Title: A Review of the Use of 3D Printing Technology in Treatment of Scaphoid Fractures

Authors: Lily X Li FRCS[1], Angela E Kedgley PhD[2], Maxim D Horwitz FRCS[3]

1. Department of Trauma & Orthopaedics, St Mary's Hospital, Praed St, London, W2 1NY, UK.
2. Department of Bioengineering, Imperial College, Wood Lane, London, W12 7TA, UK.
3. Department of Hand Surgery, Chelsea and Westminster Hospital, Fulham Road, London, SW10 9NH, UK.

Corresponding Author:

Lily X Li

Department of Trauma & Orthopaedics

St Mary's Hospital, Praed St, London, W2 1NY, UK.

Tel +44 2033126666

E-mail: lily.li@nhs.net

ABSTRACT

Background: Three-dimensional (3D) printing technology is increasingly commercially viable for pre-surgical planning, intra-operative templating, jig creation, and customised implant manufacture. The challenging nature of scaphoid fracture and non-union surgery make it an obvious target. The aim of this review is to determine the use of 3D printed technologies in the treatment of scaphoid fractures.

Methods: This is a review of the Medline, Embase and Cochrane Library databases looking at studies looking at therapeutic use of 3D printing, rapid prototyping, or additive technology in the treatment of scaphoid fractures. All studies published up to and including November 2020 were included in the search. Relevant data extracted included modality of use (as template/model/guide/prosthesis), operative time, accuracy of reduction, radiation exposure, follow-up duration, time to union, complications, and study quality.

Results: 649 articles were identified, of which 12 met the full inclusion criteria. Analysis of the articles showed that 3D printing techniques can be utilised in myriad ways to aid planning and delivery of scaphoid surgery. Percutaneous guides for Kirschner-wire (K-wire) fixation of non-displaced fractures can be created; custom guides can be printed to aid reduction of displaced or nonunited fractures; patient-specific total-prostheses may recreate near-normal carpal biomechanics, and a simple model may help graft harvesting and positioning.

Conclusions: This review found that the use of 3D printed patient-specific models and templates in scaphoid surgery can improve accuracy and speed and reduce radiation exposure. 3D printed prostheses may also restore near-normal carpal biomechanics without burning bridges for potential future procedures.

Key words: Scaphoid; 3D printing; additive manufacturing; rapid prototyping

Level of evidence: Level III (Therapeutic)

Introduction

Three-dimensional (3D) printing, also referred to as "additive manufacturing" or "rapid prototyping", is a new technology that can be used for pre-operative planning and intra-operative templating (such as in colorectal, pelvic, maxillofacial, renal, cardiac, and spinal surgery).[1-6] One-to-one sized models may help with visualisation, pre-operative planning and patient communication. Patient-specific templates and jigs may aid intra-operative accuracy and efficiency. Implants can be entirely 3D printed to ensure a custom-fit, particularly when there is abnormal anatomy.[7] 3D models may also aid teaching in a safe environment, for example it is possible to create abnormal embryological models without raising ethical concerns.[8] The commercialisation of 3D printing has made it easier and cheaper to produce these anatomical models for everyday practice.[9]

Within hand surgery too, 3D printing may be used to create patient-specific models, templates or jigs to help surgeons tackle complex distal radius fractures, non-unions or deformities.[10-11] For example, a recent systematic review and meta-analysis by Zhu et al found that "3D printing-assisted surgery was better than routine surgery and led to a decrease in operation time, frequency of intraoperative fluoroscopy, and blood loss".[11] Much less attention, however, has been devoted to research into the use of 3D printing technology in non-radius hand surgery. When operating on the scaphoid, precise hardware placement can be challenging due to the scaphoid's complex three-dimensional shape and size.[9] Repeated passes of Kirshner (K) wires are often required, increasing operative time and risking injury to small bony fragments. This can lead to compromise of the already tenuous blood supply or bony fragmentation, and increase the need to convert any percutaneous attempt to open surgery. Repeated use of fluoroscopy to view multiple guidewires passes also increases radiation exposure for the patient and surgical team.[12] Furthermore, in scaphoid nonunion, restoration of normal anatomy can be especially challenging.[13] The challenging nature of scaphoid surgery makes it an obvious target for 3D printing technology.

The aim of this review is to determine the use of 3D printed technologies in the treatment of scaphoid fractures. The review aims to answer the question: in patients requiring scaphoid surgery (participants), do 3D printed technologies (e.g. jigs, templates, models and/or implants) (intervention) confer additional benefits (e.g. speed of surgery, outcomes, radiation exposure) (outcomes) over standard techniques (comparator)?

Methods

The Preferred Reporting Items for Systematic review and Meta-Analysis Protocols (PRISMA-P) checklist was used as the reporting standard throughout.[14] There was no existing review protocol and so a custom literature search was devised and performed using the Medline (OVID interface, 1946 onwards), Embase (OVID interface, 1947 onwards) and Cochrane Library (Wiley interface, current issue) databases in November 2020. Screening, eligibility, and inclusion were initially performed by the lead author and subsequently reviewed by the senior author (for strategies see Supplementary Materials section).

Papers were selected based on title and abstract review. Studies were included if they contained scaphoid surgery, use of 3D printing, rapid prototyping, or additive technology. Exclusions were studies focused solely on education or training rather than therapeutic intent, studies focused only on bracing, orthoses or rehabilitation, studies with non-human subjects, and those not written in English. Duplicates and non-full papers (e.g. conference abstracts or letters to the editor) were removed. All studies published up to and including November 2020 were included in the search. Studies were screened for inclusion by the lead author. Relevant data extracted included modality of use (as template/model/guide/prosthesis), operative time, accuracy of reduction, radiation exposure, follow-up duration, time to union, complications, and study quality (**Tables 1** and **2**).

The Methodological Index for Non-Randomised Studies (MINORS) tool was chosen to critically appraise the quality of the studies as it is a validated and surgery-specific tool.[15] MINORS is composed of eight methodological items applicable to all non-randomised studies and four additional items applied for comparative studies. Each item scores 2 for reported and adequate, 1 for reported but inadequate, or 0 for not reported, giving a maximum score of 16 for noncomparative studies or 24 for comparative studies.[16] There were no relevant randomised controlled trials in this review. Ethical approval was not required.

Results

A total of 649 titles were returned from the initial database search. Papers were screened using the inclusion and exclusion criteria. 112 titles remained after paper review and removal of duplicates. Assessment of eligibility and elimination of non-full text articles resulted in 12 papers (**Figure 1**; **Table 2**).

The twelve included studies, were divided into four groups based on study purpose (**Table 3**): five described the creation of 3D printed guides to aid percutaneous K-wire passage for nondisplaced or minimally displaced scaphoid fractures which did not need fracture reduction.[12,17-19,25] Two papers described the creation of 3D printed templates that aided the reduction of displaced fractures or nonunions[13,20] Three papers described the creation of 3D true-to-size models to aid bone graft retrieval.[21,22] or implant positioning.[9] The final two papers described the creation of 3D printed whole-bone prostheses for scaphoid replacement.[23,24]

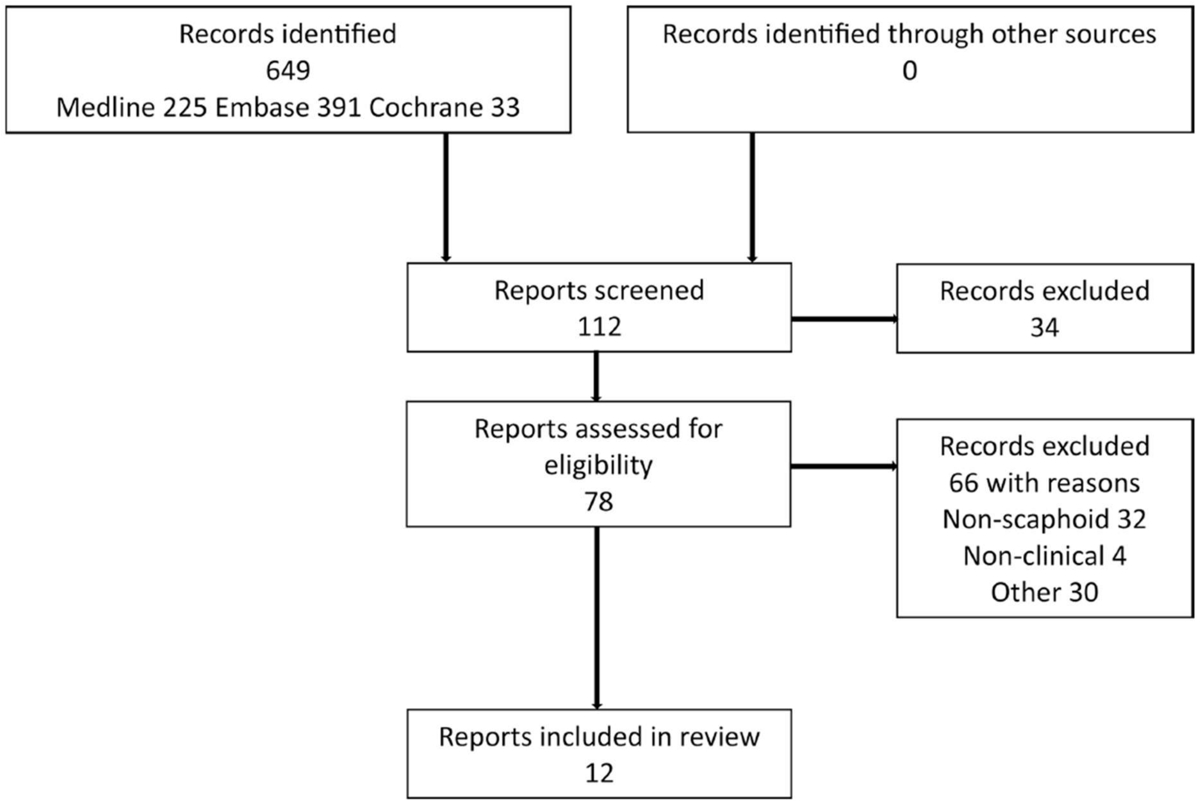

Figure 1. Flowchart showing study selection

All five studies for percutaneous K-wire templates required a pre-procedure CT. The researchers used proprietary software to manipulate the CT data to calculate optimum wire trajectory, depth and screw length using a mould that would be affixed to the patient's skin. In all five studies, the patient-specific resin mould was 3D printed based on the computer-aided design model. The mould was then sterilised by conventional techniques for use intra-operatively. All studies in this group reporting results were cadaveric studies.[12,17-19)] All studies found that it was possible to achieve accurate percutaneous K-wire passage using this technique. The fifth paper in this group by Yin et al merely reported their technique but did not include any results.[20]

Out of this group of five papers, two compared the printed template against the conventional freehand technique: Salabi et al found that the use of the template gave better accuracy of K-wire trajectory relative to the scaphoid mid-axis, fewer wire passes ("single-shot"), and reduced fluoroscopy exposure, all reaching statistically significant levels ($p<0.05$). Operative times were the same.[19)] DeWolf et al found that their 3D printed patient-specific targeting device provided similar accuracy to the freehand technique whilst significantly reducing intraoperative radiation exposure and procedure time.[18)] In both Guo and Wan's papers where there was no comparator to the templated technique, single-shot wire passage resulted in accurate wire trajectory (within the central one-third of the scaphoid on post-procedure CT scanning)[12,17)] Four out of five papers mentioned hand volume potentially adversely affecting the accuracy of the K-wire trajectory by disrupting the seal at the template-skin interface.[12,18,19,25)] A technical pearl to mitigate this problem suggested by Yin's group was for the guides to be made as soon as possible after CT to avoid post-traumatic skin interface changes.[25)]

The second group of papers reported results of using 3D printed templates to correct nonunion or displaced fracture.[13,21] Out of this group of two studies, Haefeli et al used the contralateral uninjured side to base a CT template which was mirrored. A 3D printed titanium template was temporarily affixed to the proximal and distal poles of the scaphoid to reduce and hold the scaphoid in the anatomically corrected position and bone graft placed in the defect. A headless compression screw was then inserted through the mid-axis of the scaphoid using the standard freehand technique. Results in their one illustrative clinical case demonstrated painless union at three months and good range of motion.[13)] In Schweizer's paper a similar technique was used to plan and 3D print a template to aid reduction (made of polyamide instead of titanium), with the addition of an extra guidewire hole to ensure accurate passage of the K-wire for the compression screw. Compared with the freehand technique, Schweizer's group found that reconstructions were significantly more anatomic when the 3D printed guides were used. The guide group also had a significantly shorter operative time although planning time before surgery was longer. Faster union was observed, although the authors do not mention if statistical significance was calculated or achieved.[20)]

The third group of studies by Jew, Schmidt and Taylor all describe using CT images to 3D print a 1:1 sized model.[9,21,22)] Intraoperatively, Schmidt's group found the model useful in determining the precise osteotomy plane for scaphoid nonunion. Their model was also used to plan the most suitable harvest site, allowing the exact size, shape and curvature to be marked intraoperatively.[21)] Jew et al used their 3D printed model to plan their approach and fixation modality in the office rather than in the operating theatre.[9)] Taylor's paper described how open source, instead of proprietary, imaging software could be used to convert CT images to 3D models and printed easily in the outpatient setting.[22)] No quantitative results were presented in these papers.

The fourth group of studies by Honigmann et al. and Rosello both report individual cases of 3D printed scaphoid replacement. Honigmann et al. used alumina in a cadaveric model with flexor carpi radialis tendon suspension; Rosello used titanium in a 34-year-old patient with labral tape suspension.[23,24)] Honigmann et al. aimed to overcome the problems encountered by historical implants which were unstable and not anatomically contoured to the patient, causing abnormal wear on the adjacent carpus. Honigmann's group found that both the patient-specific 3D printed prosthesis and the scapholunate interval remained stable during physiological range of movement, although the prosthesis extended excessively in extension and ulnar abduction.[24)] Rosello's 3D printed prosthesis was distally wedged into a hole made in the trapezium and was proximally secured with labral tape to recreate the scapholunate ligament. Results at one year showed near-normal carpal biomechanics and significant improvement in pain and function.[23)]

Discussion

Level III and below evidence from this review has shown that 3D printing techniques can be utilised in myriad ways to improve the outcome of scaphoid surgery, in particular regarding operative time, accuracy of reduction, radiation exposure, and complications. Additive technology can be used to create percutaneous guides for K-wire fixation of non-displaced fractures.[12,17,19,20)] Custom guides can also be printed to facilitate more accurate reduction of displaced or nonunited fractures.[13,20)] Patient-specific total-prostheses can recreate near-normal carpal biomechanics,[23,24)] and even a simple 1:1 sized model can help graft harvesting and positioning.[9,21)] The use of 3D printed augments use has been shown to improve fixation accuracy, increase operative speed, and reduce radiation exposure. 3D printed patient-specific hardware, in particular arthroplasty, reduces the surgical challenge of anatomic variability between patients, resulting in significantly more accurate reconstructions.[23] This may lead to reduced stresses through the joint during load transmission, resulting in better functional outcomes and possibly greater reconstructive longevity.

It can be difficult to assess the complex three-dimensional shape of the scaphoid using standard two-dimensional radiographic techniques. Indirect measurements are possible, such as using the position of the lunate relative to the radius and capitate, but rotational deformity cannot be assessed by these means.[13)] A pre-operative CT not only permits 3D printing, it also enhances surgical planning in all dimensions.[26)] The additional radiation exposure from the pre-operative CT scan required for 3D printing only becomes an issue if the surgeon has not already ordered one for planning purposes. In fact, in current practice, many hand surgeons choose to obtain a pre-operative planning CT regardless of the use of 3D printing technology. The post-procedure CT to confirm screw trajectory for research purposes included in the studies of this review may be omitted in routine clinical practice.

The use of the uninjured, contralateral side as the base for a CT template is a long-established technique in Trauma & Orthopaedic surgery.[27)] For a small bone such as the scaphoid, Haefeli et al found that congruence between the left and right sides was within 1 mm,[13)] although Letta et al found surface-to-surface size differences between right and left scaphoids in individuals to be between 0.73 and 1.9 mm, and bigger in men than women. This must therefore be considered when using the mirrored contralateral bone as a template.[24,28)]

A challenge to the wider use of 3D printing technology is the need for specialist equipment and/or software. The small size of components required for scaphoid surgery, as compared with larger joints, has both positive and negative impacts. Less material translates to cheaper manufacturing costs, but smaller sizes require greater manufacturing precision. Until manufacturing processes are simplified, surgeons would expect to commission complex prostheses from external companies, rather than manufacturing their own custom-made implants in the office. For example, a temperature-controlled print bed is required to create the titanium template as used by Haefeli et al, highly impractical for the average orthopaedic office.[13)] Planning and production costs of €1800 (US$1760) were reported by Haefeli et al for their custom-made, 3D printed, titanium whole-scaphoid replacement.[13] Although this figure appears large at first glance, it is comparable to implants commonly used in orthopaedic surgery: the cost of a total hip replacement stem was estimated to be between £750 and £3000 (US$1189-4756) ~~in 2012~~.[29)] The use of resin templates by other investigators is much more clinically-applicable. A 1:1 sized resin model can be relatively easily and cheaply printed in the outpatient setting. As described in Taylor's paper, the cost of office-based printing would consist of initial purchase of the machine (US$350) and printing filament (US$14-18/spool) plus the cost of any proprietary computer software and sterilisation of the template/model. Thereafter running costs would be minimal in replacing the printing filament.[22)]

The strengths of this review article lie in its comprehensiveness and its topic. As outlined above, there is growing interest in the use of 3D printing techniques to support distal radius surgery, but there have been few publications on its use in the rest of the hand and carpus. This review collated and scrutinises the current state of the art in these techniques as they apply to scaphoid surgery. There are several limitations to this review. Firstly, it was based on twelve papers of level III evidence or lower, and of varied quality (MINORS score range: 1/16 – 19/24). The included studies were significantly heterogenous in their study technique, methods of analysis and outcome measures. Sample sizes for each technique were therefore small, with some studies merely describing the technique without offering any results, which would have impacted the reliability of the conclusions drawn. Secondly, the literature search was limited to electronic databases only. In the interests of time, although the lead author searched multiple databases to maximise the number of studies, she did not perform the other recommended supplementary search methods such as hand searching references in the identified studies, key journals, or regulatory agency websites.[~~31~~ 30)] Thirdly, this review is at risk of publication bias due to its exclusion of non-English studies. Although the lead author identified a significant minority of relevant studies from the Far East, her lack of fluency in academic written Chinese meant that this review was limited to English studies only. Fourthly, this review did not include all recent relevant work as all non-full text publications were excluded (e.g. letters to the editor and conference abstracts), as they had not passed the rigorous process of peer-review. The lead author identified a handful of conference abstracts from 2020 which were deliberately excluded from this review. It is hoped that the work presented in these abstracts would be incorporated into peer-reviewed papers in due course.
3D printing technology is increasingly commercially viable. The challenging nature of scaphoid fracture and nonunion surgery make it an obvious target. This review has found that by using 3D printing technology to create patient-specific models and templates in scaphoid

surgery, accuracy, speed, and radiation exposure may be improved. Furthermore, 3D printed prostheses may restore near-normal carpal biomechanics without burning bridges for potential future procedures.

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Table 1. Quality Assessment of Studies

	1	2	3	4	5	6	7	8	9	10	11	12
Methodological item for non-randomized studies	**Haefeli**	**Taylor**	**Schweizer**	**Yin**	**Honigman n**	**Guo**	**Jew**	**Wan**	**Salabi**	**Rosello**	**deWolf**	**Schmidt**
1. A clearly stated aim	2	0	2	1	2	2	0	1	2	1	1	2
2. Inclusion of consecutive patients	0 cadaveric	0	0	0	0 cadaveric	0 cadaveric	0	0	0 cadaveric	0	0 cadaveric	0 cadaveric
3. Prospective collection of data	2	1	2	2	0	2	1	2	2	2	2	0
4. Endpoints appropriate to the aim of the study	2	0	2	0	2	2	1	2	2	2	2	1
5. Unbiased assessment of the study endpoint	2	0	2	0	2	2	1	2	2	2	2	1
6. Follow-up period appropriate to the aim of the study	0	0	2	0	0	0 cadaveric	1	0	0	1	0	0
7. Loss to follow up less than 5%	0 cadaveric	0	2	0	0 cadaveric	0 cadaveric	0	0	0 cadaveric	0	0 cadaveric	0
8. Prospective calculation of the study size	0	-	0	-	-	-	-	-	0	-	0	-
9. An adequate control group	1	-	2	-	-	-	-	-	2	-	2	-
10. Contemporary groups	1	-	1	-	-	-	-	-	2	-	1	-
11. Baseline equivalence of groups	1	-	2	-	-	-	-	-	0	-	0	-
12. Adequate statistical analyses	2	-	2	-	-	-	-	-	2	-	2	-
TOTAL	**13/24**	**1/16**	**19/24**	**3/16**	**6/16**	**8/16**	**4/16**	**7/16**	**14/24**	**8/16**	**12/24**	**4/16**

Score 0 (not reported), 1 (reported but inadequate) or 2 (reported and adequate).

Table 2. Summary of Included Studies

First author (publication date) Country	Type of study, Sample size	Intervention	Comparison	Outcome measures	Imaging modality basis	Result	Conclusions	Complications/other comments
Haefeli (2014) Switzerland	Case series, 10 cadaveric wrists and one 29 year old patient	PS titanium scaphoid template for anatomical reduction after nonunion excision	None	Deviation of surface of reconstructed scaphoid from virtual counterpart from pre and post-procedure CT reconstructions	CT	Deviation good in 5 (<1.5 mm), moderate in 1 (<3 mm), inadequate in 4 (>3 mm)	Custom-built titanium template for intraoperative control of scaphoid reconstruction after scaphoid non-union is feasible. Precision pitfalls mainly in template design. Need to incorporate cheaper materials and more efficient planning software for clinical application.	-
Taylor (2016) USA	Narrative, None described	Office-based printing as adjunct for vascularised bone flap transfers. Use of open-source software to print 3D models from CT. Sterile models used as intra-operative templates for graft harvest	None	None described	CT	PS 3D templates allows precise creation of anatomic defects and ability of rapid bone contouring. Convenient and cheap.	Surgeon-based 3D printing is feasible and allows for precise and rapid contouring of models. Easy to use, convenient, cheap.	-
Schweizer (2016) Switzerland	Case-control, 22 patients in two groups: Group 1: 9 using PS guides; Group 2: 13 using CF technique	Intra-operative PS guides to aid reduction of fragments of displaced fracture or nonunion	CF technique	Union rate, reconstruction accuracy, pain, return to work, planning time, operative time, complications	CT	Group 1: 8/9 union after 2-6 months, 1 case partial union after 9 months. Group 2: 11/13 union after 2-34	Reconstructions significantly more anatomic using 3D printed guides than from freehand technique.	3 cases carpal tunnel syndrome (group 1:2; group 2: 1). 1 case screw removal due to prominent metalwork (group

						months, 2 nonunions. Group 1 reconstruction significantly more accurate Group 1 6/9 pain-free, 6/9 returned to work Group 2: 4/13 pain-free, 10/13 returned to work		2). 3 cases spur excision (group 2)
Yin (2017) China	Surgical technique description, None described	CT-based intra-operative PS guides for percutaneous K-wire passage for non/minimally displaced scaphoid fractures	None	None described	CT	Single-shot K-wire placement accomplished	Single-shot percutaneous scaphoid fixation possible using PS guide	Technical pearl: guides should be made ASAP after pre-operative CT to avoid skin interface changes
Honigmann (2018) Switzerland	Case report, One cadaveric wrist	3D printed PS titanium scaphoid replacement with FCR suspension	None	Static (CT) and dynamic (cinematography) motion analyses	CT and cinematography	Physiological motion patterns maintained for prosthetic and original scaphoid, scapholunate interval stable throughout range	Suspended 3D printed PS prosthesis can be alternative treatment option for very difficult or non-reconstructable scaphoid pathology. No bridges burnt for future salvage procedures.	None described
Guo (2019) China	Case series, 12 cadaveric wrists	CT-based intra-operative PS guides for percutaneous K- wire passage for scaphoid fractures	None	Angular and linear deviation between pre-procedural simulation (aiming for scaphoid centre) and post-procedural actual guidewire position	CT	Mean angular deviation was 3.85 $^{\circ}$ +/-1.32 $^{\circ}$. Linear deviation <1.1 mm. No repeated drilling or misdirection of screw axis	It is possible to reliably insert a screw guidewire in the central third of the scaphoid in cadaveric wrists from either palmar or dorsal approach	Limitations: no osteotomy, no control group. Only indicated for minimally-displaced fractures

							without the need to violate the trapezium.	
Jew (2019) USA	Surgical technique, 4 illustrative cases (63, 30, 20, 11 years old)	Description of technique to print true-to-size model for pre-op implant planning and positioning	None	Optimum approach and strategy to address size and orientation of fracture fragments	CT	Successful union in all 4 cases	3D printing is useful tool for preoperative planning of complex scaphoid fractures. Better visualisation of fracture allows more detailed preoperative planning and facilitate optimal operative fixation. Most useful for complex fracture patterns or small fragments	None described
Wan (2019) China	Case series, 6 cadaveric wrists; 4 patients with acute scaphoid waist fractures	CT-based intra-operative PS guides for percutaneous K- wire passage for scaphoid fractures	None	Distance and angle deviation of entry point and screw trajectory compared to pre-procedural simulation, operative time, fluoroscopy time	XR, CT, gross visualisation	Cadavers: Mean total operative time 20.3 min Mean distance deviation of entry point 1.86 mm, angular deviation screw trajectory 2.67 ° Patients: Mean total operative time 19.8 min, 2 fluoroscopy checks, all wires/screws in scaphoid centre on fluoroscopy/XR, all united	PS guides can assist in accurate placement of screw but also shorten operation time and reduce insertion and X-ray exposure times. Its use can also improve surgeons' learning curve	Some deviation between design values and real results but discrepancies were within acceptable ranges, postulated due to cadaveric skin forming poor seal around template, screw insertion causing movement of soft tissue/bone

Salabi (2019) France	Case series, 12 cadaveric wrists divided into 2 groups of 6 each of CF technique and PS guides	CT-based intra-operative PS guides for percutaneous K- wire passage for undisplaced scaphoid fractures	CF technique	Deviation between pre-procedural simulation and post-procedural screw position, operative time, extent of exposure to radiation	CT	PS group: mean screw positioning relative to axis direction 1.6 ^{o} and position in scaphoid 3.3 ^{0}; CF group: 13.8 ^{o} and 9.2 ^{o} ($p < 0.05$) PS group: single wire pass, CF group: mean 4.7 passes ($p<0.05$) PS group: 5 fluoroscopy shots, CF group 17 shots ($p<0.05$) No significant difference in operative times although CF group had wider range.	PS K-wire guide improved accuracy of screw placement and decreased radiation time compared with conventional technique for percutaneous screw fixation of non-displaced scaphoid waist fractures	Technical pearl: change in volume of hand due to reduction in oedema in days following trauma could theoretically lead to insufficient stability of template.
Rosello (2020) Italy	Case report, One 34 year old male patient with three year old chronic scaphoid waist nonunion	3D printed PS titanium scaphoid replacement with suture anchor to recreate scapholunate ligament	None	Pre- and post-operative pain, ROM, pinch and grip strength, DASH scores and radiographic evidence of stability	CT and XR	Improvement in pain and function after 12 months, near-normal carpal biomechanics.	Total scaphoid implant should be considered in patients with specific indications	Manufacturing cost and time (three weeks) [Author note: no costs given in paper]
deWolf (2020) USA	Case series, 14 cadaveric wrists divided into two groups of 7	CT-based intra-operative PS guides for percutaneous K-wire passage	CF technique	Number of fluoro-scopic images, fluoroscopy time, radiation exposure, procedure time, number of K-wire passes, and number of K-wires within central third of scaphoid	CT	CF group: mean fluoroscopy time 120 s, mean number of images 117, 2.45 milligray radiation. Mean procedure time 21 min, mean number of wire passes 6.4. 4/7 K-wires within	Compared to freehand scaphoid guide wire insertion, 3D printed PS targeting device provides similar accuracy while significantly reducing intraoperative	Pre-procedure planning for targeting device group was aimed at maximising K-wire length within scaphoid, but came at expense of some K-wire trajectories traveling outside central axis.

						central third of scaphoid. Guided group, no fluoroscopy exposure. Mean procedure time 30s. Number of wire passes 1. 4/7 within central third of scaphoid. Mean linear deviation of wire from planned trajectory 2.1 mm, maximum linear deviation 3.75 mm. All K-wires contained entirely within scaphoid.	radiation exposure and procedure time	Maximum linear deviation of 3.75 mm in 1 specimen may have resulted from motion of cadaver during transport or from freeze-thaw cycle between guide placement and wire insertion. Changes in swelling and motion in actual patients may lead to less predictable K-wire placement.
Schmidt (2020) Austria	Surgical technique, Two patients with scaphoid nonunion	3D printed model of avascular proximal scaphoid pole on handlebar to facilitate vascularised free flap harvesting from medial femoral condyle.	None	More accurate and ease in harvesting free flap graft sung guide	CT for pre-procedure planning	All intraoperative steps considerably facilitated by 3D model as compared to conventional procedure. Including static evaluation of osteotomy line and alignment, and also allows dynamic and mechanic evaluation of future bone flap.	3D printing is innovative, feasible technology to assist various surgical steps for scaphoid nonunion and can enhance surgeon’s perception and accuracy	Authors emphasise handlebar on model for easy viewing and handling