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Observational Study

Comparison of Robot-Assisted and Fluoroscopy-Assisted Percutaneous Kyphoplasty for Bone Cement Distribution and Clinical Efficacy

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Background: The distribution of bone cement after percutaneous kyphoplasty (PKP) affects its clinical efficacy in patients with osteoporosis. Robotic and traditional treatment of osteoporotic vertebral compression fractures (OVCFs) have both been established as effective, but no studies have compared these 2 modalities in terms of bone cement distribution and clinical outcomes.

Objective: To compare the bone cement distribution and clinical efficacy of robot-assisted percutaneous kyphoplasty to those of fluoroscopy-assisted percutaneous kyphoplasty for the treatment of OVCFs.

Setting: Department of Orthopedics and Spine Surgery, First Affiliated Hospital of Anhui Medical University, Hefei, China.

Study Design: A single-center, retrospective observational study.

Methods: Data from 151 patients with OVCFs who underwent PKP between January 2020 and July 2022 were analyzed retrospectively. The patients were divided into 3 groups: robot-assisted unipedicular percutaneous kyphoplasty (RAUPK), fluoroscopy-assisted unipedicular percutaneous kyphoplasty (FAUPK), and fluoroscopy-assisted bipedicular percutaneous kyphoplasty (FABPK). The operation time, intraoperative blood loss, bone cement injection volume, bone cement distribution, and complications (vascular and nerve injury, bone cement leakage, and re-fracture) of each procedure were recorded. The visual analog scale (VAS) score, Oswestry Disability Index (ODI) score, Cobb angle, and anterior height of the injured vertebrae were compared among the 3 groups preoperatively, one day postoperatively, and at the final follow-up.

Results: No puncture failures occurred in any of the 3 groups. The mean follow-up period was 20.0 ± 5.2 months. The postoperative VAS scores, ODI, anterior vertebral heights, and Cobb angles of all patients were significantly improved compared to the preoperative values ($P < 0.05$). There were no significant differences in the VAS score, ODI score, Cobb angle, anterior vertebral height ratio preoperatively or one day postoperatively among the 3 groups ($P > 0.05$). The groups' comparative rates of intraoperative blood loss and complications also showed no significant differences ($P > 0.05$). At the last follow-up, the VAS and ODI scores of the RAUPK group were lower than those of the FAUPK group ($P < 0.05$), as were the anterior height of the injured vertebra and Cobb angle of the RAUPK group ($P < 0.05$). The operation time, bone cement injection volume, and bone cement distribution in the RAUPK group were superior to those in the FAUPK group ($P < 0.05$). Nevertheless, there were no significant differences in the VAS, ODI, Cobb angle, or anterior vertebral height at the last follow-up between the FABPK group and the RAUPK group ($P > 0.05$). Those 2 groups also showed no significant difference in operation time, intraoperative blood loss, bone cement distribution, or complication rate ($P > 0.05$). However, the patients in the RAUPK group were injected with a greater volume of bone cement than were those in the FABPK group ($P < 0.05$).

Limitations: This was a single-center, retrospective, nonrandomized study, which is a major limitation.

Conclusion: Robot-assisted percutaneous kyphoplasty can establish an optimal path via the unipedicular approach, thereby effectively mitigating the potential risks associated with vascular nerve and cortical bone injuries. Additionally, RAUPK ensures a more favorable distribution of bone cement and provides superior pain relief for patients. Furthermore, RAUPK has greater long-term efficacy than does FAUPK.

Key words: Percutaneous kyphoplasty, TiRobot, unilateral pedicle approach, osteoporotic vertebral compression fractures, optimal path, bone cement distribution

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An osteoporotic vertebral compression fracture (OVCF) is a prevalent type of fracture, with a reported incidence as high as 20% among individuals aged 50 years and above (1). In recent years, the incidence of OVCFs has risen, resulting in approximately 1.4 million new fracture cases annually. This substantial increase significantly affects the quality of life in the elderly and imposes a considerable societal burden (2-4). These fractures result in chronic pain, reduced mobility, and decreased overall quality of life and may lead to increased morbidity and mortality. The economic impact is also substantial, with the annual cost of osteoporotic fractures in the United States estimated to exceed $19 billion (5,6). Effective therapeutic strategies are required to address these health problems. The primary objective of clinical interventions for OVCFs is to restore the physical structure and biomechanical equilibrium of the affected spinal segments. Percutaneous kyphoplasty (PKP) has emerged as a prominent therapeutic approach for OVCFs because of the procedure's minimal invasiveness, expedited recuperation, and notable amelioration of kyphosis (7). The fundamental mechanism underlying vertebroplasty involves the reinforcement of vertebral stability through the injection of bone cement into the vertebral body, thereby stabilizing microfractures. Consequently, the spatial dispersion of the bone cement is intricately linked to the procedure's clinical effectiveness (8).

Unipedicular PKP offers reduced surgical trauma and shorter operation time, whereas bipedicular PKP provides the advantages of a uniform distribution of bone cement and stress balance. Whether the approach is unilateral or bilateral, the success of PKP relies heavily on the accuracy of the puncture path. Inaccurate puncture paths can result in inadequate bone cement distribution, cement leakage, nerve and vascular damage, and even surgical failure (9-11). Currently, the use of navigation robots in spinal surgery has allowed for a more consistent implementation of PKP. TiRobot® (TINAVI Medical)-assisted orthopedic robots can register 3-dimensional (3D) image data using a computer navigation system. These data enable operators to plan puncture paths precisely and establish an optimal unilateral PKP approach, resulting in the effective distribution of bone cement (11). Therefore, it is necessary to achieve optimal biomechanical balance and minimize the risk of intraoperative nerve and vascular damage as well as bone cement leakage by employing an accurate, safe unilateral puncture path. However, studies comparing robot-assisted PKP with unipedicular optimal paths to fluoroscopy-assisted PKP are lacking. In this study, we retrospectively analyzed the clinical data of patients with OVCFs who underwent robot-assisted unilateral PKP between January 2020 and July 2022. The distribution type and efficacy of this approach were compared with those experienced by patients with OVCFs who underwent fluoroscopy-assisted PKP during the same period. The findings of this study are presented in the following report.

Methods

Patient Population

The data of patients who underwent PKP for thoracolumbar OVCFs at the First Affiliated Hospital of Anhui Medical University between January 2020 and July 2022 were retrospectively analyzed. The inclusion criteria were: (1) single-segment vertebral compression fracture with low back pain, (2) bone mineral density (BMD) < -2.5 SD, and (3) the receipt of ineffective conservative treatment. The exclusion criteria were: (1) a severe underlying disease that prevented the patient from tolerating surgery, (2) a spinal tumor or spinal infection in addition to an OVCF, (3) complications with neurological symptoms, and (4) a follow-up time of fewer than 12 months. A total of 151 patients with OVCFs (27 male, 124 female) were included in this study. Their ages ranged from 57 to 91 years (mean: 73.2 years). The follow-up time was 12-24 months. The patients were divided into 3 groups according to the PKP method they were to undergo. The robot-assisted unipedicular percutaneous kyphoplasty (RAUPK), fluoroscopy-assisted unipedicular percutaneous kyphoplasty (FAUPK), and fluoroscopy-assisted bipedicular percutaneous kyphoplasty (FABPK) groups included 58, 36, and 57 patients, respectively. All operations were performed by the same team of senior physicians. There were no statistically significant differences in age, gender, BMD, body mass index (BMI), or other general data among the 3 groups (Table 1). The procedures followed in this study were approved by the Ethics Committee of the First Affiliated Hospital of Anhui Medical University.

Surgical Techniques

RAUPK Group

After anesthesia was administered to the patient, the reduction pad connected to the 3D-C arm system and the TiRobot® robot system were started and calibrated. The position of the injured vertebra was recorded using C-arm fluoroscopy, and the costal margin was used as a mark. An infrared tracker was fixed to the skin of the superior part of the fractured segment, and a mechanical arm tracer and mechanical arm positioning scale were installed. Intraoperative Iso-C scanning was performed to obtain a 3D image of the surgical area, and the direction and specifications of the pedicle screw implantation were planned according to the image (Fig. 1). The robotic arm automatically adjusted its posture according to the plan, inserted the sleeve along the fixed direction of the robotic arm, determined the position of the skin incision, made a 0.5 cm transverse incision to enable blunt separation of the subcutaneous soft tissue, and then inserted the sleeve. After the placement of an avoidance pin, a blunt head separator was set. The guide pin and blunt head separator were removed after the insertion of the working cannula. The drill was manually controlled to the bone cortex of the anterior edge of the vertebral body (3 mm). Anteroposterior radiography revealed that the outer head was in the position of the spinous process. The probe of the expandable bone-forming device was inserted into the anterior third of the vertebral body using a radioactive marker. A balloon injected with the contrast medium was placed in the injured vertebral body for moderate expansion. After the bone cement hardened, the cannula was removed, and the operation was completed.

FAUPK and FABPK Groups

The patients were placed in the prone position, and a 0.3 cm longitudinal incision was made at the fixation point. Under C-arm guidance, a working sleeve with an inner core was used to enter the needle at the lateral edge of the unilateral/bilateral pedicle, and the inner core was removed. The remaining procedures were the same as those in the unilateral group.

All patients were advised to wear a thoracolumbar brace or waist circumference during early ambulation within 24 hours after the surgical procedure and were provided with standard anti-osteoporosis treatment.

Outcome Assessment

Clinical Evaluation

The preoperative and postoperative VAS and ODI scores were compared for clinical evaluation.

Imaging Evaluation

Radiographic evaluation was performed on the basis of 2 criteria: vertebral height and kyphosis.

Table 1. ***Comparison of general data among RAUPK, FAUPK, and FABPK groups.***

	RAUPK	FAUPK	FABPK	F/χ^2	*P*
No. of patients	58	36	57		
Gender				1.422	0.526
Male	13	6	8		
Female	45	30	49		
Mean age (years)	73.5 ± 7.59	73.1 ± 6.69	72.9 ± 6.84	0.105	0.900
BMD (T-score)	-3.43 ± 0.69	-3.41 ± 0.52	-3.24 ± 0.53	1.659	0.194
BMI (kg/m^2)	22.1 ± 3.44	22.7 ± 3.56	23.3 ± 3.34	1.760	0.176
Follow-up time (months)	19.3 ± 5.56	19.3 ± 5.58	21.1 ± 4.41	2.002	0.139
Operative levels				0.801	0.663
T spine ratio	39.7% (23/58)	36.8% (21/57)	30.6% (11/36)		
L spine ratio	60.3% (36/58)	63.2% (36/57)	69.4% (25/36)		

Quantitative morphometry was used to measure the anterior vertebral height and kyphosis. Anterior vertebral height (AH) and posterior vertebral height (PH) of the upper and lower end plates were measured directly on lateral radiographs. The anterior vertebral height was expressed as the sagittal index (SI) (SI=AH/PH×100%). AH and PH were measured in all patients preoperatively, one day postoperatively, and at the last follow-up visit. The kyphosis Cobb angle is the angle of the crossing line between the upper and lower endplates of the fractured vertebra. Three vertical lines were drawn in the middle of the central spinous process and the inner edge of the pedicle on both sides to divide the vertebral body into 4 regions. The distribution area of bone cement was divided into 5 types. Among them, types I-III were homogeneous, and types IV-V were heterogeneous (Fig. 2).

Evaluation of Surgery

Surgical evaluation was based on operative time, intraoperative blood loss, intraoperative radiation exposure dose, bone cement injection volume, and preoperative and post-operative complications.

Statistical Analysis

SPSS 27.0 (SPSS Inc.) was used for statistical analysis. Measurement data were expressed as mean ± SD. Analysis of variance (ANOVA) with Bonferroni correction was used to compare differences in age, BMI, BMD, follow-up time, operation time, intraoperative blood loss, bone cement volume, VAS score, ODI score, SI, and Cobb angle among the 3 groups. The chi-square test was used to analyze the differences in gender, operative level, bone cement leakage rate, and refracture rate. Repeated measurements were performed for in-group comparisons of the VAS and ODI scores,

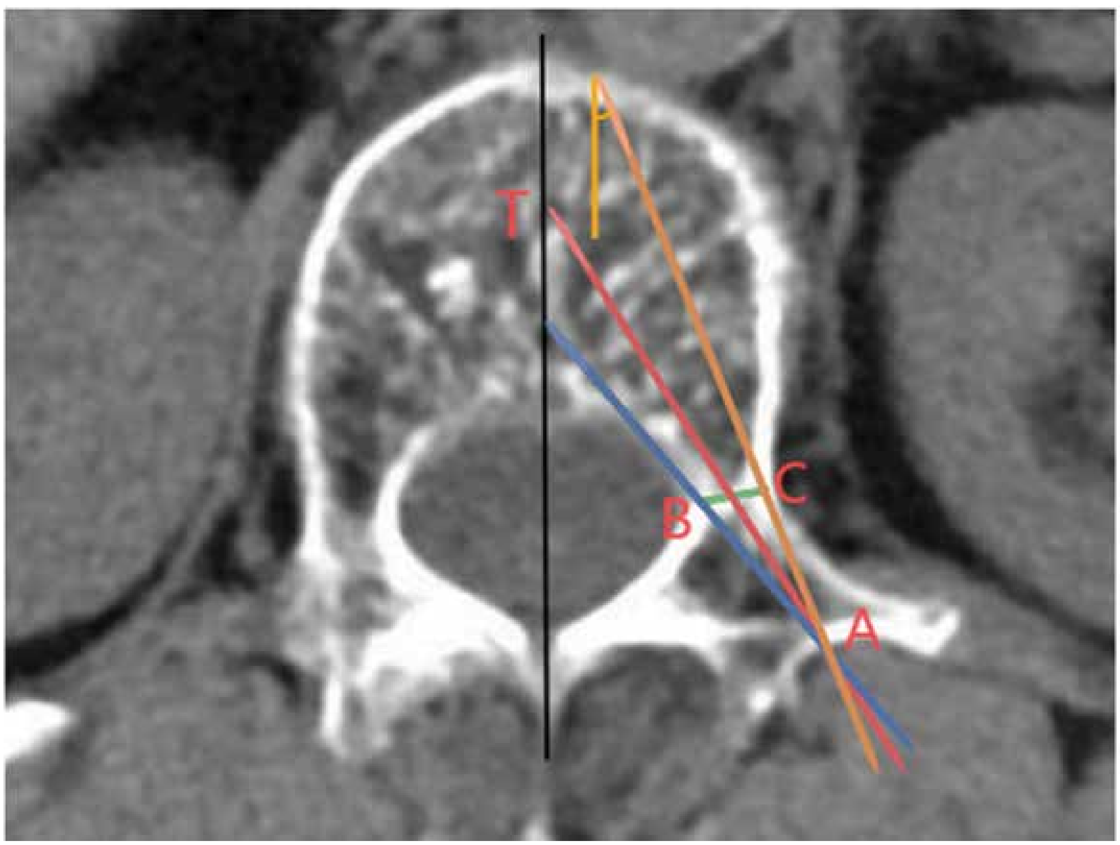

Fig. 1. *The T-line is the midline of the vertebral body, point A is the puncture point, and points B and C are the inner and outer cortical points at the narrowest pedicle, respectively. The angle between the puncture path and the T-line was the internal inclination angle.*

SI, and Cobb angle, with $P < 0.05$ indicating statistical significance.

Results

All patients were followed up for 12-24 months (20.0 ± 5.2 on average). There were no significant differences in the general data among the 3 groups ($P > 0.05$) (Table 1).

All patients in all 3 groups successfully completed the surgery. The operation time experienced in the RAUPK group (52.7 ± 12.7 min) was longer than in the FAUPK group (42.9 ± 16.3 min, $P < 0.05$). However, there was no significant difference compared with the FABPK group (54.9 ± 16.2 min, $P > 0.05$). The radiation exposure dose and bone cement injection volume in the RAUPK group (164.0 ± 29.5 mGy, 4.7 ± 0.5 mL) were greater than those in the FAUPK group (125.1 ± 26.1 mGy, 2.7 ± 1.3 mL) and the FABPK group (139.9 ± 33.0 cGy/cm^2, 3.8 ± 1.1 mL, $P < 0.05$). There was no significant difference in intraoperative blood loss among the 3 groups ($P > 0.05$) (Table 2). The distribution of bone cement was not significantly different between the RAUPK and FABPK groups and was superior in both groups to the distribution seen in the FAUPK group (Table 3, Fig. 3). The VAS and ODI scores, Cobb angle of kyphosis, and SI of the 3 groups improved postoperatively ($P < 0.05$). There were no significant differences in the VAS or ODI scores, Cobb angle of kyphosis, or SI among the 3 groups preoperatively or on the first postoperative day. At the final follow-up, the VAS and ODI scores, Cobb angle of kyphosis, and SI in the RAUPK group were significantly better than those in the FAUPK group ($P < 0.05$), and there was no significant difference between the RAUPK and FABPK groups ($P > 0.05$) (Table 4, Fig. 4). The rates of bone cement leakage and re-fracture were, respectively, 13.8% and 12.1% in the RAUPK group, 16.7% and 8.3% in the FAUPK group, and 14.0% and 8.8% in the FABPK group, and there was no significant difference in these rates among the 3 groups ($P > 0.05$) (Table 2).

Discussion

Percutaneous vertebroplasty was developed in France in the late 1980s, and some European reports

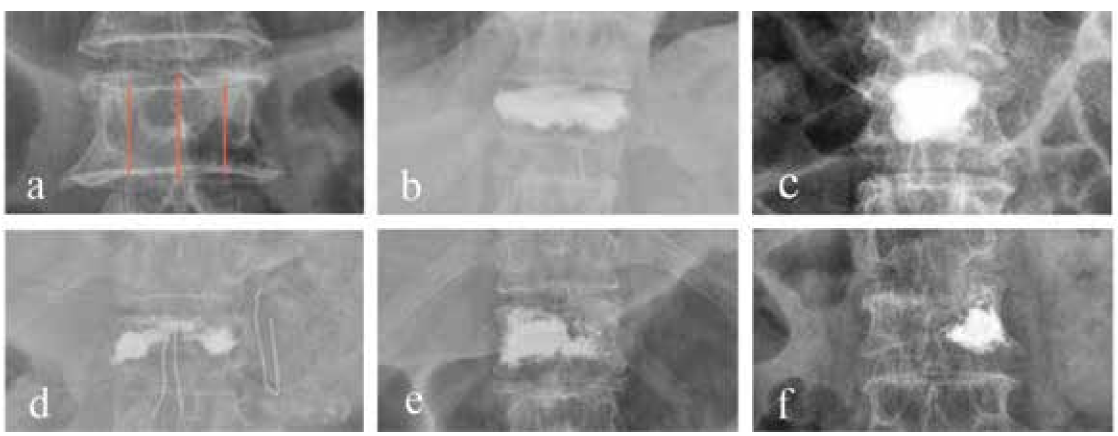

Fig. 2. *a. Three vertical lines along the center of the spinous process and the medial edge of the pedicle on both sides divide the vertebral body into four regions. b-d: evenly distributed types. e-f: unevenly distributed types.*

Table 2. *Comparison of therapeutic indexes among the RAUPK, FAUPK, and FABPK groups.*

	RAUPK	FAUPK	FABPK	F/χ^2	*P*-value
Operation time (min)	52.7 ± 12.7	42.9 ± 16.3	54.9 ± 16.2	7.479	< 0.001
Intraoperative blood loss (mL)	9.6 ± 1.9	10.1 ± 2.8	13.3 ± 25.4	0.889	0.413
Radiation dose (mGy)	164.0 ± 29.5	125.1 ± 26.1	139.9 ± 33.0	20.174	< 0.001
Bone cement volume (mL)	4.7 ± 0.5	2.7 ± 1.3	3.8 ± 1.1	50.290	< 0.001
Bone cement leakage rate	13.8% (8/58)	16.7% (6/36)	14.0% (8/57)	0.168	0.915
Re-fracture rate	12.1% (7/58)	8.3% (3/36)	8.8% (5/57)	0.485	0.832

have described good treatment outcomes for compression fractures and tumors (12). Currently, PKP is widely used for the treatment of OVCFs; however, the specific puncture details for the practical application of PKP remain controversial. For instance, FAUKP offers advantages such as shorter operation time and lower radiation exposure dose; however, it presents challenges in achieving optimal distribution of bone cement. In contrast, bipedicular FABKP allows for a more even distribution of bone cement within the vertebral body, leading to improved biomechanical balance. Nevertheless, this approach entails increased invasiveness, prolonged operation time, and increased radiation exposure (7,13). Consequently, there is currently no consensus in the clinical community on whether the preferred application of PKP is unilateral or bilateral.

To achieve good cement distribution, the target puncture point for the unipedicular PKP procedure should be positioned at the midpoint of the anterior third of the vertebral body (14). However, when using a unilateral approach to reach the puncture target, it is necessary to increase the internal inclination angle, thereby also increasing the risk of bone cement leakage and nerve injury within the spinal canal due to the perforation of the inner wall of the pedicle. In the lumbar spine, the L1 vertebral pedicle is narrow, limiting the safe range of the inclination angle to only 9.4 ± 3.4° (15). An excessive puncture angle can easily damage the inner wall of the pedicle, leading to serious complications, such as bone cement leakage and nerve root or spinal cord injury. Although bilateral pedicle approaches offer a way to mitigate these problems, the repetition of punctures introduces a higher likelihood of nerve injury and increased radiation exposure. Finding a unilateral puncture route that addresses these concerns effectively without augmenting the surgical risk therefore remains a challenging task.

The emergence of robotic navigation technology has reduced the difficulty of PKP applications. Surgeons can simulate and plan the puncture path of the pedicle screws on the operating table, which reduces the possibility of intraoperative complications (16,17). Moreover, the learning curve of the robot is short, and the puncture accuracy meets the clinical needs (18,19). Robotic technology may also have better application prospects in cases of multi-segmental OVCF (20). Compared to PKP under traditional C-arm x-ray fluoroscopy, orthopedic robot-assisted PKP can significantly improve the accuracy of puncture, reduce intraoperative pain and puncture deviation, and improve bone cement diffusion (21). Qian (11) effectively determined the optimal puncture path using the TINAVI robot system,

Table 3. *Comparison of bone cement distribution types among the RAUPK, FAUPK, and FABPK groups.*

	RAUPK	FAUPK	FABPK
Evenly distributed types	46	20	48
Unevenly distributed types	12	16	9
χ^2	10.534		
P-value	0.005		

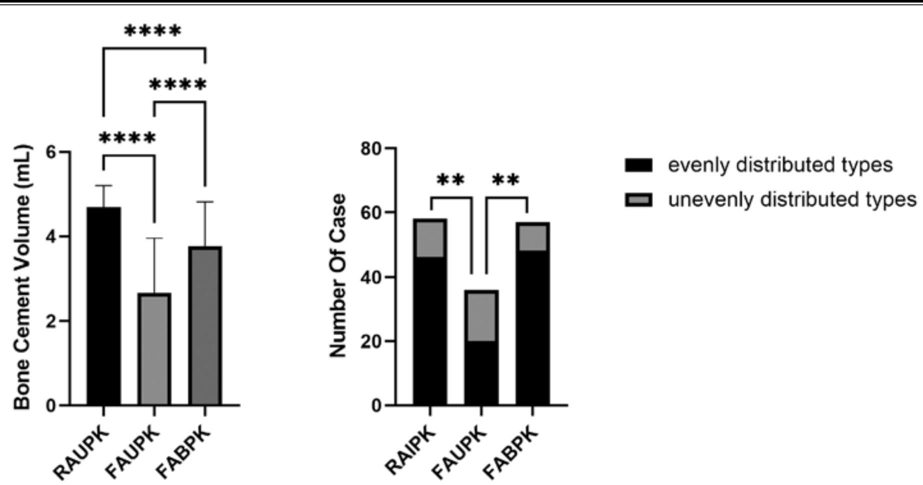

Fig. 3. *Comparison of bone cement volume and bone cement distribution types among the RAUPK, FAUPK, and FABPK groups.*

Table 4. ***Comparison of VAS scores, ODI scores, Cobb angles, and SI among the RAUPK, FAUPK, and FABPK groups.***

	RAUPK	**FAUPK**	**FABPK**	**F/χ^2**	***P*-value**
VAS					
Pre-operation	7.8 ± 0.6	7.9 ± 0.6	7.8 ± 0.6	0.625	0.537
One day post-operation	2.3 ± 0.5*	2.4 ± 0.6*	2.3 ± 0.6*	0.740	0.479
Final follow-up	2.2 ± 0.8*	2.5 ± 0.7*	2.0 ± 0.7*	4.981	0.008
ODI					
Pre-operation	73.9 ± 4.7	73.4 ± 5.0	73.7 ± 6.5	0.086	0.917
One day post-operation	30.1 ± 5.6*	33.3 ± 6.2*	31.2 ± 6.0*	1.788	0.171
Final follow-up	17.2 ± 4.0*	19.3 ± 4.7*	16.4 ± 4.1*	6.785	0.002
Cobb angle (°)					
Pre-operation	17.2 ± 6.8	16.5 ± 6.3	16.0 ± 6.0	0.576	0.622
One day post-operation	8.8 ± 4.9*	9.2 ± 5.8*	7.8 ± 5.2*	0.852	0.429
Final follow-up	10.2 ± 5.1*	13.3 ± 5.6*	10.6 ± 4.5*	4.516	0.012
SI (%)					
Pre-operation	67.2 ± 18.8	73.1 ± 17.6	72.5 ± 20.8	1.517	0.223
One day post-operation	80.8 ± 13.6*	80.7 ± 17.2*	74.0 ± 14.8*	0.803	0.450
Final follow-up	77.1 ± 19.1*	68.5 ± 18.8*	79.8 ± 15.7*	4.606	0.011

*P, Compared with preoperative value, $P < 0.05$.

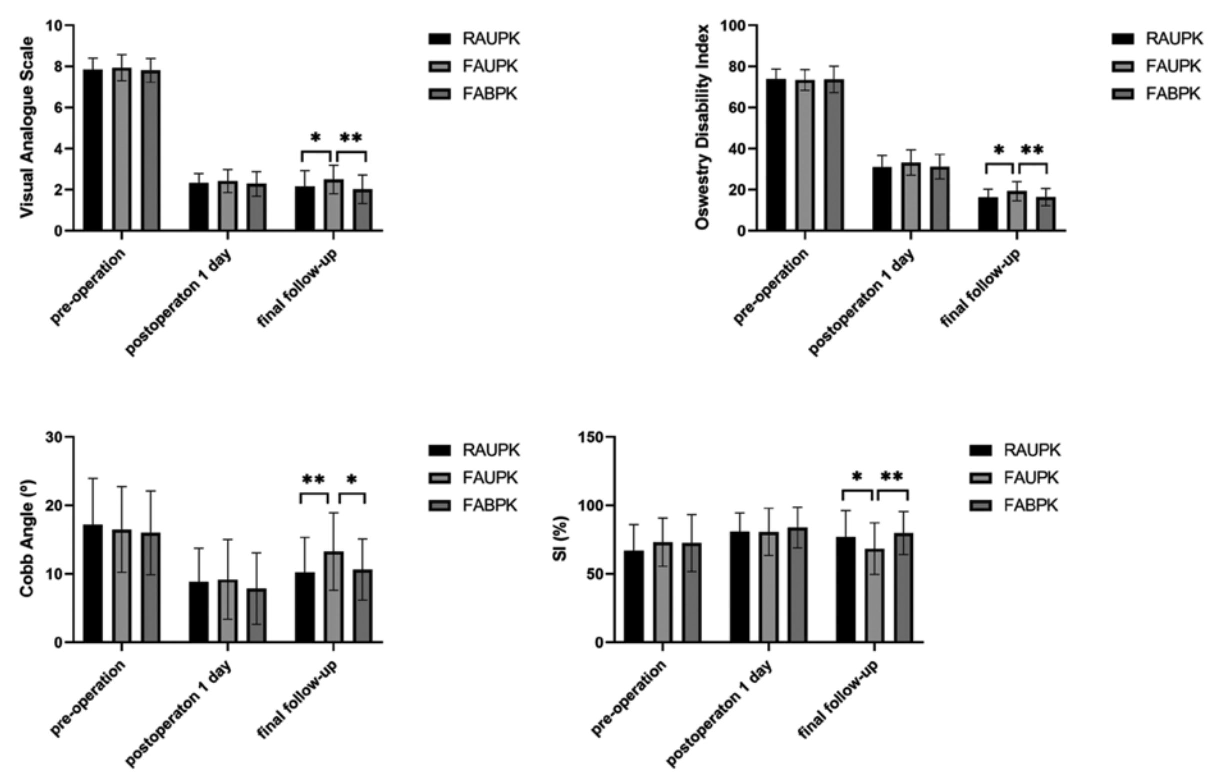

Fig. 4. ***Comparison of VAS, ODI, Cobb angle, and SI among the RAUPK, FAUPK, and FABPK groups.***

which resulted in the alignment of the bone cement injection point with a predetermined ideal position prior to surgery. Despite the unilateral approach, the distribution of the injected bone cement within the vertebral body was uniform.

Bipedicular PKP is one of the primary methods used for treating OVCFs. Nevertheless, unipedicular PKP has also been proven to provide sufficient clinical and imaging improvement and is favored by surgeons because it has such advantages as shorter operation time, lower bone cement consumption, and higher complication rates (22). However, because of the relative width of the lumbar vertebral body, it is difficult to achieve a symmetric distribution of bone cement in the injured vertebra using a fluoroscopy-assisted unilateral transected approach. Asymmetric reinforcement of the fractured vertebral body may lead to mechanical imbalance in the lumbar spine, which may affect clinical efficacy. In a study by Wang et al (15), when the puncture angle was small, bone cement was mostly deposited on the approach side, and the contralateral vertebral body was not enhanced. PKP has the potential to enhance the uniform strengthening of both sides of the vertebra, whereas unilateral PKP can establish a state of biomechanical equilibrium based on the distribution of cement. In instances when cement reinforcement is limited to one side, the stiffness of the nonreinforced side is notably lower than that of the reinforced side, potentially resulting in an imbalance in the stress on the vertebral body. However, when the cement reinforcement is extended across the midline, the stiffness on both sides increases uniformly, thereby achieving biomechanical equilibrium (10). A study by Zhang et al (9) suggested that although both unipedicular and bipedicular PKP could restore the stiffness of the vertebral body, unipedicular PKP that did not cross the midline of the vertebral body resulted in higher VAS scores than did bipedicular PKP. In the same study, Zhang et al (9) suggested that bipedicular PKP should be performed when bone cement is distributed on only one side in unilateral PKP. The present study's RAUPK group showed significantly better results than did the FAUPK group and achieved an effect similar to the FABPK group's in terms of bone cement distribution. We hypothesized that RAUKP could effectively improve the distribution of bone cement.

In the treatment of OVCFs with unipedicular PKP, the distribution of bone cement is a potential factor affecting the reconstruction. A broader distribution of cement correlates with improved vertebral body recovery, albeit with an increased likelihood of cement leakage as well. To achieve a more favorable cement dispersion, the quantity of bone cement administered via the unilateral approach is proportionally higher, which may thereby elevate the risk of cement leakage (23). In the context of PKP, the appropriate distribution of bone cement plays a crucial role in facilitating the recovery of vertebral strength and height. Polymethylmethacrylate (PMMA) is commonly used in PKP. Since the distribution mode of PMMA is mainly a bulk solid, PMMA fails to provide adequate support to certain regions of the vertebral body, and studies have found that vertebral recollapse usually occurs in these areas without PMMA support (24-26). A study conducted by Chen et al (27) suggested that bipedicular PKP was more effective in restoring vertebral height than was unipedicular PKP, and Feng et al (28) obtained similar findings in a separate study; however, the latter argued that unipedicular PKP was more effective at alleviating pain. In the present study, there was no significant difference in the vertebral height among the 3 groups on the first postoperative day. At the last follow-up, the vertebral height in the FABPK group was significantly greater than in the FAUPK group. This finding suggests that the bilateral approach is superior to the unilateral approach in maintaining vertebral height, which is consistent with the results of Chen et al. Meanwhile, although FABPK was superior to FAUPK in restoring vertebral height, the data did not imply that FAUPK was more effective at relieving pain. At the last follow-up, the VAS and ODI scores of patients who underwent FABPK were better than those who received FAUPK. This difference may be due to the more uniform cement distribution in the FABPK group, which can better prevent recompression of the vertebral body. It is worth mentioning that the RAUPK group was not inferior to the FABPK group in terms of vertebral height or kyphosis Cobb angle, and the RAUPK group experienced superior pain relief to the FAUPK group. These results suggest that the robot can inject bone cement through the best puncture path and obtain a good stress balance with the assistance of the navigation system. Chang et al (6) reported that at 6 months after their operations, patients who received robot-assisted PKP showed significantly greater improvements in pain than did patients who received fluoroscopy-assisted PKP, which is consistent with our follow-up results. We speculate that greater pain relief is a benefit of the improved cement distribution afforded by robot assistance. However, some studies comparing robot-assisted PKP to fluoroscopy-assisted PKP have shown that surgeons observe superior short-term pain improvements in patients who receive the former, and there is no significant difference in postoperative pain relief between the 2 groups during long-term follow-up (17,29). Long-term follow-up with more patients is needed to clarify this benefit.

The quantity of injected bone cement is another important factor affecting the reconstruction outcome. Belkoff's spinal test on cadaveric bodies showed that although 2 mL of bone cement was injected to restore vertebral strength and 4 mL to restore vertebral stiffness, more injections were required in the thoracolumbar and lumbar segments (30). In addition, Boszczyk (31) has suggested that a minimum filling of 13-16% of the vertebral volume is required to restore the relevant biomechanical effects of vertebral strength. According to Boszczyk (31), the thoracolumbar vertebrae that receive the most frequent treatment have a volume of approximately 30 mL, and these vertebrae require at least 4 mL of PMMA for effective filling. Boszcyzk elaborates that as the lumbar spine descends, the anatomical and, consequently, required filling volumes increase (31). In the present study, the amount of bone cement injected in the FAUPK, FABPK, and RAUPK groups was more than 2 mL. After the procedures, the patients' pain and vertebral height improved from their preoperative states. The patients in the RAUPK group were injected with the largest quantity of bone cement, approximately 4.7 mL, which was similar to the amount of bone cement suggested by Belkoff et al and Boszczyk (30,31). Currently, a special system for robot-assisted bone cement injection has emerged, which further improves the application of robots in PKP (32).

When employing the unilateral pedicle approach, it is imperative to ensure a highly accurate cement injection point to attain consistent dispersion of cement within the vertebral body. To accomplish this, the puncture trajectory must be meticulously planned and executed under the precise guidance of the surgical robot. Despite the favorable cement distribution achieved through RAUKP, 8 cases of cement leakage occurred in the RAUPK group in the present study. Facilitating the injection of bone cement into the contralateral side involves augmenting the internal inclination angle of the puncture, which has the undesired effect of increasing the likelihood of bone cement leakage to an extent. Notably, the patients who underwent RAUPK were injected with more bone cement than were those who underwent FAUPK or FABPK. These findings underscore the necessity of a meticulously designed puncture path and the careful consideration of the timing of the bone cement injection.

Furthermore, robot-assisted PKP entails a significantly elevated dose of radiation exposure. During the procedure, x-ray fluoroscopy is required to determine the implantation path, which increases the radiation exposure dose for patients. The dose of radiation exposure in the present study's RAUPK group was significantly higher than in either fluoroscopy-assisted group because of the need for preoperative 3D CT scan registration. However, because the physician can move away from the radiation area during fluoroscopy, the actual radiation received by the physician will be lower; nonetheless, the patient's increased exposure to radiation should not be ignored. This finding is consistent with the conclusion of Yuan et al that robots reduce intraoperative radiation for the operator but increase intraoperative radiation for the patient (33). Compared to robot-assisted PKP, fluoroscopy-assisted PKP does not rely overly on the advantages of high-tech equipment, and doctors with surgical experience can complete fluoroscopy-assisted PKP well, which can also be confirmed from our data. The advantages and disadvantages of robot-assisted PKP remain controversial; however, it is worth acknowledging that robots have brought progress to the development of spinal surgery.

Limitations

This study has several limitations that should be acknowledged. Firstly, the single-center design limits the generalizability of our findings to other institutions or broader patient populations. The retrospective nature of the study also may introduces inherent biases, such as selection bias and the potential for incomplete or inaccurate data recording, which could affect the reliability of the results.

Conclusion

RAUPK can establish an optimal path through a unipedicular approach, thereby effectively mitigating the potential risks associated with vascular nerve and cortical bone injuries. Additionally, this technique enables superior bone cement distribution and provides superior pain relief for patients. Furthermore, the long-term effectiveness of RAUPK has been shown to exceeded that of FAUPK.

Author Contributions

HT, ZWH, and CLS designed the study. HT wrote the manuscript. ZWH, SZS, and RYY collected the data and performed the data analysis. KY, YSZ, WL, FLD, and JQ reviewed the final draft. All authors read and approved the final manuscript.

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Supplemental Table 1. *Age distribution among RAUPK, FAUPK, and FABPK groups.*

Age Range (Years)	RAUPK	FAUPK	FABPK
50-59	0	1	0
60-69	22	12	19
70-79	22	18	27
80-89	13	5	11
90-99	1	0	0
Total	58	36	57