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General

What's New in Hand Surgery: Transformative advancements and Emerging Trends

Wendy Ghanem, MD[1], Hady Ezzeddine, MD[1], Elyssa Kiwan, MD[1], Joseph Najjar, MD[1], Rita Saad, MD[1], Majed Ali, MD[1], Emanuel-Youssef Dib, MD[1], Mohamad Badra, MD[1], Ramzi Moucharafieh, MD[1]

[1] Department of Orthopedics and Traumatology, Faculty of Medicine, University of Balamand, Beirut, Lebanon

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Hand surgery has undergone remarkable evolution over the past decade, driven by advances in microsurgery, biologics, imaging, and digital technologies. Key areas of progress include high-resolution imaging, minimally invasive surgery, wide-awake local anesthesia (WALANT), and biologic therapies such as platelet-rich plasma and stem cells. Reconstructive strategies have advanced with vascularized bone and nerve grafts, tendon repair techniques, and the integration of biologics with scaffolds and 3D printing. Technological innovations—artificial intelligence, virtual and augmented reality, robotics, and telemedicine—are redefining surgical education, intraoperative navigation, and rehabilitation. Despite rapid growth, challenges remain regarding validation, equity of access, and ethical considerations. This review highlights transformative developments, focusing on innovations that have reshaped diagnostic accuracy, surgical precision, and patient-centered outcomes.

INTRODUCTION

Hand surgery has undergone a significant transformation over the past decade, driven by rapid advancements at the intersection of biotechnology, microsurgery, and digital health. From 2015 to 2025, the field has witnessed the integration of high-resolution imaging modalities, regenerative biologics, and minimally invasive surgical techniques—each contributing to improved diagnostic accuracy, patient outcomes, and surgical efficiency. Concurrently, the adoption of digital technologies, including artificial intelligence (AI), telemedicine, and intraoperative navigation systems, has reshaped clinical decision-making and perioperative care.[1,2]

This review article aims to summarize the most impactful innovations in hand surgery over the past decade, emphasizing developments supported by robust clinical evidence. Key areas of focus include imaging advancements, tissue engineering applications, robotics and augmented reality in microsurgery, and the role of wearable technology in postoperative rehabilitation. By highlighting these trends, we provide an overview of the evolving landscape of hand surgery and its implications for future practice.

1. ADVANCES IN IMAGING

Recent developments in imaging have significantly enhanced the ability to diagnose hand diseases and plan surgeries. High-resolution ultrasonography now permits thorough examination of nerves and tendons, revealing diseases before they emerge on regular radiographs.[3-5] For example, high-definition ultrasound (22 MHz) allows detailed visualization of the ulnar nerve's intraneural architecture in both normal and diseased states, providing normative data that improve diagnostic confidence in peripheral neuropathies.[3] Combined high-frequency and contrast-enhanced ultrasound (CEUS) has also been used to better characterize extensor tendon injuries in the fingers, enhancing preoperative diagnostic accuracy. Standard ultrasound alone may be obscured by edema, hematoma, or soft tissue contusion, making partial and complete ruptures difficult to distinguish. CEUS provides distinct perfusion patterns for complete rupture, partial rupture, and contusion, while also localizing tendon ends. This improves diagnostic confidence, guides tailored surgical planning, and helps optimize functional recovery.[4] Additionally, high-resolution musculoskeletal ultrasound proves valuable in assessing early, undifferentiated hand and wrist pain, identifying synovitis, tenosynovitis, erosions, and other pathologic changes before radiographic abnormalities emerge.[5]

Dynamic MRI evaluates ligamentous and carpal motion in real-time, revealing instabilities that are imperceptible to static imaging.[6-8] Real-time MRI during active motion (e.g., continuous radioulnar deviation) has been employed to differentiate partial vs. complete scapholunate ligament tears by quantifying joint width changes over the full range of motion, revealing patterns and thresholds not visible in static imaging.[6] A novel volumetric dynamic MRI technique using a flexible 8-channel receive coil and radial sampling (achieving ~48 ms/frame temporal resolution) has demonstrated feasibility in tracking carpal bone motion in 3D, enabling quantitative kinematic assessment for wrist instability.[7] Also, “real-time 3D MRI” has been tested during wrist motion (radial-ulnar deviation, clenched fist) demonstrating sufficient image quality and speed to visualize scapholunate gap and dynamic carpal instability.[8]

2. ADVANCES IN MINIMALLY INVASIVE HAND SURGERY

Minimally invasive (MI) techniques in hand surgery using small incisions, endoscopic/arthroscopic tools, and image guidance are rapidly expanding. These methods aim to reduce tissue trauma, pain and recovery time while maintaining excellent clinical outcomes.

Endoscopic carpal tunnel release (ECTR) is a widely adopted minimally invasive technique that achieves outcomes comparable to open surgery with less scar-related morbidity. Evidence indicates it enables faster return to work, improved grip strength, and higher patient satisfaction. Both single- and two-portal approaches are safe, effective, and provide reliable results in CTS treatment.[9]

Likewise, wrist arthroscopy plays an important role in evaluating ulnar-sided wrist pain and suspected ligament injuries. In a cohort of 500 patients, it confirmed TFCC tears in ~74% of cases and identified additional pathology such as scapholunate injuries or cartilage damage in ~30%, findings that guided either immediate arthroscopic procedures or subsequent open surgery in most patients.[10] Performed through 2–3 portals less than 1 cm, these minimally invasive procedures allow direct repair or debridement of TFCC lesions, ligament tears, ganglia, or cartilage without the need for a large open approach.[10]

Ultrasound-guided releases are increasingly used for compressive tendon and nerve conditions, such as trigger finger, carpal tunnel syndrome, and cubital tunnel syndrome.[11] These minimally invasive outpatient procedures employ small instruments, like hook knives guided by ultrasonography, to cut the A1 pulley or the transverse carpal ligament through tiny punctures, avoiding long incisions. In a series of 106 trigger-finger releases using a specially designed guide, the success rate was 97%, with most patients resuming strenuous activity within two weeks and minimal complications. Ultrasound guidance improves visualization, enhancing safety and reducing risk to surrounding tendons, nerves, and vessels. Compared to open surgery, these procedures allow faster rehabilitation, better cosmetic outcomes, and earlier return to work.[11]

3. WIDE-AWAKE LOCAL ANESTHESIA NO TOURNIQUET (WALANT)

WALANT has transformed hand surgery by improving patient outcomes, satisfaction, and safety, while reducing costs and environmental impact. Unlike traditional techniques which require sedation and a tourniquet, WALANT relies on local lidocaine with epinephrine, keeping patients awake without these constraints. By avoiding sedation, WALANT circumvents systemic anaesthesia risks and enables surgery even in high-risk patients. The absence of a tourniquet also eliminates ischemic limb pain and nerve compression, allowing longer and more comfortable operations.[12]

Clinical evidence confirms that WALANT can achieve surgical results equivalent to or better than traditional anaesthesia.[13] In a randomized trial comparing WALANT to local anaesthesia with sedation, intraoperative pain, patient comfort, and postoperative opioid use did not differ between groups, and no increase in complications was observed.[14] Only minor hematomas were noted, with no severe adverse events.[14] A 2024 systematic review and meta-analysis, including a total of 5 RCTs and 15 observational studies and comprising a cohort of 1800 patients, showed higher patient satisfaction with WALANT and no differences in postoperative pain or operative time relative to tourniquet-assisted anaesthesia.[13] Notably, the local anaesthetic effect of WALANT often persists into the post-operative period, reducing opioid requirements compared to systemic anaesthesia.[12]

A transformative aspect of WALANT is the opportunity for active intraoperative patient involvement. Unencumbered by a tourniquet or motor block, the patient can be engaged while the surgeon directly assesses tendon repairs and fracture fixations during the procedure. Real-time movement allows fine-tuning of tendon tension and joint alignment in complex repairs, helping prevent technical errors and averting the need for revision surgery.[12]

Beyond clinical advantages, WALANT confers economic and environmental benefits. Avoiding general anaesthesia leads to shorter hospital stays and lower costs, enabling many cases to be performed in outpatient settings. This technique also significantly reduces anaesthetic gas use and tourniquet-related waste, minimizing its environmental footprint.[12] Efficiency is improved as well; no preoperative fasting or complex setup is required, increasing surgical throughput and proving especially valuable in resource-limited settings as in the COVID-19 pandemic.[13] Moreover, WALANT can often be used without interrupting anticoagulation and offers a safe alternative for patients who cannot tolerate a tourniquet.[12]

Initially used for minor cases in hand surgery such as trigger finger release, carpal tunnel release, cubital tunnel release, de Quervain’s tenosynovitis release, and ganglion cyst excision, WALANT is now applied to more complex surgeries as experience grows.[12,13] It has been extended to many trauma scenarios like tendon laceration repair and fracture fixation, with outcomes and infection rates comparable to standard care when performed wide awake in outpatient settings. For tendon reconstructions and multi-joint procedures, WALANT is increasingly the preferred technique to optimize intraoperative precision and rehabilitation, underscoring its transformative role in hand surgery.[12]

4. BIOLOGICS IN HAND SURGERY

PLATELET-RICH PLASMA (PRP) IN HAND SURGERY

PRP, an autologous concentrate of platelets and growth factors, has gained popularity for promoting tissue repair. In hand surgery, PRP applications are emerging but still under investigation. Animal models suggested PRP could enhance tendon healing, though clinical studies have yet to confirm significant benefits in human hand tendinopathies.[15,16] Early clinical reports were promising: for example, PRP injections in distal radius fracture patients and in those with thumb carpometacarpal (CMC) osteoarthritis showed improved pain relief and functional scores in small case series.[15] A recent systematic review of PRP for thumb CMC arthritis (115 patients) found statistically significant pain reduction and improved pinch strength, with 74% of patients resuming daily activities without major complications.[17] Notably, PRP's efficacy appears more pronounced in early osteoarthritis; patients with mild-to-moderate CMC arthritis achieved better pain and disability outcomes than those with advanced disease.[15] Overall, these findings suggest PRP can be a safe adjunct for joint degeneration in the hand, although heterogeneous protocols and mixed results mean that high-quality trials are needed to establish definitive indications.[16]

BONE MORPHOGENETIC PROTEINS (BMPS)

BMPs are osteoinductive growth factors that have been applied to challenging bone-healing scenarios in the upper extremity. Their most frequent use in hand surgery has been as an adjunct for carpal bone avascular necrosis and nonunions.[15] In Kienböck's disease, case reports demonstrate that adding BMP to a vascularized bone graft can yield durable clinical improvements, including complete pain resolution and restored range of motion at 6 years post-operatively in one report.[18] Similarly, a small series using arthroscopic bone grafting with BMP-2 for stage III Kienböck's showed favorable mid-term outcomes.[19] In scaphoid nonunion, evidence is mixed. A randomized trial observed that supplementing bone graft with BMP-7 (OP-1) accelerated union (median 4 weeks vs. 9 weeks with graft alone).[20] However, other studies did not find higher union rates with BMP-2 and reported complications, notably heterotopic ossification (HO) in a majority of patients.[21] HO is a well-recognized risk of BMP use in the hand, occurring in up to 70% of cases. Today, BMP-2 is used off-label for refractory upper-limb nonunions, balancing its bone-healing benefits with the risk of HO and other potential complications.[22]

ADIPOSE-DERIVED BIOLOGICS (MICROFAT)

Adipose tissue-derived therapies represent a new frontier in hand surgery orthobiologics. Fat contains a rich stromal vascular fraction (SVF) replete with mesenchymal stem cells (MSCs), which can support cartilage repair and modulate inflammation.[23] "Microfat" refers to finely minced or mechanically emulsified fat graft (lobule size ~0.6 mm) obtained via specialized cannulas, which preserves viable adipose-derived stem cells for injection. Microfat can be used alone or mixed with PRP to create a combined regenerative injectate. Recent pilot work has applied autologous PRP-mixed microfat injections for wrist osteoarthritis. In a 2019 first-in-human report, three patients with end-stage radiocarpal OA received a microfat/PRP injection, and all showed >50% reduction in pain at 12 months, with clinically meaningful improvements in grip strength and validated functional scores (DASH, PRWE).[23] No major adverse events were noted aside from transient donor-site soreness, and all patients exceeded the minimal clinically important difference in outcomes. These findings suggest adipose-derived biologics can safely provide pain relief and functional gains in degenerative hand conditions, potentially delaying the need for invasive procedures. Ongoing studies are further evaluating the efficacy and longevity of microfat-based treatments in thumb CMC and wrist arthritis.

5. BONE RECONSTRUCTION

Research in orthopedic surgery has primarily focused on evaluating the effectiveness of different grafting approaches, including non-vascularized, vascularized, and bone biomaterial grafts. Each technique carries its own complication risks, such as donor site morbidity, infection, and graft failure.[24] Biomaterials, synthetic or natural, can mimic the biomechanical and biological characteristics of bone, and thus provide a promising modality that eliminates risks like infection and donor site morbidity.[24] A range of biocompatible substitutes include calcium phosphate ceramics, bioactive glass, and polymer-based composites; and integration of growth factors and bioactive agents – such as Bone Morphogenetic Protein-2 (BMP-2) and Vascular Endothelial Growth Factor (VEGF) – have been proven to promote osteogenesis and angiogenesis at the fracture site.[24] A recent systematic review and meta-analysis by Karimnazhand et al. has reported superior outcomes of healing rate, time to union, range of motion, Modified Mayo Wrist Score (MMWS), and grip strength, in patients treated with vascularized bone grafts (VBG) as compared to nonvascularized bone grafts (NVBG) for scaphoid fracture non-unions.[24] After the use of cortico-cancellous non-vascularized inlay bone grafts, followed by graft interposition, local vascularized grafts from the distal radius became popular, and recently an increase in the use of free vascularized bone grafts from the medial femoral condyle or iliac crest is observed among surgeons.[25] Baamir et al. conducted an umbrella review in 2024 and demonstrated no significant difference in union rates, functional results, or re-operation rates between VBGs and NVBGs.[25] Dorsal pedicled distal radius grafts treat proximal nonunions, while volar grafts address waist or humpback deformities; and they are contraindicated in radiocarpal arthritis.[26,27] Dorsal grafts rely on four pedicles – 1,2 and 2,3 intercompartmental supraretinacular artery, 4+5 extensor compartmental arteries, and capsular-based/fourth extensor compartment artery; while volar grafts are based on the radial carpal artery, pronator quadratus flap, and pisiform flap.[26,27] Arthroscopic-assisted scaphoid reconstruction enables faster recovery with similar union rates, functional outcomes, and complication rates as open grafting. It minimizes tissue damage and preserves blood supply but is technically demanding and unsuitable for cases with avascular necrosis, severe deformity, or advanced arthritis.[28,29] Free vascularized fibular grafts (FVFG) offer high survival and union rates and remain a gold-standard option for upper limb bone reconstruction after trauma.[30,31] They combine structural strength, vascularity, and versatility, enabling effective repair even for large or complex defects. The main limitations lie in technical difficulty and moderate donor-site morbidity.[31]

Recent innovations have greatly expanded reconstructive options beyond traditional VBGs. While distal radius pedicled grafts and FVFGs continue to provide reliable union in complex cases such as scaphoid nonunion, Kienböck's disease, and segmental bone loss, emerging biologic and bioengineered strategies are reshaping the field. A 2025 systematic review and meta-analysis demonstrated that 3D-printed scaffolds loaded with bone morphogenetic protein-2 (BMP-2) significantly enhanced bone regeneration in preclinical models, yielding higher bone volume and new bone formation compared with controls.[32] Karimnazhand et al. also demonstrated comparable outcomes of healing and union rate between collagen/polyglycolic acid (CPGA) biomaterial scaffold enriched with bone marrow mesenchymal stromal cells (BM-MSC) and iliac crest bone graft. However, limitations of biomaterials include high cost, restricted availability, and potential complications, including immune reactions and mechanical failure.[24] Parallel advances in 3D bioprinting have enabled the creation of patient-specific scaffolds with hierarchical porosity, tunable mechanical strength, and biologically active surfaces. These scaffolds—constructed from composites of metals, ceramics, and polymers—can be functionalized with growth factors, stem cells, and nanomaterials to promote osteogenesis and angiogenesis.[33] Collectively, these developments suggest a transition from static graft reconstruction toward biologically active, regenerative bone engineering, where VBGs, BMP-enhanced scaffolds, and biofabrication technologies complement each other to restore both structure and function in complex skeletal defects.

6. NERVE RECONSTRUCTION

Evidence suggests that PRP supports nerve healing by protecting neurons from apoptosis, enhancing vascular and axonal regeneration, modulating inflammation, reducing muscle atrophy, and improving overall neural function.[34,35] In clinical settings, PRP has shown promise as an adjunct therapy—either injected around injured nerves or incorporated into nerve conduits or grafts—leading to faster and better sensory and motor recovery compared to conventional repair alone.[34] Multiple studies report that PRP can accelerate recovery and enhance functional outcomes when used in both surgical and non-surgical carpal tunnel syndrome (CTS) treatments. Meta-analyses and clinical trials indicate that PRP injections outperform corticosteroids and glucose treatments, leading to significant improvements in pain, nerve function, and sensory recovery, with effects lasting up to one year. However, a few trials—particularly in diabetic or short-term follow-up cases—found limited benefits, likely due to impaired healing capacity.[35]

Stem-cell therapy is emerging as a powerful adjunct for peripheral nerve repair, aiming to overcome the limitations of conventional grafting and transfers. Mesenchymal stem cells (MSCs)—particularly those derived from adipose tissue, bone marrow, and dental pulp—promote nerve repair through neurotrophic secretion, immunomodulation, angiogenesis, and Schwann cell activation. Experimental studies across sciatic, facial, and peroneal nerve models demonstrate superior functional recovery compared with autografts.[36,37]

Recent advances in 3D printing have revolutionized nerve regeneration, enabling patient-specific nerve guide conduits (NGCs) that overcome the limitations of autografts (e.g. donor scarcity, morbidity). Liu et al. reviewed how 3D printing enables customizable, biomimetic NGCs from natural and synthetic polymers, with controlled structure and degradation profiles, offering enhanced Schwann-cell support and axonal guidance over traditional fabrication methods.[38] Huang et al. further emphasized functionalized 3D-printed NGCs that integrate physical, chemical, and biological cues—such as microgrooved surfaces, multichannel designs, and incorporated neurotrophic factors—to promote axonal elongation and myelination.[39] More recently, Maeng et al. developed biodegradable multichannel hydrogel conduits that mimic native nerve fascicles and achieved superior nerve recovery in vivo.[40] In 2024, Ikeguchi et al. conducted the first human trial using scaffold-free Bio 3D nerve conduits made from patients' own dermal fibroblasts. In three cases of hand nerve defects (≤20 mm), the 3D-printed autologous conduits were transplanted without adverse events, leading to significant sensory and functional recovery over 48 weeks. The study confirms the safety and feasibility of autologous, scaffold-free 3D bioprinted conduits as a promising alternative to nerve grafts.[41] Collectively, these studies mark a major leap toward precision-engineered, bioresorbable nerve conduits that could redefine peripheral nerve regeneration.

7. TENDON RECONSTRUCTION

Advances in tendon repair techniques have significantly improved outcomes by integrating stronger mechanical constructs, biologic adjuncts, refined anesthesia strategies, and enhanced rehabilitation protocols. Modern multistrand core suture methods, coupled with peripheral epitendinous stitches, provide robust repair strength that permits early active mobilization, producing over 80% good-to-excellent results after flexor tendon repair in zone II and reducing rerupture and tenolysis rates.[42]Biologic augmentation, particularly PRP, has shown promise at molecular and clinical levels, though results remain inconsistent due to heterogeneity in preparation methods and patient factors.[43] Future directions emphasize refining PRP formulations and tailoring applications to different stages of tendinopathy to minimize scar formation and restore normal tendon biomechanics. Concurrently, the use of WALANT has enhanced surgical precision and efficiency: patients can actively move repaired tendons intraoperatively, allowing immediate identification of gapping, adjustment of pulley management, and assurance of smooth tendon gliding before wound closure.[44,45] This intraoperative testing reassures surgeons to safely initiate midrange protected active motion postoperatively, further reducing stiffness and adhesion formation. Rehabilitation advances complement these surgical improvements, with structured home exercise programs designed to balance motion for adhesion prevention against loading thresholds that protect the repair. Patient adherence remains a critical determinant of success, with self-efficacy strongly influencing engagement.[46]

8. ARTHROPLASTY & JOINT PRESERVATION

Management of osteoarthritis in the hand rarely requires surgical intervention except when conservative therapy fails. Early silicone and metallic implants provided pain relief and functional improvement but were limited by high rates of loosening and long-term complications. Newer pyrocarbon and hydroxyapatite-coated implants offer improved biomechanical compatibility, reduced subsidence, and enhanced early functional outcomes, though complications persist.[47] For joint-preserving reconstruction, graft-based approaches such as the Osteochondral Autologous Transfer System (OATS), originally developed for larger joints, have been successfully adapted to the hand, enabling restoration of carpal bones, metacarpal heads, interphalangeal joints with favorable functional outcomes and low donor-site morbidity.[48] Emerging three-dimensional bioprinting (3DBP) techniques hold promise for generating patient-specific, vascularized osteochondral constructs, potentially reducing donor-site complications and improving anatomical fidelity. While largely preclinical, 3DBP may provide a transformative, biologically integrated alternative to both arthroplasty and autologous grafting, pending advances in construct standardization, vascularization, and regulatory approval.[49]

9. MICROSURGICAL ADVANCES

Microsurgical and super microsurgical techniques have become central in treating conditions such as lymphedema and complex hand injuries. Lympho-venous anastomosis (LVA) and vascularized lymph node transfer (VLNT) show promise to restore lymphatic drainage. LVA is preferred for patent lymphatics and mild-to-moderate disease, while VLNT is indicated for obstructed lymphatics, often with distal placement for optimal outcomes. Advances in robotic-assisted microsurgery, using systems like Symani and Da Vinci®, have enhanced precision, tremor control, and dexterity in vascular, lymphatic, and nerve anastomoses, although operative times may initially be longer.[50,51] Similarly, 3D exoscopes offer ergonomic advantages, high-resolution stereoscopic visualization, and shared imaging for surgical teams, facilitating complex microsurgical procedures in hand and reconstructive surgery while reducing fatigue and shortening learning curves.[52]

10. ARTIFICIAL INTELLIGENCE (AI) IN HAND SURGERY

Compared to other orthopedic subspecialties, the application of AI in hand surgery is still modest. Its most common applications in this domain include image analysis of anatomic structures, fracture detection and automated screening for other hand and wrist pathologies such as carpal tunnel syndrome, rheumatoid arthritis or osteoporosis.[1] A systematic review and meta-analysis of 42 studies done by Kuo et.al showed a comparable performance in fracture detection between clinicians and AI (sensitivity of 92% and specificity of 94%).[1] In 2019, Gan at.al investigated the use of an AI algorithm based on deep learning to identify a possible fracture of the distal radius on anteroposterior and lateral views of 2340 wrist radiographs. In distinguishing normal radiographs from distal radius fractures, the algorithm showed an accuracy of 93%, sensitivity of 90% and specificity of 96%. Also, its diagnostic performance was similar to the one of the orthopedic surgeons and superior to the one of the radiologists.[53] However, for scaphoid fractures, a substantial amount is still being missed by AI due to a lack of a visible fracture line.[54,55]

Furthermore, AI plays a role in the assessment of osteoporosis. Tecle et al analyzed a total of 4,000 posteroanterior (PA) radiographs of the hand and they used the second metacarpal cortical thickness as the predictor of osteoporosis. Osteoporosis predictor was 88.4% accurate with a sensitivity of 82.4% and specificity of 95.7% which makes AI a good screening tool for osteoporosis or an adjunct to dual-energy x-ray absorptiometry scans.[56] Similarly, some authors suggested AI to be a method of detecting rheumatoid arthritis by automated analysis of joint space narrowing on hand radiographs and the degree of synovitis in ultrasound images or magnetic resonance imaging.[1,57]

11. VIRTUAL REALITY (VR) AND AUGMENTED REALITY (AR) IN HAND SURGERY

VR completely immerses the user in a digitally created world using a head-mounted device creating a 360-degree view of an artificial world. It has prominent use in simulation-based medical training, especially microsurgery and arthroscopy, where trainees can practice surgical interventions in a virtual, stress-free environment leading to improvement in their technical skills and procedural accuracy. It has an important role in preoperative planning allowing to visualize the operative field from various perspectives leading to a more personalized approach to each patient. Unfortunately, VR applications lack in hand surgery.[58]

However, VR has a particular role in orthopedic hand therapy and rehabilitation. In 2024, Lattré et al reported a case of a 47-year-old man who sustained a traumatic complete thumb avulsion with successful thumb replantation. He suffered hypersensitivity on the volar aspect of the thumb, complex regional pain syndrome and severe neuropathic pain post operatively for which the application of VR was an effective solution for restoring the hand-brain connection and minimizing his symptoms during his therapy sessions. They also reported another case of 34-year-old man who suffered from a traumatic amputation of the distal interphalangeal joints of the two long fingers with an unsuccessful replantation. Rehabilitation was initiated 2 days post-operatively and VR represented a complete hand during his rehabilitation session which prevented of onset of phantom limb pain due to normal cortical representation.[59]

As for AR, it overlays or augments the real world with virtual content. The digital content can be displayed through AR glasses or via screens, tablets, smartphones. It allows to overlay fluoroscopic images, radiographs, CT scans on the surgeon's operative field allowing for aid in point visualization and percutaneous drilling. However, its application in hand surgery is still very limited.[58]

12. ROBOTICS AND THREE-DIMENSIONAL (3D) PRINTING IN HAND SURGERY

Robotic-assisted surgery offers improved surgical precision allowing precise movements with submillimeter accuracy which is particularly beneficial in nerve repairs and microsurgical interventions. It also allows minimized soft tissue trauma resulting in a decrease in postoperative pain, faster recovery times, enhancing overall patient satisfaction.[60]

3D printing enables patient-specific implants which are tailored to each patient's unique anatomy which enhances the implant's fit and optimizes its functionality.[59]In 2018, Lu et al reported 11 patients with giant cell tumors of the distal radius who underwent an en-bloc resection followed by an uncemented 3D-printed prosthetic reconstruction. All 11 patients demonstrated improvements in pain scores, range of motion, grip strength, and functional outcomes during the follow-up period, with postoperative results showing clear improvement over preoperative levels.[61]

Similarly, in 2021, Keller et al reported a defect-lesion of the index finger after a chainsaw accident. Due to insufficient bone stock at the proximal phalanx, regular implants were not a favorable option. They used a patient-specific 3D-printed partial joint replacement that resulted in improvement in range of motion at the proximal interphalangeal joint from 20 degrees preoperatively to 60 degrees postoperatively.[62]

Meanwhile, 3D Computed Tomography (CT) paired with patient-specific guides improves the accuracy of corrective osteotomies and fracture reconstruction.[8,63] For complex fractures, malunions, and preoperative planning, 3D CT and patient-specific instrumentation are increasingly used. A recent comparative study of primary vs revision scaphoid nonunion reconstruction using 3D-planned and -printed patient-specific guides showed high consolidation rates (≈90%) and good functional outcomes, even in revisions.[63]

3D patient-specific instrumentation (PSI) for intra-articular malunions of the trapeziometacarpal and finger joints restores articular congruency with high accuracy. Postoperatively, range of motion, grip strength, and patient-reported outcomes improved, with function comparable to the contralateral side at medium-term follow-up. Likewise, 3D planning with PSI in corrective osteotomies of the metacarpal, finger, and trapeziometacarpal joints has improved alignment precision and surgical reproducibility.[64]

13. TELEMEDICINE & REMOTE REHABILITATION

Telemedicine and remote rehabilitation have rapidly become integral components of hand surgery care, especially since the COVID-19 pandemic accelerated their adoption. Telemedicine enables remote consultations, postoperative checks, and triage, thereby reducing travel burden, improving access in rural or underserved regions, and reserving in-person visits for cases that truly require them (e.g. complications or complex assessment). In 2020, Grandizio et al. described the utility of videoconferencing in hand and upper extremity surgery, noting its value in rural settings while cautioning regarding confidentiality and security issues. In their prospective study of postoperative upper extremity patients, telemedicine follow-up reduced travel burden without compromising care.[65] Furthermore, Van Nest et al. offered a detailed guide to conducting a hand exam over video encounters, which can enhance the reliability and safety of remote assessments.[66]

Remote rehabilitation has been equally transformative. A 2023 scoping review identified a range of telerehabilitation technologies feasible in the home for hand/wrist recovery, including smartphone-based angle measurement apps, wearable sensors, and videoconference platforms. For wrist/finger range of motion (ROM), wearable/external sensors and smartphone photography had the highest accuracy in remote settings.[67] Other systems combine mobile apps, sensor gloves, and cloud connectivity to enable remote monitoring and guidance—for example, a home-based hand telerehabilitation platform using a sensorized glove (iManus™) has been described recently.[68] Wearable IoT devices for hand therapy in stroke patients have also shown promise, enabling real-time feedback and remote therapist oversight.[69] In a broader remote rehabilitation context, a study on wearable devices for intelligent remote training demonstrated feasibility of human–computer interaction and remote feedback in upper extremity rehabilitation.[70]

14. CHALLENGES AND ETHICAL CONSIDERATIONS

These technologies offer several advantages: improved adherence, objective performance tracking, cost reduction, decreased missed workdays, and more continuous care. However, several challenges persist. Not all patients have access to reliable high-speed internet, smartphones, or sensors, which may limit adoption in underserved populations.[71] Moreover, varying telehealth regulations across jurisdictions and difficulties in billing for remote therapy can hamper implementation.[72] Also, protecting patient information transmitted over networks is critical; systems must comply with standards (e.g. HIPAA, GDPR) and guard against cybersecurity threats.[73] We must note that hand therapists' perceptions, comfort with technology, and willingness to adopt telerehabilitation vary. A recent survey of hand therapists highlighted barriers such as patient technology literacy and lack of institutional support.[74] Another qualitative study explored facilitators and barriers across different countries, including concerns about reimbursement and infrastructure.[72] High-quality randomized controlled trials (RCTs) comparing remote versus in-person rehabilitation in hand surgery are relatively scarce, especially for long-term functional outcomes.

15. FUTURE DIRECTIONS

Gene therapy is being explored for tendon, cartilage, and nerve regeneration, utilizing non-viral delivery systems like hydrogels and nanoparticles to promote healing and reduce scarring.[75] Additionally, smart bioresorbable implants are under development to deliver localized drug therapy, improving healing while minimizing systemic side effects.[76]

The next wave of innovation lies in deeper integration of telemedicine with sensor-based rehabilitation platforms and AI-driven progress monitoring to personalize care. Smart wearables and gloves could continuously measure joint kinematics, force output, and compliance, feeding data into machine-learning models to guide therapy progression. Egocentric vision via smartglasses may allow automatic exercise recognition, form evaluation, and repetition counting in remote hand rehabilitation (e.g. the REST-HANDS concept).[77] VR or AR overlays may enrich remote therapy by simulating object interactions or gamifying exercises.[78] Tele-robotics with assist-as-needed algorithms may allow remote robotic assistance in hand rehabilitation (e.g. emerging frameworks for therapist-in-the-loop control).[79]

These innovations must be guided by evidence-based validation, ethical responsibility, and global accessibility, ensuring that technology enhances, rather than replaces, surgical judgment and patient-centered care.

CONCLUSION

Hand surgery is undergoing a transformative shift, driven by innovations in biologics, robotics, artificial intelligence, and regenerative medicine. These advancements promise greater precision, personalized care, and improved outcomes for patients. However, as the field embraces these technologies, it is essential to ensure their integration remains grounded in robust clinical evidence, focused on individual patient needs, and accessible across diverse healthcare settings. The future of hand surgery lies not just in technological breakthroughs, but in their thoughtful, equitable, and ethical application.

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