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What Is the Effect of Robot Reduction in Displaced Pelvic Fractures? A Multicenter Randomized Clinical Trial

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Abstract

Background Displaced pelvic fractures present real surgical challenges because of complex three-dimensional deformity patterns and proximity to vital structures, with conventional manual reduction techniques limited by accuracy constraints and radiation exposure. Although

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Ethical approval for this study was obtained from the institutional review boards of the Jishuitan Hospital (approval no.: 20210901).
This work was performed at Beijing Jishuitan Hospital, Capital Medical University (Beijing), with multicenter participation from China-Japan Union Hospital of Jilin University (Changchun), The First Hospital of Jilin University (Changchun), Nanfang Hospital, Southern Medical University (Guangzhou), Tianjin Hospital (Tianjin), and Foshan Hospital of Traditional Chinese Medicine (Foshan).

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robotic assistance shows promise in preclinical studies, its clinical effectiveness remains unproven in randomized clinical trials (RCTs).

Questions/purposes (1) Does robotic closed reduction improve reduction quality compared with manual closed reduction in displaced pelvic fractures? (2) Can robotic closed reduction reduce intraoperative radiation exposure while maintaining functional outcomes?

Methods In this multicenter RCT conducted at six tertiary trauma centers in China involving 10 senior orthopaedic traumatologists, 92 adult patients with acute closed, displaced pelvic fractures (Tile Type B or C) were randomized 1:1 to robotic closed reduction (n = 46) or manual closed reduction (n = 46) groups. At 12 weeks, loss to follow-up for patient-reported outcomes was 9% (4 of 46) in the robotic group and 4% (2 of 46) in the manual group; the remainder were handled in a prespecified per-protocol analysis. In the robot group, reduction was planned using CT-based three-dimensional reconstruction with contralateral pelvic symmetry as the target and executed by a robotic arm with adjunct elastic traction and contralateral pelvic stabilization. In the manual group, reduction was performed using traction and manual manipulation under fluoroscopic guidance. Surgeons and patients were not blinded; radiographic outcome assessors and data analysts were blinded. Primary outcome was reduction quality assessed using Matta criteria (excellent ≤ 4 mm residual displacement, good 5 to 10 mm, acceptable 10 to 20 mm, poor > 20 mm), analyzed as the proportion of excellent to good reductions. Secondary outcomes included intraoperative surgeon fluoroscopic exposure and 12-week Majeed pelvic scores (0 to 100 points across seven domains; higher scores indicate better function). The primary analysis was intention to treat.

Results In the intention-to-treat analysis, a higher proportion of patients who underwent robotic closed reduction achieved an excellent or good reduction than did those who received manual closed reduction (96% [44 of 46] versus 48% [22 of 46], relative risk 2.00 [95% confidence interval (CI) 1.47 to 2.72]; p < 0.001). Median (IQR) intraoperative surgeon fluoroscopic exposure was lower in the robotic closed reduction group (0 [0 to 0] versus 38 [14 to 78] fluoroscopic exposures; p < 0.001). No differences were found in 12-week Majeed functional scores between groups (mean ± SD 69 ± 16 versus 71 ± 17, mean difference -3 [95% CI -11 to 6]; p = 0.55). One superficial infection occurred in the manual closed reduction group, and there were no serious complications in either group.

Conclusion Surgeons treating acute displaced pelvic ring fractures should consider robotic closed reduction, when available, to improve reduction quality and reduce intraoperative fluoroscopic exposure, although it did not result in improved patient-reported outcome scores at short term in this randomized trial. Future studies should evaluate longer term functional benefits, define the fracture patterns most likely to benefit, and evaluate implementation factors including learning curve and cost-effectiveness across varied trauma settings.

Level of Evidence Level I, therapeutic study.

Introduction

Displaced pelvic fractures, predominantly resulting from high-energy trauma, present formidable surgical challenges because of their complex three-dimensional (3D) deformity patterns and the proximity of the fracture to critical neurovascular structures. These injuries are associated with mortality rates exceeding 13%, and more than one-half of survivors experience permanent functional disability [9, 29]. Achieving anatomic or near-anatomic reduction of the pelvic ring is associated with improved functional outcomes and facilitates early mobilization [1]. The transition from open reduction to fluoroscopy-guided closed reduction techniques marked a major milestone in the evolution of pelvic fracture management [30]. Early adjunctive approaches, such as reduction frames introduced by Matta and Yerasimides [19] and Lefaivre et al. [10], provided structural assistance during closed procedures. However, these devices had notable limitations. Reduction frames often obstructed internal fixation placement, and reliance on traction tables added procedural complexity. Additionally, conventional manual reduction techniques depend on two-dimensional imaging to reconstruct 3D anatomy, inherently limiting accuracy. These constraints not only prolonged operative time and radiation exposure but also frequently necessitated conversion to open procedures when closed reduction failed [8, 30].

To overcome these limitations, our team developed an intelligent robotic system for pelvic fracture reduction. This system employs automated 3D trajectory planning by computing optimal reduction pathways from preoperative imaging data. It then executes controlled fragment repositioning with high precision, eliminating the need for manual manipulation [7, 30, 31]. Preclinical studies using synthetic bone models and preliminary clinical trials have demonstrated the technical feasibility and precision of this system in achieving target reductions [30, 31]. To clinically validate these findings, we conducted a multicenter randomized clinical trial (RCT) comparing robotic-assisted and manual closed reduction in patients with acute displaced pelvic fractures.

In this RCT, we asked: (1) Does robotic closed reduction improve reduction quality compared with manual closed reduction in displaced pelvic fractures? (2) Can robotic closed reduction reduce intraoperative radiation exposure while maintaining functional outcomes?

Patients and Methods

Study Design and Setting

We conducted a multicenter, parallel-group, RCT to compare the effectiveness of robotic closed reduction versus conventional manual closed reduction in patients with acute displaced pelvic fractures. The study protocol was approved by the institutional review boards at all participating centers, fully sanctioned by the national government, and registered with the Chinese Clinical Trial Registry (ChiCTR2200059473). The trial adhered to the Consolidated Standards of Reporting Trials (CONSORT) guidelines [23].

The study was performed between September 1, 2021, and December 31, 2023; patients were consecutively approached from six tertiary trauma centers in urban regions of China. A total of 10 orthopaedic trauma surgeons participated, each with more than 15 years of experience in pelvic fracture management and completion of protocol-based training. Written informed consent was obtained from all patients.

Participants

Eligible participants were age 18 to 80 years and presented with closed, displaced pelvic ring injuries (Tile Types B or C) undergoing reduction, with surgery scheduled within 2 weeks of injury. Exclusion criteria included fractures undergoing emergency procedures (such as pelvic packing or arterial embolization), bilateral posterior ring injuries that were judged unsuitable for contralateral template-based closed reduction with the robotic system, serious systemic comorbidities contraindicating surgery, and recent participation in other clinical trials (Appendix 1; http://links.lww.com/CORR/B508).

A total of 138 patients were screened, of whom 92 were enrolled across six centers in China (with 45, 25, 7, 7, 7, and 1 patient enrolled at each center, respectively) (Fig. 1). Participants were randomly assigned in equal numbers to the robotic closed reduction and manual closed reduction groups (n = 46 per group). Demographic and baseline characteristics were generally well balanced between groups (Table 1), although the robotic closed reduction group had a higher proportion of male patients (72% [33 of 46] versus 50% [23 of 46]) and a longer mean interval from injury to surgery (9 ± 4 days versus 6 ± 3 days). Of the 92 randomized patients, six (four in the robotic closed group and two in the manual closed group) were lost to follow-up, and 86 completed the 12-week follow-up.

Randomization and Blinding

Randomization was conducted using a block design with a 1:1 allocation ratio. A statistician generated the allocation sequence using SAS 9.4, and assignments were concealed in sealed opaque envelopes, opened on the morning of surgery. Because of the nature of the interventions, blinding of patients and treating surgeons was not feasible. However, outcome assessors and investigators remained blinded to group allocation.

Interventions

All patients received standardized preoperative care, including hemodynamic stabilization (pelvic binders for all patients; skeletal traction for vertically unstable fractures) and comprehensive imaging (AP, inlet, and outlet radiographs, along with pelvic CT). Thromboprophylaxis with low–molecular weight heparin and symptomatic treatment (including analgesia) were administered as part of routine care.

Manual Closed Reduction

In the manual closed reduction group, patients underwent conventional closed, percutaneous reduction under general anesthesia, guided by intraoperative fluoroscopy. Patients were positioned supine on a radiolucent table. Two or three Schanz pins were inserted bilaterally for stabilization. Manual longitudinal traction of the lower extremity was applied, and the pelvic fragments were manipulated under C-arm fluoroscopic monitoring, with surgeons protected by lead aprons. Definitive fixation was selected based on fracture type: posterior ring injuries were stabilized using percutaneous cannulated screws or small iliac wing plates and anterior ring injuries were treated with external fixator, INFIX, or cannulated screw fixation.

Robotic Closed Reduction

In the robotic closed reduction group, patients underwent closed, percutaneous reduction assisted by our intelligent robotic system, which integrates real-time optical navigation and automated reduction functionality. The robotic platform consists of three primary components (Fig. 2A): (1) specialized pelvic reduction planning software, (2) a Polaris Vega optical tracking system (NDI), and (3) an UR16e robotic arm (Universal Robots USA).

A passive holding mechanism was mounted on the operating table, supplemented by an elastic traction device

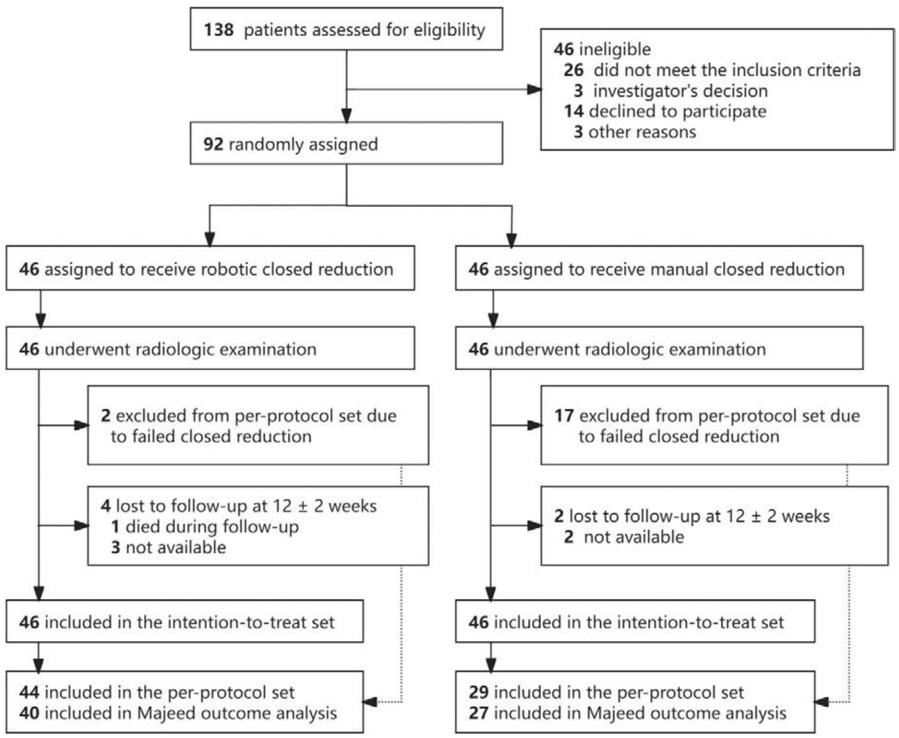

Fig. 1 The trial profile with inclusion and exclusion criteria for this study.

capable of exerting up to 30 kg of force to overcome soft tissue resistance [13].

Before surgery, the planning software processed each patient's 3D CT images to identify fracture fragments and generate a customized reduction pathway aimed at restoring pelvic symmetry (Fig. 2B-C) [5, 16]. With the patient under general anesthesia, optical trackers were affixed to the anterior superior iliac spines, and a cone-beam CT (CBCT) scan was performed to register pelvic and tracker positions. This data set was then fused with preoperative CT images using the navigation software for real-time tracking. Using a navigation-guided hand drill system (Supplemental Video 1; http://links.lww.com/CORR/B509 and Supplemental Fig. 1; http://links.lww.com/CORR/B508), Schanz holding pins were accurately placed. Two gripping pins on the intact hemipelvis (LC-2 corridor and iliac crest) were connected to passive holding arms, and three pins on the displaced hemipelvis (LC-2 corridor, iliac crest, and supraacetabular region) were connected to the robotic arm, allowing the LC-2 pins to be incorporated into external fixation or INFIX constructs and percutaneous pubic screws when indicated (Supplemental Fig. 1; http://links.lww.com/CORR/B508). For vertically displaced fractures, supracondylar skeletal traction was applied via the elastic traction device [13].

The robotic arm subsequently executed automatic fragment repositioning along the preplanned trajectory under continuous 3D navigation. Intraoperative fluoroscopy was employed to confirm reduction quality. Definitive fixation was performed according to the same principles and protocols used in the manual closed reduction group (Appendix 1; http://links.lww.com/CORR/B508 and Supplemental Video 2; http://links.lww.com/CORR/B510). In both groups, if closed reduction failed despite senior surgeon consultation, open reduction was performed and documented as an unsuccessful procedure.

Postoperative Care and Rehabilitation

Postoperative rehabilitation protocols were identical for both groups. All patients received rehabilitation counseling and were encouraged to initiate early active and passive muscle exercises. Upright sitting was permitted as soon as tolerated, and weightbearing was gradually introduced between 3 and 6 weeks postoperatively, based on patient tolerance.

Outcome Measures

The primary outcome was the quality of reduction, assessed using Matta and Tornetta's criteria [18], which classify reduction as excellent (≤ 4 mm displacement), good (5 to 10

Table 1. Baseline patient characteristics (intention-to-treat set)

Characteristic	Manual closed reduction (n = 46)	Robotic closed reduction (n = 46)
Age in years	46 ± 17	49 ± 15
Male	50 (23)	72 (33)
Height in cm	165 ± 10	168 ± 7
Weight in kg	66 ± 15	71 ± 15
BMI in kg/m^2	24.1 ± 4.5	25.0 ± 4.3
Hypertension	17 (8)	24 (11)
Diabetes	4 (2)	9 (4)
Cardiovascular disease	9 (4)	7 (3)
Injury mechanism		
Road traffic accident	61 (28)	57 (26)
Fall from height	22 (10)	26 (12)
Fall from ground level	4 (2)	4 (2)
Crush injury	13 (6)	13 (6)
Tile classification		
B1	7 (3)	4 (2)
B2	20 (9)	11 (5)
B3	11 (5)	7 (3)
C1	37 (17)	65 (30)
C2	20 (9)	13 (6)
C3	7 (3)	0 (0)
Associated injury[a]		
Upper limb injury	20 (9)	20 (9)
Lower limb and vertebra injury	39 (18)	48 (22)
Head, chest, and abdomen injury	26 (12)	46 (21)
Time from injury to surgery in days	6 ± 3	9 ± 4

Data presented as mean ± SD or % (n).
[a]Because some patients had injuries in more than one region, the percentages in this category do not sum to 100%.

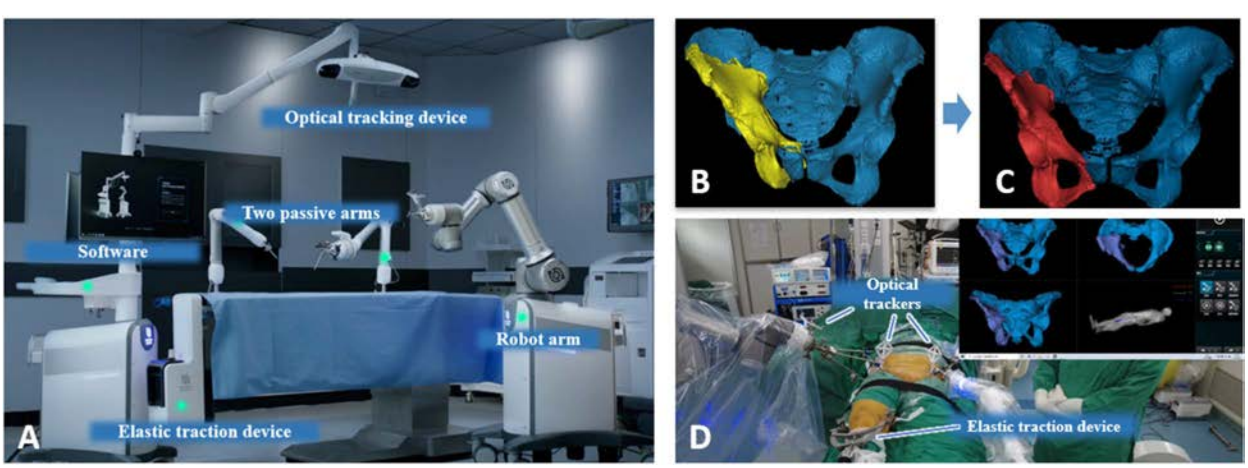

Fig. 2 Illustration of the intelligent robotic closed reduction system. (**A**) Layout and spatial positioning of the robotic system within the operating room. Position of fragments (**B**) before and (**C**) after autonomous reduction planning. (**D**) Autonomous robotic closed reduction under 3D real-time navigation.

mm), acceptable (10 to 20 mm), and poor (> 20 mm). Standardized AP, inlet, and outlet radiographs were obtained 3 to 5 days postoperatively. Two blinded orthopaedic surgeons not involved in the index surgeries (YG, FG) independently measured maximum displacement. Maximum displacement was defined as the largest residual gap or step at any point in the anterior or posterior pelvic ring on postoperative pelvic series radiographs. If the two assessors agreed on the Matta grade, it was accepted; otherwise, a third evaluator (HX) adjudicated. Displacement was averaged only when grades agreed. Interobserver agreement for Matta classification was $\kappa = 0.87$ (95% confidence interval [CI] 0.74 to 0.97). In accordance with the prespecified intention-to-treat analysis plan, patients in whom a satisfactory closed reduction could not be achieved and who therefore underwent conversion to open reduction were retained in the intention-to-treat set and classified as having poor closed reduction quality.

Secondary outcomes included reduction accuracy, surgeon radiation exposure, functional recovery, and the proportions of patients with radiographic union by 12 weeks. Reduction accuracy was assessed by comparing preoperative 3D target models with postoperative CT reconstructions using Geomagic Qualify 2013 (Geomagic Inc), calculating the mean global 3D deviation in a point-cloud-based reduction analysis [30]. Intraoperative surgeon radiation exposure was quantified by counting the number of fluoroscopic images in which the surgeon appeared, representing direct exposure, throughout the entire procedure from skin incision to wound closure, including both reduction maneuvers and implant insertion. CBCT acquisitions performed for image registration in the robotic group were not included in this measure because surgeons were not in the beam during those scans. Functional recovery was assessed at 12 weeks using the Majeed pelvic score, a validated 100-point scale assessing seven domains (such as pain and walking ability), with higher scores indicating better function [17]. For fracture patterns with bony components, healing was defined radiographically as obscuration of the fracture line with evidence of trabecular bridging. For purely ligamentous sacroiliac or symphyseal disruptions, healing was defined as maintenance of reduction without progressive diastasis or implant failure on serial radiographs at 6 and 12 weeks.

Adverse-outcome assessments encompassed both clinical and radiologic parameters. Clinical evaluations included intraoperative iatrogenic fractures, robotic system malfunctions, neurovascular injuries, and wound-related complications (such as infections and dehiscence). Radiologic evaluations at 6 and 12 weeks postoperatively included assessments for secondary displacement and implant integrity (loosening or breakage).

Sample Size

This superiority trial was designed to detect a difference in the proportion of excellent to good reductions between the robotic closed reduction and manual closed reduction groups. Based on prior data suggesting an excellent to good reduction rate of approximately 40% with manual closed reduction and approximately 95% with robotic reduction in younger patients undergoing early surgery [30], and accounting for the broader inclusion criteria in the present study (age up to 80 years; surgery within 2 weeks), we conservatively estimated a 70% excellent to good rate in the robotic closed reduction group. Using a one-tailed α of 0.025, 80% power, and a superiority margin of 0%, and accounting for a 10% dropout rate, the required sample size was calculated as 46 patients per group.

Ethical Approval

We obtained ethical approval for this study from the institutional review boards of the Jishuitan Hospital (approval no.: 20210901).

Statistical Analysis

Descriptive statistics were reported as means with SDs, medians with IQRs, or proportions, as appropriate. Continuous variables were compared using the Student t-test or the Mann-Whitney U test; categorical variables were compared using the chi-square or Fisher exact test. The intention-to-treat set included all randomized patients analyzed in the groups to which they were allocated (46 in the robotic closed reduction group and 46 in the manual closed reduction group). For the primary endpoint (excellent to good reduction by Matta criteria), patients who underwent conversion to open reduction were retained in the intention-to-treat set and classified as having a poor reduction. A per-protocol analysis was conducted as a supportive analysis and included patients who completed the allocated closed-reduction strategy without conversion to open reduction (44 in the robotic group and 29 in the manual group [Fig. 1]). The primary outcome was analyzed primarily in the intention-to-treat set, with the per-protocol analysis treated as a supportive analysis. Secondary outcomes were analyzed mainly in the per-protocol analysis, whereas adverse outcomes were assessed in the intention-to-treat set. For categorical outcomes, including the primary endpoint, we calculated relative risks with 95% CIs. Prespecified multivariate logistic regression and subgroup analyses were conducted to explore effect modification for the primary outcome. All analyses were performed using R, version 4.1.1 (R Foundation for Statistical Computing). A two-sided p value < 0.05 was considered statistically significant.

Results

Improvement in Reduction Quality

Robotic closed reduction resulted in better radiographic reduction quality than manual closed reduction. All 92 randomized patients completed the primary outcome assessment and were included in the intention-to-treat set (Fig. 1). In the intention-to-treat set, 96% (44 of 46) of patients in the robotic closed reduction group and 48% (22 of 46) in the manual closed reduction group had excellent or good reductions (relative risk 2.00 [95% CI 1.47 to 2.72]; $p < 0.001$) (Table 2). In the per-protocol analysis, which excluded patients converted to open reduction (44 in the robotic group and 29 in the manual group), 100% (44 of 44) of patients in the robotic group and 76% (22 of 29) in the manual group had excellent or good reductions (relative risk 1.32 [95% CI 1.07 to 1.62]; $p < 0.001$) (Table 2).

Sensitivity analyses using multivariate logistic regression (adjusting for sex, presence of concomitant injuries [head, chest, abdomen], time from injury to surgery, and center effects) confirmed the robustness of the primary findings (Supplemental Tables 1 and 2; http://links.lww.com/CORR/B508). Subgroup analyses consistently favored the robotic closed reduction group across predefined strata.

Reduction in Intraoperative Radiation Exposure

Robotic closed reduction reduced intraoperative surgeon fluoroscopic exposure without compromising early functional outcomes. Median (IQR) intraoperative surgeon radiation exposure was lower in the robotic closed reduction group than in the manual closed reduction group (0.0 [0.0 to 0.0] versus 38 [14 to 78] fluoroscopic exposures; $p < 0.001$) (Fig. 3A). Reduction accuracy, assessed in the per-protocol set, did not differ significantly between groups, although the mean 3D deviation was lower in the robotic group (Fig. 3B).

At 12 weeks, in the per-protocol set of patients who completed follow-up, Majeed functional scores did not differ between the manual and robotic closed reduction groups (Table 3). All fractures healed uneventfully, with no patients with delayed union or nonunion.

Other Findings

Adverse events did not differ between the groups. Only one adverse event occurred—a superficial incision infection in the manual closed reduction group, which resolved with local wound care. No iatrogenic fractures, neurovascular injuries, robotic system malfunctions, or secondary failures of bone or hardware were observed radiographically.

Discussion

Effective management of unstable pelvic ring fractures is critical to restoring pelvic anatomy, maintaining mechanical stability, and preventing long-term disability in severely injured patients [27]. Less invasive strategies such as closed reduction and percutaneous fixation are now preferred over open approaches because they limit soft tissue trauma and perioperative risk, and robotic assistance

Table 2. Primary outcome (intention-to-treat set and per-protocol set)

	Intention-to-treat set			Per-protocol set[a]		
Outcome	Manual closed reduction (n = 46)	Robotic closed reduction (n = 46)	p value	Manual closed reduction (n = 29)	Robotic closed reduction (n = 44)	p value
Matta grade of reduction[b]			< 0.001			0.004
Excellent	15 (7)	30 (14)		24 (7)	32 (14)	
Good	33 (15)	65 (30)		52 (15)	68 (30)	
Acceptable	15 (7)	0 (0)		24 (7)	0 (0)	
Poor	37 (17)	4 (2)		0 (0)	0 (0)	
Proportion of patients with excellent or good reduction (Matta grading system)	48 (22)	96 (44)	< 0.001	76 (22)	100 (44)	< 0.001

Data presented as % (n).
[a]Per-protocol set includes patients who completed the allocated closed reduction strategy without conversion to open reduction.
[b]Patients who underwent conversion to open reduction were classified as having poor reduction quality without further radiographic measurement.

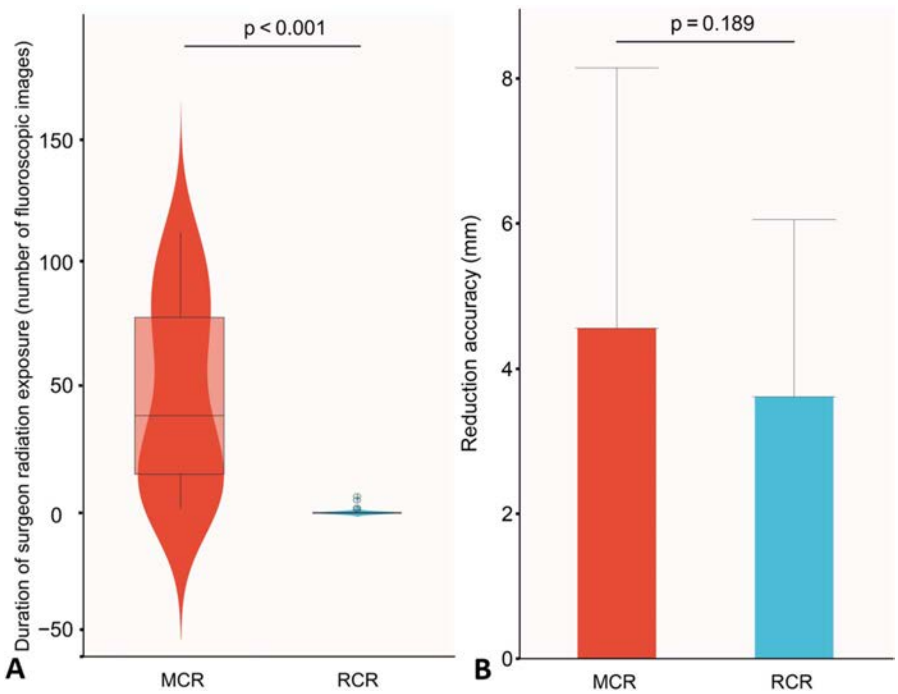

Fig. 3 This graph shows the secondary outcomes in the per-protocol set in terms of (**A**) median (IQR) number of fluoroscopic images in which the surgeon appeared and (**B**) mean ± SD reduction accuracy. MCR = manual closed reduction; RCR = robotic closed reduction.

is increasingly used to improve the accuracy and reproducibility of these procedures [12, 28]. However, whether applying robotic technology specifically to the closed reduction step can meaningfully improve reduction quality and reduce surgeons' direct radiation exposure, without compromising functional recovery, has remained uncertain. We therefore conducted a multicenter randomized trial comparing a robotic closed reduction workflow with standard manual closed reduction in adults with displaced Tile Type B or C pelvic ring fractures. In this study,

Table 3. Comparison of Majeed functional outcomes in the per-protocol set

	Preinjury		12 weeks		
Majeed outcome	Manual closed reduction (n = 29)	Robotic closed reduction (n = 44)	Manual closed reduction (n = 27)	Robotic closed reduction (n = 40)	p value
Pain	30 ± 0	30 ± 0	27 ± 4	27 ± 5	0.96
Work	20 ± 0	20 ± 0	10 ± 6	9 ± 5	0.61
Sitting	10 ± 0	10 ± 0	9 ± 1	8 ± 2	0.58
Sexual intercourse	4 ± 0	4 ± 0	3 ± 1	3 ± 2	0.55
Walking aids	12 ± 0	12 ± 0	9 ± 3	9 ± 3	0.55
Gait unaided	12 ± 0	12 ± 0	7 ± 4	7 ± 4	0.52
Walking distance	12 ± 0	12 ± 0	7 ± 4	7 ± 3	0.71
Total	100 ± 0	100 ± 0	71 ± 17	69 ± 16	0.55

Data presented as mean ± SD. Functional outcomes were prespecified to be analyzed in the per-protocol set, defined as patients who completed the allocated closed-reduction strategy and had available 12-week Majeed scores. Because scores were not collected for patients lost to follow-up, a true intention-to-treat analysis was not feasible for this endpoint. Per-protocol analyses may overestimate or underestimate the apparent advantages of the robotic treatment and should be interpreted with caution.

robotic closed reduction achieved better radiographic reduction quality and markedly less direct surgeon fluoroscopic exposure, with early functional outcomes comparable to those of manual closed reduction. These findings suggest that, in centers where the technology and expertise are available and the fracture pattern is amenable to closed management, robotic closed reduction can reasonably be considered a preferred strategy in terms of reduction accuracy (although we found no differences in patient-reported outcomes at short term), while manual techniques remain appropriate where robotic systems are not accessible.

Limitations

First, the current robotic workflow requires a relatively intact contralateral hemipelvis as a reduction template; patients with bilateral posterior ring injuries judged unsuitable for template-based closed reduction were therefore excluded, so the results are most directly applicable to displaced Tile Type B or C fractures with at least one relatively intact hemipelvis rather than the most complex bilateral patterns. Second, in accordance with the prespecified intention-to-treat analysis, patients who underwent conversion to open reduction were retained in the intention-to-treat set and classified as having poor closed reduction quality. This preserves a primary comparison between closed-reduction strategies and inevitably accentuates between-group differences in excellent to good proportions; the per-protocol analyses should therefore be interpreted as supportive, illustrating performance among successfully completed closed reductions. Given the potential for per-protocol analysis to inflate treatment effects, the lack of a difference in 12-week Majeed scores strengthens our conclusion that robotic assistance was not associated with better short-term patient-reported outcomes. Third, reduction quality was assessed with Matta and Tornetta criteria on standardized pelvic radiographs rather than routine postoperative CT, which may have underestimated small residual displacements, particularly in the posterior ring.

Improvement in Reduction Quality

In this trial, robotic closed reduction substantially increased the proportion of excellent or good reductions compared with conventional manual techniques in the intention-to-treat analysis (96% [44 of 46] versus 48% [22 of 46]) and remained superior in the per-protocol cohort (100% [44 of 44] versus 76% [22 of 29]). These results extend prior work on frame-assisted and Schanz-pin–assisted closed techniques, in which reported excellent or good rates frequently ranged from 50% to 80% in selected series despite substantial fluoroscopic effort and operator dependence [2, 11, 19, 22, 24]. Classic methods described by Routt and colleagues and later by Matta and Yerasimides use strategically placed iliac and anterior pins combined with traction and fluoroscopy [19, 22]. The Starr and modified Starr frames further improved mechanical control during closed manipulation but still rely on two-dimensional fluoroscopic projection of a highly irregular 3D ring and require the surgeon to "translate" fluoroscopic views into complex multiplanar corrections [2, 3, 11]. Our robotic platform builds directly on this historical evolution by combining LC-2 and iliac crest holding pins with a custom passive arm to rigidly fix the contralateral hemipelvis, automated planning via CT-based mirroring of the intact side as a template, and CBCT-based registration to the intraoperative position [5, 15, 21, 31]. Treating the pelvis as an integrated 3D structure and executing the preplanned pathway with a load-controlled robotic arm likely explains why a higher proportion of patients achieved Matta excellent or good categories than with manual, experience-dependent maneuvers.

The apparently smaller between-group difference in 3D reduction accuracy (mean point-cloud deviation 4 ± 2 mm versus 5 ± 4 mm in the robotic and manual groups, respectively) compared with the more pronounced differences in Matta grading does not contradict our main finding but rather reflects how these metrics are defined and where they were applied. Matta classification, used in both the intention-to-treat and per-protocol analyses, is driven by the single worst residual gap or step on standardized AP, inlet, and outlet radiographs, making it highly sensitive to small changes near the 4 to 5 mm and 5 to 10 mm category thresholds [18, 19]. In contrast, the 3D point-cloud measure averages global surface deviations and was calculated only in the per-protocol set after excluding open conversions; in this restricted cohort, distributions overlapped and sample size (particularly in the manual group) limited statistical power. Moreover, peak displacement on radiographs and mean surface deviation on CT-based models capture different aspects of residual deformity. Small improvements in peak displacement near category cutoffs may therefore shift Matta grades without producing large changes in the mean 3D deviation. Consistent with recent work, different pelvic displacement metrics appear to have variable reliability and only modest agreement, suggesting that no single measurement fully characterizes reduction quality [20]. In this context, our findings support using Matta grades to summarize the clinical success of a closed strategy at the whole-cohort level, while 3D accuracy provides a complementary quantitative description within successfully reduced fractures [5, 7, 15, 30, 31]; future work should standardize how these complementary metrics are combined and linked to long-term functional outcomes.

Reduction in Intraoperative Radiation Exposure

Robotic closed reduction also substantially reduced direct surgeon radiation exposure, with a median of 0 fluoroscopic images in which the surgeon appeared in the beam, compared with 38 images (IQR 14 to 78) during manual closed reduction. Most prior pelvic ring studies have reported fluoroscopy time or dose-area product from the patient's perspective during percutaneous sacroiliac or transsacral screw fixation or navigated procedures, often documenting long screening times and substantial cumulative dose but rarely quantifying the specific exposure to the operating surgeon [12, 28]. In our workflow, the key difference is that image registration and 3D navigation are handled through preoperative and intraoperative CT or CBCT fusion with an optical tracker; the surgeon leaves the room during CBCT acquisition and then relies on navigation guidance for implant placement, with fluoroscopy reserved for final verification in projections that do not require the surgeon to stand in the beam [4, 6, 25, 26]. By contrast, conventional manual reduction depends on repeated live fluoroscopy while the surgeon and assistants apply traction and manipulate Schanz pins, making exposure essentially unavoidable despite shielding. Our data therefore add to the research by demonstrating that, in complex pelvic fracture surgery, a robot- and navigation-assisted reduction strategy can practically eliminate direct surgeon fluoroscopic exposure while maintaining reduction quality and early functional recovery [12, 28, 30].

From a broader perspective of occupational health, these findings may help surgeons and hospitals adhere to international recommendations to minimize staff dose in fluoroscopically guided orthopaedic procedures, but they also highlight an area that remains understudied: surgeon exposure during demanding, multiplanar pelvic reductions. Whereas many radiation-reduction initiatives focus on decreasing patient doses, our results suggest that reengineering the reduction workflow itself, through stable contralateral fixation with LC-2 and iliac crest pins, navigation-guided pin placement, elastic supracondylar traction to offload the robotic arm, and automated execution of the planned pathway, may provide a step change in protecting the surgical team without compromising, and possibly enhancing, technical quality [14, 21]. Future studies should complement our image-count metric with dosimeter-based measurements of scatter dose to surgeons and staff, examine how the learning curve and center experience influence radiation savings, and compare this robotic workflow with alternative dose-reduction strategies such as low-dose pulsed fluoroscopy or navigation-assisted manual reduction. Together, such work will help define where robotic closed reduction offers the greatest value in balancing radiographic accuracy, radiation safety, and resource use across different trauma care settings.

Conclusion

In this multicenter RCT of adults with displaced Tile Type B or C pelvic ring fractures, robotic closed reduction resulted in a higher proportion of patients achieving excellent or good reductions than manual closed reduction in the intention-to-treat analysis (96% [44 of 46] versus 48% [22 of 46]) and almost eliminated direct surgeon fluoroscopic exposure, whereas 12-week functional recovery and fracture healing did not differ between groups. Because patients who underwent conversion to open reduction were classified as having poor reduction quality, the magnitude of benefit observed for the robotic technique should be interpreted with appropriate caution. Clinically, these findings support the use of robotic closed reduction in centers with the necessary expertise and infrastructure when a closed strategy is feasible and when improving reduction quality and reducing surgeon radiation exposure are priorities, while manual reduction and timely open procedures remain essential when an adequate closed reduction cannot be obtained. Future studies are needed to determine whether these radiographic advantages translate into long-term functional and patient-reported benefits and to evaluate learning curve, workflow integration, and cost-effectiveness in different trauma care settings.

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