CLINICAL ARTICLE

Rate and Risk Factors of Superior Facet Joint Violation during Cortical Bone Trajectory Screw Placement: A Comparison of Robot-Assisted Approach with a Conventional Technique

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Objective: To compare the incidence and risk factors of superior facet joint violation (FJV) during cortical bone trajectory screw placement in robot-assisted approach versus conventional technique.

Methods: A retrospective study, including 69 patients having cortical bone trajectory (CBT) screw instrumentation for symptomatic degenerated diseases or trauma, was conducted between June 2015 to January 2019. All patients underwent CBT surgery performed by the same team of experienced surgeons. Patients were randomly divided into two groups: a conventional group (CG, 46 cases) and a robot group (RG, 23 cases). The surgical robotic system was used for screw instrumentation in the robot group and the traditional screw instrumentation with fluoroscopic guidance was used in the conventional group. Cortical screws followed a medio-to-lateral path in the transverse plane and a caudal-to-cephalad path in the sagittal plane. Preoperative and postoperative computed tomography (CT) scans were obtained to determine the degree and incidence of FJV. The violation status of facet joint was evaluated according to the modified classification: grade 0, no violation; grade 1, screw shaft, screw head or rod within 1 mm of or abutting the facet joint, but did not enter the articular facet joint; grade 2, screw shaft, screw head or rod clearly in the facet joint. The following factors that may contribute to the occurrence of FJV were analyzed: age, sex, body mass index (BMI), proximal fusion level, fusion length, the side of screw, preoperative vertebral slip, superior facet angle, and degenerative scoliosis. The chi-squared test and Student's t-test were used for analysis of the variables for significance ($P < 0.05$).

Results: FJV occurred in 41.3% of patients in CG and 17.3% of patients in RG. A chi-squared analysis revealed a significantly lower rate of FJV for RG compared with CG ($P = 0.04$). In the CG, 17 of the 109 cephalad screws were grade 1 (15.6%), and five were grade 2 (4.6%). In the RG, three of the 46 cephalad screws were grade 1 (6.5%), and three were grade 2 (6.5%). There was a statistically significant difference in the incidence of FJV between the left and right screw with fluoroscopy-assisted CBT screw instrumentation ($P < 0.05$). A significant correlation between scoliosis with the FJV was found in CG ($P < 0.05$) and in RG ($P < 0.05$). With regard to superior facet angle, a measurement ≥45° was a significant risk factor of FJV in CG ($P < 0.05$) and in RG ($P < 0.05$).

Conclusions: A robot-assisted approach could reduce the incidence of FJV compared with the conventional approach in CBT technique.

Key words: Cortical bone trajectory; Facet joint violation; Risk factors; Fluoroscopy; Robot

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Introduction

Cortical bone trajectory (CBT) screw placement has emerged as a novel technique of instrumentation with superior mechanical properties. First reported by Santoni *et al.*[1], CBT screw follows a medial-to-lateral path in the transverse plane and a caudal-to-cephalad path in the sagittal plane. This approach increases the screw purchase by maximizing thread contact with dense cortical bone. CBT technique is also considered to be more minimally invasive compared with traditional pedicle screw (PS) placement, as wide muscle dissections are avoided in the medial approach[2]. Some cadaver studies[3,4] have shown CBT screw fixation is superior to traditional pedicle screw fixation in posterior lumbar fusion surgery. Furthermore, some clinical studies[5,6] investigated that CBT was superior to PS with a significantly lower postoperative Oswestry Disability Index (ODI) and higher Japan Orthopaedic Association (JOA) recovery rate. Therefore, CBT technique is expected to update traditional lumbar fixation strategies.

Superior facet joint violation (FJV) is a common complication during lumbar screw placement, which was defined as a screw within 1 mm of the facet joint. Facet joints are situated on the dorsolateral aspect of the spine between the adjacent vertebrae, playing a critical role in balancing the lumbar spine unit by sharing load in compression and extension, thereby protecting the disk from anterior shear forces and excessive rotational strain. Injury of facet joint is associated with the alternation in spine stability and load-bearing ability, ultimately leading to the adjacent segment disease. Levin *et al.*[7] have demonstrated that FJV was independently associated with a higher reoperation rate and diminished improvement in quality of life. Another two studies[8,9] showed that FJV resulted in higher back pain scores quatified via VAS and ODI. Therefore, a concern in these cases is the development of adjacent-segment FJV. Several studies have reported the incidence and risk factors of FJV during pedicle screw placement[10,11]. In open surgery, the radiographic rate of FJV was reported to occur in 8.6% to 100% of patients and in 4.3% to 100% of screws. In minimally invasive surgery, the reported rates of FJV varied from 6.3% to 76% in patients and 2.8% to 62% in screws. The wide variation is explained by the variability in surgical techniques. Moreover, conditions such as patient characteristics (age, sex, Body Mass Index [BMI]), proximal fusion level, fusion length, the side of screw, vertebral slip, superior facet angle, and degenerative scoliosis) may also be risk factors.

With the development of minimally invasive approaches, minimally invasive surgery has been widely adopted due to its advantages in less intraoperative blood loss, fast recovery, and shorter hospitalization. However, with percutaneous techniques, anatomical landmarks are not directly visualized, several recent studies raised the concern that these techniques may have a higher incidence of violation of the superior cephalad unfused facet joint[12]. Thus, a variety of robots have been introduced for use in spinal procedures, attracting more and more attention. However, there have been conflicting results regarding the safety and accuracy of robot-assisted fixation[13,14]. The TiRobot orthopaedic robot (TINAVI Medical Technologies Co., Ltd., Fenton, Missouri, USA) provides a new technology for the precise screw placement in minimally invasive percutaneous surgery. Intraoperative 3D imaging may allow improved accuracy in cortical screw placement. The emergence of this technology may simplify the surgeon's selection of the screw entry point and trajectory, and thus open the route to image-guided minimally invasive therapy with decreased rates of the violation of the superior cephalad unfused facet joint. Theoretically, the rate of FJV could be reduced with robot-assisted approach when the entry point is selected farther away from the facet joint.

A thorough review of the literature revealed only one study that investigated the incidence of risk factors of FJV secondary to CBT screw instrumentation. Due to the CBT entry point being near the pars articularis, which is far from the superior facet joint, Matsukawa *et al.*[15] showed that lumbar pedicle screw placement via CBT would reduce damage to the adjacent cranial facet joint, and special care should be taken in patients aged >70 years, with vertebral slip >10%, and facet degeneration. However, they only investigated patients with fluoroscopy-assisted instrumentation in open surgery. Furthermore, no previous study has defined strict grade criteria of FJV with CBT technique. Therefore, we know little about the incidence of facet violation with robot-assisted CBT screw instrumentation.

In this study, we focused on three major points: (i) comparison of the rates of FJV during CBT screw placement with robot-assisted approach versus conventional technique; (ii) risk factors including the patient characteristics and anatomical factors of superior FJV with robot-assisted approach and conventional technique; and (iii) comparison of the performance between robot-assisted approach and conventional technique.

Patients and Methods

Participant Demographics

All participants provided their informed consent for this study. The study was conducted in Beijing Jishuitan Hospital and was approved by the Ethics Committee of Beijing Jishuitan Hospital.

From June 2015 to January 2019, the inclusion criteria for open surgery with CBT screw instrumentation were the following: (i) patients presented with recurrent low back pain or lower limb symptoms due to symptomatic degenerated disks, spinal stenosis, spondylolisthesis (grade I/II) or trauma; (ii) patients previously underwent posterior lumbar interbody fusion (PLIF) or transforaminal lumbar interbody fusion (TLIF) using CBT technique; (iii) placement using fluoroscopy-assisted technique or robot-assisted technique; (iv) conservative treatment failed to relieve the recurrent pain; and (v) received open surgery. Exclusion criteria were as following: (i) spinal infections or tumors; (ii) requiring revision procedures; (iii) age < 18 years; and (iv) congenitally small pedicles or congenital pars defects. All patients underwent surgery performed by the same team of experienced surgeons.

Patients were randomly divided into two groups: a conventional group (CG, 46 cases) and robot group (RG, 23 cases). Forty six patients underwent CBT screw instrumentation using fluoroscopic guidance and 23 patients underwent CBT screw instrumentation using robotic guidance. The decision to operate using robotic assistance or conventional technique was based on the surgeon's discretion and logical reasons. The demographic and clinical data for both groups included age, sex, BMI, spine surgery level, and diagnosis.

Surgical Procedures
After the induction of general anesthesia, patients were placed in the prone position. An incision was made through a posterior median approach and the soft tissue were dissected until the cortical screw entry points were exposed. Cortical screws (CD Horizon Solera Spinal System 4.75, Medtronic, Memphis TN, USA) were inserted according to the original method[1].

In the conventional group (CG), by identification of anatomical landmarks with fluoroscopy guidance, the cortical screw entry point was supposed to be the junction located at the center of the superior articular process and 1 mm inferior to the inferior border of the transverse process[16]. The cortical trajectory was confirmed by a ball-tip pedicle probe and then the appropriately chosen screws were inserted and secured with rods.

In the robot group (RG), the robot workstation was connected to the data line of the C-arm scanner (Siemens Medical Solutions, Erlangen, Germany). The cortical screw trajectories and screw length and diameter were adjusted appropriately on the robot computer. K wires were inserted using the robotic system and the surgeon determined whether the position of the wires should be adjusted or not according to experience after the AP and lateral images from the C-arm were performed[17]. The cortical screws were placed after the safety of the trajectory was confirmed.

Fluoroscopy was used to confirm the position of the K-wire and/or screws. In both groups, subsequent decompression or arthrodesis were performed where necessary.

Clinical Assessment
Each participant was asked to complete preoperative and postoperative computed tomography (CT) scans with a 1-mm thickness slice, including coronal and sagittal reconstructions.

Screw Violation Grade
The screw violation grade of the FJV at the proximal adjacent segment was evaluated according to the modified classification described by Yson *et al.*[18] and Moshirfar *et al.*[19]: grade 0, no violation (Fig. 1); grade 1, screw shaft, screw head or rod within 1 mm of or abutting the facet joint, but did not enter the articular facet joint (Fig. 2); and grade 2, screw shaft, screw head or rod clearly in the facet joint (Fig. 3). The slice with the largest violation was chosen for grading. The assessment of FJV included the adjacent cranial segments of patients with degenerative disease and all fixation segments of patients who had experienced trauma. Because decompression in patients with degenerative disease destroys the facet joints, fracture patients did not require decompression. The violation status of facet joint was determined by three independent spine surgeons, who were blinded to surgical approaches. When two or more observers agreed on the violation status, it was considered the consensus grade.

Vertebral Slip
The vertebral slip grade represents the displacement of one vertebral body over the inferior one on plain lateral lumber radiograph, which was classified in five subtypes by Meyerding[20]: grade I, less than 25% of displacement; grade II, between 25% and 50%; grade III, between 50% and 75%; grade IV, between 75% and 100%; and grade V, representing more than a 100% slip or spondyloptosis.

Superior Facet Angle
Superior facet angle was used to calculate the facet joint orientation using the method described by Noren *et al.*[21] The first line was drawn passing through the center of the disk and the center of spinous process, and the second line was

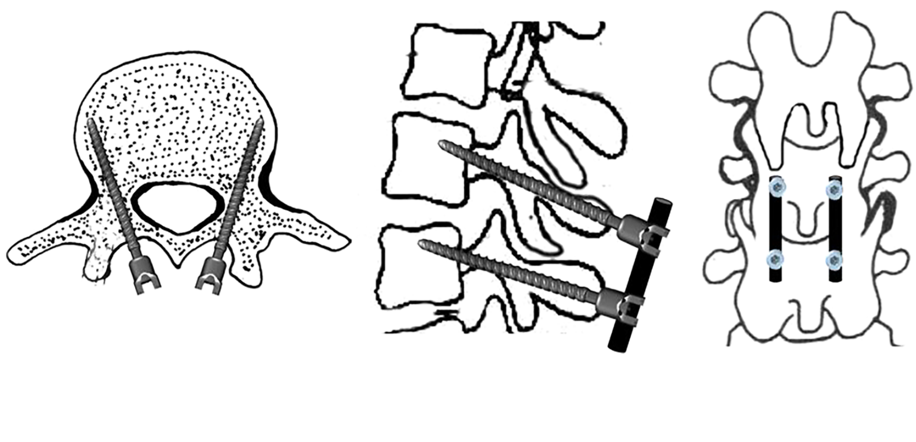

Fig. 1 Grade 0 violation: no facet joint violation is evident in the axial, sagittal, or coronal computed tomography scans.

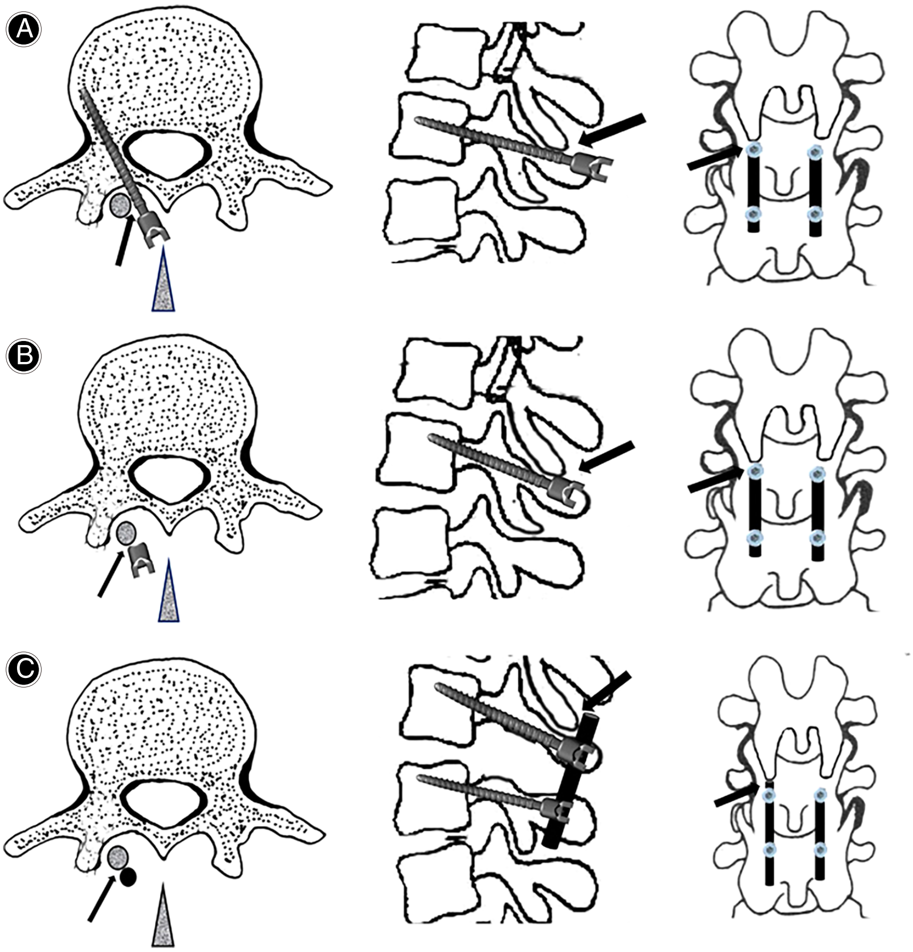

Fig. 2 Grade 1 violation: axial, sagittal, and coronal computed tomography images showing the screw shaft (A), screw head (B) or rod (C) within 1 mm of or abutting the facet joint.

formed by connecting the two end points of each facet. The facet joint angle is defined as the angle between the two lines (Fig. 4). In addition, proximal fusion level, fusion length, degenerative scoliosis, and the side of screw were documented.

Statistical Analysis

Statistical analyses were performed with SPSS, version 20.0 software (IBM Corp., Armonk, New York, USA). All variables were described by their absolute (no.) and relative (%) frequencies and continuous variables as the mean and standard deviation. The chi-squared test was used for analysis of within-group variables and the Student's *t*-test for independent samples was carried out to compare the two sets of data when a Gaussian distribution was expected. The Wilcoxon test was used for samples that were not normally distributed. Statistical significance was set at $P < 0.05$.

Results

Demographic Data

In total, 69 patients were studied, 46 in the CG and 23 in the RG. The mean BMI was significantly higher in RG than CG (28.5 ± 3.6 *vs.* 25.3 ± 3.4, $P < 0.01$). In terms of the other parameters, including age, sex, or preoperative diagnosis, no significant difference between the two groups was found (Table 1).

Clinical Outcomes

There was a statistically significant difference in the incidence of FJV between the left and right screw with fluoroscopy-assisted CBT screw instrumentation ($P < 0.05$). Moreover, a significant correlation between scoliosis with the FJV was found in CG ($P < 0.05$) (Table 2). Similarly, a significant correlation between scoliosis with the FJV was found in RG ($P < 0.05$) (Table 3). However, no significant differences in the incidence of FJV were found in the two groups in terms of proximal fusion level and fusion length.

Screw Violation Grade

FJV occurred in 41.3% of patients (19 of 46) for CG and 17.3% of patients (four of 23) for RG. A chi-squared analysis revealed a significantly lower rate of FJV for RG compared with CG ($P = 0.04$) (Table 4). CBT screw violation grades were detailed in Table 5. In the CG, 17 of the 109 cephalad screws were grade 1 (15.6%), and five were grade 2 (4.6%).

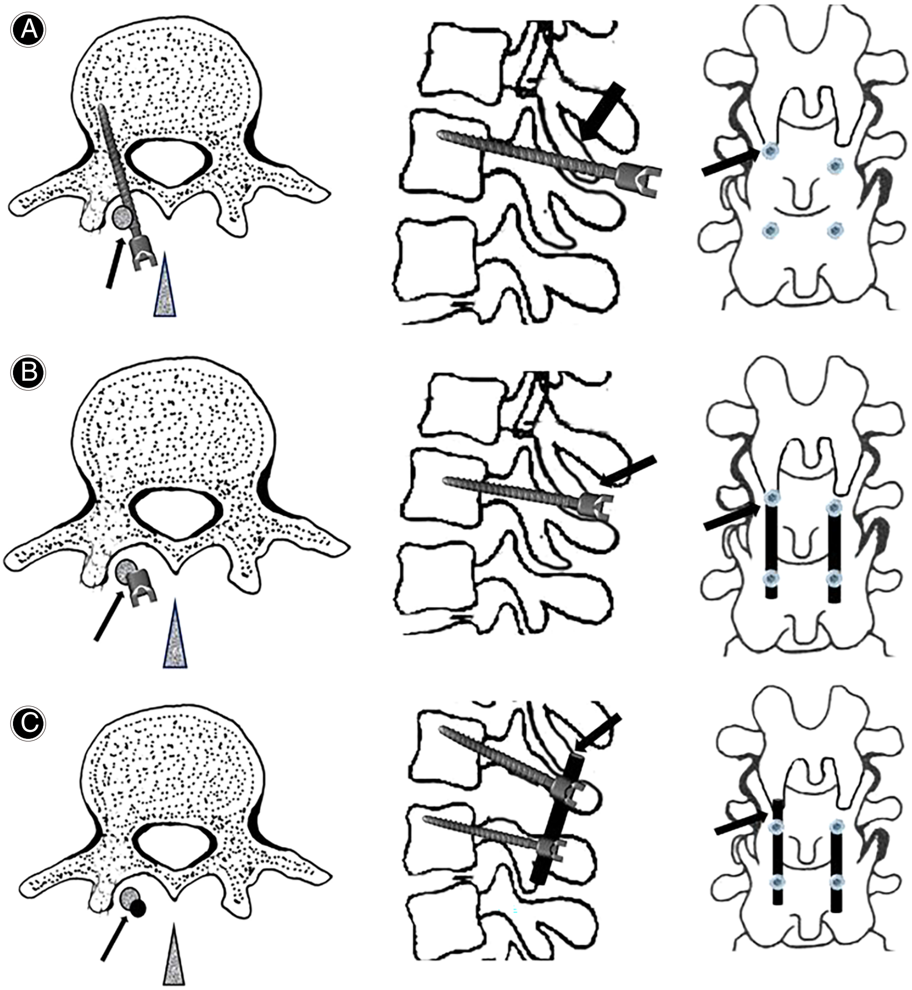

Fig. 3 Grade 2 violation: axial, sagittal, and coronal computed tomography images showing the screw shaft (A), screw head (B) or rod (C) clearly in the facet joint.

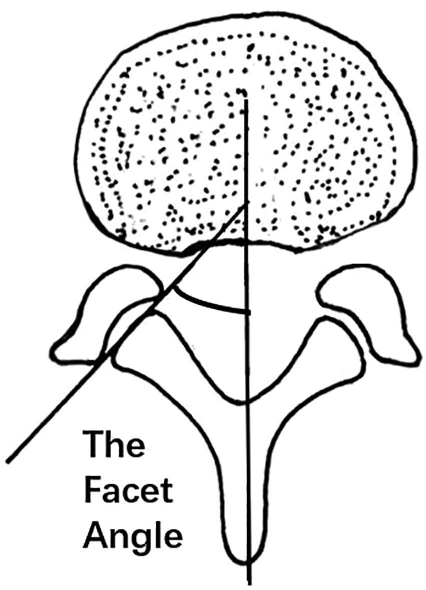

Fig. 4 The measurement of facet angle.

In the RG, three of the 46 cephalad screws were grade 1 (6.5%), and three were grade 2 (6.5%). Although the FJV rate of screw in RG tended to decrease compared with CG, there was no statistical difference. However, when we only compared the FJV rate of screw shaft between the two groups, the rate in RG was significantly lower than that in CG (P = 0.021).

TABLE 1 Baseline characteristics

Variables	CG (109 screws)	RG (46 screws)	*P* value
Patients (cases)	46	23	-
Age (years, mean±SD)	58.9 ± 13.0	65.1 ± 8.0	0.052
Sex (female/male)	31/15	17/6	0.587
BMI (kg/m^2, mean±SD)	25.3 ± 3.4	28.5 ± 3.6	0.001
Pathologic entity (cases)			
Degeneration	42	23	0.29
Trauma	4	0	

BMI, Body Mass Index; CG, conventional group; RG, robot group.

TABLE 2 Effect of different factors in fluoroscopy-related FJV (cases)

Variable	Cephalad facet joint: Intact	Cephalad facet joint: Violated	*n*	χ^2	*P* value
Age (years)					
<70	21	14	46	0.102	0.508
≥70	6	5			
Sex					
Female	16	15	46	1.967	0.139
Male	11	4			
BMI (kg/m^2)					
<30	24	17	46	<0.001	0.667
≥30	3	2			
Proximal fusion level					
Upper lumber (L_1-L_3)	5	2	46	0.106	0.38
Lower lumber (L_4-L_5)	22	17			
Fusion length					
1 or 2 segments	13	11	46	0.124	0.363
3 segments or more	14	8			
The side of screw					
Right	49	5	109	7.928	0.004
Left	38	17			
Vertebral slip grade					
0	22	13	46	3.584	0.147
I	4	6			
II	1	0			
III	0	0			
IV	0	0			
Facet angle					
<45°	71	10	109	12.024	0.001
≥45°	16	12			
Scoliosis					
Yes	2	6	46	3.009	0.042
No	25	13			

BMI, body mass index; FJV, facet joint violation.

TABLE 3 Effect of different factors in robot-related FJV (cases)

Variable	Cephalad facet joint: Intact	Cephalad facet joint: Violated	*n*	χ^2	*P* value
Age (years)					
<70	16	2	23	0.707	0.194
≥ 70	3	2			
Sex					
Female	15	2	23	0.327	0.27
Male	4	2			
BMI (kg/m^2)					
<30	13	2	23	0.016	0.435
≥30	6	2			
Proximal fusion level					
Upper lumber (L_1-L_3)	4	0	23	0.06	0.456
Lower lumber (L_4-L_5)	16	4			
Fusion length					
1 or 2 segments	17	3	23	<0.001	0.453
3 segments or more	2	1			
The side of screw					
Right	20	3	46	< 0.001	0.667
Left	20	3			
Vertebral slip grade					
0	8	3	23	1.714	0.658
I	10	1			
II	1	0			
III	0	0			
IV	0	0			
Facet angle					
<45°	37	2	46	8.311	0.005
≥45°	4	4			
Scoliosis					
Yes	1	3	23	6.858	0.009
No	18	1			

BMI, body mass index; FJV, facet joint violation.

Vertebral Slip

There was no significant correlation between vertebral slip and FJV in CG ($P = 0.147$). Vertebral slip is not a significant risk factor of FJV with CBT technique in RG ($P = 0.658$).

Superior Facet Angle

With regard to superior facet angle, a measurement ≥45° was a significant risk factor of FJV in CG ($P < 0.05$). Similarly, superior facet angle ≥45° was a risk factor of FJV in RG ($P < 0.05$).

Discussion

CBT is a novel technique for lumbar fusion, and FJV is one of the most common complications, which have attracted more and more attention in recent years. Although several studies have reported the incidence and risk factors of FJV for PS, only one study of FJV for CBT screw with fluoroscopic assistance in open surgery has been reported so far. Recently, a variety of robots have been introduced for use in spinal procedures. However, there have been conflicting results regarding the safety and accuracy of robot-assisted instrumentation[13,14]. Therefore, in this study, we compared the incidence and risk factors of superior FJV with robot-assisted insertions versus fluoroscopy-assisted insertions in open surgery for CBT technique.

Rate of Facet Joint Violation

The current study demonstrated that the FJV rate of patients was lower for the robot-assisted approach (17.3%) than the conventional approach (41.3%). Although there was no difference in the total incidence of FJV for the screw between the two groups, the FJV rate of screw shaft in the RG (0%) was significantly lower than that in the CG (11.0%). This difference can be explained by the mechanism of guidance. In the CG, relying on the two-dimensional intra-operative radiographic images, it was difficult to choose the perfect trajectory. However, in the RG, by selecting the ideal screw trajectory in three planes on the blueprint preoperatively, it was

TABLE 4 Comparison of two groups regarding different FJV grades of patients (cases [%])

FJV	CG (46 cases)	RG (23 cases)	*P* value
Intact	27 (58.7)	19 (82.6)	0.04
Violated	19 (41.3)	4 (17.3)	

CG, conventional group; FJV, facet joint violation; RG, robot group.

TABLE 5 Comparison of two groups regarding different FJV grades of screws (cases [%])

FJV	CG (109 cases)	RG (46 cases)
Grade 0	87 (79.8)	40 (87.0)
Grade 1	17 (15.6)	3 (6.5)
Screw shaft	9	0
Screw head	5	1
Rod	3	2
Grade 2	5 (4.6)	3 (6.5)
Screw shaft	3	0
Screw head	1	2
Rod	1	1
	P = 0.206	

CG, conventional group; FJV, facet joint violation; RG, robot group.

possible to avoid the facets without compromising on screw purchase within the pedicle. Nevertheless, there is a problem that has rarely been noticed before. The robotic guidance only can help us to choose the perfect trajectory of screw shaft on the workstation, but this often leads the surgeon to ignore the FJV of the screw head and the rod. The latter usually depends on the screw type and the operation of the surgeon, which can't be solved by the robot. Therefore, our results showed that although the robot reduced the rate of FJV by the screw shaft, the FJV by the screw head and the rod did not change significantly. This factor should be taken into account in future robot improvements or operations of surgeons.

A report from Matsukawa *et al.*[15] showed that the FJV rate by CBT screws with the conventional approach was 11.8%, which was lower than our results of the CG. The difference may result from the evaluation methods. In most studies[19,22–24], FJV was defined as a screw within 1 mm of the facet joint. However, in their study, FJV occurred when the screw was in contact with the facet joint, which was more rigorous than ours. Overall, our study proved the advantages of robot-assisted placement over traditional placement in CBT technique for FJV.

Risk Factors of FJV

We also explored different factors that may contribute to FJV in CBT technique. Our results demonstrated that left-side CBT screw, facet angle ≥45°, and scoliosis were risk factors for FJV of CBT with fluoroscopy-assisted instrumentation. Meanwhile, the risk factors affecting FJV for robot-assisted instrumentation included: facet angle ≥45° and scoliosis. Our study indicated that age, sex, BMI, proximal fusion level, fusion length, and slippage grade had no correlation with the incidence of FJV.

The Side of Screw

One possible explanation for the lower FJV rate of right-side CBT screw in the CG is the difference between right-hand and left-hand. It may be because the insertion of CBT screws, particularly at L and S (due to their caudal and medial trajectory), are easier for a right-handed surgeon from the patient's right side rather than the left. Moreover, all the surgeons are right-handed in our department. Therefore, this study showed that the right screw had a lower rate of FJV. Interestingly, the application of the robot seems to weaken the effect of the side. Nevertheless, it is not a formal study, because we have no routine record on the position of the attending surgeon and assisting surgeon (i.e., right or left side of the patient). In future studies, assessing this variable to see if there is a statistically significant learning curve would be interesting.

Superior Facet Angle

Our study showed that the facet angle was a risk factor for FJV in CBT technique, both in the CG and in the RG. When the facet angle is greater than 45°, the risk of FJV increases. One possible explanation for this is the trajectory of CBT screw. The orientation of the facet joint gradually changes to the coronal direction when the facet angle increases, which blocks the pathway of the CBT screw. This is determined by the screw trajectory, regardless of the type of screw placement assisted by the technique. Thus, the screw is more likely to violate the facet joints, leading to a higher FJV. Another possible explanation for this might be the projection of facet joint. In the intraoperative C-arm fluoroscopy, there is overlap between the oval-shaped pedicle ring and projection of the facet joint. Moreover, the overlap is more significant when the facet angle is larger. When the facet joint projection covers most of the oval-shaped pedicle ring, even covering the lateral edges of the pedicle rings, the incidence of FJV is bound to increase[25].

Degenerative Scoliosis

Scoliosis is another risk factor for FJV. There are two possible explanations. First, the instrumentation of most scoliosis patients involves L_1 to L_2 levels, where the pedicles are smaller and the facet-screw distance is shorter than other levels[15,26]. This will increase the difficulty of choosing the perfect trajectory. Second, osteoporosis often occurs in patients with spinal deformities, which increases the difficulty of identifying bone markers for surgeons[26]. This may lead to an increase in the difficulty of operation.

Limitations

There were limitations in this study. First, considering the small sample size, additional studies involving more participants are needed. Second, we did not investigate the relationship between different grade FJV and clinical outcomes, which may be an interesting topic for future research.

Conclusion

Robot-assisted placement is more advantageous than conventional approach in CBT technique for FJV.

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