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Robot-assisted percutaneous scaphoid fixation: patient-reported outcomes and learning curve at two centres

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Abstract

This study describes patient-reported outcomes of robot-assisted percutaneous scaphoid fracture fixation of 62 patients from two medical centres and the learning curve of this new technique. One attempt to place the guidewire was sufficient in 97% of cases. All fractures achieved radiographic union at a mean of 9 weeks. There were no complications observed. At a mean follow-up of 36 months (range 12–68 months), the mean patient-rated wrist evaluation (PRWE) was 2 (range 0–22) and the mean Mayo Wrist Score was 96 (range 70–100). After the initial ten to 20 cases, the learning phase was reasonably surmountable with a marked reduction of operative duration and improvement of the screw accuracy.

Level of evidence: IV

Keywords

bony union, computer-assisted surgery, learning curve, percutaneous fixation, robotic surgical procedures, scaphoid fractures

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Introduction

Scaphoid fractures account for 60%–90% of all carpal fractures (Brogan et al., 2015; Tysver and Jawa, 2010) and predominantly affect young people. Percutaneous screw fixation is an ideal surgical method for non- or minimally displaced scaphoid fractures, with shorter time to union compared to conservative management (Alnaeem et al., 2016). Traditional freehand percutaneous scaphoid fracture fixation (SFF) under two-dimensional (2-D) fluoroscopic guidance requires a thorough understanding of the scaphoid's three-dimensional (3-D) morphology. It also requires excellent intraoperative planning capacity and punctilious surgical technique (Luchetti et al., 2018) that can prove challenging even in experienced hands. Suboptimal screw placement is common and can lead to unacceptable outcomes such as poor fracture stability or screw penetration through the far cortex of the scaphoid (Bond et al., 2001; Dias et al., 2020).

Computer-assisted freehand surgery for SFF has demonstrated safety and accuracy among skilled surgeons, but there is a steep learning curve and potential implant inaccuracy (Liverneaux et al., 2008; Walsh et al., 2009). With robotic technologies, errors were less than with freehand SFF (Guo et al., 2022). Moreover, robot-assisted spine surgery offers advantages during pedicle screw insertion

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(Tian et al., 2014) and sacroiliac screw fixation (Wang et al., 2017). These advantages include intraoperative multidimensional guidance for accurate screw placement and the lack of human physiological limitations such as fatigue and loss of dexterity. We previously published our experience with ten cases of robot-assisted SFF and demonstrated the feasibility and efficacy of this technique (Liu et al. 2019). The cases came from a single hospital with less than 6 months of follow-up.

The learning curves for different robot-assisted surgeries have been closely investigated because it is important to understand whether experience has an influence on the execution of these new surgical procedures. Understanding this will help establish guidelines for the number of supervised operations required for surgeons to master this technique (Soomro et al., 2020).

In the present study, we aimed to report the radiological results, patient-reported outcomes, and learning curve analysis of robot-assisted SFF in a larger number of patients from two medical centres and a longer follow-up.

Methods

This was a double-centre retrospective study, and written consent was obtained from all the patient participants. The ethics committee of both local hospitals involved in this study approved the study (K2022-111-01 and RC201911001). The surgical procedures were performed by two dedicated hand surgeons (surgeons A and B) from two different hospitals. Surgeon A (BL) was of level-five expertise and surgeon B (WQ) was of level-three expertise according to Tang and Giddins (2016). Because surgeon A pioneered this procedure, surgeon B observed surgeon A's workflow and use of the robotic system prior to embarking on his own branch of the experiment. Neither surgeon had performed this type of surgery on other patients prior to this study.

Patients

All patients underwent a preoperative CT scan to assess the fracture configuration. Inclusion criteria for this study were skeletally mature patients (aged 16 years or older) with acute, bicortical, non- or minimally displaced scaphoid waist fractures undergoing robot-assisted percutaneous single screw SFF. The exclusion criteria included: (1) moderately or severely displaced scaphoid fractures; (2) history of previous surgery or additional pathologies of the affected upper limb (e.g. distal radial fractures or dislocations in this injured hand); (3) severe preoperative comorbidities; and (4) coagulopathic conditions.

Surgical technique

Details on the steps of this surgical procedure has been described in previous studies (Liu et al., 2019; Yi et al., 2023). The injured wrist was extended and firmly fixed onto a custom-made wrist jig with a mounted reference tracker. A fluoroscopy unit was used for 3-D image capture, and a commercial robotic system (TiRobot, TINAVI Medical Technologies, Beijing, China) (Figure 1(a), (b)), was used for surgical planning and screw insertion. The acquired 3-D images were transferred to the robotic workstation and reconstructed in the coronal, sagittal and axial planes. The surgeon can determine the optimal trajectory and length of the scaphoid screw based on the reconstructed 3-D images in the workstation (Figure 1(c)).

A 0.5-cm incision was made and a wire aiming guide was placed on the distal pole of the scaphoid. The robotic arm moved automatically in response to the commands that were made at the robotic workstation by the surgeon. The guidewire and cannulated drill were inserted in this preplanned trajectory (Figure 1(d)) and a headless cannulated compression screw was inserted.

Unacceptable guidewire placement was defined as the guidewire not being in the central third of the scaphoid waist based on both posteroanterior and lateral radiographs taken intraoperatively. If encountered, replanning would be performed at the surgical workstation, and a second robot-assisted attempt was done.

Postoperatively, a removable short-arm thermoplastic splint was used for protection for a total of 8 weeks, but patients were allowed to engage in non-weight-bearing gentle wrist motion exercises under the guidance of surgeons or physical therapists in the early postoperative period. All patients were reviewed at regular intervals until fracture union was confirmed by CT scans. We checked for the presence of screw penetration by obtaining fluoroscopic posteroanterior, lateral, semi-pronation and semi-supination images in the outpatient clinic. At least 50% of continuous trabecular bridging across the fracture site in the CT scans was considered to be evidence of radiographic union, sufficient for mobilization (Li et al., 2023).

Assessment of the accuracy of the screw placement

The accuracy of the screw placement was evaluated based on the postoperative CT images with Mimics,

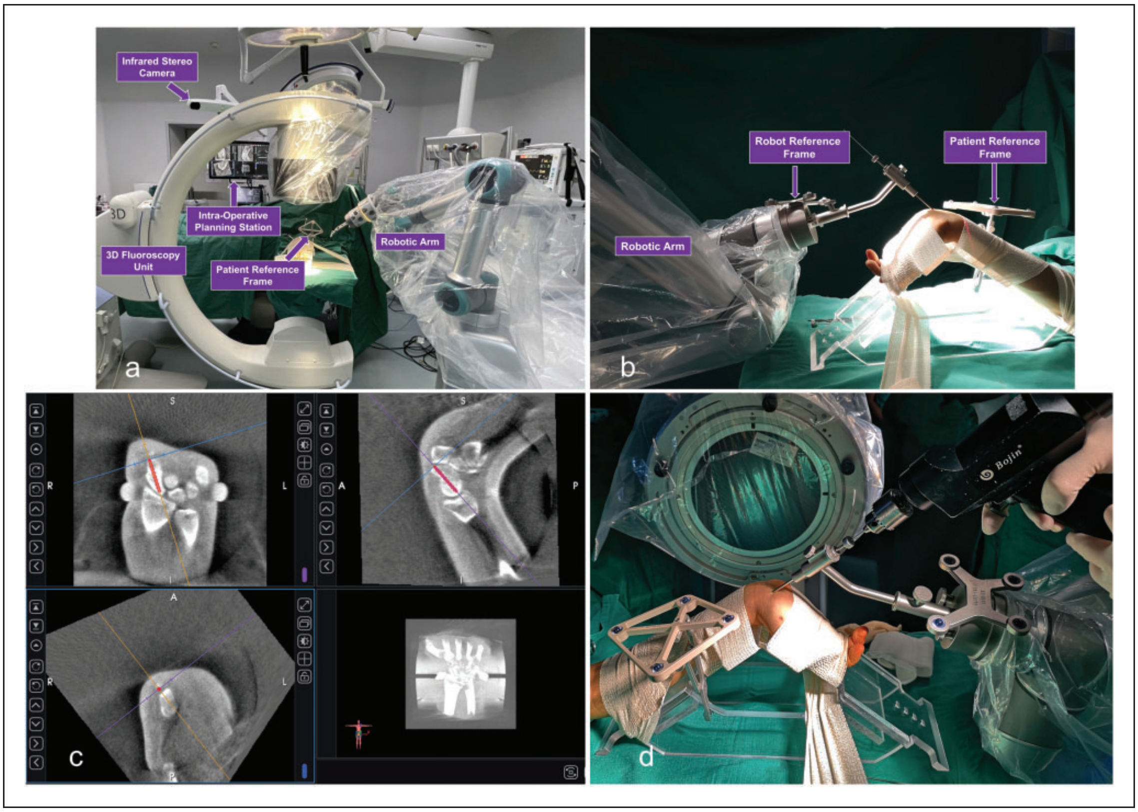

Figure 1. The process of robot-assisted percutaneous scaphoid fracture fixation. (a, b) Set-up of the surgical equipment. (c) The surgical planning software in the TiRobot workstation and (d) A 1.1-mm guidewire is advanced into the scaphoid along the planned path via the wire aiming guide attached to the robotic arm.

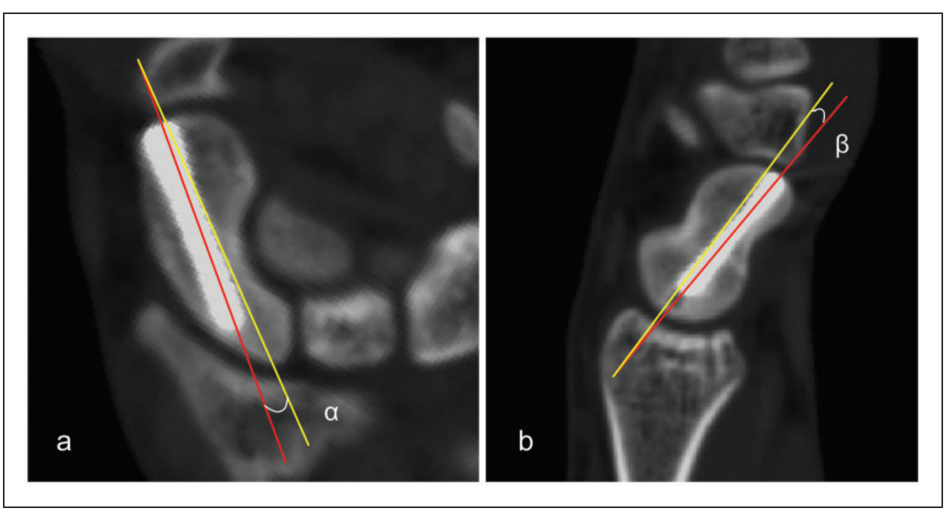

Figure 2. Accuracy of screw placement on postoperative CT images of the scaphoid is determined by the α and β angles between the long axis of the scaphoid (yellow line) and the screw (red line). (a) α angle in the coronal view and (b) β angle in the sagittal view.

version 21.0 (Materialise NV, Leuven, Belgium) by an observer (ZY) who had not performed the robotic SFF. The accuracy of the screw placement was defined by two angles, α and β, between the long axis of the scaphoid and the screw in the coronal and sagittal plane, respectively (Figure 2). The long axis of the scaphoid in the coronal view was defined as a line between the centre of the distal tuberosity and the most convex point of the proximal pole of the scaphoid according to Hoffmann et al. (2015), and we defined the long axis of the scaphoid in the lateral view as a line between the centre of the distal and the proximal cortex of the scaphoid.

Data such as patient demographics and operative duration were collected from the personal databases of the two surgeons and the patient record systems of the two hospitals by two of the authors (ZY and WC). At the latest follow-up, patient-reported outcome data, including visual analogue scale score for pain, PRWE (MacDermid et al., 1998) and Mayo Wrist Score (Cooney et al., 1987) were assessed by telephone or questionnaire. No patients were lost to follow-up.

Learning curve assessment

The overall operative duration was determined to be from the point of skin preparation to confirmation of satisfactory placement of the implant. This includes the time taken to set-up the robot, planning of the implant placement using the workstation, guidewire insertion and screw implantation. Operation duration had been monitored by the surgical teams of both surgeons. Fitting the cumulative sum (CUSUM) method was used to determine the turning point of the learning curve based on the operative duration and accuracy of the screw placement (Yu et al., 2021). The CUSUM method calculates the cumulative sum of the difference between the observed value and the target value in the process of acquiring skills. It takes into consideration complete information of the sample sequence, providing exact judgement of the learning curve. The turning point of the CUSUM curve indicates the minimum number of cases required to exhibit mastery of the technique (Bolsin and Colson, 2000).

For each surgeon, the CUSUM value of the operative duration ($CUSUM_T$) of his first patient was operative duration (T_1) minus the mean operative duration (M_T); the $CUSUM_T$ value of the other case was as follows: $CUSUM_{(n)} = T_{(n)} - M_T + CUSUM_{(n-1)}$. This formula was used to compute data for all the scaphoid cases, and polynomial curve fitting was performed on $CUSUM_T$ to calculate the model's fit. The turning point of $CUSUM_T$ fitting curve is the transition point between a rise and fall of the curve followed by the descent. This is indicative of the minimum number of surgical cases required to cross the learning phase. Early stage (the initial learning stage) and late stage (the proficiency stage) were divided according to this turning point (Yu et al., 2021). Operative duration and accuracy of the screw placement were then compared between the two stages. One of the authors (ZY) assessed the learning curve independently from the surgeons who performed the robotic operations.

Statistical analysis

The Shapiro–Wilk test was used to test the normality of continuous variables. Normally distributed variables, such as operative duration and screw accuracy (α angle and β angle), were presented by the means (SD) and an independent sample *t*-test was used for comparison between groups. Non-normally distributed variables were reported by median and IQR, and comparison between groups was performed using the Wilcoxon rank sum test. Intergroup *p*-values were defined as the comparison between all patients' data of surgeon A and all patients' data of surgeon B. $p < 0.05$ was considered statistically significant. The model fitting of the learning curve was performed on the horizontal axis – number of cases and the vertical axis – CUSUM value. R^2 (the fitting coefficient) was used to judge the quality of the curve fitting. The curve fitting was judged to be successful when $p < 0.05$.

Results

From July 2018 to January 2023, 62 consecutive patients were included in this study, of whom 32 came from surgeon A's centre and 30 came from surgeon B's centre. Short-term outcomes of the first ten patients operated by surgeon A have been published previously (Liu et al., 2019). Table 1 demonstrates the patients' demographics and their patient-reported outcomes at a mean follow-up of 3 years. Acceptable guidewire placement on the first attempt was achieved in 60 of the 62 patients. In both cases of unacceptable placement, the orientation of guidewires deviated from the central axis of

Table 1. Demographics and functional outcome scores of 62 patients with scaphoid fractures treated with robot-assisted percutaneous scaphoid fixation.

Variable	Value
Age (years)	33 (16–66)
Sex (male)	56 (90)
Dominant side affected	32 (52)
Duration from injury to surgery (days)	6.5 (1–26)
Operative duration (minutes)	32 (15–75)
Follow-up (months)	36 (12–68)
Visual analogue scale for pain	0.4 (0–4)
Patient-rated wrist evaluation	1.6 (0–22)
Mayo Wrist Score	96.3 (70–100)

Data expressed as *n* (%) or mean (range).

the scaphoid. Replanning was performed at the surgical workstation, and a second robot-assisted attempt was done. There were no cases that required more than two attempts. All fractures achieved radiographic union at a mean of 9 weeks (range 7–16 weeks). No postoperative complications, such as screw penetration of the scaphoid cortex were observed in any of our patients.

The learning curves for surgeons A and B based on operative duration and screw accuracy are presented in Figure 3. The learning curves were divided into two stages based on the shape of the curve (Figure 3(b) and 3(d)). For surgeon A, the first 11 cases were in the early stage as the $CUSUM_T$ fitting curve continued to rise, representing the initial learning of the operative technique. Thereafter, from the case 12 onwards, the learning curve transitioned to the late stage as the $CUSUM_T$ fitting curve continued to decline, representing mastery of the operative technique (Figure 3(b)). As for surgeon B, the turning point was at case 10, as shown in Figure 3(d).

The accuracy of the screw placement of 62 patients expressed with a mean (SD) α angle of 6° (3.6°) and a mean (SD) β angle of 6° (3.4°). There was no turning point found in the learning curves based on the accuracy of the screw placement of the α angle for both surgeons. For β angle, the turning point of the learning curves was at case 7 in surgeon A, and case 17 in surgeon B (Figure 4).

The comparison of the variables in the early and late stages of the learning curves based on operative duration for both surgeons is shown in Table 2. The operative duration of surgeon B in the late stage was significantly less than that in the early stage ($p = 0.01$). No significant difference was found in operative duration between surgeons A and B ($p > 0.05$). In terms of screw accuracy, only the β angle of surgeon A was significantly smaller than that of surgeon B ($p < 0.001$) and there was no significant difference between the α angle of surgeons A and B ($p = 0.35$).

Discussion

Our present study showed that the robot-assisted SFF technique is safe, reproducible and can accurately place implants into the scaphoid with a low number of guidewire attempts. The accuracy of the screw placement in our case series of 62 patients expressed with a mean (SD) α angle of 6° (3.6°) and a mean (SD) β angle of 6° (3.4°) was comparable with

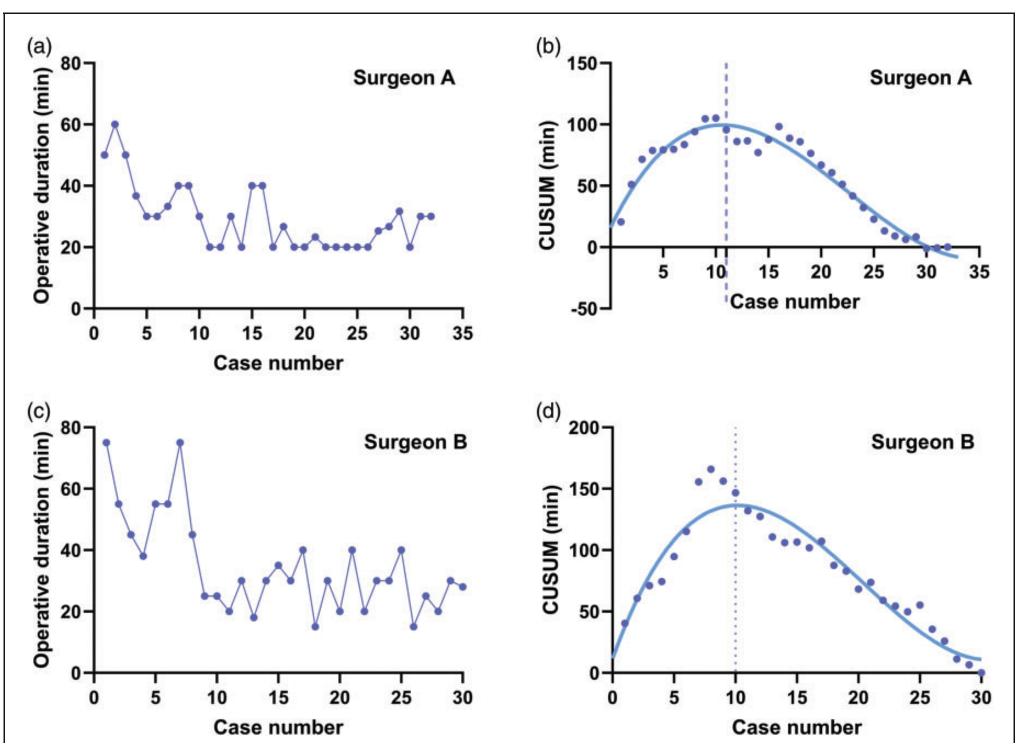

Figure 3. Scatter plot graphs of the operative duration and learning curve of the two surgeons. (a) Operative duration for surgeon A. (b) Learning curve of surgeon A. (c) Operative duration for surgeon B and (d) Learning curve of surgeon B. CUSUM: cumulative sum.

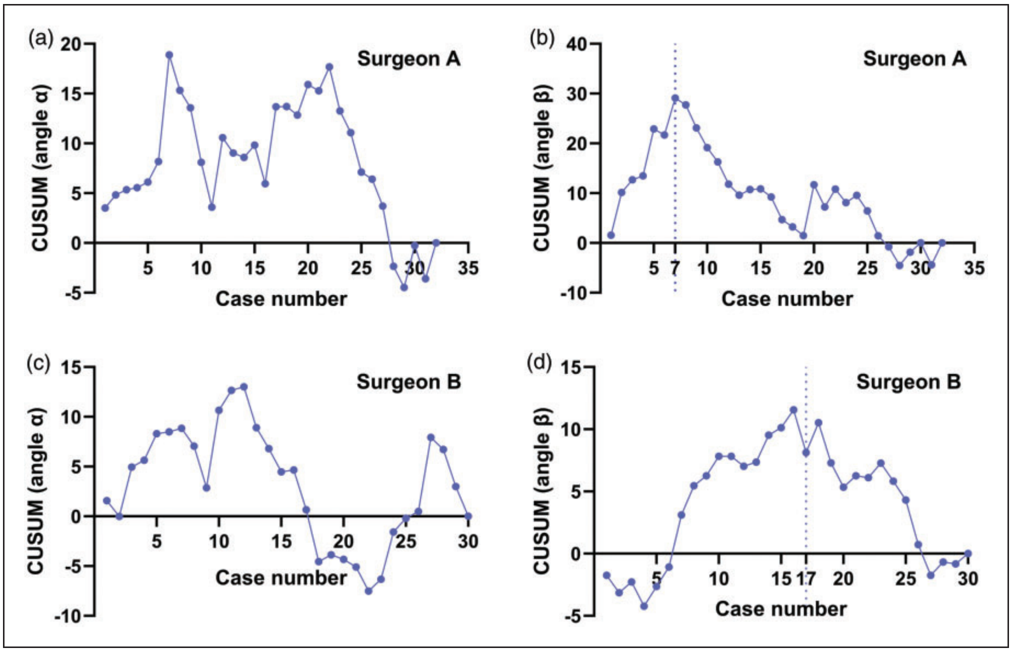

Figure 4. (a) Learning curve of surgeon A in the coronal plane based on the α angle and (b) in the sagittal plane based on the β angle. (c) Learning curve of surgeon B in the coronal plane (α angle) and (d) in the sagittal plane (β angle). CUSUM: cumulative sum.

Table 2. Comparison of operation duration and screw accuracy in the early and late stages of learning curves of both surgeons.

	Surgeon A			Surgeon B			
	Early stage	Late stage	Subgroup *p*-value	Early stage	Late stage	Subgroup *p*-value	Inter-group *p*-value
Number of cases	11	21		10	20		
Operative duration (minutes)	38 (12)	25 (7)	0.06	49 (18)	27 (8)	0.01	0.06
Screw accuracy							
α (°)	6.8 (4.5)	6.3 (3.7)	0.89	7.0 (3.5)	5.4 (3.1)	0.81	0.35
β (°)	7.2 (5.0)	5.0 (3.8)	0.27	6.7 (2.0)	5.5 (1.8)	0.91	<0.001

Data are expressed as means (SD). α and β represent the angles between the long axis of the scaphoid and the screw in the coronal and sagittal plane, respectively.

a previous case series of nine patients (mean (SD) α angle of 4° (0.8°) and mean (SD) β angle of 4° (0.8°)) (Xiao et al., 2023).

It is necessary to determine whether experience has an influence on the execution of the robot-assisted SFF and, if so, to provide guidelines on the number of supervised operations required for surgeons who are new to this technique. For example, in robotic spine surgery, Schatlo et al. (2015) found that inaccurate screw placement mainly occurred between cases 10 and 20 in robot-assisted pedicle screws placement. This finding made them advocate for supervision in the initial 25 operations for surgeons who are starting out. Similarly, Yu et al. (2021) described the initial learning stage of robot-assisted pedicle screw fixation to be surmountable after completing 17 to 18 operations.

In our study, the two surgeons involved were from separate medical centres with different levels of expertise. We found that although surgeon A had a faster overall operative duration compared to surgeon B, and the turning points of the curves for each of them remained at the tenth to 11th operative case. Surgeons' level of experience may not be important in surmounting the learning curve for robotic hand surgery.

Our study found that in the CUSUM learning curves of both surgeons in the coronal plane (α angle) did not demonstrate an obvious turning point. The CUSUM learning curves in the sagittal plane (β angle), however, did show appreciable turning points at cases 7 and 17 of surgeons A and B, respectively. We postulate that this may be because the surgeon was required to manually plan the entry point of the guidewire insertion and optimal trajectory was determined in the coronal, sagittal and axial planes. Recognition and appreciation of the 3-D anatomical morphology of the scaphoid is paramount, and a surgeon's experience is contributory, which may be the reason for the surgeon A's better performance. In addition, most surgeons start off with being more familiar in using the coronal instead of the sagittal plane to judge the scaphoid screw trajectory. The sagittal plane and oblique views are more difficult to comprehend, which may be another reason why surgeon B, with relatively less experience, needed more cases to pass the learning phase, particularly on the screw accuracy in the sagittal plane.

During routine upper limb surgery, the affected limb needs to be extended and placed on an operating table, which is unstable. During robotic surgery, the relative micro-movement between the wrist and tracker after registration may introduce unacceptable errors, even if the wrist stabilization frame is applied. Despite the constraints of the robotic arm and sleeve, the surgeon's operating details may result in a deviation in the guidewire's direction. This could be the reason for the initial deviation of the guidewire during the two operations in which a second attempt was needed. After the robotic arm automatically moves to the planned position, soft tissue needs to be cut until the distal cortex of the scaphoid is exposed before inserting the sleeve. When the sleeve is close to the bone cortex, based on our clinical experience, we recommend that the robotic arm needs to be registered again. Gently driving the guidewire is key to minimizing the deviation and improving the accuracy of internal fixation.

Recently, artificial intelligence has been used to improve this area and leaves much room for further development. There have been studies demonstrating the use of learning image analysis technology and paired attention-enhanced adversarial model technology to achieve preliminary automation of scaphoid fracture patient image recognition and segmentation (Chen et al., 2021; Chen et al., 2023). Developing an automated and intelligent planning system for wrist fractures may further reduce the operative duration (especially the intraoperative planning time) and improve the accuracy and usability of robot-assisted wrist surgery.

The purchase of the TiRobot system is an investment for the hospital because it can be used not only in wrist surgeries, but also for spine, trauma and bone tumour cases (Li et al., 2024; Wang et al., 2017; Yu et al., 2021). This diffusess the financial burden to an institution. Robot-assisted SFF is more costly for patients compared to traditional freehand percutaneous fixation. Both the hospitals where surgeons A and B work charge approximately 1100 USD per use of this robotic system. In surgeon A's centre, the expenses from using the robotic system are mostly covered under the hospital insurance system, which markedly reduces the financial burden of the patients. Further popularization of the robots and expansion of medical insurance coverage will help to defray the upfront and running costs in larger specialist units through joint purchasing and usage agreements (Liu et al., 2019).

There are limitations to our study. It was a retrospective one and range of motion of the wrist and grip strength were not determined at final follow-up. We did not compare our outcomes with the traditional freehand technique; hence, no evidence could be provided in this study that outcomes were better with than without robot-assisted surgery. In addition, although both surgeons involved in this study had different levels of expertise, they were both accredited hand surgery specialists. One of the postulated merits of robotic surgery is to nullify the amount of expertise required for the surgery so that young or inexperienced surgeons could achieve safe and accurate placement of the screw into the scaphoid. Additional data from surgeons of lower levels of expertise would be required to prove this point. Robot-assisted percutaneous scaphoid fixation offers a viable and safe method for the treatment of scaphoid fractures with a low number of guidewire attempts required. After the first ten to 20 cases, the learning phase is reasonably surmountable with significant reduction of operative duration and improvement of implant accuracy. We therefore suggest close supervision during the first 20 cases for surgeons new to the technique.

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Ethical approval Ethical approval for this study was obtained from the institutional review board of Beijing Jishuitan Hospital (K2022-111-01) and Xuzhou Renci Hospital (RC201911001).

Informed consent Written informed consent was obtained from all the participants before the study.

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References

Alnaeem H, Aldekhayel S, Kanevsky J, Neel OF. A systematic review and meta-analysis examining the differences between nonsurgical management and percutaneous fixation of minimally and nondisplaced scaphoid fractures. J Hand Surg Am. 2016, 41: 1135–44.

Bolsin S, Colson M. The use of the cusum technique in the assessment of trainee competence in new procedures. Int J Qual Health Care. 2000, 12: 433–8.

Bond CD, Shin AY, McBride MT, Dao KD. Percutaneous screw fixation or cast immobilization for nondisplaced scaphoid fractures. J Bone Joint Surg Am. 2001, 83: 483–8.

Brogan DM, Moran SL, Shin AY. Outcomes of open reduction and internal fixation of acute proximal pole scaphoid fractures. Hand (N Y). 2015, 10: 227–32.

Chen C, Liu B, Zhou K et al. Csr-net: Cross-scale residual network for multi-objective scaphoid fracture segmentation. Comput Biol Med. 2021, 137: 104776.

Chen C, Qi S, Zhou K, Lu T, Ning H, Xiao R. Pairwise attention-enhanced adversarial model for automatic bone segmentation in ct images. Phys Med Biol. 2023, 68.

Cooney WP, Bussey R, Dobyns JH, Linscheid RL. Difficult wrist fractures. Perilunate fracture-dislocations of the wrist. Clin Orthop Relat Res. 1987, 214: 136–47.

Dias JJ, Brealey SD, Fairhurst C et al. Surgery versus cast immobilisation for adults with a bicortical fracture of the scaphoid waist (SWIFFT): A pragmatic, multicentre, open-label, randomised superiority trial. Lancet. 2020, 396: 390–401.

Guo Y, Ma W, Zlotolow D, Wang C, Tong D, Liu K. A comparison between robotic-assisted scaphoid screw fixation and a freehand technique for acute scaphoid fracture: a randomized, controlled trial. J Hand Surg Am. 2022, 47: 1172–9.

Hoffmann M, Reinsch OD, Petersen JP et al. Percutaneous antegrade scaphoid screw placement: a feasibility and accuracy analysis of a novel electromagnetic navigation technique versus a standard fluoroscopic method. Int J Med Robot. 2015, 11: 52–7.

Li K, Li J, Li Z et al. Robot-assisted percutaneous radiofrequency ablation for the treatment of osteoid osteomas. Orthop Surg. 2024, 16: 1246–51.

Li NY, Dennison DG, Shin AY, Pulos NA. Update to management of acute scaphoid fractures. J Am Acad Orthop Surg. 2023, 31: e550–e60.

Liu B, Wu F, Chen S, Jiang X, Tian W. Robot-assisted percutaneous scaphoid fracture fixation: a report of ten patients. J Hand Surg Eur. 2019, 44: 685–91.

Liverneaux PA, Gherissi A, Stefanelli MB. Kirschner wire placement in scaphoid bones using fluoroscopic navigation: a cadaver study comparing conventional techniques with navigation. Int J Med Robot. 2008, 4: 165–73.

Luchetti TJ, Hedroug Y, Fernandez JJ, Cohen MS, Wysocki RW. The morphology of proximal pole scaphoid fractures: implications for optimal screw placement. J Hand Surg Eur. 2018, 43: 73–9.

MacDermid JC, Turgeon T, Richards RS, Beadle M, Roth JH. Patient rating of wrist pain and disability: a reliable and valid measurement tool. J Orthop Trauma. 1998, 12: 577–86.

Schatlo B, Martinez R, Alaid A et al. Unskilled unawareness and the learning curve in robotic spine surgery. Acta Neurochir (Wien). 2015, 157: 1819–23.

Soomro NA, Hashimoto DA, Porteous AJ et al. Systematic review of learning curves in robot-assisted surgery. BJS Open. 2020, 4: 27–44.

Tang JB, Giddins G. Why and how to report surgeons' levels of expertise. J Hand Surg Eur. 2016, 41: 365–6.

Tian W, Han X, Liu B et al. A robot-assisted surgical system using a force-image control method for pedicle screw insertion. PLoS One. 2014, 9: e86346.

Tysver T, Jawa A. Fractures in brief: scaphoid fractures. Clin Orthop Relat Res. 2010, 468: 2553–5.

Walsh E, Crisco JJ, Wolfe SW. Computer-assisted navigation of volar percutaneous scaphoid placement. J Hand Surg Am. 2009, 34: 1722–8.

Wang JQ, Wang Y, Feng Y et al. Percutaneous sacroiliac screw placement: a prospective randomized comparison of robot-assisted navigation procedures with a conventional technique. Chin Med J (Engl). 2017, 130: 2527–34.

Xiao C, Wei D, Zhu Z et al. Robot-assisted vs traditional percutaneous freehand for the scaphoid fracture treatment: a retrospective study. Int Orthop. 2023, 47: 839–45.

Yi Z, Qi W, Chen S, Zhang Y, Liu B. A novel mini-invasive technique of arthroscopic-assisted reduction and robot-assisted fixation for trans-scaphoid perilunate fracture dislocations. Orthop Surg. 2023, 15: 1203–9.

Yu J, Zhang Q, Fan MX, Han XG, Liu B, Tian W. Learning curves of robot-assisted pedicle screw fixations based on the cumulative sum test. World J Clin Cases. 2021, 9: 10134–42.