Computer-Assisted Percutaneous Scaphoid Fixation: Concepts and Evolution

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J Wrist Surg 2013;2:299–305.

Abstract

Background The treatment for undisplaced scaphoid waist fractures has evolved from conventional cast immobilization to percutaneous screw insertion. Percutaneous fixation reduces some of the risks of open surgery, but can be technically demanding and carries the risk of radiation exposure. Recently, computer-assisted percutaneous scaphoid fixation (CAPSF) has been gaining interest.

Materials and Methods Conventional percutaneous scaphoid fixation is performed under fluoroscopic guidance and involves insertion of a guide wire along the length of the scaphoid to facilitate placement of a cannulated screw. Adapting computer-assisted techniques for scaphoid fixation poses several unique challenges including patient tracking and registration.

Results To date, five groups have successfully implemented systems for CAPSF. These systems have implemented wrist immobilization strategies to resolve the issue of patient tracking and have developed unique guidance techniques incorporating 2D fluoroscope, cone-beam CT, and ultrasound, to circumvent patient-based registration.

Conclusions Computer-aided percutaneous pinning of scaphoid waist fractures can significantly reduce radiation exposure and has the potential to improve the accuracy of this procedure. This article reviews the rationale for, and the evolution of, CAPSF and describes the key principles of computer-assisted technology.

Keywords

- scaphoid
- fracture
- internal fixation
- percutaneous fixation
- computer-assisted surgery

Nondisplaced scaphoid waist fractures are typically treated with a long- or short-arm thumb spica cast for ~8–12 weeks until fracture union is observed.¹ This treatment is effective in excess of 90%.² Displaced waist fractures, unstable fractures, and proximal pole fractures have a much higher risk of nonunion,² and for this reason, many surgeons elect to treat these fractures surgically with internal fixation.

Percutaneous scaphoid fixation was first reported in 1970 by Strelis³ and has since evolved to be a standard technique for internal scaphoid fixation. Several studies have reported excellent clinical results with the percutaneous approach^{4–6} and improved outcomes in comparison to cast immobilization^{7,8} and open fixation.⁹

Performing the procedure percutaneously, however, is associated with its own risks and challenges. The scaphoid has a complex, twisted, highly variable three-dimensional shape.¹⁰ As a result, fixation using standard two-dimensional fluoroscopy can be cumbersome. The standard technique requires a high reliance on X-ray use, which poses a radiation exposure risk to both the patient and the surgical team.^{11,12} The mechanical stability and clinical outcome of the procedure have been linked to maximizing the central placement of the fixation screw along the scaphoid axis,^{13–15} demanding good accuracy of guidewire placement and the avoidance of screw breaches.¹⁴

An alternative may be to use computer-assisted surgical techniques to solve the problems associated with

percutaneous scaphoid fixation. Computer-assisted surgery utilizes computer technology for preoperative planning and intraoperative guidance of surgical interventions. Initially developed for use in neurosurgery,¹⁶ this technology has become prominent in several orthopaedic applications including spine pedicle screw insertion,¹⁷ orthopedic hip arthroplasty,¹⁸ pelvic osteotomy,¹⁹ total knee arthroplasty,²⁰ high tibial osteotomy,²¹ and distal radius osteotomy.²² Computer-assisted techniques have demonstrated a reduced radiation exposure and improved accuracy in many of these procedures.

Although computer-assisted technology is attractive for scaphoid fixation, the conventional workflow for computer-assisted orthopedic surgery does not translate readily to scaphoid fractures. This article aims to educate the reader about the general principles of computer-assisted orthopedic surgery and the evolution of these techniques for scaphoid fixation. The current progress of five groups implementing such systems is also reviewed and compared.

Conventional Computer-Assisted Workflow

In a typical computer-assisted workflow,²³ a preoperative series of two-dimensional (2D) computed tomography (CT) images are used to develop a three-dimensional (3D) model of the anatomy of interest, as depicted in ►Fig. 1. This is typically accomplished through a process known as *image segmentation*, whereby the pixels that belong to the anatomy of interest (e.g., the scaphoid bone) are identified in each 2D image.²⁴ This can be done automatically using computer algorithms,²⁵ but typically also requires some degree of manual user intervention. The identified pixels in the image series are combined to form voxels that represent the corresponding 3D digital model. The resulting 3D digital model can be used for virtual planning or simulation of the surgical procedure and/or intraoperatively for image-guided navigation.

The navigation system uses a position sensor to track targets attached to the anatomy or to surgical instruments to provide a local coordinate reference (LCR) for each object.²⁶ Common navigation technologies include (i) optical systems with a camera and either passive reflective markers or active infrared-emitting diodes (IREDs); (ii) electromagnetic systems comprising an emitter coil and target receiver coils. The advantage of using electromagnetic tracking is that a direct line of sight between the sensor and the target is not needed. However, current electromagnetic systems are not as accurate, and the tracking volume is smaller, compared with optical systems.

For navigation using digital images, the spatial relationship between the image and the anatomy (patient) must be known. This is referred to as the image-to-patient *registration*.^{23,26} Intraoperatively, a local coordinate reference attached to the anatomy of interest is spatially mapped to the 3D digital model (►Fig. 2). This can be accomplished by using a digitizing probe to touch the anatomy and collect surface probe points, which are then fitted to the 3D model to estimate the image-to-patient relationship (*surface-based* registration). An alternative is to implant radiopaque markers prior to imaging, which are localized in the image and the patient to establish the relationship (*fiducial-based* registration). Fiducial registration is normally more accurate but requires surgical intervention to insert the markers.

The 3D digital model, position tracking, and image-to-patient registration are used to create a virtual object for surgical navigation. The local coordinate reference frames of the patient and tracked surgical tools are expressed in the common coordinate frame of the camera, permitting a relative transformation between the patient and surgical tools to be recognized. After image-to-patient registration is established, a virtual image of a tracked tool can be displayed relative to the anatomy on a computer monitor (►Fig. 2).

Fig. 1 Preoperative tasks in a conventional computer-assisted workflow as illustrated for a distal radius osteotomy. A CT scan of the wrist is obtained which is represented as a series of contiguous 2D X-ray images spanning the length of the wrist (left). Each 2D X-ray slice is segmented to denote pixels belonging to the radius and ulna (middle). The series of segmented 2D images are combined forming 3D voxels to produce virtual models for planning the osteotomy (right) and later for surgical navigation.

Fig. 2 Intraoperative tasks in a conventional computer-assisted workflow as illustrated for a distal radius osteotomy. A local coordinate reference (LCR) is attached to the radius and is tracked by the position sensor. Image-to-patient registration is accomplished by spatially mapping the radius to the virtual model using a probe tracked by the position sensor. After image-to-patient registration is established, a virtual image of a tracked drill (green) can be displayed relative to the anatomy on a computer monitor to navigate the surgical plan.

Limitations of the Conventional Computer-Assisted Workflow

Although computer-assisted technology is attractive for scaphoid fixation, the conventional computer-assisted surgical workflow is problematic. First, preoperative CT is costly. Second, the image processing required for computer navigation is expensive and time consuming. Third, due to the small size of the scaphoid, attaching a reference body directly to the scaphoid to establish patient tracking is not feasible. Lastly, registration is problematic because the small size also limits fiducial (i.e., reference) marker implantation and because open exposure would be needed to collect surface points, thereby negating the benefits of percutaneous fixation.

Alternative Computer-Assisted Technology

Due to its widespread use in orthopedics, plain fluoroscopy was subsequently adapted for computer-assisted navigation. This is typically accomplished by instrumenting a C-arm with a calibration grid comprising several optical markers such that each 2D image can be located relative to the position sensor.²⁷ Tracking of the C-arm as well as the patient anatomy allows the real-time position of tracked instruments to be displayed relative to intraoperatively acquired X-ray projections, similar to continuous fluoroscopy but with much less radiation exposure²⁸ and the capacity to see the projected anatomy and instruments simultaneously in two or more planes. One key advantage of this method is the ability to bypass patient-based registration. However, there are also several drawbacks. First, maintaining a line of sight for imager tracking is necessary. Second, a portion of the calibration grid must remain visible for registration, which limits the visibility

and quality of the images. Fluoroscopic navigation is not truly 3D in that it utilizes two-dimensional images, but the surgeon must still mentally create the 3D model.

The use of cone beam computed tomography (CBCT) for direct navigation was conceived shortly after navigated plain fluoroscopy was reported.²⁹ In essence, CBCT consists of an X-ray source mounted to an automated C-arm, such that a 3D image can be acquired by rotating the C-arm and capturing several contiguous 2D images. The C-arm rotates about a static isocenter; if the tracking system is also static, a calibration can be performed to register the imager space to the tracking system for direct navigation on intraoperatively acquired images. Direct navigation using CBCT has been used in several orthopedic trauma applications where fluoroscopy is routinely used.^{30–32}

Conventional Surgical Technique

Conventional percutaneous scaphoid fixation is typically performed under general or regional anesthesia. The scaphoid guide wire can be inserted percutaneously or through a mini open approach from either a volar or dorsal approach for a scaphoid waist fracture. However, for proximal pole fractures a dorsal antegrade approach is often preferred. The guide wire can be inserted with or without traction.^{5,7,33}

Results

Liverneaux^{34,35} was the first to report the application of computer-assisted percutaneous scaphoid fixation (CAPSF) using 2D fluoroscopy for direct intraoperative navigation. To resolve scaphoid tracking, the wrist was immobilized using a malleable, radiotransparent device similar to a “lead hand,” equipped with a trackable LCR to establish a patient reference

frame (►Fig. 3a,b). Surgical instruments were also equipped with optical markers to permit navigated placement of a surgical screw. Walsh et al³⁶ reported a similar system using a short-arm splint to immobilize the scaphoid. Both cadaver-based studies yielded similar results; there was no significant difference in the accuracy of screw placement when compared with conventional fluoroscopic navigation, but there was a significant reduction in radiation exposure. Walsh et al also noted significantly fewer drilling attempts were required using navigation. Liverneaux found that navigation took slightly longer than in conventional fixation, while Walsh et al found no difference in procedure times.

In 2006, Beek et al³⁷ presented a means to circumvent the surface-based registration by using intraoperative ultrasound. They used an optically tracked ultrasound probe to capture two-dimensional intraoperative images of the scaphoid, which were registered to a preoperative 3D CT model of the scaphoid, providing the necessary image-to-patient registration for navigation. A subsequent in vitro evaluation of the system demonstrated improved accuracy at placing a wire along a surgical target compared with standard fluoroscopy.³⁸

Smith et al³⁹ proposed a navigation system using intraoperative CBCT with the Innova C-arm (GE Healthcare, Little Chalfont, Buckinghamshire, UK) featuring a novel preoperative calibration for imager-to-tracking registration. The system was evaluated using an in-vitro model to assess both volume rendering³⁹ and volume slicing⁴⁰ of the 3D image (►Fig. 4). Both studies demonstrated improved accuracy of guidewire insertion, fewer drilling attempts, and reduced radiation exposure when compared with conventional fluoroscopic insertion. A comparison of both methods⁴¹ showed that volume rendering was superior in maximizing central placement, while volume slicing was superior in maximizing the length of wire placement, advocating the use of a hybrid visualization interface.

Navigation of percutaneous scaphoid fixation using CBCT has also been reported by Citak et al in cadavers and at least one patient.⁴² They used the Siremobil Iso-C^{3D} system (Siemens, Erlangen, Germany) for imaging and a custom plastic platform splint instrumented with reflective markers for patient tracking.

A recent study by Catala-Lehnen et al⁴³ compared 2D fluoroscopic navigation to 3D C-arm navigation for dorsal percutaneous scaphoid fixation in cadavers. Their 2D navigation technique used the same method as Liverneaux et al,³⁵ except that a dorsal approach was employed, and the drill guide was navigated. Their 3D technique made use of an Arcadis Orbic 3D C-arm (Siemens, Erlangen, Germany). The study compared operative time, fluoroscopic time, wire passes, and insertion accuracy. They found that 3D navigation took almost twice as long and required three times more radiation than the 2D technique. There was a tendency toward greater precision in the 3D group, but this was not statistically significant.

Discussion

The shape of the scaphoid has been likened to that of a peanut: a complex, twisted three-dimensional shape with high variability.¹⁰ As a result, performing the procedure with good accuracy using two-dimensional fluoroscopy is technically demanding. Centrally placed screws have been found to have an increased biomechanical advantage¹³ and a higher union rate.¹⁴ Dodds et al¹⁵ demonstrated that longer screw length relative to the long axis of the bone also had a biomechanical advantage.

Subsequent investigations aimed to develop guidelines for optimizing screw placement. Menapace et al⁴⁴ defined a “safe zone” for the guide-wire entry point from a cadaveric examination of bone vascularity and morphology. More recently, Leventhal et al⁴⁵ performed a CT study of 9 scaphoids that

Fig. 3 Percutaneous scaphoid navigation using navigated 2D fluoroscopy as demonstrated by Liverneaux et al.^{34,35} (a) A standard C-arm was equipped with a special calibration grid such that each 2D image can be located relative to the position sensor. For patient tracking, the wrist was immobilized using a malleable, radiotransparent stabilization device. Reproduced with permission of Elsevier.³⁴ (b) Tracking of the C-arm, wrist stabilization device, and drill guide allow a virtual image of the guidewire to be displayed relative to intraoperatively acquired X-ray projections. Reproduced with permission of John Wiley and Sons.³⁵

Fig. 4 Percutaneous scaphoid navigation using navigated 3D fluoroscopy as demonstrated by Smith et al.^{39,40} (a) A 3D fluoroscopic C-arm was calibrated preoperatively, thereby eliminating imager tracking and image-to-patient registration. Screenshots of the custom navigation interface showing (b) volume rendering, and (c) volume slicing of the 3D X-ray image for navigating guidewire placement. Parts (a) and (c) reproduced with permission of Springer.⁴⁰

were randomly selected from a CT scan database at their institution. They computed a safe zone that was located 2.3 mm inside the original cortical bone surface, based on a 1.7-mm screw radius (Acutrak 2 Mini; Acumed LLC, Hillsboro, OR), a 0.035-mm cortical bone thickness, and an additional 0.25-mm safety margin. They found that the central axis of a 1.7-mm best-fit cylinder down the central axis was partially or completely obstructed by the trapezium in all of the specimens. When they looked at the longitudinal axis that allowed them to place the maximum-length screw, however, they found the safe zone passed on average $1.8 \text{ mm} \pm 0.8 \text{ mm}$ away in primarily a dorsal and slightly radial direction (0.2 mm) from the apex of the scaphoid tubercle and exited ulnar and slightly dorsal to the longitudinal axis. They did acknowledge that placing the wrist in traction and ulnar deviation might provide greater access by further increasing the distance from the screw axis to the trapezium. Use of a larger-diameter screw would also change these findings.

Levitz and Ring⁴⁶ attempted to quantify the guidelines for optimal scaphoid screw insertion for scaphoid waist fractures via a volar retrograde insertion technique with a Synthes cannulated-headed screw (Synthes, Paoli, Pennsylvania, USA) by using quantitative computer analysis of CT images of 15 unfractured scaphoids. They defined the optimal screw place-

ment as consisting of a 2-mm safe margin between the central axis of the screw and at least 5 mm of screw tip crossing the fracture site and engaging the apex of the proximal pole. They found that in all of the insertion planes there was a substantial concavity of the volar surface of the scaphoid, which posed a problem for potential screw cutout. A more radial insertion point minimized this risk, but there was little margin for error, because the average clearance of the trapezium measured 4 mm, which is the same diameter as most scaphoid screws. They also found that the most likely place for a volarly inserted screw to perforate the articular surface is the dorsal-radial surface of the scaphoid, which is exacerbated by any angular or humpback deformity.

The standard percutaneous technique demands high reliance on X-ray use for guidewire insertion, fracture reduction, and screw placement. This poses a radiation exposure risk to both the patient and the surgical team. Surgeons typically have their hands in the radiation field during imaging, so occupational exposure to the hand is a concern in these procedures.^{11,12} To reduce X-ray reliance, arthroscopy has been suggested to enhance visualization,^{47,48} which has the added benefit of the ability to identify and repair accompanying soft tissue injuries, which are not radiographically evident.

The application of computer-assisted surgical technology for scaphoid fixation is still in its early stages, as there are many challenges associated with adapting standard computer-assisted techniques for this procedure. Computer-assisted techniques have employed wrist immobilization to resolve the issue of scaphoid tracking and are exploring direct fluoroscopic or CBCT navigation and ultrasound to circumvent patient-based registration.

The studies to date have demonstrated that navigation has the capacity to reduce X-ray exposure significantly when compared with conventional fluoroscopy. These same studies have shown a tendency toward improved accuracy, but without statistical significance, likely because of the small number of cadaver specimens used. Citak et al⁴² is the only group to report in vivo CAPSF, while other studies have used ex vivo or in vitro models.

Most groups have also reported increased length of time for computer-assisted procedures. This may be the result of the additional preoperative planning phase associated with the computer-assisted workflow, but it may also be associated with a “learning-curve” in utilizing the technology, as noted by Citak et al,⁴² Smith et al,⁴⁰ and Catala-Lehnen et al.⁴³

It is clear that CAPSF is still in its infancy. The technology holds promise in reducing harmful radiation exposure and easing the technical difficulty of this procedure. We expect that the technology will continue to develop as surgeons gain experience with the tools and adapt them to clinical practice.

Conflict of Interest

None

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