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Full Length Article

JHS(E)

Journal of Hand Surgery
(European Volume)
0(0) 1–7
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DOI: 10.1177/1753193419848595
journals.sagepub.com/home/jhs
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Robot-assisted percutaneous scaphoid fracture fixation: a report of ten patients

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Abstract

This study reports the technique, efficacy and safety of robotic-assisted, computer-navigated, percutaneous fixation of scaphoid 手舟骨fractures. Ten males with acute undisplaced waist fractures underwent fixation with this method using a commercially available three-dimensional fluoroscopy unit and robotic navigation system. The mean total operative duration was 40 minutes, which comprised of a set-up time of 18 minutes and planning and surgical time of 22 minutes. All patients required only a single guidewire insertion attempt, and there were no screw protuberances螺钉突起 or other complications. All fractures united at a mean of 8 weeks. At a mean follow-up of 6.5 months (range 6–8), the mean Mayo wrist score was 96, patient-rated wrist evaluation was 2, flexion-extension arc 屈伸弧was 96% and grip strength 握力was 91% of the contralateral side对侧. We conclude from our patients that robotic-assisted percutaneous scaphoid fixation is feasible, safe and accurate, and is a satisfactory method for treating these injuries.

Level of evidence: IV

Keywords

Robotic surgical procedures, scaphoid, wrist injuries, computer-assisted surgery

Date received: 11th March 2019; revised: 9th April 2019; accepted: 14th April 2019

Introduction

Scaphoid fractures account for approximately 60% of all carpal fractures (Tysver and Jawa, 2010). Percutaneous fixation of this fracture is an alternative to open surgery (Walsh et al., 2009). However, this technique is technically demanding due to the small size and complex anatomy of the scaphoid. A suboptimal screw position can result in poor fracture stability and a longer time to union (Bond et al., 2001). The majority of the scaphoid is covered by articular cartilage关节软骨, which is at risk of damage if the screw does not reside wholly within the bone. As a result of these inherent difficulties, even in undisplaced waist fractures, the incidence of compli-cations is as high as 30% (Bushnell et al., 2007; Dias et al., 2005; Luchetti et al., 2018b; Suh and Grewal, 2018).

Studies have tried to reproducibly improve screw position within the scaphoid and to ensure complete intraosseous containment骨内封闭 of the screw (Levitz and Ring, 2005; McCallister et al., 2003). However, des-pite using modern fluoroscopic methods, an experienced hand surgeon can still struggle to accurately place the screw (Bushnell et al., 2007; Geurts et al., 2011; Suh and Grewal, 2018; Walsh et al., 2009). Computer-assisted navigation has been proven to be safe and effective for screw placement in pelvic and spine surgery and reduces operative time and radiation exposure (Day et al., 2007; Gebhard et al., 2006; Kim et al., 2008; Tian and Lang, 2010; Tian et al., 2017b). Cadaveric

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experiments have demonstrated computer-assisted navigation to be reproducibly accurate and reduces operative time in both volar and dorsal percutaneous scaphoid screw fixations (Kam and Greenberg, 2014; Walsh et al., 2009).

The aim of this study was to describe the technique and report the efficacy, accuracy and safety of using a similar robotic-assisted, computer-navigated technique for percutaneous fixation of the scaphoid in ten patients.

Methods

Patients and inclusion criteria

This study was performed at Beijing Ji Shui Tan Hospital, China, and was approved by the local institutional review board. The clinical records of all patients who underwent robotic-assisted, computer-navigated, percutaneous scaphoid fracture fixation with a minimum of 6 months follow-up were analysed.

All surgical procedures were performed by a single surgeon, a specialist with level IV expertise in the management of scaphoid fractures according to a classification system devised by Tang and Giddins (2016). The inclusion criteria for this technique were patients with acute, undisplaced, scaphoid waist fractures who had not had previous scaphoid surgery. All patients underwent preoperative computed tomography (CT) for assessment of fracture configuration.

Surgical technique

The patient is positioned supine 仰卧with the injured hand extended on a radiolucent arm table. Regional anaes-thesia麻醉 with an axillary brachial plexus block anaes-thesia is administered. No tourniquet is used. The wrist is extended and securely affixed to a custom-built, radiolucent, re-usable wrist positioning jig.

A three-dimensional (3-D) fluoroscopy unit (ISO-C^{3D}, Siemens, Erlangen, Germany) and TiRobot, a commercially available robotic navigation system (TINAVI Medical Technologies, Beijing, China) were used for 3-D image capture and K-wire guidance positioning. The TiRobot consists of a surgical planning workstation, a stereotactic robotic arm with six degrees of freedom and an optical tracking device. The optical tracking system consists of an infrared stereo camera and two reference frames, the patient reference and the robotic reference. The patient reference is securely fixed onto a dedicated attachment on the wrist positioning jig. The robotic reference frame is attached to the robotic arm

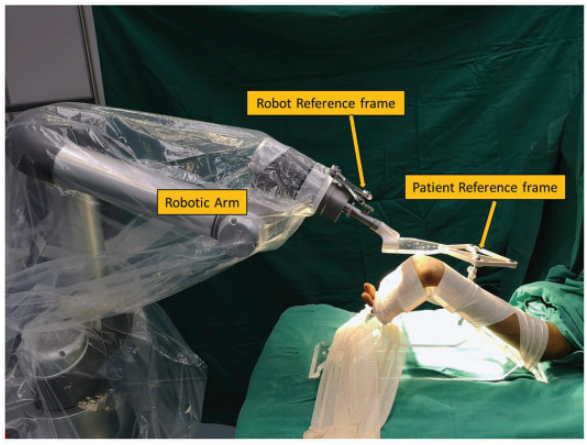

Figure 1. The wrist is extended and securely affixed to a wrist positioning jig. The patient reference frame is fixed onto the positioning jig. The robot reference frame is attached to the robotic arm.

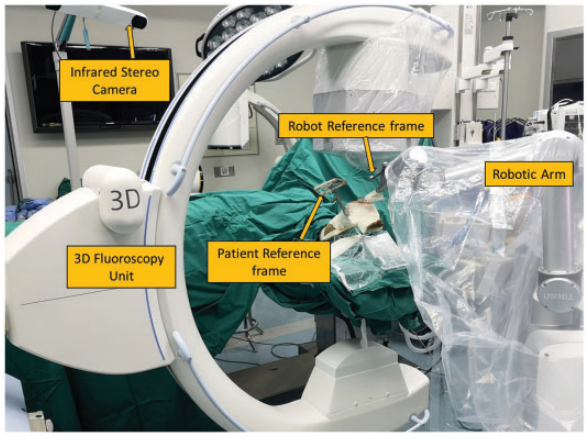

Figure 2. Intraoperative set-up of the surgical equipment. Care is taken to ensure all reference trackers can be detected by the optical tracking system before obtaining the registration scan.

(Figure 1). This enables the optical tracking system to identify the position of the robotic arm relative to the patient's wrist and to guide the arm to a planned position. The 3-D fluoroscopy unit consists of a C-arm reference tracker and a 3-D C-arm that collects circumferential images around the anatomic area of interest. The 3-D C-arm is positioned such that it can rotate unhindered through a 190° arc centring on the scaphoid (Figure 2). Once the reference frames and the C-arm are appropriately positioned, an automated registration scan is performed, which captures a set of 100 projections in fixed angular

steps as it rotates about the patient's wrist. The acquired images are processed and reconstructed in the sagittal, axial and coronal planes, which are then transferred to the TiRobot workstation to form a 3-D volumetric image for intraoperative planning.

Using the reconstructed 3-D data, the scaphoid is targeted on the TiRobot workstation, and a simulated path and length for percutaneous screw fixation is precisely visualized and planned with six degrees of freedom. The simulated insertion and target points are selected by the surgeon and modified in the sagittal, axial and coronal planes to achieve an optimal position within the central zone of the scaphoid (Figure 3). The 3-D data accurately model the volumetric dimensions of the scaphoid with an accuracy of less than 1 mm. This enables the TiRobot workstation to simulate different screw lengths to be implanted within the reconstructed 3-D visualization of the scaphoid along the optimal trajectory. The surgeon can thus choose an ideal screw length that provides 2 mm of clearance between the screw end and the scaphoid cortex, both proximally and distally (Slade et al., 2003). Once the optimal screw path and length are confirmed, the planning is communicated to the stereotactic robot arm and the attached effector gripper, which is robotically manoeuvred to the planned trajectory.

After the robotic arm is in position, a 0.5 cm incision is made over the distal pole of the scaphoid immediately under the effector gripper. A wire aiming guide is then introduced through the gripper to sit on the cortex of the scaphoid's distal pole (Figure 4). A 1.1-mm K-wire is advanced through the wire-aiming guide to the scaphoid, from the distal pole to the proximal pole cortex (Figure 5). The K-wire trajectory is checked by fluoroscopy, and a cannulated drill is used over the wire before inserting a headless compression screw (Mini Acutrak, Acumed, Hillsboro, OR, USA) of the planned length. Fluoroscopy is used for final evaluation of the screw position and length. The wound is closed with steri-strips and dressed with a soft bandage only, which is removed at 2 weeks following surgery.

Postoperative care and follow-up

Postoperatively, all patients undergo early mobilization under the guidance of a dedicated hand therapy team. Gentle range of motion of the fingers are permitted beginning 2 days after surgery. The patient

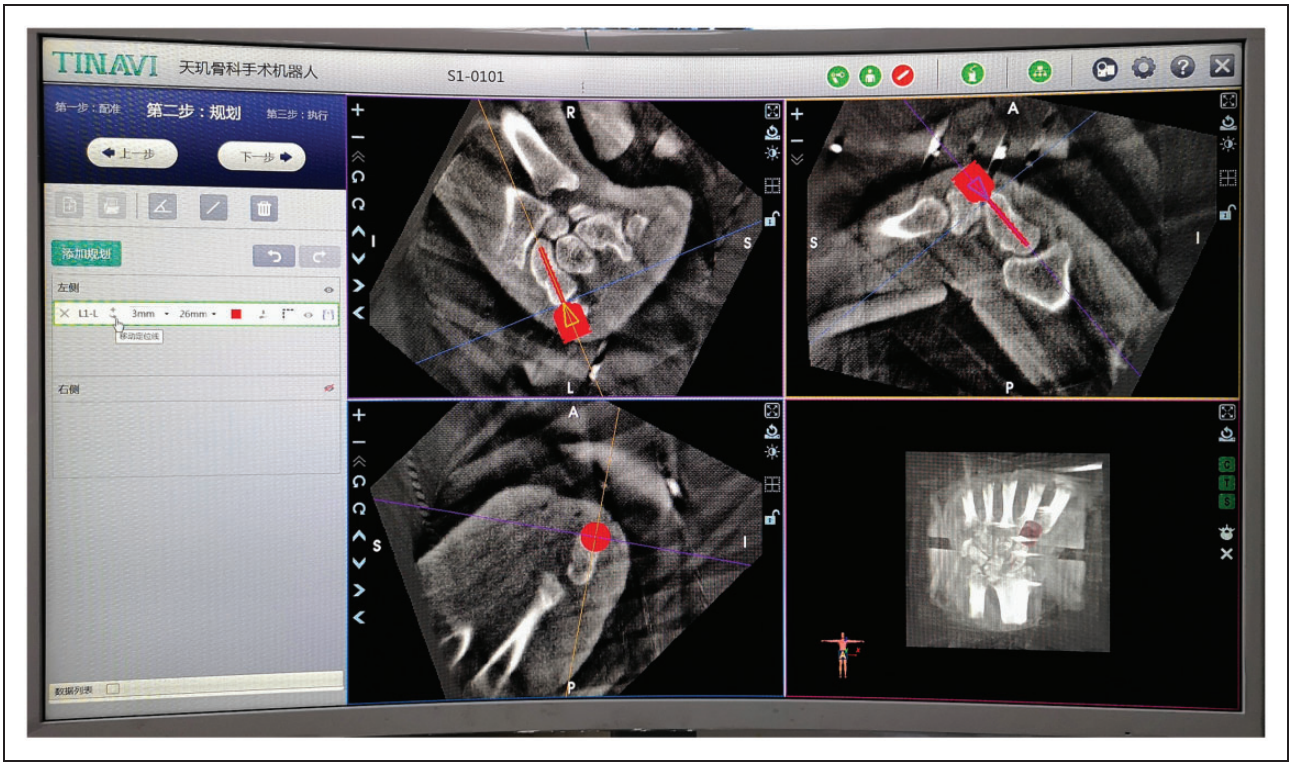

Figure 3. Graphical user interface of the surgical planning software in the TiRobot workstation. The surgeon can determine the optimal screw trajectory in the central zone of the scaphoid by modifying the screw path in the sagittal, axial and coronal planes.

Figure 4. The surgical planning is communicated to the stereotactic robot arm, which automatically manoeuvres an effector gripper attached to a K-wire aiming guide to the planned trajectory.

Figure 5. A 1.1-mm K-wire is advanced from distal to proximal through the wire aiming guide.

also starts wrist flexion–extension and radial–ulnar deviation exercises at the same time and gently increases the range under supervision. Weight-bearing of the operated hand was allowed after 4 weeks and increased over four more weeks.

Patients were reviewed at regular intervals until union was confirmed by CT scanning. The mean follow-up duration was 6.5 months (range 6–8 months). At the final review, the flexion–extension and radial–ulnar deviation range of the operated and contralateral wrists were measured. Grip strengths were assessed using a calibrated Jamar dynamometer (Asimov Engineering, Los Angeles, CA, USA). The Mayo wrist score and the patient-rated wrist evaluation (PRWE) were also recorded.

Results

Between January and September 2018, 10 patients underwent robot-assisted percutaneous scaphoid fixation. All patients were male. Three had injuries of the dominant wrist injuries. The mean age was 31 years (range 14–55). The mean duration between injury to surgery was 5 days (range 3–11). All injuries were nondisplaced scaphoid waist fractures.

Operating time

The mean total operative time was 40 min (range 27–56). This comprised of a mean set-up time of 18 min (range 11–30), which consisted of patient and equipment positioning and performing the registration scan, and a mean surgical time of 22 min (range 15–26), which included the steps from performing the intraoperative planning on the TiRobot workstation to skin closure. In all patients, only a single guide wire insertion attempt was needed.

Accuracy of screw placement during surgery

Postoperative X-ray and CT imaging showed that the implanted screw in each patient was within the central zone of the scaphoid, corresponding to the intraoperative planning from the workstation (Figure 6). The screw length used in each patient matched exactly with the planned length. There were no cases of cortical violations of either the proximal or distal pole. There were no intraoperative or postoperative complications.

Fracture healing time and functional recovery

The mean time to union was 8 weeks (range 7–10). Fracture union was confirmed by CT in all cases, which also confirmed that all screws remained in their original implanted positions. At final follow-up, the mean flexion–extension arc of the operated wrist was 96% (range 80–100%), and radial–ulnar deviation was 94% (range 90–100%) compared with the uninjured side. The mean grip strength was 91% (range 78–96%). The mean Mayo wrist score was 96 (range 85–100) and the mean PRWE was 2 (range 0–11). All patients returned to their original occupations.

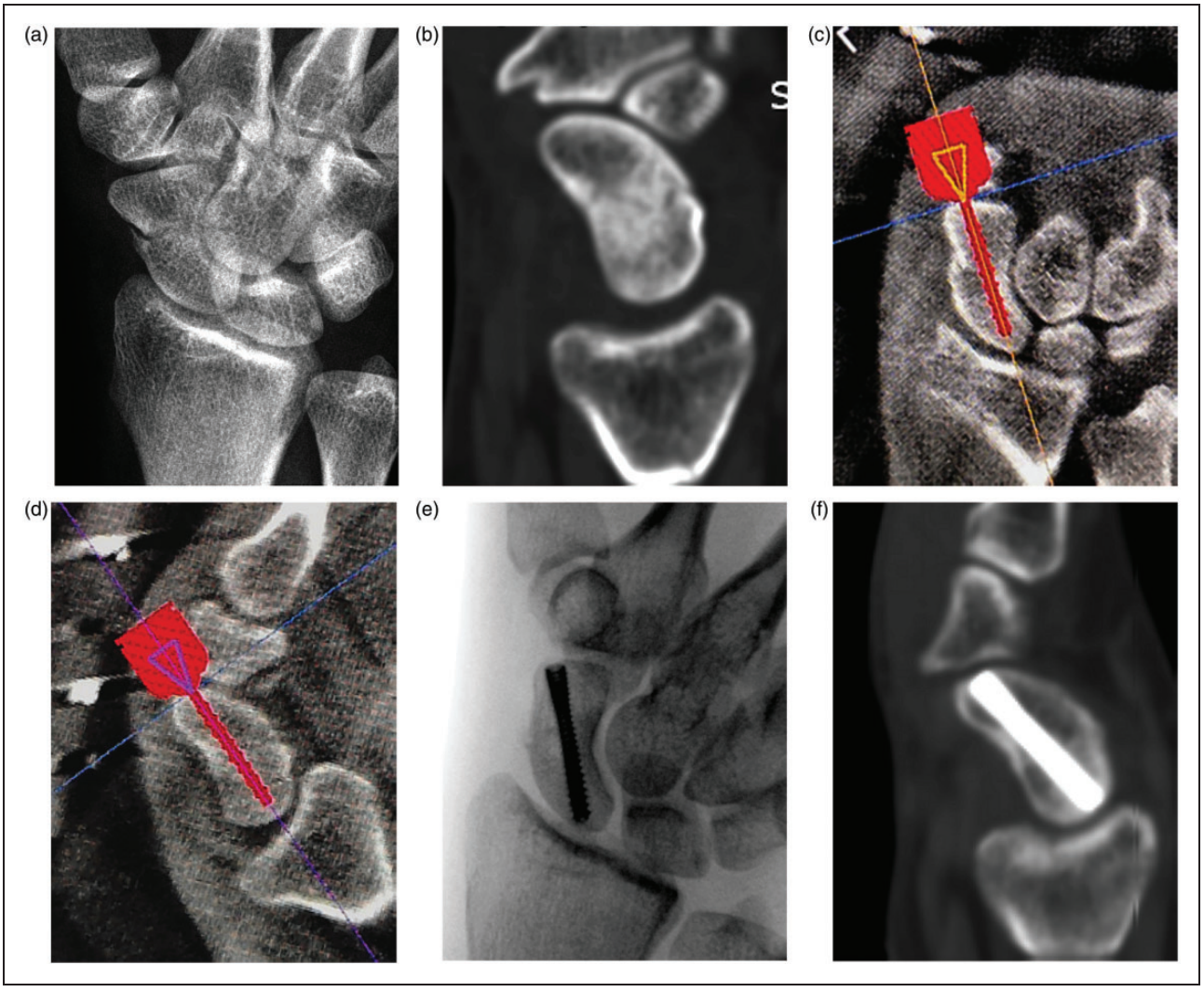

Figure 6. (a) and (b) X-ray and a sagittal CT reconstruction of a 6-day old undisplaced scaphoid waist fracture in a 35-year-old man. (c) and (d) The optimal positioning of the simulated screw in the sagittal and coronal planes determined by the surgeon during intraoperative planning. (e) and (f) X-ray and CT image at 2 months postoperatively. There was union of the fracture and the screw remained well implanted within the central zone of the scaphoid.

Discussion

Placement of a screw within the central axis of the scaphoid offers superior stiffness, increased load to displacement, greater mechanical stability, decreased time to union and a reduced risk of violating a cortical surface (Dodds et al., 2006; Luchetti et al., 2018a; McCallister et al., 2003; Suh and Grewal, 2018). Accurate evaluation and fixation of scaphoid fractures with 2-D fluoroscopy can be a challenging task, however, even for experienced hand surgeons. Liverneaux et al. (2008) demonstrated the feasibility of 2-D navigation in four cadaveric scaphoids. Cadaveric studies to corroborate these findings include the work of Walsh et al. (2009), who compared traditional volar percutaneous screw placement with a computer-assisted 2-D fluoroscopic guidance technique in ten matched cadaveric wrists. They found that with computer-assisted guidance, there was reduced overall radiation exposure and number of K-wire passes compared with traditional volar percutaneous screw placement. The advent of 3-D fluoroscopy offered further improvements in accuracy, with smaller screw divergence from the anatomical axis of the scaphoid compared with using 2-D fluoroscopy (Catala-Lehnen et al., 2011).

Although computer-assisted navigated surgery can be safe and accurate in experienced hands, it has a steep learning curve and implant

misplacement can still occur (Liverneaux et al., 2008; Walsh et al., 2009). In all navigated techniques, the surgeon freehands the drill and is guided by an image on a nearby screen. Therefore, small errors are inevitable due to the natural tremor of the surgeon's hand in addition to the errors introduced by the demand for precise hand–eye coordination in such a small bone. Such errors may be acceptable for navigated surgery of large joints, such as the knee or the hip, but may be an important reason why navigated techniques in hand surgery have not progressed beyond the experimental stage decades after its introduction.

The advent of robotic-assisted technologies allows achievement of smaller margins of error than by 'freehand' navigated surgery. Robotic-assisted techniques are now widespread in neurosurgery and urological surgery. The recently introduced orthopaedic robotic navigation system from TINAVI (TiRobot) has proven to be safe and effective in surgery for the spinal column (Le et al., 2018; Liverneaux et al., 2009; Tian, 2016; Tian et al., 2014, 2016, 2017a). Following its success, we adapted this system for use in percutaneous scaphoid fixation. Traditional navigation relies on relatively big optoelectronic targets in the operating field, which confer acceptable precision for large joints, but the TiRobot system has proven its efficacy and safety in the relatively confined anatomy of spinal pedicles and the odontoid process.

Our current technique uses a re-usable radiolucent positioning jig and intraoperative 3-D fluoroscopy, without the need for preoperative CT or patient-specific custom orthoses described in previous studies (Kam and Greenberg, 2014; Walsh et al., 2009), thereby reducing operative complexity. This is reflected in our mean set-up and surgical time of 18 and 22 minutes, respectively, which compares favourably with the existing published techniques of navigated and non-navigated percutaneous scaphoid fixation (Catala-Lehnen et al., 2011; Haddad and Goddard, 1998; Kam and Greenberg, 2014; Walsh et al., 2009). It is important to ensure that the wrist is securely affixed to the positioning jig, as any movement between the wrist and jig after the reference scan has been performed will introduce errors into the navigation. The wrist must also be adequately extended while positioned, which moves the trapezium away from the guidewire entry point at the distal pole of the scaphoid, thus preserving the trapezium and the distal scaphoid articulation. The scaphoid has a complex morphology that can make accurate assessment of screw position using traditional 2-D fluoroscopy difficult (Luchetti et al., 2018a), therefore it is vital to confirm optimum screw position in all images in the coronal and sagittal planes during the planning phase. Once the position is confirmed and the robotic arm is manoeuvred into position, the surgeon must ensure that the aiming guide sits directly on the distal scaphoid pole. The 1.1-mm K-wire is flexible and we found during early cadaveric experiments that any gap between the aiming guide and the scaphoid can cause the wire trajectory to be deflected by interposing soft tissues or by the edge of the trapezium. By paying close attention to these key points, we did not encounter any difficulties in our robot-assisted technique, which required only a single guidewire attempt in all cases and generated no complications.

There are a number of limitations. Owing to its nature as a pilot study, the patient numbers are small and we also do not have a comparison group of traditional non-navigated percutaneous fixations or navigated freehand percutaneous fixations. Only undisplaced fractures were included in this cohort as a preliminary demonstration of the feasibility of this technique. Our requirement of the re-usable positioning jig reduces set-up time and cost, but patients who cannot tolerate the temporary extended wrist position would not be suitable for this system. Another concern is possible displacement of the non-displaced fracture when positioning the wrist in the re-usable jig. Should displacement occur, it would be seen on the reference 3-D fluoroscopic reconstructions and the robotic-assisted technique would be abandoned. No displacement, however, was observed in any case in the current study. The TiRobot system is considerably more costly upfront compared with traditional percutaneous scaphoid surgery and may not be economically viable for all institutions. However, the potential reduction in operative complications from erroneous wire and screw placement may result in long-term cost savings. Navigated surgery has also been shown to reduce radiation exposure and operative time (Kam and Greenberg, 2014; Walsh et al., 2009). The TiRobot system can also be used in other orthopaedic specialities, such as spinal surgery, which will help to spread the upfront and running costs in larger specialist units through joint purchasing and usage agreements.

Robot-assisted percutaneous scaphoid fixation may be particularly helpful for surgeons who are less experienced in percutaneous scaphoid fracture surgery. Further in vivo studies are required to compare this method to traditional percutaneous fixation and also to demonstrate its effectiveness in the treatment of displaced fractures.

Declaration of conflicting interests The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethical approval The local ethical committee approved the research protocol in advance.

Funding The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research received grants from National Key R&D Program of China [Grant No. 2017YFC0110603] and Beijing Municipal Administration of Hospitals Incubating Program [code: PX2018018].

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