Review Article

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Insights and trends review: the role of three-dimensional technology in upper extremity surgery

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Abstract

The use of three-dimensional (3-D) technology in upper extremity surgery has the potential to revolutionize the way that hand and upper limb procedures are planned and performed. 3-D technology can assist in the diagnosis and treatment of conditions, allowing virtual preoperative planning and surgical templating. 3-D printing can allow the production of patient-specific jigs, instruments and implants, allowing surgeons to plan and perform complex procedures with greater precision and accuracy. Previously, cost has been a barrier to the use of 3-D technology, which is now falling rapidly. This review article will discuss the current status of 3-D technology and printing, including its applications, ethics and challenges in hand and upper limb surgery. We have provided case examples to outline how clinicians can incorporate 3-D technology in their clinical practice for congenital deformities, management of acute fracture and malunion and arthroplasty.

Keywords

Three-dimensional printing, three-dimensional model, three-dimensional printing, preoperative planning, rapid prototyping, computer assisted

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Introduction

Three-dimensional (3-D) technology is an increasingly popular tool used to assist the hand surgeon in the diagnosis and treatment of upper limb conditions. The clinical applications for this technology range in complexity from virtual 3-D imaging to the production of patient-specific implants. Highly detailed virtual 3-D images of body parts (often using a normal contralateral side as a template) complement traditional imaging techniques, allowing precise evaluation of anatomy and pathology that is otherwise challenging to appreciate in traditional two-dimensional (2-D) views. This information can further guide the surgeon in preoperative planning, including the selection and positioning of implants. If needed, 3-D printing can complement the virtual plan, and patient-specific models can be produced, as well as instruments and implants (Skelley et al., 2019; Zheng et al., 2018).

The technology is evolving as computer software programs become more user friendly and the cost of highly accurate 3-D printers become more affordable, allowing the creation of in-hospital 3-D printing labs. Despite the growing popularity, there is ongoing debate as to the complexity, the real benefits and the cost efficiency of each step in this technology. In addition, the surgeon needs to be mindful that the responsibility for the surgical plan and its execution remains with them and that any technology must be seen as a tool only. In this review article, we aim to explain how 3-D technology is created, used in

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clinical practice and how a hand surgeon can introduce it to their hospital.

The process of creating a 3-D model

Creating 3-D images

To create a 3-D image, data is obtained from cross-sectional imaging (CT – computed tomography or MRI – magnetic resonance imaging) of body parts, in the digital imaging and communication in medicine (DICOM) data format. With dedicated computer software, the DICOM data are segmented into separate virtual 3-D anatomical parts, known as standard triangle language (STL) files (Skelley et al., 2019). This produces a 3-D image that can be manipulated on screen, allowing precise evaluation and better understanding of pathologic conditions, such as acute fracture patterns or deformity following nonunion or malunion of fractures. The STL files can then be used to produce a 3-D printed anatomical model for further visual, tactile aid or educational purposes (Farrell et al., 2020; Prsic et al., 2020; Raeker-Jordan et al., 2022) (Figure 1). Following sterilization, these 3-D printed models can be made available in the operating room to facilitate the procedure and assist with implant selection, contouring and positioning.

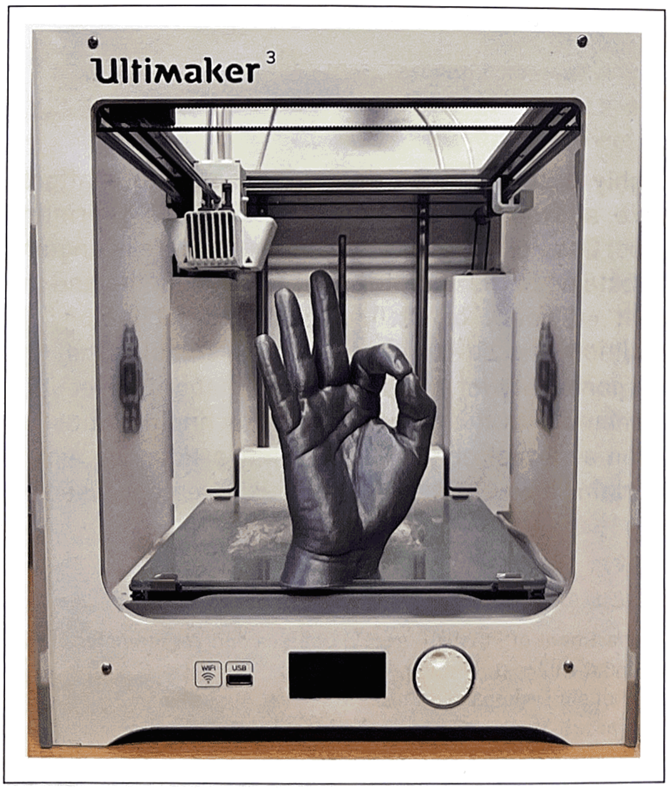

Figure 1. A three-dimensional (3-D) printer extrudes melted thermoplastic filament, which a printer nozzle deposits layer by layer to build up a 3-D hand.

A further step is virtual planning of surgical procedures on the computer, from fracture reduction and fixation to reconstruction of non-united or malunited fractures and planning of joint replacement surgery. Typically, the mirror image of the contralateral intact bone is used as a template to plan precise restoration of anatomy. The optimal implants for final fixation can be selected and screw orientation and length determined.

If necessary, patient-specific surgical instruments or guides can also be designed and 3-D printed, based on the virtual surgical plan. These guides need to be positioned precisely on the matched patient anatomy to facilitate a preplanned surgical procedure. A variety of possible applications have been suggested: guides for K-wire positioning to facilitate percutaneous surgery or reduction of bony fragments; cutting guides for tumour resection; graft preparation or osteotomies and drill guides for screw fixation.

The advent of metal 3-D printing allows for the production of patient-specific implants (Wixted et al., 2021). Following corrective osteotomies or tumour resection, patient-specific fixation devices can be produced as an alternative for standard implants to obtain better bone contouring, facilitate reduction and better fixation options and bone ingrowth. Furthermore, printed metal parts can be polished and used to replace articulating parts or complete carpal bones when reconstruction is no longer possible (Ma et al., 2020; Rossello, 2021).

Displaying 3-D imaging

CT data is generally displayed as a series of 2-D slices. The transformation of these data into 3-D representations can provide an enhanced appreciation of injury or deformity, as well as improved planning and delivery of surgical solutions. Such technologies have seen an expansion in the form of 3-D virtual modelling, 3-D printing, augmented/virtual reality and patient-specific surgical planning guides and implants.

In the application of 3-D imaging technology there are two important factors to consider: the first is what is 3-D – and what is not. In the medical world there are essentially two 3-D imaging presentations: volume rendering (VR) and surface/mesh rendering (SR) (Sandow, 2014; Zhou et al., 2022). VR is widely used in CT presentations, and this is the apparent 3-D imaging that most surgeons (and radiologists) would be familiar with – and assume it is a real 3-D object. It is typically integrated in the main imaging platform, and while it may look like a 3-D object, such images are a 2-D screen projection of the 3-D data set – analogous to taking a picture of a hologram. While parts of the image can be hidden and enhanced, there is no capability to spatially manipulate or move parts the image, nor measure distances.

In contrast, SR 3-D images are created by defining thresholds (boundaries between different tissue types) or regions of interest (e.g. individual bones) within the volumetric data set, and then from those points in space, create a true 3-D model (geometric primitive), composed of a surface of polygonal shapes (Figure 2). This displayed image is a mesh model, derived from the primary scan data, but importantly, is not actually the primary data.

This leads to the second of the important factors to consider. In the creation of a SR 3-D model, the defining of thresholds and region of interest is at the discretion of the computer graphics operator, which can be modified to facilitate segmentation (the separation of the 3-D model into individual objects) and (inadvertently) may not include important anatomical features. These images may not always be a true representation of the primary anatomy, and should be referenced against the primary scans, which remain the most reliable imaging information.

Because of the relatively clear density differences between bone and soft tissues, 3-D modelling is most easily performed on CT scans, although MRI scans can also be utilized – but requires increased manual boundary identification.

For true 3-D modelling, virtual surgery and arthroplasty templating, SR is the principal technology (Sandow, 2014) (Figure 3). As most radiology departments do not produce this data, it needs converting with specialized computer programs. Within the medical and surgical environment, 3-D imaging software systems comprise three types of programs.

1. *SR software.* Generally designed for industrial and commercial modelling and printing but can import patient slice data to create anatomical representations. This is frequently open source, often free, but is generally not registered or regulated for medical use. Any technology, including patient data imaging and 3-D modelling software must be approved by local regulators.
2. *Specific medical 3-D model creation software.* Typically available from a 3-D anatomical modelling service, as part of a prosthesis vendor planning system, or from custom implant manufacturers. Such software is registered for medical use, but is expensive, complex, time-consuming to use and requires skilled computer operators to create the model and custom implant. Clinicians usually have little direct access or interaction with the software.
3. *Clinician accessible 3-D modelling software.* This technology can be integrated within the local radiology service and image delivery systems. Clinicians can perform secondary image manipulation and independent 3-D virtual surgery, and 3-D templating – particularly if 3-D prosthesis data is accessible in a secure and non-distributable form.

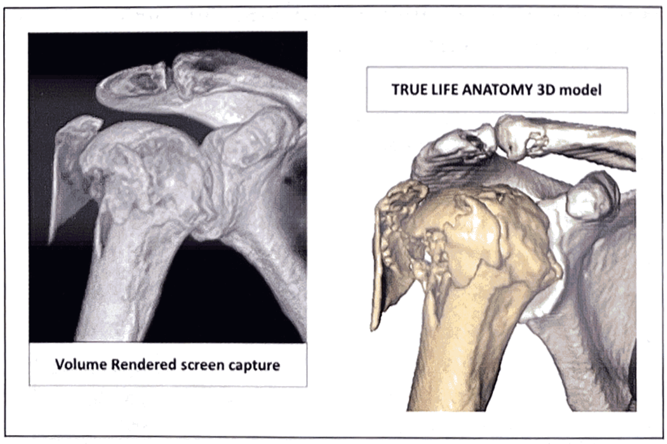

Figure 2. Computed tomography data is often displayed as a volume rendered image (left). A surface rendered image can be created to provide a true three-dimensional object (right), which can be manipulated and measured.
Adapted by permission from www.truelifeanatomy.com.

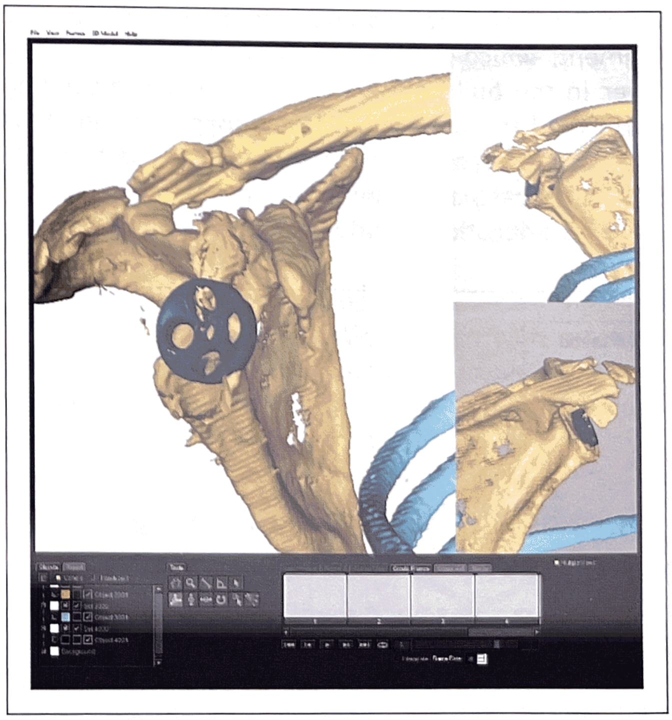

Figure 3. Three-dimensional modelling for implant planning software for shoulder arthroplasty.
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It is essential that surgeons have a good working relationship with their radiology and engineering departments and regard the 3-D modelling data as representative of the relevant anatomy. However, they should always validate this against the primary scan data, which remains the most reliable imaging source. The 3-D modelling is principally to assist in the interpretation of the primary imaging and should not be used as the final arbitrator of decision-making.

3-D printing modalities

3-D printing is an additive manufacturing process that allows the production of unique but complex objects in a cost-efficient manner (Skelley et al., 2019; Zhang et al., 2021) (Figure 1). An object is built up into a 3-D shape by progressive, layer-by-layer deposition of material based on a computer 3-D STL file. An anatomical body part can be produced from cross-sectional imaging (CT or MRI) or a specific object, for example patient-specific instruments or implants.

Common 3-D printing options for medical applications are fused deposition modelling, stereolithography and selective laser sintering (Figure 4). Fused deposition modelling and stereolithography printers are affordable and available as desktop printers (Skelley et al., 2019). The former is the most widely used form of 3-D printing at the consumer level and builds parts by melting and extruding thermoplastic filament, which a printer nozzle deposits layer by layer in the build area. Fused deposition modelling parts tend to have visible layer lines and can show inaccuracies around complex features. The technology is typically used for printing anatomical parts, used for educational and surgical training purposes. Stereolithography have a higher resolution and accuracy and a smoother surface finish and so are commonly used by clinicians and in hospital 3-D laboratories. These resin printers use a laser beam to cure liquid resin into hardened plastic in a process called photopolymerization. Support structures are printed with the object and need to be removed with further post-processing, which involves rinsing, washing and curing under ultraviolet light to provide the desired part properties (Figure 5). Medical grade resins are available so that parts produced can be used for surgical applications. They have a high melting point, compatible with steam sterilization in hospital units for intraoperative use. A disadvantage is the fact that parts tend to be brittle and tend to break under higher loads.

Selective laser sintering printers are industrial devices that only recently have become more affordable and start finding their way into hospital 3-D printing labs. In a layer-by-layer process, a high-powered laser is used to fuse small particles of powder, until the final part is completed and the remaining powder around the printed part is removed (Figure 6). Medical grade polyamide can be used that provides very accurate, lightweight but strong parts, and is the preferred material for patient-specific guides and instruments. To produce patient-specific titanium implants, similar printing technology, direct metal laser sintering or selective laser melting with titanium powder, is used.

Setting up an in-hospital 3-D printing service

There is increased interest in setting up an in-hospital 3-D printing lab as clinicians gain more experience with the use of this technology in patient care.

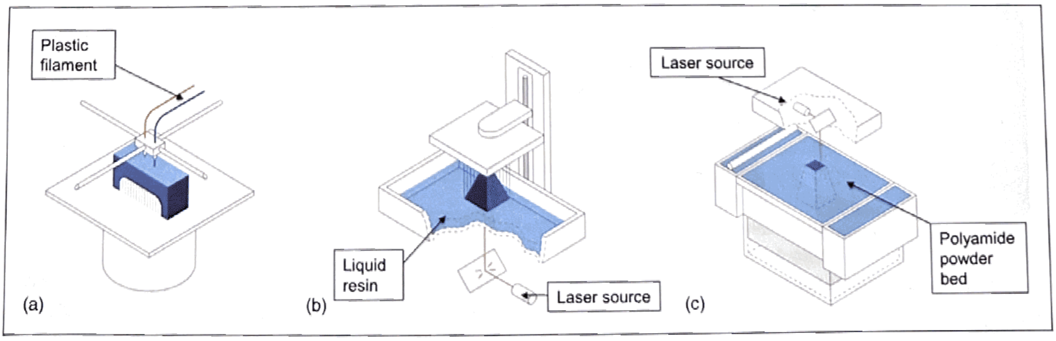

Figure 4. Methods of three-dimensional printing. (a) Fused deposition modeling; (b) stereolithography and (c) selective laser sintering.
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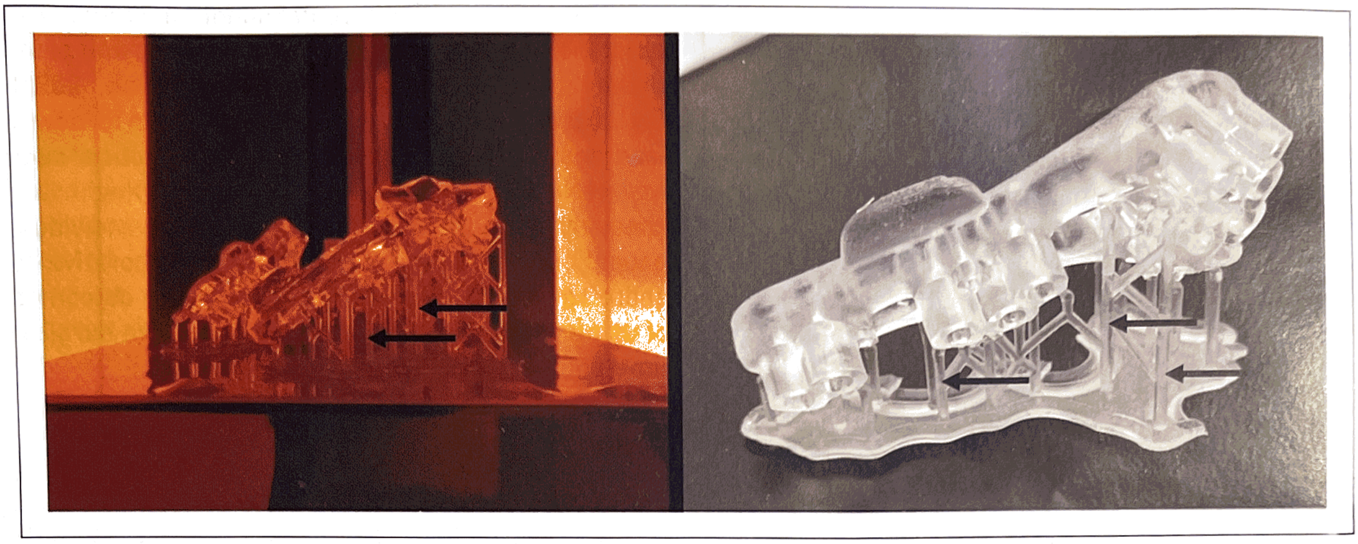

Figure 5. In stereolithography three-dimensional printing, support structures (depicted by arrows) are printed alongside the object, which need to be removed later.

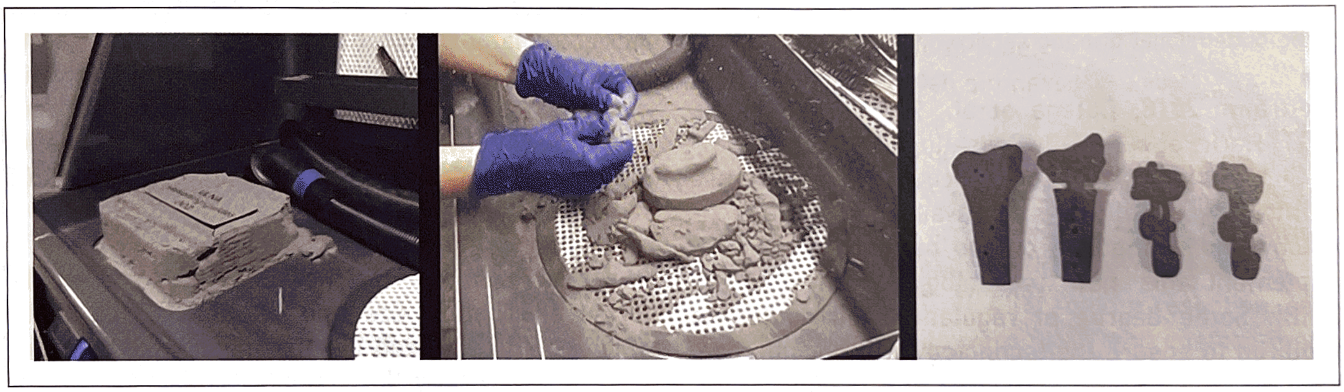

Figure 6. In selective laser sintering, particles of powder are fused with a laser, and the remaining powder is removed and washed away.

In comparison to working with external companies that often provide expensive 3-D services, an in-house lab can allow more flexibility, expand treatment indications, work with shorter lead times and eventually reduce costs.

A first step is bringing colleagues of different departments together who share an interest in the technology. The radiology department is an important partner to provide high-quality imaging for the technology. Producing medical devices in the hospital has legal implications and full support and collaboration with the hospital administration is essential. With all stakeholders, clarity is required around all clinical, technical, legal and financial challenges. Clinical engineers and technicians are needed to assist with the design and printing of anatomical parts, instruments and implants. Funding needs to be to cover initial expenses (primarily computer hardware and software and a 3-D printer suitable for medical applications) and the running costs of the lab. For example, a printer may cost £800 and to print an object, the running costs may be £15, but there are additional costs of personnel and expertise.

However more complex projects, for example titanium implants require collaboration with a reliable external partner, for the planning expertise and the ability to print titanium, which may be more costly (Ma et al., 2020; Rossello, 2021) (Figure 7).

The current role of 3-D printing in upper extremity surgery

In the last few years, there has been a surge in publications on the use of 3-D technology to plan and practice complex procedures, although few articles have reported high-quality data on the outcomes of clinical applications. Most studies on the upper extremities have been limited to small cohorts or case reports spanning multiple indications

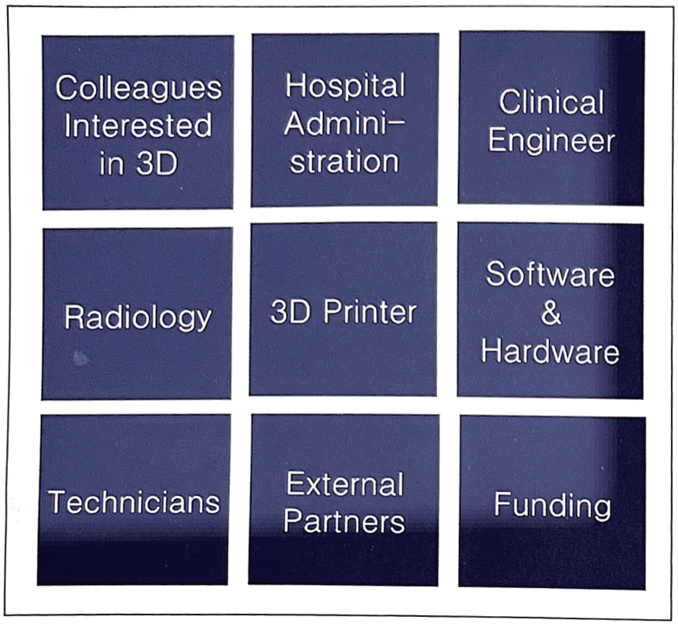

Figure 7. Factors to consider in setting up an in-hospital three-dimensional printing service.

(Beltrami, 2018; Catena et al., 2022; Chan et al., 2021; Hariri et al., 2013; Rossello, 2021).

Clinical use is curtailed by regulations on the use of implants, cost factors, the availability of the technology and hesitations on the part of surgeons to implement this new technology (Vaishya et al., 2018). Some degree of regulation and control is required to ensure the technology is fit for purpose, that the information is reliable and minimizes the risk to patients. A regulatory framework must strike a delicate balance between facilitating access, while ensuring patient safety. 3-D imaging should always be seen as an aid to the interpretation of primary scan data; however, the responsibility remains with the surgeon to deliver patient care and should not be circumvented or compromised by the complexity of the technology.

Nevertheless, studies have shown that surgeons benefit from 3-D technology when dealing with complex cases (Meyer-Szary et al., 2022) and that the use of 3-D models contributes to patient education (Bizzotto et al., 2015; Samaila et al., 2020). There have been continuous efforts to validate applications of this technology as well as its cost effectiveness (Keller et al., 2021; Samaila et al., 2020). Cost effectiveness has been successfully demonstrated in other fields (Chamo et al., 2020); assistance to surgeons, especially with complex cases, should result in shorter operating times and fewer indirect costs. Multiple digital platforms and printing options will probably also lower the direct costs of 3-D technology (Zhang et al., 2021).

Thus far there is little information on the clinical outcome of customized implants, orthoses and prosthetics (Vaishya et al., 2018; Wong et al., 2021). Collaboratives offer open-source projects to download designs for 3-D printed hand prosthetics, such as e-Nable (enablingthefuture.org), which are cheaper, and custom made for each individual patient. Further studies should be collaborative to share results, helping us understand the outcomes of using custom implants and the impact on surgical time and ease of a procedure.

Fractures

The computer-aided treatment of fractures or malunited fractures takes place in several stages, with promising results that this increases accuracy and reduces operative time (Caiti et al., 2020). For example, a study comparing 3-D preplanning to postoperative CT scans in acute distal radius fracture fixation indicated that 3-D modelling resulted in greater accuracy of fracture reduction (2 mm error between marked points on the radius radiocarpal joint surface), and more effective maintenance of this reduction after 6 months (Yoshii et al., 2019; 2021). These authors suggested that the 3-D preplanning allowed for a better choice of implant, including placement of longer screws that did not penetrate the dorsal cortex and better size and position of the plate, which could be placed distal enough while avoiding joint penetration by the screws (Totoki et al., 2018; Yoshii et al., 2019). An image fusion system that displayed the outline of the pre-planned reduction and fixation over the fluoroscopy image during the procedure resulted in more accurate positioning of the implant and screw choice (Yoshii et al., 2019a).

Acquiring fracture images

The resolution of the CT images to produce a 3-D preoperative model needs to be adequate for surgical planning: in distal humeral fracture fixation, there was good correlation between preplanning scans and the actual reduction and fixation when using a CT scan with a slice width of 2 mm or less (Yoshii et al., 2020). However, to print a distal radius fracture 3-D model, a slice width of 0.5 mm using an ultra-low-dose CT scan is required for sufficient diagnostic properties (regardless of the lesser quality of the scans), along with a considerable reduction in radiation exposure (Xiao et al., 2021).

Navigation of the operative procedure using custom guides. Several studies have compared the treatment of upper extremity fracture malunion using

3-D printed guides for the osteotomy and positioning of the fixating plates and screws with standard techniques. Bauer et al. (2017) reported a retrospective account of 31 patients treated with computer-assisted corrective osteotomy of the forearm compared with 25 patients treated with conventional osteotomies (Bauer et al., 2017). In the computer-assisted group, shorter surgical times were recorded, and the outcome measures did not differ between the groups after a mean follow-up of over a year. In a multicentre randomized controlled trial, correction of malunited extra-articular distal radius fractures using computer-assisted preplanning and guide fabrication in 20 patients was compared with non-assisted surgical treatment in 17 patients (Buijze et al., 2018) with superior accuracy in deformity correction reported in the computer-assisted group. The authors reported a trend towards improved outcomes in the 3-D group at 12 months, although the post-hoc analysis revealed statistical underpowering of the trial, despite the sample size that was pre-planned (James, 2018; Leong et al., 2010). Other prospective randomized studies of the fixation of humeral and distal radius fractures have reported shorter operating times and radiation exposure in the 3-D model groups as compared with the standard fixation groups; however, the outcomes or time to fracture healing did not differ between the groups (Chen et al., 2019; Kong et al., 2020; Zheng et al., 2018). Faster union rates have been found for the fixation of tibial plateau fractures (Xie et al., 2018). Improvement in functional outcomes was reported for the lower extremity and spine but has not been demonstrated in elbow or wrist surgery (Wong et al., 2021).

Navigation templates for the fixation of scaphoid fractures have used custom-printed splints to encompass the wrist with integrated jig-ports for K-wire fixation. A comparison of eight patients with scaphoid nonunion using custom splints, to eight patients treated by standard bone grafting and fixation showed that the 3-D group had shorter operating times and no difference in outcome measures at 6 months (Yin et al., 2020). Marcano-Fernandez et al. (2021) also demonstrated a reduction of surgery time by 43% and fluoroscopy time by 52% when using a 3-D printed guide as compared with a control freehand group.

Fracture fixation with modified or custom implants. Shuang et al. (2016) reported shorter operating times using 3-D printed plates after digital preplanning in six patients with humeral fractures versus standard procedures in seven patients, with no difference in outcome. Reports on the use of templates and plate fixation generally do not detail implant modification, or the use of custom-made implants. The advantages may be obvious, but future studies should examine whether there are improved outcomes using these patient-specific implants, in comparison with standard implants.

Other elective procedures

Arthroplasty

Ma et al. (2020) reported that the use of prefabricated lunate implants following resection of the lunate in five cases of Kienböck's disease led to improvement in pain and function after a mean follow-up of 14 months. The implants were designed using CT and MRI scans of the contralateral wrist, were made of a titanium alloy and included tunnels for the passage of sutures for implant fixation (Rossello, 2020).

Tumour resection

Custom-made guides enable the planning and accurate resection of a tumour. In 12 patients treated with limb salvage procedures, including one forearm, the maximal measured error with guides was 3 mm, thus leaving adequate healthy bone margins in all specimens (Park et al., 2018). After tumour resection, several of these patients were fitted with custom-made implants as well. The ability to resect a simulated tumour with accurate margins, in contrast to freehand procedures, was reported in a synthetic pelvic bone model using patient-specific guides when performed by senior as well as less experienced surgeons (Cartiaux et al., 2014).

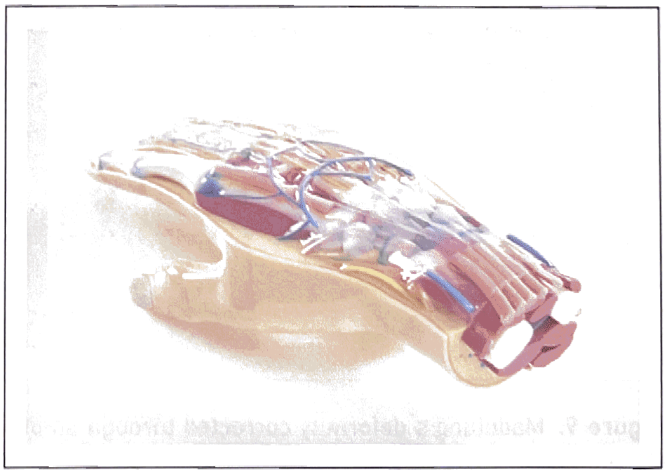

Figure 8. A three-dimensional printed model offers cheap anatomical models that can be customized, for example for hand differences or trauma.
Adapted by permission from Stratasys Inc, Rehovot, Israel.

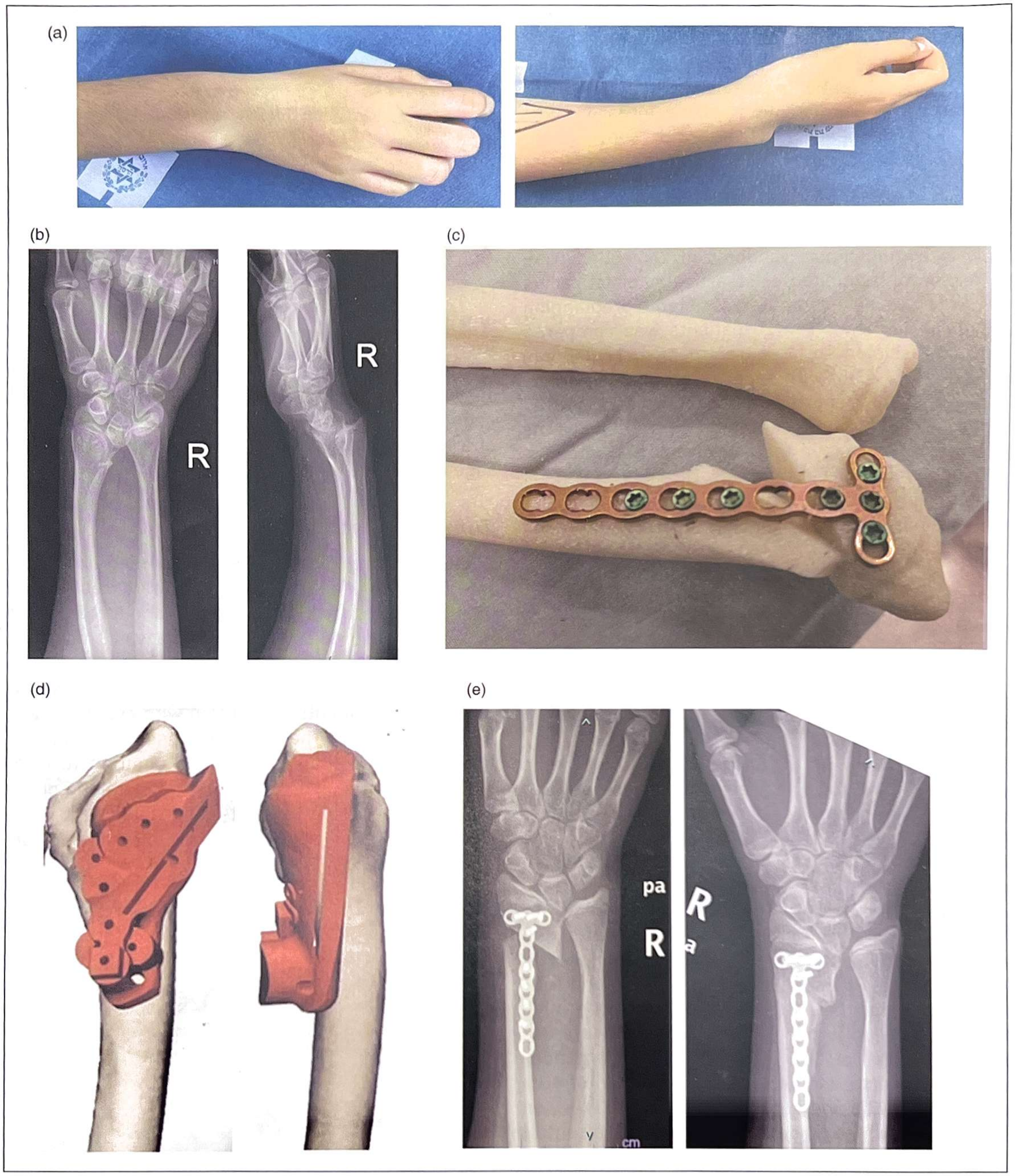

Figure 9. Madelung's deformity corrected through an osteotomy with a patient-specific jig. (a) Madelung's clinical deformity, presenting with wrist pain. (b) Preoperative radiographs demonstrating increased radial inclination and distal radioulnar joint (DRUJ) mal position. (c) A three-dimensional printed model from a planning CT allowed preoperative planning of an osteotomy and plate placement. (d) Three-dimensional planning of multi-planar osteotomies at one level with a patient-specific jig and (e) Postoperative radiographs after Madelung deformity correction and union on 6-month radiographs.

The value of custom designs of implants was reported in three patients with large deforming giant cell tumours in the metacarpal bones. Titanium alloy implants were custom designed and printed to partially replace the resected bone segment with high patient satisfaction (Xu et al., 2021). Another study (Wang et al., 2020) compared 30 patients with large distal radius giant cell tumours in which 15 patients were treated with allograft reconstruction and 15 with a custom-designed distal radius implant, with a mean follow-up of 34 and 31 months, respectively. The implant was reported to yield superior functional results as compared with the allograft group, where significant bone resorption was seen. These superior results were observed even though several patients developed a subluxation of the carpus over the implants. The authors recommended addressing carpal bone morphology when designing the implant and delaying rehabilitation of these wrists (Wang et al., 2020).

Training and teaching

The role of 3-D printing in teaching and training has not previously been significantly discussed and described. Current synthetic training models in terms of drilling bone are not completely accurate in terms of feedback and it is now possible to create a bone with either realistic anatomical or pathological structures (Prsic et al., 2020; Raeker-Jordan et al., 2022). Further it is also possible to create models with realistic anatomy not only at bone level but also creating soft tissues (Farrell et al., 2020) (Figure 8).

Complex surgical models can be created allowing training or research without the need for cadavers or real patients. This work is developmental and at this time there are cost constraints and haptic feedback is still not optimal, however this is an important pathway for future work.

Case examples

The following clinical cases demonstrate the wide variety of applications for this technology.

Madelung's deformity

A 13-year-old healthy female complained about a gradual increase in wrist deformity and ulnar-sided wrist pain (Figure 9). Radiographs showed a Madelung's deformity (Figure 9(a)). A 3-D model allowed surgical preoperative planning and contouring of a plate to this model (Figure 9(b)), followed by

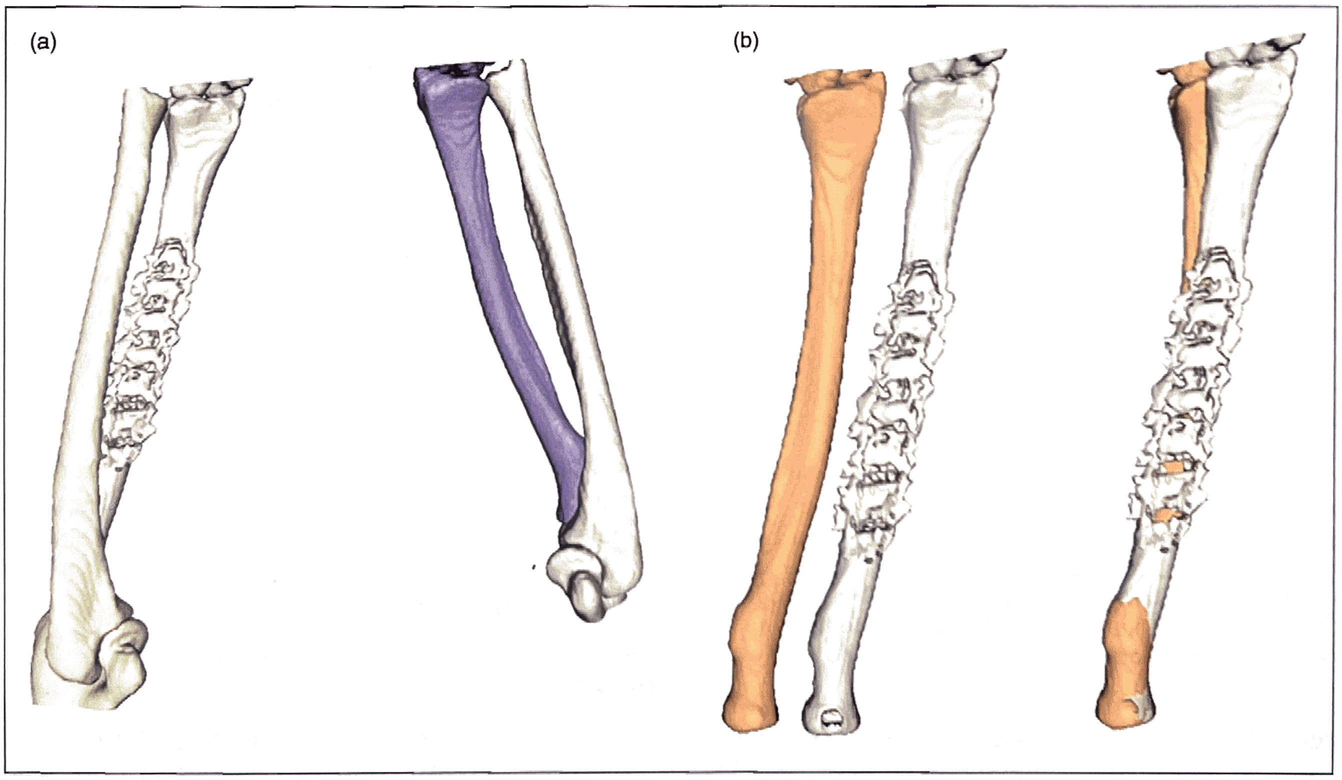

Figure 10. Corrective forearm osteotomy for a malunion after fracture fixation. (a) Three-dimensional imaging was created with CT scans, which demonstrated a mal-united radius with loss of pro-supination and (b) The normal radius (in orange) is mirrored onto the mal-united radius to confirm the incorrect fixation. A 12° corrective osteotomy restored forearm rotation.

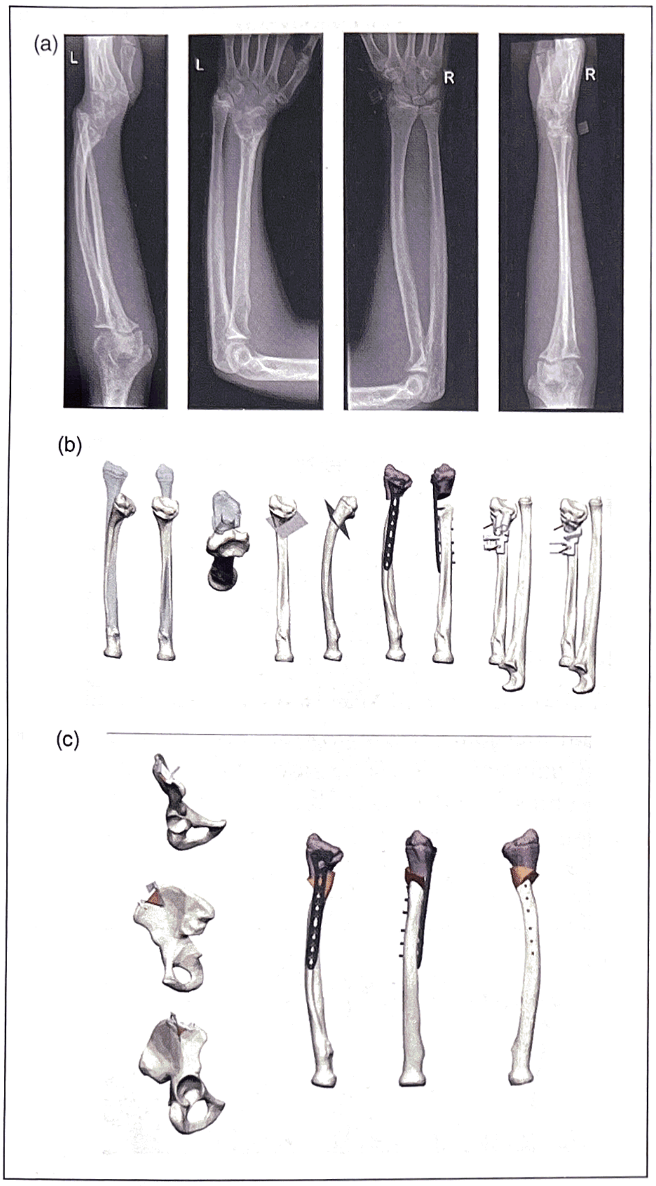

Figure 11. A paediatric forearm osteotomy case after a distal radius growth arrest. (a) Paediatric forearm radiographs showing deformity and distal radius growth arrest, with ulna positive. (b) A three-dimensional (3-D) planning model produced with CT data, allowed surgical planning and position of a plate and patient-specific jigs. (c) Planning images showing patient-specific jigs to take an iliac crest bone graft to match the distal radius bone defect. (d) A sterilized 3-D printed bone model was used intraoperatively to help understand the jig and plate placement on the corrective osteotomy. (e) and (f) Postoperative radiographs at 4 months demonstrate the corrective osteotomy, reduction and union.

correction of the complex deformity in one location using two cuts through one jig (Figure 9(c) and (d)). After surgery, the range of motion improved and pain subsided. Radiographs after surgery and 6 months later demonstrate healing of the osteotomy (Figure 9(e)).

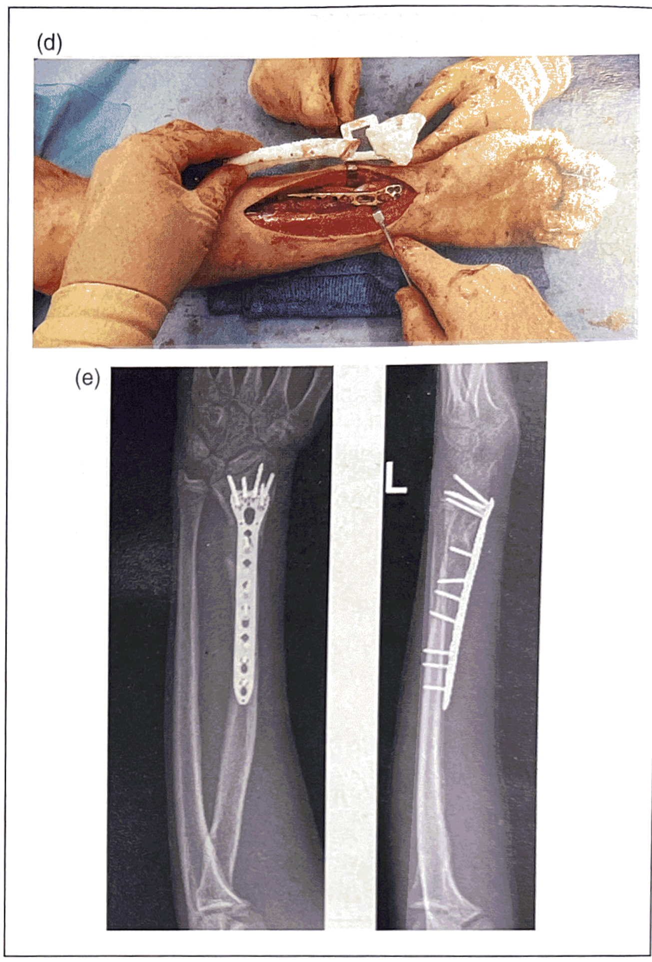

Figure 11. Continued.

Case example: corrective forearm osteotomy for a malunion after fracture fixation

A 40-year-old otherwise well woman, presented with loss of forearm rotation. She had sustained a previous radius shaft earlier treated initially with compression plating, which achieved union. CT scans of both forearms were used to mirror the contralateral side onto the symptomatic side, demonstrating a 12° corrective osteotomy was required (Figure 10).

Case example: paediatric forearm osteotomy after a distal radius growth arrest

A 13-year-old boy presented with progressive deformity of the forearm with pain, loss of motion and weakness (Figure 11). He sustained a fracture of the left distal radius 6 years earlier, treated by closed reduction and immobilization. Radiographs confirmed a significant deformity of the distal

Figure 12. Scaphoid arthroplasty with a three-dimensional (3-D) printed titanium implant. (a) Avascular necrosis of the scaphoid on CT arthrogram and radiographs. (b) Titanium 3-D printed scaphoid based off the contralateral side CT scan with tunnels for passing restraints and (c) The scaphoid implant was stable on stress radiographs.

radius, which was shortened and angulated (Figure 11(a)). CT-scans were used to generate 3-D STL files of the bones of both forearms and the deformity was compared with the mirror image of the contralateral radius. A virtual surgical reconstruction to restore anatomy was planned and patient-specific instruments were designed (Figure 11(b)). A precise matching cortico-cancellous graft was planned with cutting guides for the iliac crest (Figure 11(c)). The surgery was performed with 3-D printed models and patient-specific instruments (Figure 11(d)). Radiographic outcome precisely matched the preoperative 3-D plan and bone healing was confirmed at 4 months (Figure 11(e)). The clinical result was excellent with return of pain-free wrist function (Figure 11(f)).

Case example: arthroplasty for avascular necrosis and collapse of the scaphoid

A 71-year-old lady complained of chronic pain in the left wrist, caused by avascular necrosis and collapse of the scaphoid (Figure 12). Her symptoms deteriorated to the extent that she requested further surgical treatment. To avoid or at least delay salvage procedures, a 3-D printed scaphoid prosthesis was designed based on the shape of the contralateral scaphoid (Figure 12(b)). Following removal of the necrotic scaphoid, the prosthesis was inserted through a combined palmar and dorsal approach. The patient is now 5 years post-operation and has maintained pain-free function with a stable scaphoid on stress radiographs (Figure 12(c)).

Conclusion

The use of 3-D planning and intraoperative augmentation offers the clinician exciting benefits in terms of surgical capability and accuracy. Surgeons may plan and practice complex procedures, using bespoke implants and jigs. 3-D technology is a proven modality that is evolving in terms of availability, indications and reducing cost. It is not a replacement for surgical skill and decision making, but should be considered as part of the surgical toolbox, however, when used appropriately, these technologies can allow a more accurate operation, and procedures performed more easily with better patient outcomes.

Declaration of conflicting interests The authors declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: MJS has a commercial interest in a 3-D technology company (truelifeanatomy.com); FV is a consultant for Cadskills and Materialise and receives royalties from Cadskills and Materialise; MDH has worked as a paid consultant for Alloyed. No other author has a conflicting interest

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