The deformity correction surgery with cMIS technique faces lots of challenges and one of the most important is the difficulty in screw placement. Adverse factors such as osteoporosis, severe degeneration of facet joints, pedicle rotation and anatomic variation, loss of anatomic landmark, and sclerosis have greatly increased the difficulty of screw placement.[7,8] The reported pedicle wall breach rate using freehand technique ranges from 1.7% to 30% in the literature.[9,10] Additionally, besides the security problem in pedicle screw placement, the proper pedicle screws trajectory is also important in ADS. The fixation strength is related with the effect of curve correction and postoperative complications such as internal fixation failure and proximal junction kyphosis (PJK).[11,12] As a result, for the difficulties in pedicle screw placement in ADS, the pedicle screw placement in deformity correction surgeries require extremely high surgical skills and experiences.

Recently, robot assisted spinal surgeries become more and more popular all around the world, with lots of advantages like enhanced screw accuracy, reduced radical exposure, reduced invasiveness, and enhanced pre-operation planning and visualization.[13] The reported screw accuracy ranges from 83.6% to 100% with the help of robotics. And when compared with traditional techniques, more and more evidence support the application of robotic techniques considering the improved screw accuracy and simplicity in operation. Also, the robotic techniques are able to reduce the violence to the facet joint, which is believed able to reduce the adjacent segment degeneration. The potential of application of robotic techniques in scoliosis got more and more attention, but the data is limited in the literatures in terms with cMIS technique for ADS.[14–17] Even, some specialist against the robotics as the robot-related preparation procedures are so complex and though superior screw accuracy, no better functional outcomes can be found against the traditional techniques. Nowadays, the data about the application of robot in treating ADS with cMIS is limited in literatures. The present study aims to compare the short-term clinical and radiological outcomes between the robot-assisted technique and the fluoroscopy guided technique in treating adult degenerative scoliosis with cMIS technique.

Method

The study retrospectively analyzed 51 consecutive cases diagnosed as degenerative scoliosis treated in Ruijin hospital from January 2018 to January 2024. All of the patients underwent CMIS technique with staged surgeries. The first-stage surgery is OLIF and about one week later the second-stage surgery with percutaneous pedicle screw (PPS) fixation. Some patients also received additional procedures during the second-stage surgery, such as laminectomy with MIS-technique. Before January 2023, all patients underwent fluoroscopy guided PPS fixation during the second-stage surgery and were enrolled in Fluoroscopic group. After January 2023, all patients underwent robot-assisted PPS fixation and were enrolled in Robotic group. All patients were evaluated and diagnosed depended on comprehensive medical history inquiries, physical examinations, X-rays (anteroposterior, lateral, hyperextension and hyperflexion views, and full-length spine films), bone mineral density, 3D computed tomography (3D-CT), and magnetic resonance imaging (MRI). All surgeries were performed when failed with at least 6 months of systematic conservative treatment. This study was reviewed and approved by the hospital's medical ethics committee, and all subjects signed informed consent forms. This study was conducted in compliance with the ethical principles established in the 1964 helsinki Declaration.

All patients were included according to the following criteria. Inclusion criteria: (1) Adult degenerative scoliosis of grade III or more in Lenke-Silva classification and grade II or more in modified MISDEF classification. (2) Primary complaint of low back pain during sit and walk, with or without neurological symptoms of lower limbs. (3) Failed with at least 6 months of strict conservative treatment including bed rest, brace support, functional exercise, symptomatic treatment with analgesic medications, as well as systematic anti-osteoporosis therapy. Exclusion criteria: (1) Patients with a history of previous lumbar spine surgery. (2) Combined with other types of scoliosis (eg, adult idiopathic scoliosis, congenital scoliosis), ankylosing spondylitis, or spinal deformities caused by other diseases, such as spinal tuberculosis. (3) History of severe spinal cord injury. (4) Spinal tumor. (5) History of retroperitoneal surgery.

Operation Methods

All patients underwent staged surgeries. The first-stage surgery involved a lateral lumbar approach, where OLIF cages were implanted into the segments near the apex vertebra. Three days after the first-stage surgery, patients were allowed to stand up wearing a lumbar brace. Full length spine X-rays, 3D-CT, and MRI were then performed to assess the deformity and stenosis. Based on the patient's postoperative symptoms and radiographic findings, the plan of the second-stage surgery was made, for example PPSF only or addition with decompression or osteotomy procedures. The second-stage surgery was typically performed one week after the first-stage surgery with PPSF. If the coronal and sagittal balance parameters were satisfactory after the first-stage surgery, the fixation rods could be implanted in situ; if necessary, further correction could be achieved using rod-bending techniques. If the sagittal balance remained significantly impaired after the first-stage surgery (eg, sagittal vertical axis [SVA] > 10 cm or PI - LL > 40°), osteotomy correction was performed. If the patient still presents with lower limb neurological symptoms caused by conditions such as spinal canal stenosis or disc herniation after the first-stage surgery, posterior MIS decompression surgeries such as MIS-laminectomy was performed during the second-stage surgery. For patients requiring pelvic fixation, a small incision was typically made in the lumbosacral region during the second-stage surgery to perform L5-S1 TLIF and S2AI screws placement. All surgeries were performed by the same team of senior spine surgeons.

Robotic group patients performed robot assisted PPS fixation during second stage surgery. The OrthBot® system was used in this study as described previously.[18,19] The robot is designed based on machine vision tracking algorithm, and is comprised of a robotic workstation, a coordinate position plate, a tracking camera, and a 6-degree of freedom (6-DOF) robotic arm. There is an automatic bone drill integrated in the mechanical arm, which can insert K-wires into the pedicle autonomously. Also, a pressure sensor is integrated in the mechanical arm, which is able to record the real-time axial pressure data during drilling of the K-wire. The working procedures were as follows: Briefly, the patient was placed in the prone position under general anesthesia, with the abdomen suspended. After disinfection and draping, a coordinate position plate was placed on the patient's body surface. After obtaining anteroposterior and lateral fluoroscopic images with a C-arm machine, the intro-operative X rays were registered with the preoperative 3D-CT scan. Once the registration was successful, the robot identified the coordinate position plate and inserted Kirschner wires according to the pre-planned pedicle screw trajectory. Finally, the pedicle screws were placed with the guide of the K-wires.

Fluoroscopic group patients performed fluoroscopy guided PPS fixation during second stage surgery. Briefly, the Jamshidi puncture needle was placed into the pedicle with the help of anteroposterior and lateral fluoroscopic images. The guiding needle was inserted into the Jamshidi puncture needle and the screws were then planted with the help of the guiding needle.

Postoperative Management

After surgery, standard pain management with celecoxib were applied for all the patients. And patients were encouraged to begin walking with brace 2–3 days postoperatively, lumbar-back muscle exercises were also encouraged at the same time. Normal daily activities and exercise could be fully resumed after 3 months. Standard postoperative pain management, neurotrophic treatment, and systematic anti-osteoporosis treatment (such as zoledronic acid/denosumab/teriparatide + vitamin D + calcium supplements) were initiated immediately.

Clinical Outcomes

The operation time, radiation exposure, and pressure curve were recorded intro-operatively. The Visual Analog Scale (VAS) score for low back pain was recorded on the first postoperative day after the second stage surgery.

Radiological Examination

The 3D-CT scan and full-length spine x-ray were performed for all patients after surgery. The CT images were evaluated by doctors who were not involved in the surgeries. The modified Gertzbein-Robbins grading system was used to evaluate each patient's axial, coronal, and sagittal images to determine whether the pedicle screws had breached the cortical bone. Grade A indicates no cortical breach; Grade B indicates a breach of 1–2 mm; Grade C indicates a breach of 3–4 mm; Grade D indicates a breach of 5–6 mm; and Grade E indicates a cortical breach greater than 6 mm. And Grade R screws were defined as screws that had to be revised during surgery manually. Facet joint violations were also evaluated according to the classification described by Kim.[20] Grade 0 represented pedicle screws which did not encroach the facet joint. Grade 1 defined pedicle screws which violated the facet joint surface by $\leq$ 1 mm. Grade 2 represented pedicle screws which were clearly violating the facet joint. Additionally, the inward tilt angle (ITA) was defined as the angle between the axis of the screw and the axis of the spinous process, so as to reflect the quality of the screw trajectory. The larger but safe ITA means a better inward tilt and possible longer screw length and better fixation strength. Also, the Cobb angle and PI-LL mismatch angle were evaluated according to the full-length X-ray.

Statistical Analysis

The statistical analysis was performed using GraphPad Prism 10.1.2. Continuous variables were expressed as mean ± standard deviation and compared using the Student's *t*-test. Categorical variables were evaluated using the chi-square (χ^2) test. A p-value of less than 0.05 was considered to indicate a statistically significant difference. Post-hoc power analysis was performed with the Grade R screw rate as primary outcome and a-value of 0.05.

Results

A total of 51 patients diagnosed with degenerative scoliosis were enrolled in this study, all the patients were treated with cMIS technique via staged surgeries. There were 21 cases in Robotic group treated with robot-assisted technique, and 30 cases in Fluoroscopic group treated with fluoroscopy guided technique. There were 7 male and 14 females enrolled in Robotic group, and 11 male and 19 females enrolled in Fluoroscopic group. The mean age was 70.2 ± 9.9 in Robotic group and 66.7 ± 5.9 in Fluoroscopic group. There were 6 cases of grade II, 11 cases of grade III, and 4 cases of grade IV in Robotic group. And there were 9 cases of grade II, 16 cases of grade III, and 5 cases of grade IV in Robotic group. The mean number of screws placed were 10.8 ± 2.4 in Robotic group and 10.3 ± 2.1 in Fluoroscopic group (p = 0.471). The mean number of fixed segments were 5.0 ± 1.7 in Robotic group and 4.5 ± 1.5 in Fluoroscopic group (p = 0.280). The mean number of fusion levels were 3.2 ± 0.40 in Robotic groupnd 3.2 ± 0.43 in Fluoroscopic group (p = 0.721). No statistical difference was found regarding these basic characteristics (Table 1).

Operation Time

The operation time was divided into two kinds. One is the preparation time, define as the time needed from the end of the drape to the begin of the first incision making. And another is the K-wire placement time, defined as the time needed from the end of the drape to the end of the placement of the k-wires. The average preparation time were 23.4 ± 2.8 min in Robotic group, much higher than that of Fluoroscopic group (3.1 ± 1.0 min, p < 0.0001). But for the K-wire placement time, there were no statistical difference between the two groups (62.7 ± 12.5 vs 55.7 ± 20.6 min, p = 0.174, Table 2).

Radiation Exposure

The average fluoroscopic scan number were 9.4 ± 1.7 in Robotic group, much lower than that of Robotic group (27.7 ± 5.9, p < 0.001, Table 2).

Table 1 The Basic Characteristics of the Patients

		Robot Assisted	Fluoroscopy Guided	P value
Cases		21	30	
Mean Age		70.2 ± 9.9	66.7 ± 5.9	0.332
Gender	Male	7	11	0.806
	Female	14	19	
Modifies MISDEF classification	I	0	0	0.975
	II	6	9	
	III	11	16	
	IV	4	5	
Mean screws		10.8 ± 2.4	10.3 ± 2.1	0.471
Mean no. of fixed segments		5.0 ± 1.7	4.5 ± 1.5	0.280
Mean no of fusion levels		3.2 ± 0.40	3.2 ± 0.43	0.721

Table 2 The Clinical and Radiological Outcomes Between the Groups

		Robot Assisted	Fluoroscopy Guided	P value
Mean preparation time (min)		23.4 ± 2.8	3.1 ±1.0	<0.0001
Mean K-wire placement time (min)		62.7±12.5	55.7±20.6	0.174
Mean radiation exposure		9.4±1.7	27.7±5.9	<0.0001
Post-operation VAS		2.9 ± 0.5	3.1 ± 0.7	0.294
GRS	A	185	228	A 0.038
	B	28	43	
	C	14	23	A+B 0.018
	D	0	12	
	E	0	3	
	R	3	22	<0.0001
ITA (°)		21.5 ± 4.7	16.9 ± 6.3	<0.0001
Screw length	40mm	41	98	0.0008
	45mm	112	138	
	50mm	74	73	
Facet joint violation	0	209	247	<0.0001
	1	18	47	
	2	0	15	
Adverse events	Dural tears	1	1	<0.0001
	Neurological complications	2	3	<0.0001
	Infections	0	0	<0.0001

VAS Scale

The VAS scale was measured the first day after the second stage surgery. The average VAS scale was 2.9 ± 0.5 in Robotic group and 3.1 ± 0.7 in Fluoroscopic group, no statistical difference was found between the groups ($p = 0.631$, Table 2).

Screw Accuracy

According to the GRS system, among the 227 screws planted in Robotic group, there were 185 screws of grade A, 28 screws of grade B, 14 screws of grade C, and 0 screws of grade D and E. Among the 309 screws planted in Fluoroscopic group, there were 228 screws of grade A, 43 screws of grade B, 23 screws of grade C, 12 screws of grade D, and 3 screws of grade E. No matter considers only screw of grade A as perfect screws (81.5% vs 73.8%) or considers both grade A and B as acceptable screws (93.8% vs 87.7%), Robotic group demonstrated significant higher screw accuracy than Fluoroscopic group ($p = 0.038$, $p = 0.018$, respectively). Grade R screws were defined as screws that had to be revised during surgery manually. And there were 3 screws of Grade R in Robotic group, much less than that of Fluoroscopic group (22 screws, $p < 0.0001$, Table 2). The screw accuracy was the most important outcome of the study and the Grade R screws that must be revised inter-operatively (most dangerous) was considered as primary endpoint. The post-hoc power analysis was performed with it and the power was 99.2%, suggesting the population number is enough for the present study.

The mean ITA was 21.5 ± 4.7° in Robotic group, much larger than that of Fluoroscopic group (16.9 ± 6.3°, $p < 0.0001$). For the screw length, there were 41 screws of 40mm, 112 screws of 45mm, and 74 screws of 50mm in Robotic group, much longer than that of Fluoroscopic group (98 screws of 40mm, 138 screws of 45mm, 73 screws of 50mm, $p = 0.0008$) (Table 2).

Facet Joint Violation

Facet joint violations were evaluated according to the classification described by Kim.[20] There were 209 screws defined as Grade 0, 18 screws defined as Grade 1, and 0 screws defined as Grade 2 in Robotic group. And there were 247 screws defined as Grade 0, 47 screws defined as Grade 1, and 15 screws defined as Grade 2 in Fluoroscopic group. When consider both Grade 1 and 2 screws were hazardous orientations for facet joint violation, the robot-assisted technique demonstrated significant less violence than fluoroscopy guided technique ($p<0.0001$, Table 2).

Correction of the Deformity

The correction of the deformity is related with the pedicle screw strength and trajectory. Therefore, the better screw trajectory may result to better deformity correction. However, we failed to find any difference between the groups with the correction of Cobb angle and PI-LL mismatch angle of the second stage surgery ($p = 0.141$ and $p = 0.640$, respectively).

Adverse Events

The prevalence of total adverse events showed no difference between the groups, such as dural tears, infections and neurological complications.

Pressure Curve

The OrthoBot® system was able to record the real-time axial pressure data of the mechanical arm during drilling of the K-wire, so that reflect the status of the K-wire in pedicle. The drill strategy used in this robot system was high rotation speed (1200 r/min) but slow advance (0.3 mm/s) to minimize the drift of the K-wire. And the pressure curve patterns could divide into 6 kinds according to the CT scan and pro-operation planning: A. The regular pattern. There is a peak in the beginning, which means the breakage of the cortex bone at the puncture site. And the following is a stable and low curve, which means successful advance in cancellous bone (Figure 1A). B. Hyperostosis of the cortex bone at the puncture site. The characteristic is the extremely high peak in the beginning (Figure 1B). C. Pedicel breach. There are two peaks spacing about 1 cm in the curve, and the second peak means the possible breach of the pedicel (Figure 1C). D. Sclerotic bone formation in the vertebra. The pressure curve may be diverse, for example multiple peaks (D1,

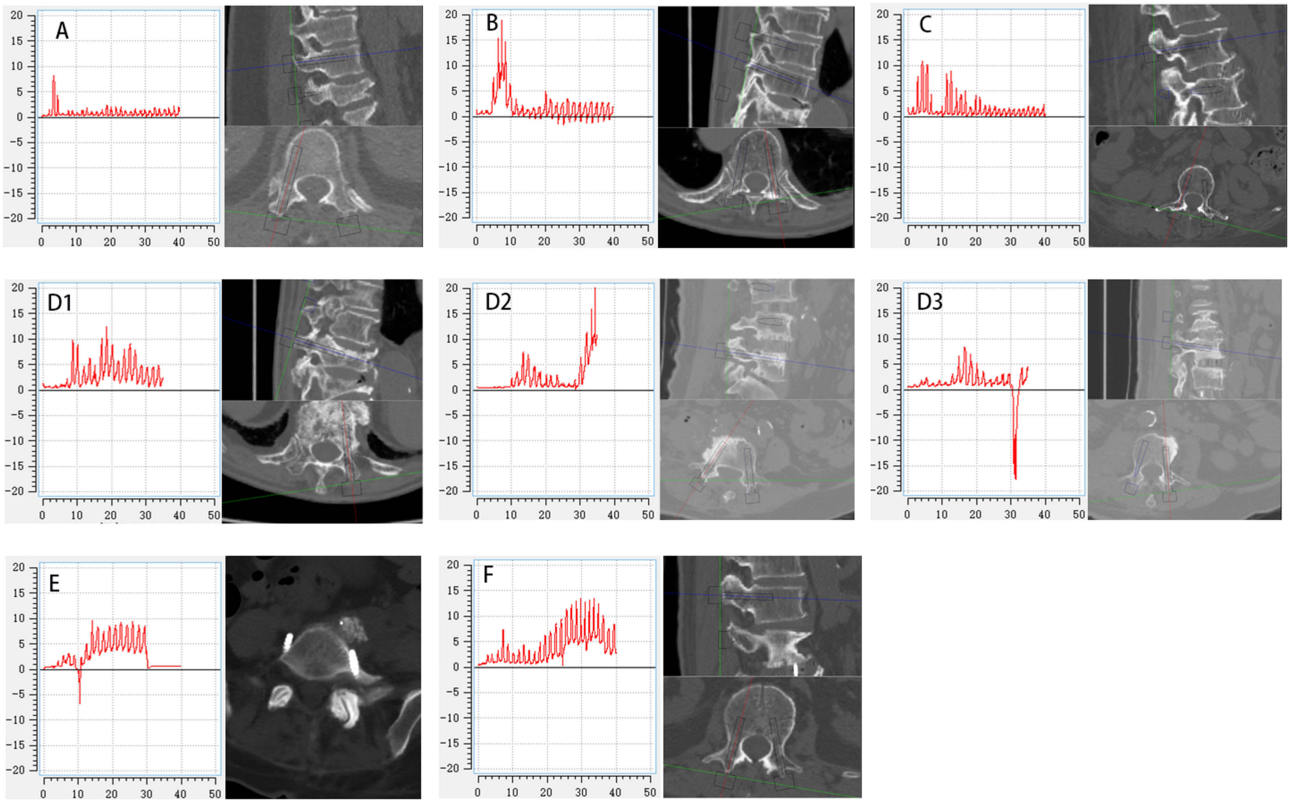

Figure 1 The pressure curve of the mechanical arm. It indicates the forces that the K-wire receives during drilling. The Y axis represent the pressure and the X axis represent the distance. (**A**) The regular pattern. (**B**) Hyperostosis of the cortex bone at the puncture site. (**C**) Pedicel breach. (**D**) Sclerotic bone formation in the vertebra. (**E**) Break through the cortex. (**F**) The other types of curves.

Figure 1D1), extremely high peak (D2, Figure 1D2), and even reverse peaks (D3, Figure 1D3). The position of peaks depends on the position of the sclerotic bone, it's important to figure it during pre-operative planning to predict where the peaks will appear, and to distinguish it from pedicle breach. The reverse peak is hard to explain, the possible reason may be the extremely sclerotic bone formation that able to immobilize the K-wire and at the same time influenced by the breath to create a reverse tensile force. E. Break through the cortex. There's a flat curve with nearly zero pressure (Figure 1E). F. The other types of curves, which are hard to recognize the status of the K-wire in the vertebra (Figure 1F, an example of type F, it's hard to explain the second progressively elevated peak).

Discussion

The use of robotics in spine surgery is promising with significantly improved screw accuracy.[16,21] As patients with degenerative scoliosis always exhibit complex anatomy, developmental abnormalities, and significant individual variations, the use of robotics gets a lot of attention but the data is limited in the literature. And the present study demonstrated significant advantages with the robot-assisted technique against the fluoroscopy guided technique in treating adult degenerative scoliosis with CMIS.

One of the most important reasons holding back the extension of the spinal robots is the complex preparation period for the robots, for example the registration process. The average preparation time for robots is around 30 mins, it's so long that almost long enough to place 6 or more puncture needles. So, in some spine specialists' mind, for regular spine surgeries evolving one or two segments, there's no need to use robotics at all. But for ADS, the situation is much different. The ADS always need 8 or more screws, it's worth to wait a minute for the preparation period as the following puncture needle placement period is so easy and fast. The K-wire placement time is similar for the robot-assisted and fluoroscopy guided techniques in this study, and there's a trend that, the more screws are placed, the fewer time is needed for the robotics when compared with the fluoroscopy guided technique.

However, though the K-wire placement time is similar, there are still a lot of issues that need to be improved to simplify the preparation procedure. For example, the registration process of the robot needs to match the intro-operative X ray with the pre-operation CT. The C-arm can only include 5–6 vertebras at a time, but the correction of ADS always involves 4–8 vertebras. The intro-operative X ray and registration process must be performed twice, it's a huge waste of time (at least 10 mins). Also, the registration efficiency should be improved largely for the OrthoBot system. A clear intro-operative anteroposterior and lateral X ray scan is needed for accurate registration. However, it's quite hard to get a clear X ray image in a deformity patient, especially for patients with obvious osteoporosis. Sometimes, we have to position the patient or the C-arm once and once to get a clear image for better registration. It's a huge waste of time and the software of the robot system should be improved to be smarter to recognize the X ray images with low quality.

The reported screw accuracy in this study is 81.5% of grade A and 93.8% of grade A and B for the robotics, slightly different from other reported papers with the OrthBot system.[18] One of the possible reasons may be the special choice of the diameter and trajectory of the pedicle screws in this study. To get an improved fixation strength, we always use 6.0 mm screws in thoracic vertebras even the pedicle is narrow, so a lot of screws of this situation is of grade B and C. Also, sometimes to avoid possible breakage of the medial wall of the pedicle, the trajectory is always planned to be lateral and sometimes break the lateral wall intentionally. And those screws are always of grade B and C.

The pressure sensor is able to record the pressure change of the k-wire during drilling, and it's supposed to reflect the status of the k-wire, importantly, to figure out the status like breaching the pedicle and even intruding into the spine channel. The pressure curve should be an important feed-back mechanism for the surgeons, like a substitute of hand feeling during free-hand technique. However, the pressure curve is of low sensibility in this study, it's hard to give enough feed-back. It's really bad for surgeons with no reliable feed-backs. Sometimes, especially in severe deformity cases, when watching the robot drill the k-wire with a quite unusual trajectory and the pressure curve record an extremely high peak or a double peak, it's real terrible for the surgeons. The only way is to believe the robot, and fortunately, the outcomes of the screw accuracy is satisfactory enough, we can have much faith on it. Further updates of the robot system should focus on improving the sensibility and accuracy of the pressure sensor.

The spinal assisted robot used in this study is OrthBot, and its most special characteristic is the active system which is able to drill the k-wire into the pedicle automatically. This special design makes the robot much different from the other robot systems, and to some extent, the OrthBot should belong to the semi-automatic robot or next generation robot, as it works automatically under the control of the surgeons. It's a big advance of the robot-assisted technique. However, still a lot works should be done with the robot. For example, the clinical application of the robot only limited to screw placement. It's of great use for young surgeons but not for experienced specialist. More application should be explored, for example, laminectomy and fusion.

We also wonder if an association exists between the accuracy of screw placement and scoliosis correction, but the study failed to figure out the difference. The deformity correction is determined by a lot of factors, and the trajectory and fixation strength are just a small part. Also, for the proximal facet joint violations, though the robotics demonstrated less violations, no difference was found with the post-operation VAS scale, and most importantly, the adjacent segment degeneration after long terms follow-up. Further studies with large population and functions outcomes should be performed in terms of these topics.

Some limitations exist about the present study. Firstly, the small sample size and study design. Randomized controlled trial with larger sample size is with higher level of evidence much better. Secondly, a long-term follow-up with clinical and radiological outcomes is needed to figure out the exact benefits of the robotics, especially the deformity related issues. Thirdly, as consecutive cases were enrolled in this study, the transition from fluoroscopy-guided to robot-assisted surgery within the study period (namely, learning curve) may affect the outcomes. Though the learning curve is quite short and the conclusion will not be affected. Finally, is the lack of the analysis of cost-effectiveness, which is an important issue influencing the extension of the robotic technique.

Conclusion

Taken together, the robot-assisted technique demonstrated significant higher pedicle screw accuracy, better trajectory, less radiation exposure, and similar operation time compared with fluoroscopy guided technique in treating adult degenerative

scoliosis with CMIS technique (staged surgeries: OLIF+PPS). The robot-assisted technique demonstrated significant advantages and can be a good choice for ADS treatment.

Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

Qiang Zhang and Zhe Chen are co-first authors for this study. The authors declare that they have no conflicts of interest in this work.

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