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Review

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A comprehensive review of the educational, clinical and rehabilitative applications of 3D printing technology in hand surgery

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Abstract

With the rapid development of 3D printing (3DP) technology in both educational and perioperative settings, a thorough evaluation of the latest literature is warranted. This semi-systematic review explores the current educational, clinical, and rehabilitative applications of 3DP technology in hand surgery. In educational settings, student and trainee education improved with the use of inexpensive, accessible models for anatomy and surgical simulation, demonstrating an enhanced understanding of spatial relationships and increased confidence in surgical skills. Patient education and consent can be improved with the use of patient-specific models. Studies showed that patient-specific models led to higher patient comprehension and satisfaction during the consenting process. Patient-specific models also offer more comprehensive preoperative planning, and cutting guides facilitate more precise surgical techniques. Clinical outcomes indicated reduced operative times and radiation exposure, along with improved surgical accuracy. Additionally, 3DP enables the creation of cost-effective implants that precisely conform to each patient's anatomy. For rehabilitative purposes, 3DP can make splints that have the potential to reduce costs and improve compliance. Preliminary data indicated higher patient comfort and improved functional outcomes with 3D-printed splints. Overall, the current literature is mixed on the benefits of 3DP in hand surgery; however, many studies show promising results. As 3DP becomes more streamlined and the equipment becomes less expensive, its applications will continue to expand, and future research will be needed. Future studies should focus on long-term clinical outcomes and cost-effectiveness to fully ascertain the efficacy and value of 3DP in hand surgery.

Keywords: Hand surgery, 3D printing, surgical education, patient education, preoperative planning, intraoperative guides, implants, bioprinting

INTRODUCTION

The introduction of 3D printing (3DP) technology in the early 2000s marks a pivotal shift in the field of medicine, initiating a new era in surgical training and perioperative care. This technology offers novel solutions to long-standing challenges within hand surgery. Traditional methods of surgical training, particularly those relying on cadaveric dissections, struggle with issues related to ethics, cost, and availability. These challenges are accentuated in the context of hand anatomy, an area known for its complexity and thus posing a significant learning curve for surgical trainees and students.

Additionally, standard approaches in patient education can fall short in effectively communicating complex hand-associated diseases, leading to gaps in patient understanding and informed consent. In the preoperative phase, conventional imaging techniques, such as computed tomography (CT) scans and X-rays, require surgeons to mentally reconstruct three-dimensional structures from two-dimensional images, which may be prone to errors, especially for novice surgeons and trainees. Intraoperatively, the intricate nature of hand surgery demands a high degree of precision and spatial understanding, which can also be challenging and potentially result in prolonged operative times and increased costs. Furthermore, current hardware for bony fixation in hand surgery is often limited to a set of standard sizes in a one-size-fits-all approach, which may be suboptimal due to the unique and complex anatomy of each patient's hand.

The rehabilitation phase in hand surgery is also fraught with challenges. Current practices involving orthoses and prosthetics are often limited to a set of stock sizes, which may not adequately meet the diverse needs of individual patients. Moreover, conventional immobilization techniques frequently lead to issues with discomfort and poor hygiene. Ensuring patient compliance with rehabilitation protocols also remains a pressing issue in hand surgery.

Given these challenges, hand surgery is particularly poised to benefit from the advancements brought by 3DP. Recent progress in additive manufacturing has positioned 3DP as a valuable tool in addressing these problems. With the rapid development of 3DP in both educational and perioperative settings, a thorough evaluation of recent literature is warranted. This review utilizes a literature review to explore the educational, clinical, and rehabilitative applications of 3DP technology in hand surgery.

METHODS

An online literature search was explored to assess the role of 3DP in Hand surgery. PubMed, Google Scholar, and MEDLINE were utilized to identify articles in English that investigated or commented on 3DP and hand surgery up until February 2024. Keywords queried included various arrangements of the following terms: "3-dimensional model", "3-dimensional printing", "hand surgery", "pre-operative planning", "surgical planning", "post-operative care", "intra-operative printing", "surgical education" "rehabilitation", "bioprinting", and "intra-operative guides". Eligibility criteria excluded articles, abstracts, case reports, presentations, and papers not written in English. Additional queries were also performed based on relevant references of the searched articles.

SURGICAL EDUCATION

Currently, cadaver-based education is widely accepted as the standard for anatomy instruction. The use of cadavers, however, is expensive and often complicated by ethical issues and lack of availability[1]. Recent reforms in medical education, alongside cultural and ethical shifts particularly catalyzed by COVID-19, have led to a marked decrease in the number of cadavers available per student. This reduction has had a considerable impact on the quality of anatomical education[2-4]. Furthermore, the degradation of cadaveric tissue over time and the anatomical variability between cadavers further complicate the learning process. These disadvantages are compounded in hand surgery as it is commonly listed as one of the most complicated regions of the body to study for trainees[5]. However, recent advancements in 3DP technology may offer a solution. Novel developments within 3DP now allow for more accurate and multi-color printing with various textured materials, rendering them ideal for improved anatomy education[6]. Historically, 3DP was commonly isolated to single anatomical structures such as bone or soft tissue, but multiple multi-layered 3DP hand models have been recently described[7-9]. These anatomical hand models accurately display the relationship between tendons, muscles, and neurovascular structures at the superficial and deep with a spatial resolution of 1 mm[10]. When implemented, medical students reported that 3D models significantly improved their learning by enhancing their understanding of spatial relationships and allowing for a more active role in their education[11,12]. While cadaveric dissection is a cornerstone of anatomical education and a hallmark of medical education, its utility can be further augmented with the addition of more accurate 3DP models, especially within hand anatomy given its complexity.

For surgical residents and fellows, 3DP provides opportunities for inexpensive and accessible surgical simulation. While 3DP's utility in simulating soft tissue surgeries like craniofacial and breast surgery has been well documented, replicating the intricate combination of soft tissue and bone manipulation required in hand surgery presents a unique challenge[13-15]. To address this, Prsic *et al*. utilized a reusable and cost-efficient 3DP hand model designed to accurately simulate closed reduction percutaneous pinning of hand fractures. To replicate haptic feedback, the model was designed to incorporate variable densities within the 3DP bone to reflect the stiffness of the cortical surface and the medullary canal and included a silicone material to represent soft tissues. Notably, the model does not require fluoroscopy to assess successful pinning and can be produced at a cost of only 40 USD[15]. Papavasiliou *et al*. also developed a 3DP training module for flexor tendon repair in the hand. This model accurately replicated the flexor anatomy, including bony spatial configurations, pulleys, and the flexor digitorum superficialis (FDS)/flexor digitorum profundus (FDP) tendon structures. Trainees using this model reported significant confidence in flexor tendon repair skills[16].

PATIENT EDUCATION AND PREOPERATIVE PLANNING

Preoperative clinical visits play a crucial role in hand surgery, as they enable patients to understand their condition, treatment options, and associated risks. However, retention and comprehension of this information are often poor in the clinical setting[17-19]. 3D models can significantly enhance preoperative patient education by allowing patients to interact and learn from 3DP models representing their specific pathology, improving their understanding in the informed consenting process. Given the complexity of hand anatomy, patients are especially poised to benefit from the use of patient-specific 3DP models[20]. Several studies have illustrated that when patients are exposed to 3DP models of their fractures during preoperative discussions, they demonstrate a higher likelihood of understanding their condition and the details of the surgical procedure compared to conventional methods[21-26]. In ligamentous injuries, Patera and Rust demonstrated that 3DP models of the triangular fibrocartilage complex significantly enhanced patient understanding during hand clinic[20].

Moreover, 3DP can also enhance the accuracy and ease of preoperative planning within hand surgery. Traditional imaging methods like CT and X-ray require a mental conversion from two to three dimensions, a task that can be challenging and error-prone, especially for novice surgeons[27-30]. Patient-specific 3DP models can allow for a more thorough evaluation of anatomy, pathology, and surgical approaches, and even simulate surgery before the actual procedure.

The advantages of using patient-specific 3D models for preoperative planning are well-documented across various surgical specialties. In craniomaxillofacial surgery, for instance, 3D models have been instrumental in demonstrating pathological structures and planning osteotomies[31,32]. Similarly, in lower extremity and pelvic fracture repairs, the use of 3D models has led to reduced operative time and complications[33,34]. A systematic review by Tack *et al*. found that in over half of studies, preoperative planning with 3D models reduced operative time, and in more than 80% of cases, it improved outcomes[35].

In hand surgery specifically, 3DP models can provide improved visualization of complex 3D deformities such as scaphoid deformities prior to reconstruction, allowing surgeons to better plan for bone realignment, fixation options, and hardware positioning[36]. 3DP models can plan for removal of sclerotic bone and fibrous elements and determination of dimensions for bone grafting[36-39]. These models have also been used to plan osteotomies for forearm deformities and malunions[40-42]. Bauer *et al*. demonstrated the utility of preoperative 3DP models in pediatric upper extremity deformities, uncovering several rotational deformities that were missed during conventional techniques[43]. Additionally, custom-made 3DP silicon models have been used in syndactyly surgery to accurately plan the separation, potentially reducing operation duration[44]. In complex thumb reconstructions using toe transfers, 3DP bone and joint models have been associated with shorter operation times and satisfactory functional outcomes[45]. A recent meta-analysis of 51 studies indicated that 3DP preoperative planning in upper extremity and hand surgeries can significantly reduce operative time, blood loss, and intraoperative fluoroscopy use, although no significant differences were noted in long-term functional outcomes compared to conventional methods[21].

3DP technology is revolutionizing hand surgery by improving patient education, enhancing preoperative planning, and potentially influencing surgical outcomes, pointing toward a future where personalized and precise surgical care is the norm.

INTRAOPERATIVE GUIDES

3DP also has several important intraoperative applications including patient-specific guides for osteotomies and hardware insertion. One of the complexities of hand and upper extremity osteotomies is that they require a thorough understanding of three-dimensional abnormalities. Conventional radiographic preoperative planning methods have shown limitations, with less than half of patients achieving optimal results in some cases[44,46,47]. 3DP technologies offer a promising solution to these geometric surgical challenges. Patient-specific 3DP guides cater to a range of osteotomies, from simple to complex composite cuts. The recent introduction of radiolucent printing material can also assist in better estimating the amount of bone graft needed[48].

Numerous studies have documented the efficacy of patient-specific guides in forearm deformities. In a proof-of-concept study, Schröder *et al*. and Honigmann *et al*. successfully utilized 3DP guides in forearm malunion and distal radius osteotomies, respectively[49,50]. Case series for pediatric and adult patients also reported high union rates and significant functional improvements using 3DP cutting guides[43,51-54]. Comparative studies have associated patient-specific 3DP guides with shorter operative times, lower radiation exposure, and improved healing rates[7,55].

Cadaveric studies have shown that Kirschner wire (K-wire) fixation of the scaphoid with 3DP guides leads to enhanced accuracy, reduced procedure time, and less fluoroscopy use[56,57] Clinical translations of these guides by Yin *et al.* and Rong *et al.* demonstrated significant operative improvements in scaphoid fixation[58,59]. These guides facilitated anatomically precise drilling of K-wires within the scaphoid, reducing operative time significantly compared to standard fluoroscopy methods. Further studies have reinforced these findings, indicating shorter procedures and fluoroscopy times while maintaining similar functional outcomes[60-62]. One prospective study reported improved outcomes and faster healing in displaced scaphoid fractures and nonunions with 3DP guides[60]. Another use of 3DP is for complex metacarpal fractures. Fillat-Gomà *et al.* utilized 3DP guides for osteotomies and K-wire placement in the fixation of a complex malrotated malunion of a fifth metacarpal diaphysis fracture. This treatment involved a closing-wedge osteotomy of the metacarpal followed by fixation using a retrograde intramedullary screw[63].

The costs associated with 3DP patient-specific materials are an important consideration. While the price of 3DP models is decreasing, the guides can still be expensive, costing up to several hundred USD[51,60]. However, the reduction in operative time may offset these costs, as illustrated by DeWolf *et al.*, estimating potential savings of up to $750 per patient undergoing scaphoid fixation with 3DP guides[57].

An important limitation is the need for preoperative CT scans, often of both extremities, raising concerns about radiation exposure and additional costs. While most studies acknowledge this limitation, it is often noted that CT scans of both extremities are routinely obtained preoperatively in many institutions. Furthermore, the process of scanning, design, and printing of guides can extend preoperative planning time[51,54,60]. While 3DP patient-specific guides in hand surgery come with certain limitations, their benefits in surgical precision, time efficiency, and potentially cost-saving aspects signify a significant advancement in the field.

IMPLANTS

3DP offers significant advantages in creating patient-specific implants that can improve operative outcomes. The intraoperative bending of standard plates, traditionally time-consuming and dependent on the patient's anatomy and surgeon's expertise, is now being innovated with 3DP[64]. Recent advancements in additive manufacturing have facilitated the production of metallic 3DP custom plates, which show promising mechanical properties in initial studies[65-67]. However, it is important to approach these findings with caution. While 3D-printed metals have been studied for a relatively short period, approximately thirty years, compared to the centuries-long history of forged or cast metals, their long-term performance and reliability are still being evaluated. Reviews indicate that failures of 3DP implants are being observed, underscoring the need for further rigorous and longitudinal studies to fully ascertain their durability and safety[68,69] For instance, one study presented cases of limb salvage surgeries using 3D-printed custom-made implants, highlighting mechanical failures and the challenges associated with the mechanical properties of these implants[70].

A biomechanical study by Kim *et al.* compared 3DP titanium alloy volar locking plates to conventional hardware used in comminuted distal radius fractures[71]. Both types of plates were found to be sufficiently strong for early postoperative rehabilitation. Notably, the study highlighted that while traditional implants typically have stiffness greater than cortical bone, 3DP plates can be modified to more closely mimic the stiffness of cortical bone while maintaining their strength, which may result in less stress shielding and subsequent reduced bone loss around the hardware[71,72].

Patient-specific 3DP plates have shown promising results in the correction of distal radius malunions. Raad and Schep[73], and Dobbe *et al*.[74] reported pain reduction and improved alignment with these plates compared to conventional hardware. Byrne *et al*. applied patient-specific 3DP plates in pediatric forearm malunions, observing almost perfect fit, precise fixation, and 2-year improvements in pain score, grip strength, and forearm rotation[64].

Another growing application is 3DP carpal bone replacements. Studies on 3DP scaphoid and lunate[68] replacements indicate suitable geometry and mechanical properties for *in vivo* applications[75]. Honigmann *et al*. used alumina ceramic 3DP scaphoid replacements in a cadaveric study and reported physiological behavior under motion analysis compared to native scaphoids[29]. Clinically, 3DP titanium scaphoid replacements have been used with positive clinical and radiographic outcomes at 2-year follow-up[76,77]. Patient-specific 3DP lunate replacements using titanium alloy have also been described in Kienbock's disease, with significant improvements in pain and wrist function[78]. In addition, 3DP has also been used to create a custom "metal-on-polymer" proximal interphalangeal joint prosthesis with similar dynamic and static performance to normal joints in in-vitro analysis[79].

Recent advancements in 3DP technology extend beyond the customization of implant shape to include significant modifications in their intrinsic structure and composition. Fabrication techniques now enable customizable implants with varied porosity, thereby enhancing osteointegration and biocompatibility. Additionally, these implants can be engineered and printed to gradually degrade over time, effectively reducing the risks associated with permanent foreign body implants[80].

BIOPRINTING

While 3DP implants are currently in use, accurately replicating the structure and function of *in vivo* tissues remains a significant challenge. Bioprinting, an advanced form of 3DP, offers a potential solution to this challenge. This technique involves incorporating cells, biological molecules, and biomaterials into the additive manufacturing process to mimic the heterogeneity and structure of native tissues[30,81]. Promising advances in in-vitro bioprinting of skin, cartilage, tendon, muscle, bone, and adipose tissue have been described, with potential reconstructive applications within hand surgery[82-88].

However, bioprinting faces limitations in clinical application, particularly due to the prolonged time required for design and printing, as well as possible tissue degradation during surgical delays. To address these issues, intraoperative bioprinting has emerged as a promising approach[82]. This technique involves the use of handheld devices or automated intraoperative printing machines to directly print biomaterials into defects. Di Bella *et al*. developed a handheld bioprinting device for cartilage regeneration and successfully facilitated early cartilage regeneration without intraoperative or postoperative complications in animal models[89]. Albouy *et al*. describe the use of an automated printer to regenerate skin in a rat model[90]. With regard to hand surgery, Gonzalez-Fernandez *et al*. described a novel bioink used to create 3DP cell-laden scaphoid prosthesis capable of mineralization *in vivo*[91]. Bioprinting of the scapholunate interosseous ligament has also shown promising outcomes, including vascularization and collagen deposition in animal models[92]. While still in its nascent stages, bioprinting represents a potentially groundbreaking tool in hand surgery and the broader field of 3DP, offering innovative solutions for complex reconstructive challenges.

REHABILITATION

3DP offers significant benefits in hand rehabilitation, particularly in the production of patient-specific orthoses and prostheses. Traditional plaster and fiberglass casts, commonly used for upper extremity and hand immobilization, often lead to complications such as skin irritation, compression injuries, and poor hygiene[93]. 3DP splints, being water-resistant and hypoallergenic, can improve patient comfort and hygiene. Guebeli *et al*. compared 3DP splints to traditional fiberglass splints for distal radius fractures and found they were preferred by patients due to their water resistance, lightness, and modern aesthetics[94,95]. In a clinical trial, Chen *et al*. reported that custom 3DP splints for forearm fractures performed better than traditional splints in terms of pain, functional status, range of motion, and grip strength, as well as patient comfort[96,97].

Other applications of 3DP splints have been described for mallet finger and arthritis. Papavasiliou *et al*. discuss the use of a 3DP splint for mallet finger that is low cost, lightweight, and radiolucent, allowing for adjustments under radiographic guidance[98]. The use of 3DP splints has also been described for the treatment of carpometacarpal osteoarthritis. Interestingly, off-the-shelf splints were significantly more effective at reducing disability scores compared to 3DP splints[99]. As the 3DP technology and processes continue to improve, further investigation into their efficacy and patient satisfaction is necessary.

The primary downside to 3DP orthoses lies in the costs and time investment. While the materials themselves may be inexpensive, the initial setup costs of 3DP machines and the time required for orthotic design are considerable[94,95]. Streamlining and potentially outsourcing parts of the printing process will be essential for feasibility in a busy clinical hand practice.

3DP-assisted devices can also be designed to better aid patients with respect to occupational therapy and rehabilitation. Patterson *et al.* described using a 3DP orthosis to aid a patient with permanent hand neuropathy in playing the piano, and another device to assist with handling small items[94]. Mohammadi *et al*. reported on a 3DP glove designed to assist with pinch force and power grasp[100].

For prostheses, 3DP is rapidly gaining importance, especially in cases of trauma-related amputations and congenital hand deformities. Custom 3DP hand prostheses have supported daily activities and shown improved functional outcomes post-amputation[101-104]. A notable example is the Fingy3D (Morgantown, WV), which utilizes AI to create functional 3DP prosthesis based on photographs of the amputated digit[105].

3DP is also making strides in hand rehabilitation. A randomized control study found that 3DP orthoses used in conjunction with rehabilitation had better outcomes with regard to spasticity, range of motion, motor function, and swelling than standard thermoplastic splints with rehabilitation[106]. The precise fit and mechanical strength of 3DP orthoses allowed for improved passive range of motion and more effective stretching during rehabilitation[106,107]. Several researchers have also designed and investigated 3DP soft robotic hand exoskeletons for passive hand rehabilitation[108,109]. Preliminary clinical studies have found that 3DP robotic hands improve strength, hand function, and range of motion[110]. Interestingly, when 3DP is involved in rehabilitation, there is also increased patient compliance[111-113].

Overall, while 3DP in hand surgery and rehabilitation is showing promising results, continued research and refinement are essential to fully realize its potential and address its current limitations.

REGULATORY CONSIDERATIONS IN 3DP AT THE POINT OF CARE

Integrating 3DP into hand surgery offers significant advancements but requires navigating Food and Drug Administration (FDA) regulations to ensure safety and quality. Healthcare facilities (HCFs) can use a Medical Device Production System (MDPS) from a manufacturer, partner with a manufacturer, or take full manufacturing responsibilities[114].

When using an MDPS or partnering with a manufacturer, the HCF follows the system's labeling and instructions while the manufacturer ensures FDA compliance. This model leverages the manufacturer's regulatory expertise, allowing for rapid and customized device production. If HCFs assume full manufacturing responsibilities, they must comply with FDA regulations, including registration, quality system regulations, and post-market surveillance[114].

The FDA provides a comprehensive framework for additive manufacturing. It covers design and manufacturing considerations, such as device design, patient-matched device design, software workflow, material controls, post-processing, and process validation. It also addresses device testing considerations, including mechanical testing, dimensional measurements, material characterization, removal of manufacturing material residues, sterilization, and biocompatibility[115].

Additionally, the FDA clarifies the criteria under which custom devices can be exempt from certain regulatory requirements. This guidance ensures custom devices meet unique patient or physician needs without undergoing the full premarket approval process, provided they adhere to specific criteria, such as being limited to no more than five units per year of a particular device type and not being generally available in the U.S. in finished form through labeling or advertising[116].

CONCLUSION

Recent advances in additive manufacturing have resulted in increasing applications of 3DP in hand surgery. Based on the current literature, it remains evident that student and trainee education can be improved by inexpensive, accessible models for anatomy and surgical simulation. Additionally, patient education and consent can be improved with the use of patient-specific models. 3DP offers the advantages of more comprehensive preoperative planning and the facilitation of more precise surgical techniques. Additionally, 3DP enables the creation of cost-effective, tailor-made implants that precisely conform to each patient's anatomy. For rehabilitative purposes, 3DP has the potential to reduce costs, and improve compliance and outcomes. While current evidence on the outcomes of 3DP-based interventions is mixed, ongoing research is essential to fully ascertain the efficacy and value of 3DP in hand surgery. However, many current studies show promising results, and as the 3DP process becomes more streamlined and the equipment becomes less expensive, the role of 3DP in all aspects of hand surgery is poised for significant expansion.

Despite the numerous promising applications of 3DP in hand surgery discussed in this review, it is crucial to consider the more cautious perspective presented by other experts in the field. One review highlights several limitations and recommendations to ensure the future success of 3DP. It underscores the importance of mastering the entire manufacturing process to avoid overdependence on engineers and medical device companies. Additionally, it stresses that surgeons need to maintain autonomy and develop the necessary skills to fully leverage this technology. Furthermore, this review emphasizes the need for thorough and continuous evaluation of the technology's efficacy in clinical settings, noting that "3D objects cannot replace bedside training with patients or practical courses in the anatomy laboratory" and that their benefits should be continually validated through rigorous studies[113]. Therefore, while the future of 3DP in hand surgery holds significant promise, it is essential to approach its adoption with a balanced view, recognizing both its potential benefits and current limitations.

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Authors' contributions

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Literature review and writing: Baker R, Adamczyk P
Conception, design and writing: Prsic A

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