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RESEARCH

Robotic-assisted kyphoplasty demonstrates superior efficacy, safety, and procedural efficiency compared to fluoroscopy-guided techniques: a retrospective analysis of 240 patients

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Abstract

Osteoporotic vertebral compression fractures (OVCFs) are a significant health burden with increasing prevalence in the aging population. This study compares robotic-assisted kyphoplasty (RK) with conventional fluoroscopy-guided kyphoplasty (FK) for the treatment of OVCFs. A single-center retrospective study analyzed 240 patients (120 in each group) who underwent kyphoplasty for OVCFs between January 2020 and December 2022 under general anesthesia. Clinical outcomes were assessed using Visual Analog Scale (VAS) and Oswestry Disability Index (ODI). Radiological outcomes included vertebral height restoration and kyphotic angle correction. Procedural parameters including radiation exposure, procedural time, and complications were analyzed. Correlation analysis was performed to assess the impact of vertebral anatomy complexity on procedural outcomes. Both groups demonstrated significant clinical and radiological improvements with comparable pain relief and functional outcomes. The RK group showed superior vertebral height restoration (68.00% vs. 64.38%, $p = 0.004$) and significantly lower cement leakage rates (5.8% vs. 19.2%, $p = 0.002$) compared to the FK group. Radiation exposure was significantly lower in the RK group (18.76 mGy vs. 22.69 mGy, $p < 0.00001$). Total procedure time was significantly shorter in the RK group (50.91 min vs. 86.40 min, $p < 0.00001$). Correlation analysis revealed that thoracic level complexity affected both techniques similarly, with significant correlations between thoracic levels and increased radiation exposure and procedural time in both groups. However, the robotic group maintained superior absolute performance regardless of anatomical complexity. Robotic-assisted kyphoplasty provides superior safety profiles with reduced cement leakage and radiation exposure, better vertebral height restoration, and shorter procedural times compared to fluoroscopy-guided techniques. Importantly, these advantages persist across different levels of anatomical complexity, suggesting that robotic assistance offers consistently superior performance regardless of case difficulty. These findings support the adoption of robotic-assisted techniques for treating OVCFs.

Keywords Osteoporotic vertebral compression fractures · Kyphoplasty · Robotic-assisted surgery · Cement leakage · Radiation exposure

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Introduction

Osteoporotic vertebral compression fractures (VCFs) represent a significant health burden, particularly among older populations. The incidence of VCFs is notably high, with estimates suggesting over 700,000 cases annually in the United States alone [1]. The overall incidence rates of fragility fractures, including OVCF, have shown notable trends, with higher rates observed in women compared to men [2]. The annual costs of osteoporosis-related fractures are staggering, with estimates of $17 billion in the U.S. and €1.26 billion in France for severe fractures [3, 4].

Percutaneous kyphoplasty (PKP) has emerged as a widely accepted minimally invasive intervention for OVCFs, demonstrating effective pain relief, functional improvement, and partial restoration of vertebral height [5, 6]. This technique involves the insertion of an inflatable balloon into the fractured vertebral body to create a cavity, followed by the injection of bone cement to stabilize the fracture. Despite its established benefits, conventional fluoroscopy-guided kyphoplasty (FK) faces several limitations, including variable accuracy in needle placement, potential for cement leakage (reported in up to a quarter of cases), and significant radiation exposure to both patients and operators [7, 8].

Recent technological advances have introduced robotic assistance into spinal surgical procedures, offering potential solutions to these challenges [9, 10]. Robotic-assisted kyphoplasty (RK) utilizes three-dimensional imaging and computer navigation to facilitate precise preoperative planning and accurate intraoperative execution. This technology enables surgeons to predetermine optimal trajectories for needle placement, potentially enhancing the safety and efficacy of the procedure [11, 12].

While conventional kyphoplasty has demonstrated consistent improvements in pain reduction, functional recovery, and vertebral height restoration, significant concerns persist regarding radiation exposure and cement leakage complications [13]. Theoretical advantages of robotic assistance include enhanced trajectory precision, reduced radiation exposure for surgeons, improved vertebral height restoration, and decreased risk of cement extravasation [14]. However, comprehensive comparative data between these two approaches remain limited.

Emerging literature suggests potential benefits of robotic assistance in spinal procedures, including increased accuracy in pedicle screw placement and favorable outcomes in complex deformity cases [15, 16]. Initial reports on robotic-assisted kyphoplasty indicate promising results, but direct comparative studies with conventional techniques are scarce, and the clinical significance of any differences remains unclear [16, 17].

We hypothesized that robotic-assisted kyphoplasty would provide superior clinical and radiological outcomes compared to conventional fluoroscopy-guided techniques, particularly in terms of procedural safety, radiation exposure, and cement leakage. The primary objective of this study was to compare the efficacy, safety, and technical parameters of robotic-assisted versus fluoroscopy-guided kyphoplasty in the treatment of osteoporotic vertebral compression fractures. Specific aims included assessment of pain reduction, functional improvement, vertebral height restoration, kyphotic angle correction, procedural time components, radiation exposure, and complication rates.

Methods

Study design and patient population

This was a single-center retrospective study conducted according to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines. The study was approved by the institutional review board, and informed consent was obtained from all patients. We included 240 consecutive patients (120 in each group) who underwent kyphoplasty for osteoporotic vertebral compression fractures (OVCFs) between January 2020 and December 2022. Patients were divided into two groups based on the surgical technique employed: robotic-assisted kyphoplasty (RK) and conventional fluoroscopy-guided kyphoplasty (FK).

Inclusion and exclusion criteria

Inclusion criteria were: (1) age ≥ 50 years; (2) confirmed diagnosis of OVCFs; (3) treatment of 1–3 vertebral levels; (4) minimum follow-up of 3 months; (5) procedures performed under general anaesthesia; and (6) for RK group, only scan-and-plan technique patients were included.

Exclusion criteria were: (1) follow-up less than 3 months; (2) incomplete medical records; (3) age less than 50 years; (4) fractures due to pathological conditions, tumours, or infections; (5) procedures performed under local anaesthesia; and (6) concurrent spinal pathologies such as myelopathy or severe lumbar stenosis.

All procedures were performed by a single surgeon with over 20 years of experience in spine surgery and more than 2 years of experience with robotic spine surgery. The surgeon had completed 200 simple thoracolumbar procedures using the robotic system before performing kyphoplasty with robotic assistance.

Surgical techniques

All patients underwent kyphoplasty under general anaesthesia in the prone position with standard padding and support. General anesthesia was selected primarily to eliminate patient movement, which is critically important for robotic-assisted procedures where even minimal movement can cause registration errors and compromise surgical accuracy. The precision required for robotic guidance necessitates complete immobilization throughout the procedure. Additionally, general anesthesia ensures patient comfort during prolonged prone positioning and provides procedural standardization between both groups, eliminating anesthesia type as a confounding variable. Robotic-assisted kyphoplasty (RK) was performed using the Mazor™ X Stealth Edition system (Medtronic™) with intraoperative 3D imaging via the O-arm™. Following automated trajectory planning, the robotic arm guided trocar insertion through a small incision, enabling precise pedicle cannulation and channel creation. Working cannulas were positioned using real-time navigation and verified with biplanar fluoroscopy.

Fluoroscopy-guided kyphoplasty (FK) employed conventional C-arm localization. After vertebral level identification, Jamshidi needles were inserted manually under fluoroscopic guidance, and pedicle access was achieved via intermittent imaging.

In both groups, bilateral balloon kyphoplasty was performed with gradual inflation under fluoroscopic control to restore vertebral height. Polymethylmethacrylate (PMMA) cement was injected once the desired height or endpoint was reached. Cement distribution was monitored fluoroscopically, and cannulas were removed after cement polymerization. Final fluoroscopic confirmation and wound closure completed the procedure. Figure 1 provides a step-by-step visual comparison of the RK and FK approaches.

Data collection and outcome measures

Data were collected from hospital electronic records and included basic demographics, preoperative and postoperative radiographs, cement leakage (present or not), visual analog scale (VAS) scores for pain (preoperative and 1-day postoperative), vertebral body height (expressed as a percentage of expected height), Oswestry disability index (ODI) scores (preoperative and 3-months postoperative), radiation dose, and procedural times.

Pain was assessed using the visual analog scale (VAS) [18], with 0 representing no pain and 10 representing the worst imaginable pain. Functional disability was evaluated using the Oswestry disability index (ODI) [19], a validated tool for assessing disability related to spinal conditions.

Vertebral height was measured as a percentage of expected height, calculated using the mean of adjacent vertebral body heights as reference, following previously established methodology [20]. Lateral radiographs were used to measure kyphotic angle, defined as the angle formed between the lines drawn parallel to the superior and inferior endplates of the fractured vertebra. (Fig. 2).

Procedural times were categorized as follows: (1) scan and plan time—from the start of the scan to the completion of trajectory planning; (2) robotic/pin insertion time—from the start of robotic arm movement to completion of pin insertion (for RK) or from skin marking to satisfactory pin positioning (for FK); (3) cement/balloon time—from pin positioning to the completion of cement filling; and (4) pure surgical time—the sum of robotic/pin time plus balloon/cement time.

VAS scores were assessed at 1 day postoperatively to evaluate immediate pain relief, while ODI was assessed at 3 months to allow for functional recovery and more accurate assessment of disability outcomes.

Radiological assessments were performed by a blinded radiologist and an independent spine surgeon with over 8 years of experience.

Statistical analysis

Statistical analysis was performed using SPSS software version 28.0. Continuous variables were expressed as means and standard deviations. Paired t-tests were used to compare pre- and post-operative values within each group. Independent t-tests or Mann–Whitney U tests were used for comparisons between groups based on data distribution. Categorical variables were compared using chi-square tests. Statistical significance was set at $p < 0.05$. Pearson correlation coefficients were calculated to assess the relationship between the number of thoracic levels treated and procedural parameters (radiation exposure and total procedure time) within each group.

Results

Patient demographics and clinical outcomes

A total of 240 patients were included in the study, with 120 in each group. The demographic characteristics between the robotic-assisted (RK) and fluoroscopy-guided (FK) groups were comparable, with no statistically significant differences in age, sex distribution, BMI, or the number of treated levels (Table 1).

Significant clinical improvement was observed in both groups. The mean preoperative Oswestry Disability Index (ODI) score decreased from 70.38 ± 7.92 to 29.84 ± 8.83 in the RK group ($p < 0.00001$) and from 68.28 ± 8.58 to 29.00 ± 9.00 in the FK group ($p < 0.00001$). Similarly,

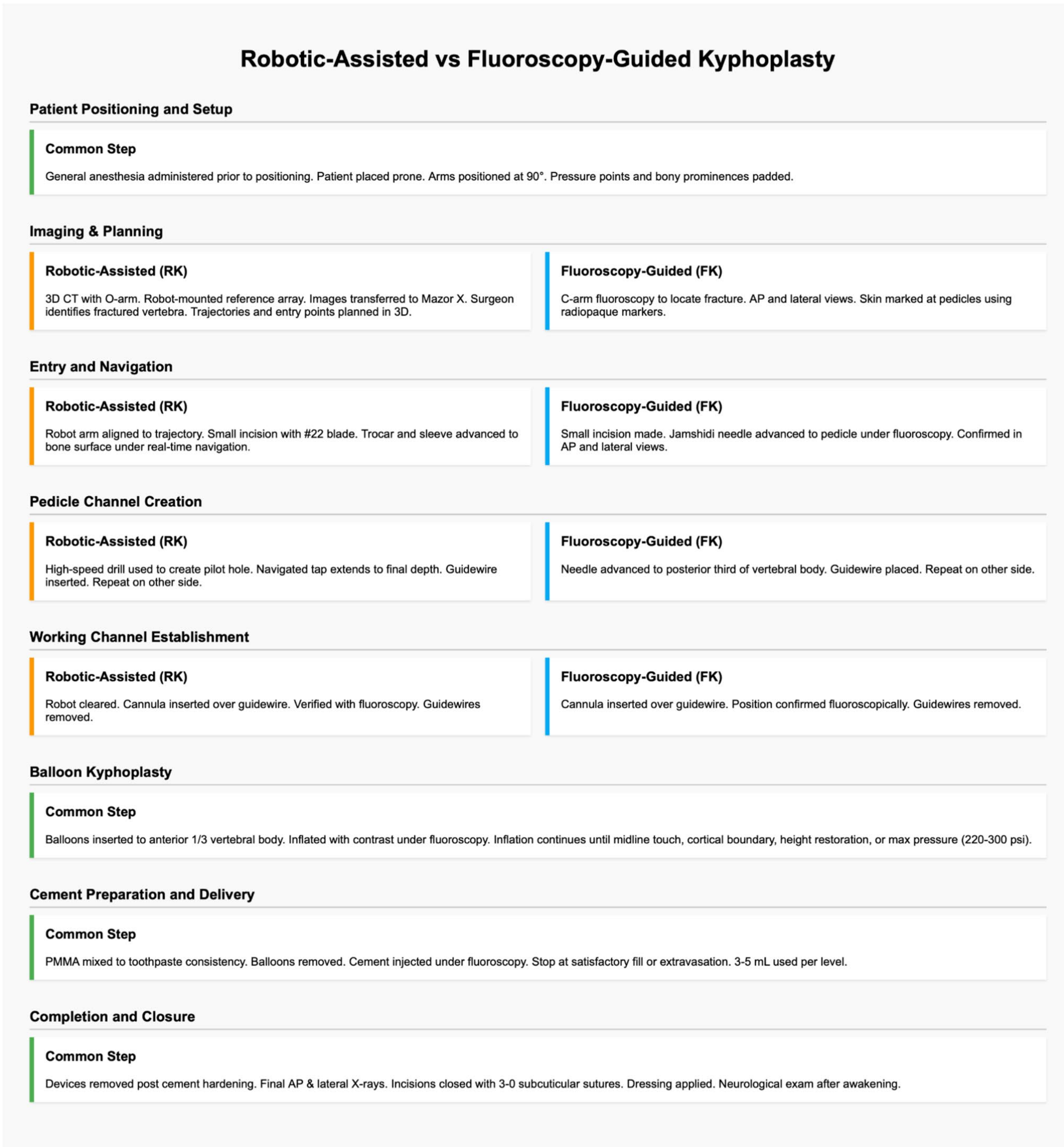

Fig. 1 Stepwise comparison of Robotic-Assisted Kyphoplasty (RK) and Fluoroscopy-Guided Kyphoplasty (FK). The flowchart illustrates the procedural sequence, highlighting shared steps and key differences in imaging, trajectory planning, and instrument navigation between the two techniques

the Visual Analogue Scale (VAS) score decreased from 8.52 ± 1.18 to 4.39 ± 1.66 in the RK group and from 8.74 ± 1.18 to 4.26 ± 1.73 in the FK group ($p < 0.00001$ within each group), indicating substantial pain relief post-operatively. No statistically significant differences were

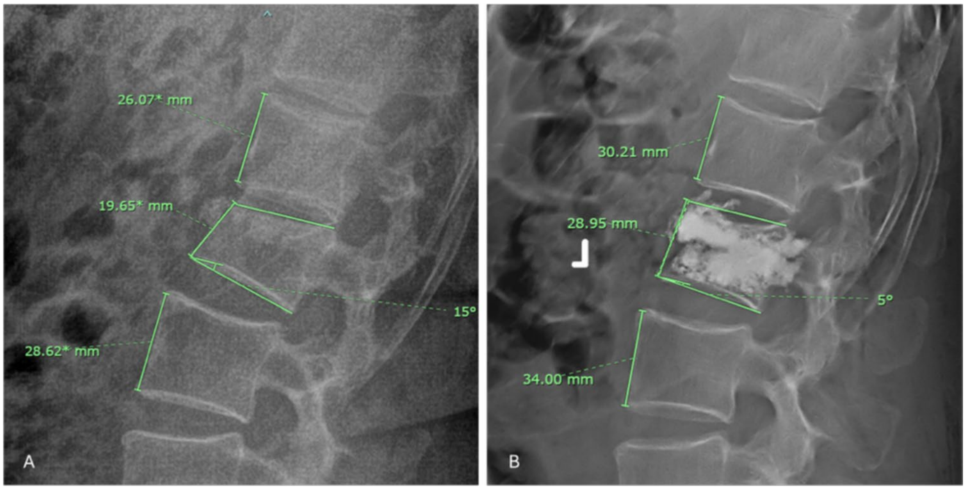

Fig. 2 Standardized radiographic measurement techniques for radiographic assessment of kyphoplasty. **A** Pre-operative image showing compressed vertebral height (19.65 mm, 71.8% of expected height) relative to adjacent levels (26.07 mm, 28.62 mm) and kyphotic angle (15°). **B** Post-operative image demonstrating restored vertebral height (28.95 mm, 90.2% of expected height) and corrected kyphotic angle (5°). Vertebral height percentage calculated as (compressed height/mean adjacent heights) × 100. All measurements performed using standardized PACS tools by blinded observers

Table 1 Demographic, clinical, and radiological outcomes in patients undergoing kyphoplasty for osteoporotic vertebral compression fractures: comparison between robotic-assisted and fluoroscopy-guided groups (n = 240) including age, sex distribution, BMI, number of treated levels, pre- and postoperative ODI and VAS scores, and vertebral height and kyphotic angle measurements

Parameter	Robotic-assisted group (n = 120)	Fluoroscopy-guided group (n = 120)	p-value
Demographics			
Age (years)	65.97 ± 14.05	68.06 ± 8.81	0.535
Sex (M/F)	48/72	43/77	0.493
BMI (kg/m^2)	27.57 ± 5.86	27.55 ± 6.61	0.984
Treated levels			
Number of treated levels	1.25 ± 0.68	1.40 ± 0.73	0.099
Thoracic levels treated, n (%)	31 (36.9%)	55 (44.4%)	0.312
Lumbar levels treated, n (%)	53 (63.1%)	69 (55.6%)	0.312
Mean thoracic levels per patient	0.35 ± 0.69	0.44 ± 0.81	0.498
ODI score			
Preoperative	70.38 ± 7.92	68.28 ± 8.58	0.049
Postoperative (3 months)	29.84 ± 8.83	29.00 ± 9.00	0.514
p-value (within group)	< 0.00001	< 0.00001	
VAS score			
Preoperative	8.52 ± 1.18	8.74 ± 1.18	0.131
Postoperative (1 day)	4.39 ± 1.66	4.26 ± 1.73	0.812
p-value (within group)	< 0.00001	< 0.00001	
Vertebral height (% of expected)			
Preoperative	54.58 ± 14.80	55.71 ± 13.23	0.326
Postoperative	68.00 ± 18.78	64.38 ± 14.89	0.004
p-value (within group)	< 0.00001	< 0.00001	
Kyphotic angle (°)			
Preoperative	17.22 ± 3.86	16.91 ± 3.44	0.513
Postoperative	4.00 ± 2.96	4.00 ± 2.52	> 0.05
p-value (within group)	< 0.00001	< 0.00001	

observed between the two groups in postoperative ODI or VAS scores (Table 1).

Radiological outcomes

Radiological assessment demonstrated improved vertebral height and kyphotic angle correction in both groups. The mean vertebral height increased from 54.58 ± 14.80% to 68.00 ± 18.78% in the RK group and from 55.71 ± 13.23% to 64.38 ± 14.89% in the FK group, with a significant intergroup difference favoring the RK group ($p = 0.004$). Kyphotic angle improved from 17.22 ± 3.86° to 4.00 ± 2.96° in the RK group and from 16.91 ± 3.44° to 4.00 ± 2.52° in the FK group; however, the difference between groups postoperatively was not significant ($p > 0.05$) (Table 1).

Procedural characteristics and safety

Radiation exposure was significantly lower in the RK group (18.76 ± 2.48 mGy) compared to the FK group (22.69 ± 3.32 mGy; $p < 0.00001$). Procedural time analysis showed a shorter total duration in the RK group (50.91 ± 10.71 min) than the FK group (86.40 ± 18.14 min; $p < 0.00001$). Robotic/pin insertion time was significantly shorter in the RK group (4.91 ± 1.93 min) compared to the FK group (23.05 ± 6.85 min; $p < 0.00001$). While scan and plan time was exclusive to the robotic group (16.92 ± 3.04 min), pure surgical time was also shorter in the RK group (33.99 ± 11.00 min vs. 52.35 ± 12.73 min; $p < 0.00001$). Balloon and cement time was similar between the groups (29.35 ± 10.47 min vs. 33.99 ± 10.93 min; $p = 0.844$) (Table 2).

The incidence of cement leakage was significantly lower in the RK group (5.8%) compared to the FK group (19.2%; $p = 0.002$). No neurological deficits, new vertebral fractures, wound infections, pulmonary embolism, or instrumentation-related complications were reported in either group.

Correlation analysis revealed that thoracic level treatment significantly impacted procedural parameters in both groups. In the robotic group, the number of thoracic levels correlated positively with radiation exposure ($r = 0.44$, $p < 0.001$) and total procedure time ($r = 0.28$, $p = 0.005$). Similarly, in the fluoroscopic group, thoracic levels correlated with radiation exposure ($r = 0.23$, $p = 0.021$) and total procedure time ($r = 0.32$, $p < 0.001$). Despite these correlations affecting both techniques, the robotic group maintained significantly lower absolute values for both radiation exposure and total procedure time.

Discussion

This retrospective study comparing robotic-assisted kyphoplasty (RK) and fluoroscopy-guided kyphoplasty (FK) for the treatment of osteoporotic vertebral compression fractures revealed several important findings. Both techniques demonstrated significant clinical improvements, with no significant differences in ODI or VAS scores between groups. However, the RK group exhibited superior vertebral height restoration, lower cement leakage rates, reduced radiation exposure, and notably shorter procedural times.

The clinical improvements observed in both groups corroborate previous studies demonstrating the efficacy of kyphoplasty for pain relief and functional improvement in patients with OVCFs [21, 22]. The comparable clinical outcomes suggest that both techniques effectively address the primary goals of pain relief and functional restoration.

The lower cement leakage rate observed in the RK group (5.8% vs. 19.2%) represents a key advantage of robotic assistance. This finding is consistent with recent studies examining robot-assisted vertebral augmentation. Tao et al. (2024) reported that robot-assisted percutaneous kyphoplasty could establish an optimal path via the unipedicular approach [23], effectively mitigating potential risks of vascular, neural, and

Table 2 Procedural Characteristics and Safety Parameters of Robotic-Assisted versus Fluoroscopy-Guided Kyphoplasty: Comparison of Radiation Exposure (mGy), Detailed Procedural Time Components (Scan/Plan Time, Robotic/Pin Insertion Time, Balloon/Cement Time, Total Procedure Time, Pure Surgical Time), and Cement Leakage Complications in 240 Patients with Osteoporotic Vertebral Compression Fractures

Parameter	Robotic-assisted group (n = 120)	Fluoroscopy-guided group (n = 120)	p-value
Radiation exposure (mGy)	18.76 ± 2.48	22.69 ± 3.32	< 0.00001
Procedural time (min)			
Scan and plan time	16.92 ± 3.04	N/A	–
Robotic/pin insertion time	4.91 ± 1.93	23.05 ± 6.85	< 0.00001
Balloon and cement time	29.35 ± 10.47	33.99 ± 10.93	0.844
Total procedure time	50.91 ± 10.71	86.40 ± 18.14	< 0.00001
Pure surgical time	33.99 ± 11.00	52.35 ± 12.73	< 0.00001
Complications			
Cement leakage, n (%)	7 (5.8%)	23 (19.2%)	0.002

cortical bone injuries. Similar results were reported by Li et al. (2024) [14], who found in their meta-analysis and validation cohort that robot-assisted surgery significantly reduced cement leakage rates compared to fluoroscopy-assisted procedures. This reduction in cement leakage is clinically significant, as leakage can lead to serious complications including neurological deficits and pulmonary embolism [7, 8].

The better vertebral height restoration achieved in the RK group (68.00% vs. 64.38%, $p=0.004$) aligns with findings from Yu et al. (2022) [16], who reported in their meta-analysis that robot-assisted kyphoplasty improves clinical and radiological features better than fluoroscopy-assisted kyphoplasty. This observation differs somewhat from Liu et al. (2025) [24], who found no significant difference in vertebral height restoration between RK and FK groups. This discrepancy might be related to differences in patient selection, as Liu et al. specifically focused on severe compression fractures (Genant Grade III) in elderly patients [25].

Our finding of reduced radiation exposure in the RK group (18.76 mGy vs. 22.69 mGy) aligns with Chang et al. (2023) [17], who found in their meta-analysis that robotic assistance reduced radiation exposure for both patients and surgeons. However, this finding differs from Liu et al. (2025) [24], who reported higher radiation exposure in the robot-assisted group. This discrepancy might be attributed to differences in the robotic systems used, scanning protocols, or measurement methodologies. In Liu's study, they noted that the radiation dose in the robot-assisted group included both continuous scanning during registration and single fluoroscopy during surgical manipulation [24], which may explain the higher values compared to our study. Our results suggest that robotic guidance reduces the need for repeated fluoroscopic checks during needle placement and cement injection, leading to an overall reduction in radiation exposure. Our correlation analysis revealed that both techniques are similarly affected by anatomical complexity, with thoracic levels correlating with increased radiation in both groups (RK: $r=0.44$, $p<0.001$; FK: $r=0.23$, $p=0.021$). However, the robotic group maintained significantly lower absolute radiation exposure despite treating comparable thoracic level complexity, suggesting that while robotic assistance doesn't eliminate the complexity effect, it provides consistently superior radiation safety profiles.

Regarding procedural time, our finding of significantly shorter total procedure time in the RK group (50.91 min vs. 86.40 min) contradicts several previous studies. Our analysis showed that thoracic levels correlated with longer procedure times in both groups (RK: $r=0.28$, $p=0.005$; FK: $r=0.32$, $p<0.001$), indicating that both techniques are affected by anatomical complexity. However, the robotic group demonstrated superior absolute efficiency despite similar complexity effects. Liu et al. (2025) reported longer total operation time in the robot-assisted group (71.14 min vs. 55.81 min) [24], while Yuan et al. (2020) and Lin et al. (2020) also reported longer procedural times with robotic assistance [12, 26]. This divergence from previous literature may reflect several factors: decreased pin insertion time as a result of meticulous planning and robotic guidance till marked depth without repeated fluoroscopic checks, familiarity and comfort of the surgeon and team with robotic workflows. Notably, our study found that robotic assistance dramatically reduced pin insertion time (4.91 min vs. 23.05 min) and overall pure surgical time (33.99 min vs. 52.35 min). Even with the additional scan and plan time (16.92 min) required for the robotic system, the total procedure time remained substantially shorter in the RK group.

The efficiency demonstrated in our RK group may be attributable to several factors. First, the surgeon in our study had completed over 200 robotic-assisted procedures before performing kyphoplasty with robotic assistance, suggesting that the learning curve had been largely overcome. This aligns with Yuan et al.'s (2020) findings on the learning curve of robot-assisted PKP [12], which suggested that procedural efficiency improves significantly with experience. Second, advances in robotic technology and software interfaces may have streamlined the planning and execution phases. Third, the precise guidance provided by the robotic system may have reduced the need for multiple needle placement attempts, which can be time-consuming in the conventional approach. These findings challenge the conventional wisdom that robotic-assisted procedures inevitably increase operative time and suggest that with experience and technological refinement, robotic assistance may actually enhance procedural efficiency.

Advantages of robotic-assisted kyphoplasty

The results of our study highlight several advantages of robotic-assisted kyphoplasty over conventional fluoroscopy-guided techniques. The most significant advantage is the substantial reduction in cement leakage (5.8% vs. 19.2%), a complication that can lead to serious adverse events. This finding is particularly important given that cement extravasation remains one of the most common complications of vertebroplasty and kyphoplasty procedures, with reported rates as high as 41% [7].

The reduced radiation exposure observed in the RK group represents another important advantage, particularly for surgeons who perform multiple procedures regularly and for patients with multiple fractures requiring treatment. Our vertebral level analysis revealed that both techniques are affected by anatomical complexity, with thoracic levels correlating with increased radiation exposure in both groups (RK: $r=0.44$; FK: $r=0.23$). However, robotic assistance maintains consistently lower absolute radiation exposure regardless of case complexity, providing a superior baseline of safety that persists across the entire spectrum of vertebral anatomy. As Chang et al. (2023) noted in their meta-analysis [17], minimizing radiation exposure is a critical consideration in vertebral augmentation procedures.

Better vertebral height restoration in the RK group is another key advantage, which may contribute to improved biomechanical stability. The precise trajectory planning and execution enabled by robotic guidance likely contributes to optimal balloon placement and more effective vertebral body restoration. This aligns with findings from Yang et al. (2025) [27], who reported that robot-assisted PKP provided superior cement distribution compared to traditional techniques.

Additionally, our study demonstrates that robotic assistance significantly reduces overall procedure time, challenging the perception that robotic procedures are inherently more time-consuming. While both techniques showed similar sensitivity to thoracic level complexity (procedure time correlations: RK r = 0.28; FK r = 0.32), the robotic group maintained superior absolute efficiency across all complexity levels. This complexity-independent advantage may translate to reduced anesthesia time, greater OR throughput, and more predictable outcomes regardless of case difficulty, particularly valuable in high-volume practices where case mix varies significantly.

Limitations and strengths

Several limitations should be acknowledged. First, as a retrospective study, it is subject to inherent biases including selection bias and information bias. Second, the follow-up period was relatively short, limiting our ability to assess long-term outcomes including adjacent level fractures or cement-related complications. Third, the study was conducted at a single institution, potentially limiting its generalizability to other settings with different patient populations or technical expertise. Fourth, we did not perform detailed analysis of cement distribution patterns using volumetric assessments, which could provide a more nuanced understanding of the differences between techniques, as suggested by Tao et al. (2024) [23].

This study has several strengths. Our relatively large sample size (240 patients, 120 in each group) provides adequate statistical power to detect clinically meaningful differences between techniques. All procedures were performed by a single experienced surgeon, minimizing operator-dependent variations in technique. We collected comprehensive data on both clinical outcomes and radiological parameters, allowing for multidimensional assessment of treatment efficacy. Finally, our detailed tracking of procedural times provides valuable insights into the workflow considerations of both techniques.

Future directions

Future research should address several questions raised by our findings. Longer-term follow-up studies are needed to assess the durability of clinical and radiological improvements and to monitor for late complications such as adjacent segment fractures. Randomized controlled trials would provide higher-quality evidence for the comparative efficacy and safety of these techniques. Studies specifically examining the role of robotic assistance in challenging cases (e.g., severe osteoporosis, complex deformities, revision procedures) could help define the optimal indications for this technology, as suggested by Li et al. (2024) in their validation cohort study [14].

Detailed analysis of cement distribution patterns using advanced imaging would provide more nuanced understanding of the differences between techniques and potential correlations with clinical outcomes, as highlighted by Tao et al. (2024) [23]. Cost-effectiveness analyses are also needed to determine whether the clinical benefits of robotic assistance justify the additional costs of equipment acquisition and maintenance, though our findings of reduced procedure time may favorably impact such analyses.

Additionally, future research should explore the potential of unilateral approaches in robotic-assisted kyphoplasty, as suggested by Qian et al. (2022) [11], who evaluated the efficacy of establishing an optimal path through unilateral pedicle under robotic assistance. This approach could further reduce procedural invasiveness and radiation exposure, as demonstrated in recent studies by Yang et al. (2025) [27].

Conclusion

Both robotic-assisted kyphoplasty (RK) and fluoroscopy-guided kyphoplasty (FK) provide significant clinical improvements for patients with osteoporotic vertebral compression fractures. While both techniques yield comparable pain relief and functional outcomes, robotic assistance offers several notable advantages: better vertebral height restoration (68.00% vs. 64.38%), significantly reduced cement leakage rates (5.8% vs. 19.2%), lower radiation exposure (18.76 mGy vs. 22.69 mGy), and, contrary to previously published studies, substantially shorter total procedure times (50.91 min vs. 86.40 min).

The efficiency advantage observed with robotic assistance challenges the conventional perception that robotic procedures inevitably increase operative time. Our findings demonstrate that RK significantly reduces both pin insertion time (4.91 min vs. 23.05 min) and pure surgical time (33.99 min vs. 52.35 min), more than offsetting the additional time required for scanning and planning (16.92 min).

Robotic-assisted kyphoplasty may be particularly valuable in complex cases where precision is paramount and cement leakage risk is high. The improved procedural efficiency, coupled with enhanced safety profiles and superior radiological outcomes, positions robotic assistance as an increasingly attractive option for treating the growing global burden of vertebral compression fractures.

As robotic technology continues to evolve and surgical teams gain more experience with these systems, the advantages of robotic-assisted procedures may become even more pronounced. Future research should focus on longer-term clinical outcomes, cost-effectiveness analyses, and further refinement of techniques to maximize the benefits of this promising technology.

Author contributions AS and SV contributed equally to the study. SV conceptualized the study. MPK and AS developed the methodology. AS and BT performed formal analysis and data curation. SV performed the surgical procedures and investigation. AS and MPK prepared the original draft. SV and BT reviewed and edited the manuscript. SV supervised and administered the project. All authors read and approved the final manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no conflict of interest.

Ethical approval This study was performed in accordance with the ethical standards of the institutional and national research committee and with the 1964 Helsinki Declaration and its later amendments. The study was approved by the Institutional Ethics Committee of Manipal Hospital, Bangalore (approval number: ECR/34/Inst/KA/2013/RR-19).

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication Patients signed informed consent regarding publishing their data.

References

1. Ostergaard PJ, Cha TD (2020) Biomechanics of Vertebral Compression Fractures. In: Razi AE, Hershman SH, editors. Vertebral Compression Fractures in Osteoporotic and Pathologic Bone [Internet]. Cham: Springer International Publishing [cited 2025 Apr 6]. p. 49–55. Available from: http://link.springer.com/https://doi.org/10.1007/978-3-030-33861-9_5
2. Avgerinou C, Petersen I, Clegg A, West RM, Osborn D, Walters K (2022) 1071 INCIDENCE OF RECORDED OSTEOPOROSIS, OSTEOPENIA AND FRAGILITY FRACTURE IN OLDER PEOPLE: ANALYSIS OF UK PRIMARY CARE DATA. Age and Ageing [Internet]. [cited 2025 Apr 17];51(Supplement_2): afac124.014. Available from: https://academic.oup.com/ageing/article/doi/https://doi.org/10.1093/ageing/afac124.014/6607981
3. Clarke BL (2020) Economic Costs of Severe Osteoporotic Fractures Continue to Increase at Expense of Refracture. Journal of Bone and Mineral Research [Internet]. [cited 2025 Apr 17];37(10):1809–10. Available from: https://academic.oup.com/jbmr/article/37/10/1809-1810/7512331
4. Burge R, Burge RT, Dawson-Hughes B, Dawson-Hughes B, Solomon DH, Solomon DH, Wong JB, Wong JB, King AB, King AB, Tosteson ANA, Tosteson ANA, Tosteson ANA (2007) Incidence and economic burden of osteoporosis-related fractures in the United States, 2005–2025. J Bone Miner Res 22(3):465–475
5. Saxena BP, Shah BV, Joshi SP (2015) Outcome of percutaneous balloon kyphoplasty in vertebral compression fractures. IJOO 49(4):458–464. https://doi.org/10.4103/0019-5413.159673
6. Jose RS, Moosa MS, Bava NK (2024) Functional and radiological outcome of percutaneous balloon kyphoplasty for the treatment of osteoporotic vertebral compression fractures—a prospective study. J Orthop Dis Traumatol 7(1):40–46. https://doi.org/10.4103/jodp.jodp_51_23
7. Jarrar S, Barbarawi MM, Daoud SS, Jaradat A, Alkalban R, Qayyas LA, Alabdallah NB, Khurfan BW, Al Barbarawi AM, Audat ZA (2024) Cement extravasation as a complication for kyphoplasty and vertebroplasty procedure: a retrospective analysis of 171 cases. Med Glas. https://doi.org/10.17392/1626-23
8. Cheng SH, Chou WH, Tsuei YC, Chu W, Chu WC (2024) Assessment of cement leakage in decompressed percutaneous Kyphoplasty. J Clin Med 13:345
9. Hu KZ, Chen SC, Xu L (2018) Comparison of percutaneous balloon dilation kyphoplasty and percutaneous vertebroplasty in treatment for thoracolumbar vertebral compression fractures. Eur Rev Med Pharmacol Sci 22(11):96–102. https://doi.org/10.26355/eurrev_201807_15370
10. Unplanned reoperation after lumbopelvic fixation with S-2 alar-iliac screws or iliac bolts. Journal of Neurosurgery [Internet] (2015) 23(1):67–76. Available from: https://thejns.org/downloadpdf/journals/j-neurosurg-spine/23/1/article-p67.pdf
11. Qian J, Qian J, Fang C, Fang C, Ge P, Ge P, Zhang R-J, Zhang R-J, Song P-W, Song P, Peng Xu, Peng Xu, Zhang Y, Zhang Y, Shen C-L, Shen C (2022) Efficacy and safety of establishing an optimal path through unilateral pedicle under the assistance of surgical robot in percutaneous Kyphoplasty. Pain Physician 25(1):E133–E140
12. Yuan W, Yuan W, Yuan W, Cao W, Cao W, Meng X, Meng X, Zhu H, Zhu H, Liu X, Liu X, Liu X, Cui C, Cui C, Tao L, Tao L, Tao L, Zhu Y, Zhu Y, Zhu Y, Zhu Y (2020) Learning curve of robot-assisted percutaneous Kyphoplasty for osteoporotic vertebral compression fractures. World Neurosurg 138:323
13. Nussbaum DA, Gailloud P, Murphy K (2004) A review of complications associated with vertebroplasty and kyphoplasty as reported to the food and drug administration medical device related web site. J Vasc Interv Radiol 15(11):1185–1192
14. Li H, Zou J, Jianlin Y (2024) Effect of robot-assisted surgery on clinical outcomes in patients with osteoporotic vertebral compression fractures after percutaneous vertebral augmentation: a meta-analysis and a validation cohort. Clin Orthop Surg 16:946
15. Macke JJ, Macke JJ, Macke JJ, Woo R, Woo R, Varich L, Varich L (2016) Accuracy of robot-assisted pedicle screw placement for adolescent idiopathic scoliosis in the pediatric population. J Robot Surg 10(2):145–150
16. Yu Zhang Y, Zhang QP, Peng Q, Sun C, Sun C, Kang X, Kang X, Man H, Man H, Zhao W, Zhao W, Liu X, Liu X, Meng B, Meng B, Yang S, Yang S, Feng X, Feng X, Zhang L, Zhang L (2022) Robot versus fluoroscopyassisted vertebroplasty and kyphoplasty for osteoporotic vertebral compression fractures: a systematic review and meta-analysis. World Neurosurg 166:120

17. Chang YT, Chen W-C, Chi K-Y, Huang AP-H, Jhang S-W, Sun L, Chen C-M (2023) Robot-assisted kyphoplasty versus fluoroscopy-assisted kyphoplasty: a meta-analysis of postoperative outcomes. Medicina 59(4):662–662
18. Hawker GA, Mian S, Kendzerska T, French M (2011) Measures of adult pain: Visual Analog Scale for Pain (VAS Pain), Numeric Rating Scale for Pain (NRS Pain), McGill Pain Questionnaire (MPQ), Short-Form McGill Pain Questionnaire (SF-MPQ), Chronic Pain Grade Scale (CPGS), Short Form-36 Bodily Pain Scale (SF-36 BPS), and Measure of Intermittent and Constant Osteoarthritis Pain (ICOAP). Arthritis Care & Research [Internet]. [cited 2025 Apr 6];63(S11). Available from: https://acr-journals.onlinelibrary.wiley.com/doi/https://doi.org/10.1002/acr.20543
19. Fairbank JCT, Pynsent PB (2000) The Oswestry Disability Index: Spine [Internet]. [cited 2025 Apr 6];25(22):2940–53. Available from: http://journals.lww.com/00007632-200011150-00017
20. Mumford J, Mumford J, Weinstein JN, Weinstein JN, Spratt KF, Spratt KF, Goel VK, Goel VK (1993) Thoracolumbar burst fractures. The clinical efficacy and outcome of nonoperative management. Spine 18(8):955–970
21. Hinde K, Hinde K, Maingard J, Maingard J, Hirsch JA, Hirsch JA, Phan K, Phan K, Asadi H, Asadi H, Chandra RV, Chandra RV (2020) Mortality outcomes of vertebral augmentation (vertebroplasty and/or balloon kyphoplasty) for osteoporotic vertebral compression fractures: a systematic review and meta-analysis. Radiology 295(1):96–103
22. Takahashi S, Hoshino M, Terai H, Toyoda H, Suzuki A, Tamai K, Watanabe K, Tsujio T, Yasuda H, Kono H, Sasaoka R (2018) Differences in short-term clinical and radiological outcomes depending on timing of balloon kyphoplasty for painful osteoporotic vertebral fracture. J Orthop Sci 23(1):51–56
23. H. Tao, Zhiwei Huang, Shanzhong Shao, Ruoyu Yang, Kunitaka Yang, Yinshun Zhang, Wei Li, Fu-xiang Dong, Jun Qian, Cailiang Shen. Comparison of Robot-Assisted and Fluoroscopy-Assisted Percutaneous Kyphoplasty for Bone Cement Distribution and Clinical Efficacy. Pain Physician
24. Liu P, Jiang H, Zhang W, Wang F, Tang L, Zhou W, Lin S (2025) Robot-assisted versus fluoroscopy-assisted kyphoplasty in treatment of severe osteoporotic vertebral compression fractures in the old patients: a retrospective study. BMC Musculoskelet Disord 26:322
25. Genant HK, Wu CY, Van Kuijk C, Nevitt MC (1993) Vertebral fracture assessment using a semiquantitative technique. Journal of Bone and Mineral Research [Internet]. [cited 2025 Apr 17];8(9):1137–48. Available from: https://academic.oup.com/jbmr/article/8/9/1137-1148/7500321
26. Lin SL, Lin S, Jiang Hu, Hu J, Wan L, Wan L, Wan L, Tang L, Tang L, Wang Y, Wang Y, Yang Yu, Yu Y, Zhang W, Zhang W (2020) Robot-guided percutaneous kyphoplasty in treatment of multi-segmental osteoporotic vertebral compression fracture. Chinese J Reparative Reconstruct Surg 34(9):1136–1141
27. R Yang, Z Huang, S Shao, J Liu, S Xia, W Li, Y Zhang, J Qian, F Dong, C Shen, H Tao (2025) Comparison of unilateral and bilateral robot-assisted percutaneous kyphoplasty in treating Osteoporotic vertebral compression fracture. World Neurosurgery