CLINICAL ARTICLE

Comparison of Robot-Assisted Percutaneous Cannulated Screws Versus Open Reduction and Internal Fixation in Calcaneal Fractures

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Objective: Accurate placement of the screws is challenging in percutaneous cannulated screw fixation of calcaneal fractures, and robot-assisted (RA) surgery enhances the accuracy. We investigated the outcome of percutaneous cannulated screw fixation of Sander's type II and III calcaneal fractures.

Methods: This retrospective study analyzed clinical data of 26 patients with fresh closed calcaneal fractures (28 fractures) who were admitted to our center from January 2022 to July 2022. All fractures were divided into the RA group and the open reduction and internal fixation (ORIF) group according to the surgeries performed. RA surgery was performed by closed reduction or open reduction combined with a tarsal sinus approach. Age, sex, operation time, preoperative waiting time, length of postoperative hospital stay, wound complications, and American Orthopaedic Foot and Ankle Society Ankle Hindfoot Scale (AOFAS) at 3 months postoperatively were compared. Preoperative and postoperative radiographic parameters (calcaneal length, width, height, Böhler angle, and fixation rate of the sustentaculum tali) were documented. The chi-square test, one-way analysis of variance, and Wilcoxon test were used for the comparison of categorical, normally distributed, and nonnormally distributed continuous variables, respectively.

Results: The calcaneal width, height, and Böhler angle were significantly corrected postoperatively in both groups. The postoperative calcaneal lengths in both groups were also corrected. However, no significant difference was found. No significant differences in calcaneal length, width, height, and Böhler angle were observed between the two groups. The operation time ($p < 0.001$), preoperative waiting time ($p < 0.001$), and length of postoperative hospital stay ($p = 0.003$) in the RA surgery group were significantly shorter than those in the ORIF group. The fixation rate of the sustentaculum tali ($p < 0.001$) in the RA surgery group was significantly superior to that in the ORIF group. All wound complications occurred in the ORIF group. All fractures healed within 3 months. The AOFAS scores at 3 months postoperatively were not significantly different.

Conclusion: RA percutaneous screw fixation of the calcaneal fracture is a safe, effective, rapid, and minimally invasive surgical option for surgeons.

Key words: Calcaneal Fracture; Open Reduction and Internal Fixation; Percutaneous; TiRobot

Introduction

Calcaneal fractures accounted for 1%–2% of all systemic fractures and 60% of tarsal fractures.[1,2] Approximately 75% of calcaneal fractures involved the subtalar joint.[3] Calcaneal fractures often result from falling from height or traffic accidents. Most calcaneal fractures occur in men of working age.[4] The treatment of calcaneal fracture remains controversial. The treatment spectrum ranges from nonoperative (early range-of-motion exercise) to operative.[5] General indications for surgical treatment of displaced intraarticular calcaneal fractures (DIACFs) are as follows: overall distortion of the anatomy (height, width, and varus/valgus deformities) plus incongruency

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at the subtalar joint.[6] Sanders type I fractures always require conservative treatment. However, recently, for types II, III, and IV, there has been a trend toward the use of surgical approaches.[7]

The traditional L-shaped extended lateral approach provided sufficient visual for fracture reduction and fixation. However, owing to the limitation of soft tissue conditions, it was necessary to delay surgery for a long time.[2] Plates also interfered with soft tissue recovery after surgery. Some minimally invasive techniques have been applied in the treatment of calcaneal fractures, and satisfactory results have been achieved.[8–10]

The techniques using percutaneous reduction and screw osteosynthesis and minimally invasive open approaches result in significantly better outcomes than with external fixation and other techniques such as Kirschner wire fixation.[11] Favorable outcomes of screw fixation with Sanders type II fractures have been replicated in multiple studies; however, the outcomes in more comminuted patterns are less clear, and more research is required. The disadvantages of percutaneous fixation include increased risk for residual subtalar displacement, potentially less rigid fixation, and inability to manage significant posterior facet depression or fractures more than 7–10 days old.[12]

Over the past 100 years, robotics has flourished. Various robotic techniques are used in medicine. Moreover, many robotic applications in orthopaedic surgeries can increase accuracy, reduce invasiveness, and decrease radiation exposure. "Tianji" has been certified by the China Food and Drug Administration and applied for clinical use in both trauma and spine surgery. Tianji orthopaedic robot (TiRobot) has been widely used in minimally invasive surgery for pelvic fractures and spine surgeries.[13] Intraoperative computed tomography (CT) in robot-assisted (RA) surgery helped accurately plan the path of the guide wire. RA cannulated screw fixation may decrease the need for open reduction, which reduces the incidence of wound complications.

Fig. 1 Incision of the tarsal sinus approach.

This retrospective study aimed to (1) compare the radiographic and clinical results of RA percutaneous cannulated screw fixation with those of open reduction and internal fixation (ORIF) and (2) analyze the advantages and characteristics of RA percutaneous cannulated screw fixation.

Methods

We retrospectively analyzed 28 closed calcaneal fractures in 26 patients who underwent RA calcaneal surgery or ORIF. All patients were admitted to the same team between January 2022 and July 2022. The inclusion criteria were as follows: (1) Sanders type II or III fractures, (2) age 18–65 years, and (3) preoperative waiting time <15 days. The exclusion criteria were as follows: (1) a history of previous ipsilateral foot or ankle fractures, (2) combined with other fractures, and (3) a history of smoking or diabetes.

The study was approved by the institutional review board of the Jishuitan Hospital, Beijing, China (No. 202107–23).

Preoperative Management

Patients were divided into two groups according to the surgeries performed: RA percutaneous cannulated screw fixation or ORIF using a plate. All patients were evaluated with preoperative X-ray imaging (lateral view of the foot and axial view of the calcaneus) and CT. Calcaneal length, width, height, and Böhler angle were recorded. The timing of surgery was determined by the same team of surgeons according to the soft tissue conditions. The procedures were also performed by this team.

Surgical Procedure

All patients received spinal anesthesia during the operation. They were placed in the healthy lateral position (patients with bilateral fractures were placed in the prone position). Routine disinfection and sterile sheets were administered.

In the RA surgery group, whether the fracture was capable of close reduction was initially assessed. In some cases, the articular surface could be lifted by percutaneous leveraging for some tongue-type fractures. Indeed, for some fractures with a small articular surface that collapsed, a 3.5-mm Kirschner wire through the 3D planned path could be used to lift the collapsed articular surface. Other severe DIACFs require open reduction with a tarsal sinus approach. A 2–3 cm long incision was made 0.5–1.0 cm below the lateral malleolus toward the base of the fourth metatarsal bone (Figure 1). The peroneus tendons and nerves should be identified and protected carefully. A part of the calcaneofibular ligament was cut to expose the subtalar joint. The posterior calcaneal articular surface was reduced, with the talar surface as a template. Varus and calcaneus length were corrected by traction and leveraging, and lateral wall fractures were reduced by manual compression. Temporary fixation was performed with 2.0-mm Kirschner wires.

A tracker was attached to the distal fibula. The TiRobot system (TINAVI Medical Technologies, Beijing, China) was used in the surgeries. This system is composed

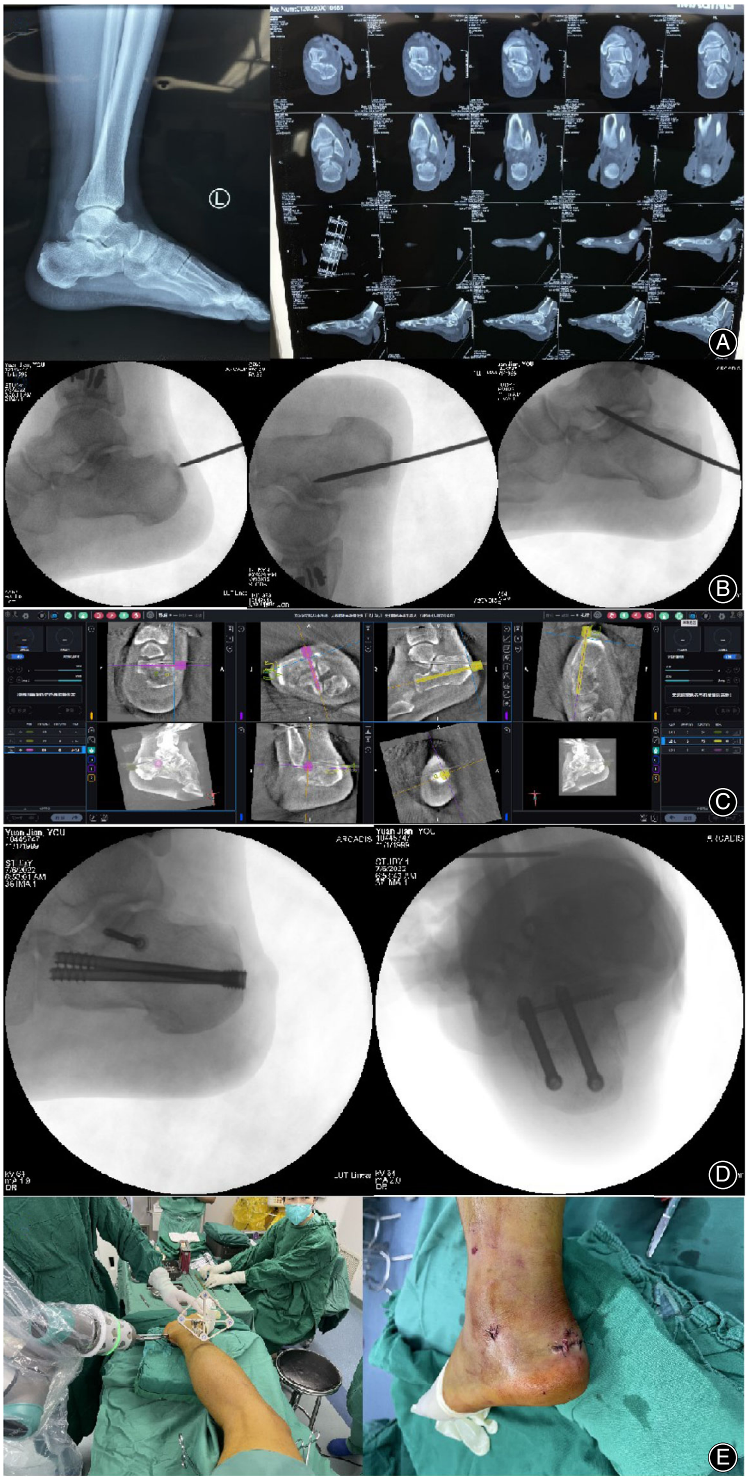

Fig. 2 A typical case. (A) Preoperative radiographic images. (B) Posterior articular surface lifted by leveraging. (C) Planning the screw on the workstation. (D) Confirming the position and length of the screws. (E) Performing the operation and the postoperative incision.

of a mechanical arm, an optical tracking system, and an operative planning and controlling workstation. All surgeons were skilled in TiRobot operation. Intraoperative CT was planned by the TiRobot system. Satisfactory reduction of the fracture was confirmed in the planning image, and the screw paths were planned. The blueprint of the surgery is shown in Figure 2.

1. A 6.5-mm screw was planned from the lateral side below the Achilles tendon insertion to the calcaneocuboid joint.

2. A 4.0- or 6.5-mm screw was planned from the medial area below the Achilles tendon insertion to the sustentacular fragment or to the calcaneocuboid joint.
3. A 4.0-mm cannulated screw was planned from the lateral articular surface fragment to the sustentaculum tali. The screw should be placed under the articular surface to support it.
4. A 4.0-mm cannulated screw was planned from the anterolateral fragment to the sustentaculum tali if there was a unique fragment.
5. In some cases, a 4.0-mm cannulated screw was planned from the bottom of the calcaneal tubercle to the collapsed articular surface.

After completion of the planning step, a 3D composition was formed in the workstation to confirm that each screw had no mutual influence. The cannulated screw guide wire was placed percutaneously under the guidance of the mechanical arm. A real-time confirmation was possible; thus, the error was <1 mm. Fluoroscopy (lateral and axis views of the calcaneus) was performed to confirm the guide wire placement. The cannulated screw was placed in turn according to the planned screw length and diameter. 3D CT was performed to verify that the screw position and length were satisfactory. Finally, the wound was closed and pressure bandaged.

In the ORIF group, the traditional L-shaped extension lateral approach was adopted. The fracture was exposed by dissecting the skin subcutaneously to the bone surface. The flap was protected by inserting Kirschner wires into the talus and cuboid and bending instead of a retractor. The lateral wall of the fracture was turned over, and the ligaments were dissected to expose the collapsed articular surface. Varus and shortening were corrected by traction and leveraging after reducing the articular surface and then fixed temporarily by 2.0-mm Kirschner wires. The lateral wall fragment was reduced, and the fracture was fixed with an anatomic locking plate. Reduction and fixation were confirmed by fluoroscopy. The wound was closed in layers, and drainage was indwelled. Drainage was removed when it fell <30 ml in 24 h.

Postoperative Treatment and Follow-Up

The patients were treated with the elevation of the affected limb, anti-inflammatory drugs, and detumescence. We extended the duration of antibiotic use in patients with wound redness and swelling or marginal necrosis. After drainage removal, X-ray imaging (lateral view of the foot and the axis view of the calcaneus) and CT were performed. The ankle flexion and extension function exercises were started immediately after the operation. Weight-bearing was allowed 8 weeks postoperatively. Postoperative follow-up was performed once a month with X-ray imaging. The AOFAS score of each fracture was evaluated 3 months postoperatively.

Outcomes

Age and sex were recorded. Preoperative and postoperative radiographic parameters (calcaneal length, width, height, and Böhler angle) were measured. The radiographic parameters were measured with Picture Archiving and Communication Systems by a doctor who was not involved in the surgeries. Each parameter was measured three times, and the average was recorded for the final analysis. Kendall's W coefficients were all >0.9, indicating high interobserver reliability in our measurements. The operation time was documented in the operative notes. All operation times started from making the incision to wound packing. The preoperative waiting time and length of hospital stay after the operation were recorded. Wound complications were recorded according to the follow-up results.

Statistical Analysis

A descriptive analysis was performed. Categorical variables were expressed as numbers and percentages. Continuous variables were expressed as mean and standard deviation for normal distributions or median and interquartile range for skewed distributions. The chi-square test, one-way analysis of variance, and Wilcoxon test were used for the comparison of categorical, normally distributed, and nonnormally distributed continuous variables, respectively. SPSS 23.0 software (SPSS) was used for statistical analysis.

Results

The study enrolled 26 patients with 28 calcaneal fractures; 15 fractures were allocated to the RA surgery group and 13 fractures to the ORIF group. No significant differences in sex distribution and age were found (Table 1). However, the operation time ($p < 0.001$), preoperative waiting time ($p < 0.001$), and length of postoperative hospital stay ($p = 0.003$) in the RA surgery group were significantly shorter than those in the ORIF group. Moreover, the rate of open reduction in the RA surgery group was significantly less than that in the ORIF group ($p < 0.001$) (Table 2).

TABLE 1 General preoperative information of the patients in the two groups

	Total ($n = 28$)	ORIF ($n = 13$)	Robot-assisted ($n = 15$)	*p*-value
Sex, *n* (%)				0.6
Female	4 (14.3)	1 (7.7)	3 (20)	
Male	24 (85.7)	12 (92.3)	12 (80)	
Age, mean ± SD	45.64 ± 10.28	46.15 ± 9.25	45.20 ± 11.40	0.812

TABLE 2 Operative information of the patients in the two groups

	Total (n = 28)	ORIF (n = 13)	Robot-assisted = 15	p-value
Operation time, median (IQR)	67.5 (35.0, 80.0)	80.0 (70.0, 90.0)	35.0 (30.0, 42.5)	<0.001*
Preoperative waiting time, median (IQR)	7.0 (4.8, 8.5)	8.0 (7.0, 10.0)	5.0 (3.0, 6.0)	<0.001*
Length of stay after the operation, mean ± SD	4.07 ± 2.43	5.46 ± 2.82	2.87 ± 1.13	0.003*
Open reduction, n (%)	16 (57.1)	13 (100)	3 (20)	<0.001*

* p-value which is minor than 0.05 was marked with "*". It showed that there was statistic difference.

TABLE 3 Comparison of radiographic parameters before and after the operation

	Methods	Preoperative	Postoperative	p-value
Böhler angle	ORIF	7.91 ± 18.19	26.16 ± 3.96	0.002*
	Robot-assisted	10.70 ± 12.85	27.16 ± 3.45	<0.001*
Length	ORIF	80.73 ± 4.65	82.85 ± 4.87	0.269
	Robot-assisted	79.83 ± 4.05	81.64 ± 4.06	0.230
Width	ORIF	45.51 ± 4.41	39.54 ± 2.60	<0.001*
	Robot-assisted	45.06 ± 4.78	40.63 ± 2.31	0.004*
Height	ORIF	38.57 ± 5.63	45.72 ± 3.26	<0.001*
	Robot-assisted	36.91 ± 4.95	44.23 ± 2.81	<0.001*

* p-value which is minor than 0.05 was marked with "*". It showed that there was statistic difference.

TABLE 4 Comparison of radiographic parameters between the two groups

	Total (n = 28)	ORIF (n = 13)	Robot-assisted (n = 15)	p-value
Pre operation				
Böhler, mean ± SD	9.41 ± 15.32	7.91 ± 18.19	10.70 ± 12.85	0.639
Length, mean ± SD	80.25 ± 4.28	80.73 ± 4.65	79.83 ± 4.05	0.588
Width, mean ± SD	45.27 ± 4.53	45.51 ± 4.41	45.06 ± 4.78	0.800
Height, mean ± SD	37.68 ± 5.24	38.57 ± 5.63	36.91 ± 4.95	0.413
Post operation				
Böhler, mean ± SD	26.69 ± 3.66	26.16 ± 3.96	27.16 ± 3.45	0.483
Length, mean ± SD	82.20 ± 4.41	82.85 ± 4.87	81.64 ± 4.06	0.482
Width, mean ± SD	40.63 ± 2.31	39.54 ± 2.60	40.63 ± 2.31	0.262
Height, mean ± SD	44.92 ± 3.06	45.72 ± 3.26	44.23 ± 2.81	0.205
Fixation rate of the sustentaculum tali, n (%)	19 (67.9)	4 (30.8)	15 (100)	<0.001*

* p-value which is minor than 0.05 was marked with "*". It showed that there was statistic difference.

TABLE 5 Wound complications

	Total (n = 28)	ORIF (n = 13)	Robot-assisted (n = 15)	p-value
Total	4 (14.3%)	4 (30.8%)	0	0.035*
Marginal necrosis	1 (3.6%)	1 (7.7%)	0	
Superficial infection	1 (3.6%)	1 (7.7%)	0	
Deep infection	2 (7.2%)	2 (15.4%)	0	
Nerve injury	0	0	0	

* p-value which is minor than 0.05 was marked with "*". It showed that there was statistic difference.

TABLE 6 Comparison of AOFAS scores at 3 months postoperatively

	Total (n = 28)	ORIF (n = 13)	Robot-assisted (n = 15)	p-value
AOFAS, mean ± SD	76.21 ± 7.79	75.15 ± 4.78	77.13 ± 4.78	0.284

Radiographic Parameters

The calcaneal width, height, and Böhler angle in both groups were significantly corrected postoperatively. Although the calcaneal length was also corrected, no significant difference was found between the preoperative and postoperative ones in both groups (Table 3). No significant differences were observed in preoperative and postoperative values between the two groups (Table 4).

Complications and Follow-Up

Postoperative complications occurred in four patients (Table 5), which all occurred in the ORIF group. One patient had wound edge necrosis that was cured with the dressing change. Three patients had wound infections, two of whom had superficial infections. The incisions had delayed healing after the dressing change. One patient had a deep infection involving the implant, the implant was removed 3 months postoperatively, and the incision finally healed. No nerve injury occurred in either group. All fractures healed within 3 months. The AOFAS score at 3 months postoperatively in the RA surgery group was slightly higher than that in the ORIF group; however, no significant difference was observed (Table 6).

Discussion

In this retrospective study, both groups achieved satisfactory reduction. RA percutaneous fixation was significantly superior to ORIF in terms of the fixation rate of the sustentaculum tali. It was the main advantage of the TiRobot system. No postoperative wound healing complication occurred in the RA surgery group with decreased open reduction rate. It may be because of the combination of RA surgery and percutaneous technology. RA surgery was inferior to ORIF in terms of preoperative waiting time and length of stay postoperatively. It was the advantage of percutaneous fixation because it could be performed in patients with soft tissue compromise.[12]

Advantages of the TiRobot

Owing to the limited space inside the calcaneus, placing multiple screws in a satisfactory position without interference is difficult when using general percutaneous techniques.[9,14] The controlling workstation of this third-generation TiRobot can real-time monitor the screw position and correct the guide wire insertion within 1 mm. The optical tracking system monitors the relative movement between the mechanical arm and the patient and determines the entry point. Finally, the mechanical arm controls the direction of the guide wire. This system enhances the accuracy of the screw position.[13]

Exposing the middle portion of the posterior articular facet, even with open reduction, is difficult because of the irregular structure of the calcaneus, which leads to poor reduction and influences long-term recovery. RA surgery has the superiority of confirming the articular surface reduction in intraoperative CT without extrainvasive procedures. Moreover, a close reduction becomes possible in some DIACFs with RA technology. Surgeons can reduce the fractures closely with Kirschner wires through the planned path of the TiRobot. Less dissection leads to fewer wound complications.

Biomechanics of Calcaneal Fractures

Some studies have demonstrated that the fixation of calcaneal fractures with cannulated screws provides adequate biomechanical stability.[15,16] The bone mineral density is better in the calcaneal tubercle and medial wall, especially at the site of the sustentaculum tali. The medial portion of the talocalcaneal joint forms a fragment containing the sustentaculum tali (sustentacular fragment), which is usually nondisplaced in relation to the talus because the intact strong interosseal ligaments prevent any significant displacement of the fragment. However, the lateral joint fragment is often grossly displaced and impacted into the body of the calcaneus. It is also the site of stress concentration with weight-bearing. Therefore, the screw should be inserted into the sustentaculum tali.[14,17] The collapsed articular surface also needs adequate support to maintain its position. In this study, all RA surgeries involved the placement of one to two screws to fix the sustentaculum tali. However, the fixation rate in the ORIF group was only 30.4%. In addition, the screw distribution may change according to the fracture morphology, and screws should be placed in bone-dense areas such as the calcaneal tubercle, sustentaculum tali, and posterior articular surface of the calcaneus.[18] With traditional technology, we have to fix freehand the sustentaculum tali and confirm the position using fluoroscopy. Several studies have confirmed the high misplacement rate of sustentacular screws in the sustentaculum tali.[14,19] Higher loading of bone tissue and greater shifting among the fragments were observed when the sustentacular screw was absent.[14] Thus, the ability to accurately fix the sustentaculum tali in RA surgery is an immense advantage in treating calcaneal fractures.

Advantage of Percutaneous Screw Fixation

The objective of surgical treatment of calcaneal fractures is to restore the alignment of the foot and reduce the collapsed articular surface.[6] The traditional extension lateral approach provides sufficient visual for fixation, but it is also associated with complications such as poor wound healing, marginal necrosis, and infection.[20] In this study, all four patients with wound complications were treated using the extended lateral approach. Percutaneous cannulated screw fixation makes it possible for close reduction and fixation. All postoperative radiographic parameters (calcaneal length, width, height, and Böhler angle) showed no difference between the groups. Significant differences were found when compared with preoperative values, except for the calcaneal length. This means that both techniques can achieve reduction, and the effect is comparable. However, only three patients in the RA surgery group had open reduction with the tarsal sinus approach. The recovery may be better in patients with close reduction because of ligament conservation.[21] Percutaneous fixation is not affected by soft tissue conditions[14]; therefore, the preoperative waiting time is shorter. In addition, the length of stay in the hospital after the operation is shorter in the RA surgery group because of the better postoperative soft conditions. The shorter operation time in the RA surgery group may be associated with decreased intraoperative fluoroscopy, exposure, fixation attempt, and suture time. The shorter operation time leads to fewer complications and better recovery.

Limitations

This study has several limitations. The study used a new technology based on TiRobot and included a small sample size. This is a retrospective study, so there may be some biases in the group allocation, such as the selection of easy fractures in the RA surgery group. Only the 3-month AOFAS was evaluated. In this study, the AOFAS score was slightly lower than those in others because of the short-term follow-up. This study lays a foundation for future studies to further clarify the advantage of RA percutaneous screw fixation. Furthermore, a well-designed prospective study with a larger sample and long-term follow-up is necessary.

Conclusion

RA percutaneous screw fixation is a safe and effective option for surgeons in the treatment of calcaneal fractures. Both RA surgery and ORIF are comparable in terms of fracture reduction and functional evaluation. However, with RA technology, surgeons can put the screws rapidly, accurately, and with minimal invasion. Further randomized prospective clinical trials with a large sample and long-term follow-up are required.

Author Contributions

Conceptualization, supervision, validation: Jing Wang and Wei Han. Funding acquisition and project administration: Junqiang Wang and Xieyuan Jiang. Methodology, investigation, formal analysis and data curation: Junqiang Wang and Yonggang Su.

Ethical Approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the Beijing Jishuitan Hospital Ethical Committee and the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all study participants.

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