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3D Printing Technology in Pediatric Orthopedics: a Primer for the Clinician

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Abstract

Purpose of Review This article reviews the basics of 3D printing and provides an overview of current and future applications of this emerging technology in pediatric orthopedic surgery.
Recent Findings Both preoperative and intraoperative utilization of 3D printing technology have enhanced clinical care. Potential benefits include more accurate surgical planning, shortening of a surgical learning curve, decrease in intraoperative blood loss, less operative time, and fluoroscopic time. Furthermore, patient-specific instrumentation can be used to improve the safety and accuracy of surgical care. Patient-physician communication can also benefit from 3D printing technology.
Summary 3D printing is rapidly advancing in the field of pediatric orthopedic surgery. It has the potential to increase the value of several pediatric orthopedic procedures by enhancing safety and accuracy while saving time. Future efforts in cost reduction strategies, making patient-specific implants including biologic substitutes and scaffolds, will further increase the relevance of 3D technology in the field of pediatric orthopedic surgery.

Keywords 3D printing · Additive manufacturing · Pediatric orthopedic surgery · Patient-specific instrumentation

Introduction

Purpose and Scope

Although the clinical applications of 3D printing are growing, justification for its widespread use has not been entirely supported by rigorous evidence. As we begin the third decade since the first surgical application of 3D printing technology in orthopedic surgery, an overview of this innovation can help us further understand its future potential. The current article reviews the technical basics of 3D printing and provides an overview of current and future applications in pediatric orthopedic surgery. This article is meant to be a primer on this technology, including some case examples in pediatric orthopedics.

What is 3D Printing?

Since its emergence as a disruptive technology in medicine, three-dimensional (3D) printing technology has since evolved into an impactful force in the field of orthopedic surgery. Also known as additive manufacturing (AM), 3D printing constructs medical products through a "bottom-up" fusion of materials in a layer-by-layer fashion [1]. Compared

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to those processed by traditional manufacturing methods, 3D-printed medical products can inherit an unprecedented level of complexity and precision [2–5]. In addition, 3D printing offers quick production runs during prototyping, creating opportunities for real-time refinement of the final product [6].

Why 3D Printing?

In orthopedic surgery, the utility of 3D printing technology can be seen at all levels of medical care. This includes patient-specific anatomic models for preoperative care team discussions with the patient and caretakers and as a visual aid in surgical planning. The use of custom anatomic models also enhances patient and trainee education. In addition, patient-specific intraoperative instrumentation and implants have been correlated with reduced operative time, cost, intraoperative blood loss, and improved operative outcomes [7•]. Outside of the operating room, 3D-printed orthotics benefit from the ease of modification and increased patient comfort while maintaining the therapeutic effectiveness of custom orthotic treatments. Equally exciting is the emerging science of tissue engineering through bioprinting, with implantable live tissues such as articular cartilage, mensci, and intervertebral disc, representing the next horizon of AM technology in orthopedic surgery.

Evolution of 3D Printing Technology

The collective history of additive manufacturing is one of rapid progression. Isolated examples of 3D fabrication based on low-resolution imaging data were reported in 1981, describing what is now known as the stereolithography (SLA) process [8]. By the end of the 1980s, SLA technology was patented and the SLA file format was developed,.STL is used for 3D printing. This was closely followed by the development of powder bed-based selective laser sintering (SLS) and material deposition-based fused deposition modeling (FDM), both in 1989 [9]. These three original AM technologies, SLA, SLS, and FDM, were the foundation of 3D printing technology. Appropriately termed "rapid proto-typing" at the time, models created during this period were predominantly utilized for prototyping products meant to be produced using traditional subtractive manufacturing methods [10]. Thereafter, 3D printing continues to mature as a result of improvements in software, with increased computational power to render complex and accurate digital models.

By the 1990s, surgical applications of 3D printing were mainly driven by maxillofacial and oral surgery. However, a rapid increase in public awareness of 3D technology was made possible by the availability of consumer-scale and affordable printers, as well as open-source software. By 2010, 3D printing technology began to be adopted widely within academic and clinical research institutions. During this time, the use of surgical models and guides became commonplace within many medical fields, including orthopedic surgery. The United States government established National Additive Manufacturing Innovative Institute (NAMII) in 2012, setting the stage for continued focus on 3D technology. At the time of this writing, there are more than 100 AM devices approved by the Food and Drug Administration (FDA) for use in the USA alone, with many more that are available globally. As more and more sophisticated products are being made and refined using inert material, the future of 3D printing technology seeks to integrate the use of highly bio-functional materials, such as live cell and tissue fabrication to enable partial or whole organ creation [11].

Basic 3D Printing Technique

Material, Equipment, and Process

For the model creation portion of the process, the individual patient's advanced radiographic images are taken using protocols designed to optimize the clarity and resolution of the final images. Isotropic pixel size in all 3 dimensions is important for creating 3D models; this prevents stair-stepping on the final model.

The images are loaded into Materialise Mimics Medical©, where they are segmented. Due to the large difference in radiodensity (represented as Hounsfield units in the software, or HU) of bone versus other tissues, the images lend themselves well to automatic segmentation. In this method, called "thresholding," only the general area around the bone needs to be specified, and the software then makes a model from only the pixels within this area that are also within a specified HU window. The resulting shape is an accurate representation of the targeted bone. This process is repeated until all desired structures are segmented.

The segmented parts are exported as 3D models and loaded into both Materialise 3Matic© and Geomagic Freeform© for processing, such as filling internal voids, smoothing, and hollowing (Fig. 1). Where necessary, struts are added between bones to connect and hold them in relative position. The final print-ready models are loaded into GrabCAD Print© if printing on the Stratasys j750 (Polyjet printing type) or HP SmartStream 3D Build Manager© if printing on the HP Multijet Fusion 580 (MJF printing type).

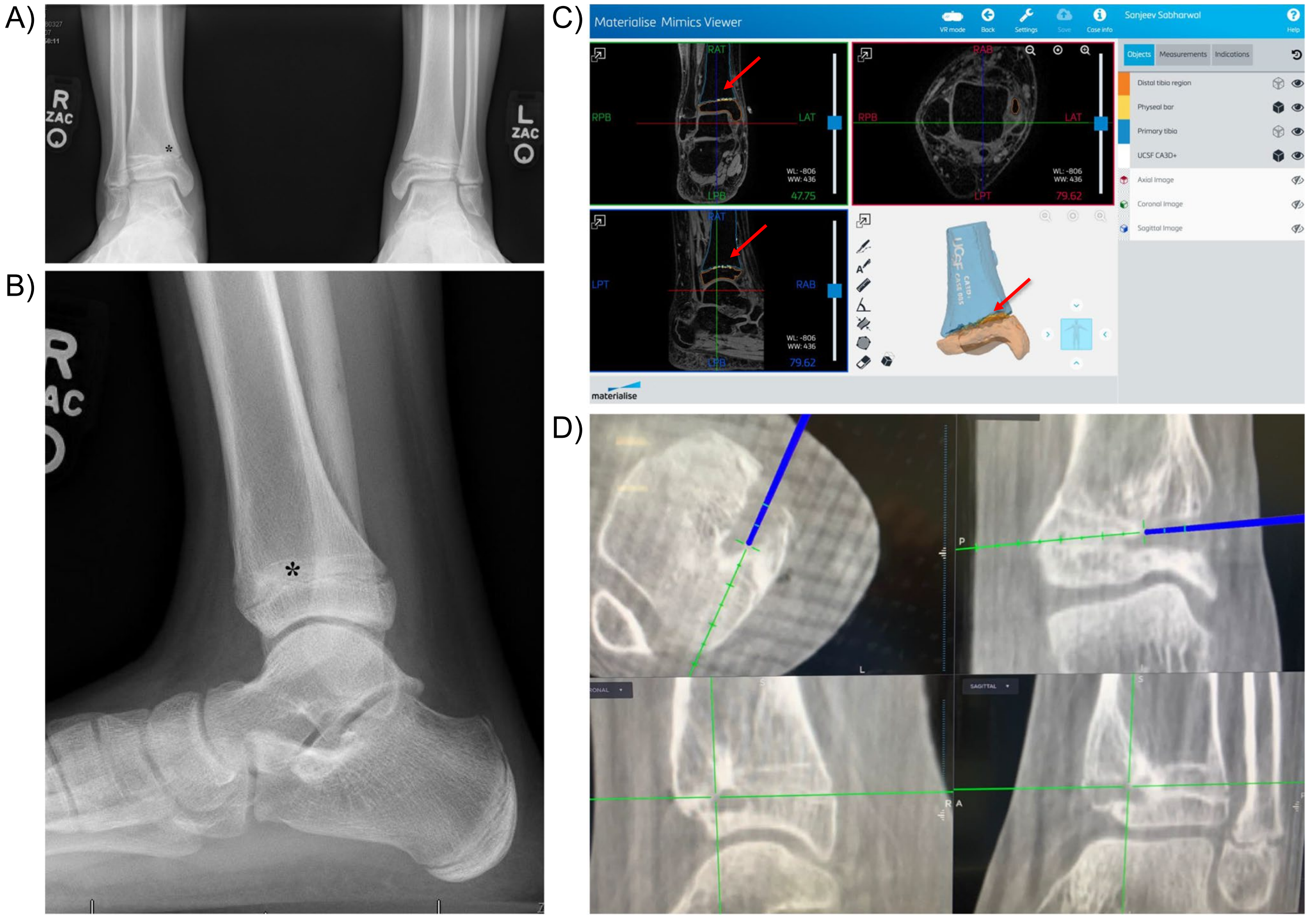


Fig. 1 Thirteen-year-old boy who sustained a right distal tibia physeal fracture treated with closed reduction and percutaneous fixation complicated by premature physeal closure of the right distal medial tibia with progressive distal tibia varus deformity. (**A**) Preoperative AP radiographs demonstrate right distal tibia physeal irregularity with the normal left side for comparison. *Physeal bar. (**B**) Preoperative lateral radiograph demonstrates right distal tibia physeal irregularity. *Physeal bar. (**C**) Screenshot of Preop MRI and 3D Print model demonstrating the physeal bar of the distal tibia. (**D**) Intraoperative fluoroscopy demonstrates the use of navigation for resection of distal tibia medial physeal bar resection. Lateral hemiepiphysiodesis of the distal tibia was also performed

The j750's Polyjet print technology uses multiple colors of liquid resin, dispensed directly onto the print bed and immediately solidified via laser. The bed then moves down slightly, and another thin layer of liquid resin is deposited on top of the now-solid layer below. During printing, the solid parts are supported and covered by an automatically generated surrounding shape of softer, waxier support resin. Once the part is printed, the entire object is placed in a lye bath, which melts away the support without damaging the model within. Support material can also be removed manually with model cleaning or dental-style tools.

The j750 allows for the use of multiple resin types in the same model, such as semi-transparent resin along with soft, flexible resin. This can be used to represent information not available to opaque-only prints, such as a transparent bone with opaque hardware visible inside or a hard bone with a soft tumor. Soft models will also flex and deform instead of cracking in response to physical impact like being dropped and can simulate softer tissues. However, soft models are also susceptible to tearing, especially in thin areas. Also, Polyjet material takes longer to print, longer to remove the encasing support structure from the final part, and is more expensive than the MJF's stiff, opaque-only models.

The MJF 580 uses Multijet Fusion technology, wherein Nylon 12 powder fills a descending print bed up to the maximum height of the part(s). A lamp heats the powder in the precise area of the part cross-section at each slice height until the powder melts and flows together with nearby particles, while it is held in place by the surrounding powder that was not heated. The areas that melted together are allowed to cool and solidify in the final desired shape. Coloring agents are also added during printing to the outer surface of the model, allowing a similar range of colors to the j750. Upon print completion, the solid part can be simply lifted out of the powder. A combination of air and sand blasting is then used to remove the residual powder.

The MJF 580 exclusively uses Nylon 12, which is both stiff and completely opaque. However, this material is much tougher than the j750 resin, tolerating even being dropped from the arm's height without breaking. Also, while the j750 will print objects embedded within one another, the MJF merely puts an outer "shell" of color on the object, and all internal material is uncolored Nylon 12. Thus, there is no additional information to gain about internal specifics by cutting the MJF model open.

In practice, the MJF printer has been the more common choice for orthopedic prints due to not requiring transparency in most cases. If transparency is not a hard requirement for a print, the MJF makes better sense due to its lower cost and faster print and cleanup time.

The specific model of printer and resin used for the MJF is used at other facilities to make models that do go on to be sterilized, so it is known to be possible. Nylon 12 is also generally able to withstand several types of sterilization processes, including the autoclaving that is usually available at hospitals. This is a future pathway that is being pursued at our facility.

The j750 models are made of a proprietary resin formula and are not guaranteed to be sterilizable, and significant further testing would be required. Printing models to be soft will also impact their ability to withstand some sterilization methods, further complicating this option.

If sterilizable parts such as cutting guides are one of the primary focuses of a 3D printing program, it would be best to carefully consider the printer and resin used to ensure it is not only possible but also regulatorily simple. Some printer outfits offer premade sterilization IFUs for their printer/resin combinations, significantly reducing the work required to satisfy regulatory requirements.

In-house Versus Outsourced 3D Printing

At our institution, we have enjoyed the benefits of in-house printing. It is easier to coordinate logistics between physicians and biomedical engineers for verification of segmentation and model accuracy. Since the models are printed on-site, they can be handed off immediately to the clinical care team once printing is completed. Feedback from physicians can be incorporated in real time, and they have the option of visiting the 3D office to use devices like AR/VR setups and haptic joysticks themselves. The ability to get hands-on simulation with surgeons and trainees opens up many new options that would be less compelling when only meeting digitally. Additionally, an in-house print facility lends itself well to bringing in a full-time 3D-specific employee, which should be considered a default choice since managing a 3D operation requires significant labor, but not the kind that requires physician-level training.

The obvious drawback to in-house manufacturing is the upfront set-up cost and resource allocation, including personnel associated with setting up a 3D print facility. While the resources required should not be underestimated, they do tend to still be relatively small compared to the overall budget of a medical facility, especially considering the surgical procedures 3D models are most often used for.

The advantages of distributed manufacturing are the same as outsourcing many other services: no need to hire staff or establish a facility and thus limited liability for those resources. These facilities can be full service, fabricating the model from provided imaging, designing any associated jigs or cutting guides or related parts, and can deliver it sterilized. These skills are still uncommon, though, so the prices tend to be substantial. It is possible to overshoot the cost of setting up an internal facility quickly at a large enough medical center. Furthermore, the same 3D print facility can be utilized by various clinical departments, with opportunities for collaborative projects. Also, research and development are an important part of finding how 3D can best be implemented for the procedures done at a particular location (at least until the understanding of 3D technology becomes more widespread in the medical community), and this is not possible when contracting out discrete cases to outside companies.

Technical Barriers

General technical barriers to 3D printing include the sometimes-complex shape of ROIs, resulting in models that can be both fragile and difficult to print or clean successfully. Printers can require significant floor space and a facilities setup that can accommodate them, including adequate ventilation.

Also, initial model creation requires a certain amount of imaging quality, which relies both on the skill of the imager and patient cooperation. It may also involve exposing the patient to a significant amount of radiation, especially when making patient-specific osteotomy guides based on a CT scan of the contralateral unaffected limb.

One additional note is that 3D medical modeling is still a growing field, and it may be difficult to locate professionals with sufficient skills to support the needs of a program.

Surgical Applications

Overview

The use of 3D printing technology in orthopedics can be broadly categorized based on the phase of surgical treatment: preoperative and intraoperative. Preoperative applications include surgical planning and education. While the diverse proposed benefits of 3D printing may be difficult to measure in this setting, results of surveys have shown an increase in surgeon's confidence and a subjective shortening of the learning curve for complex orthopedic operations with the use of preoperative planning aided by 3D-printed models. Other benefits of 3D models used in preoperative planning include decreased intraoperative blood loss, decreased operative time, decreased fluoroscopy time, and enhancement of patient-physician communication [12]. Intraoperatively, patient-specific osteotomy, drill guides, and implantable hardware for osseous fixation are used where complex or otherwise pathologic anatomy can be safely and accurately interpreted.

Preoperative Applications in Pediatric Orthopedic Surgery

Preoperatively, 3D models can provide the surgeon with a deeper understanding of a patient's anatomy and pathology, enabling him or her to better plan surgery (Fig. 1) [13]. For instance, the treatment of spinal deformity has been one area with the growing adoption of 3D models, given the complex spatial considerations of scoliosis and the level of understanding and orientation required to appropriately place pedicle screws and perform osteotomies in order to correct these deformities [14–16]. The pelvis is another region requiring visuospatial understanding that 3D-printed models may improve, particularly in the setting of hip dysplasia. For example, planning of periacetabular osteotomy in the dysplastic hip with the aid of patient-specific models has been well described, as has the pelvic triple osteotomy in the setting of Legg-Calve-Perthes disease [17•, 18, 19••]. An especially unique application of preoperative 3D printing has been documented in a child who sustained bilateral forearm amputations, in whom 3D-printed models allowed for the selection of an appropriately sized donor [20]. In addition to offering a deeper understanding of a patient's anatomy and pathology, 3D models may provide surgeons the opportunity for simulating surgery preoperatively. This was exemplified in a patient requiring complex pelvic and proximal femoral reconstruction after sustaining multiplanar hip joint deformity and instability after the late presentation of septic arthritis and osteomyelitis [21]. Indeed, accurate anticipation of intraoperative difficulties when faced with complex pathoanatomy can enhance safety (Fig. 2) and save time and resources [22•].

Intraoperative Applications in Pediatric Orthopedic Surgery

Intraoperatively, 3D printing may provide surgeons with patient-specific osteotomy guides and implants. The use of patient-specific cutting guides has been demonstrated in patients with post-traumatic deformity, such as the case of cubitus varus after supracondylar humerus fracture or multiplanar forearm deformities after fracture malunion (Fig. 3) [23]. Patient-specific instrumentation holds promise for improved accuracy and precision in those undergoing femoral or pelvic osteotomy [24]. A systematic review of 3D-printed guides for both upper and lower extremity pediatric deformity correction demonstrated substantial reductions in operative time, fluoroscopic exposure, and blood loss [25•]. In addition to patient-specific surgical guides and instrumentation, implants specific to the individual patient themselves may be additively manufactured [26•]. However, literature on 3D-printed implants in pediatric orthopedic patients is currently sparse and is a ripe opportunity for future development and investigation.

Conclusions

3D printing is rapidly advancing in the field of pediatric orthopedic surgery. Its benefits include the customizability of manufactured products, a variety of available materials, and increasing accessibility as improvements are made in both 3D software and printing hardware. Enhancing safety and accuracy while saving time by integrating this technology when indicated can potentially increase the value of several pediatric orthopedic procedures. Future efforts in cost reduction strategies, making patient-specific implants including biologic substitutes and scaffolds, will further increase the relevance of 3D technology in the field of pediatric orthopedic surgery.

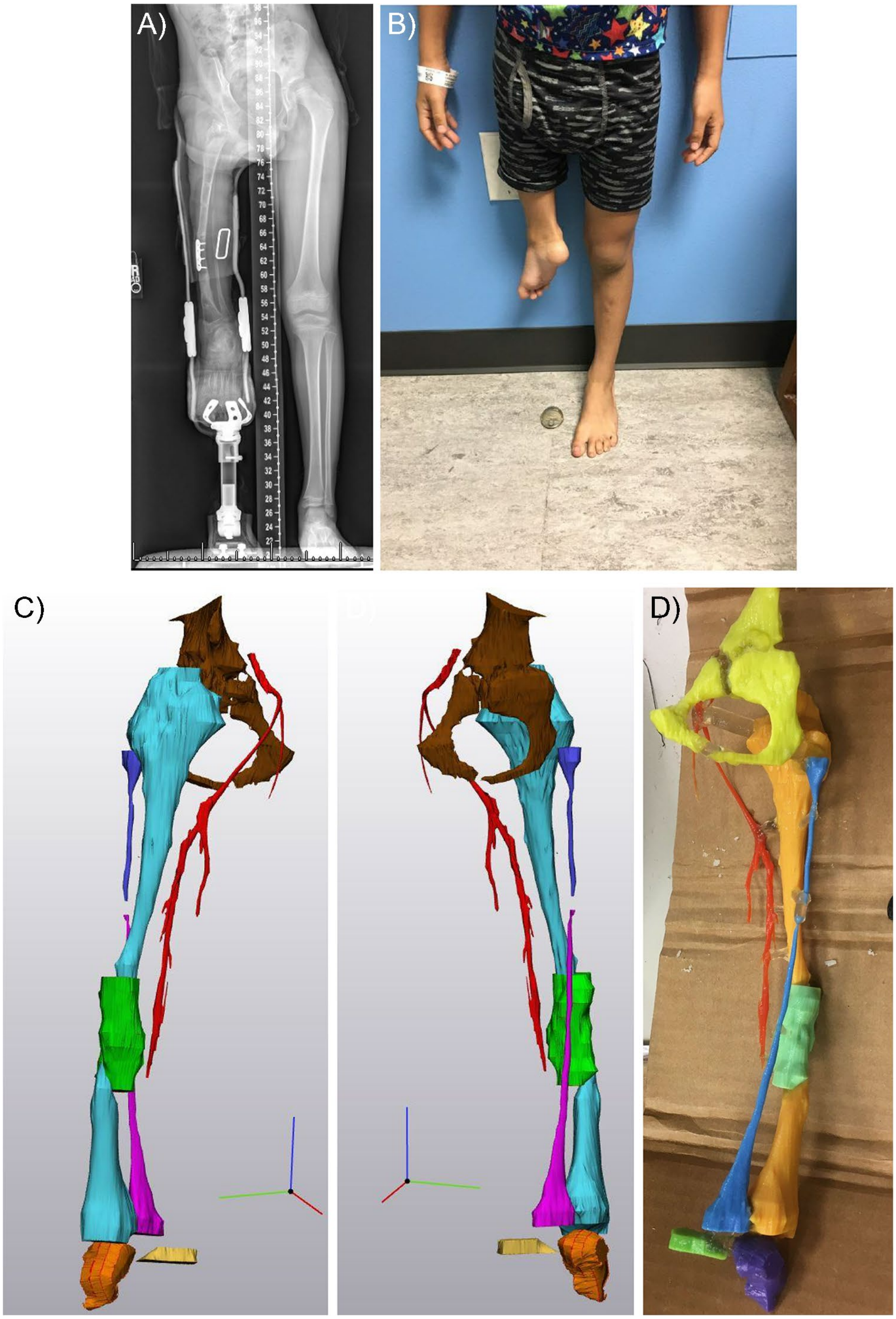


Fig. 2 Eight-year-old boy with a right congenital proximal femoral focal deficiency with the absence of approximately ¾ of femur presented s/p rotationplasty and knee arthrodesis complicated by nonunion and malposition of the heel resulting in abnormal gait and problematic prosthetic fitting that was treated elsewhere. He had subsequently had an attempt at derotational tibial osteotomy to improve rotational alignment at another institution with partial improvement. (**A**) Preoperative standing radiograph with right lower limb prosthesis. (**B**) Preoperative clinical photograph without prosthetic demonstrating a short and malrotated right distal segment. (**C**) Digital and physical 3D technology utilized to plan safe gradual derotation tibial osteotomy with lengthening, taking note of the course of the femoral artery (in red) and its relationship to the anticipated hardware position, osteotomy and plane of derotation. (**D**) 3D-printed model of the lower extremity with the location of the femoral artery (marked in red). (**E**) Postoperative clinical photographs with external ring fixator with improved length and alignment of the right lower extremity. (**F**) Status post-tibial derotation and removal of external ring fixator. His function and prosthetic wear improved following the recent procedure

Fig. 2 (continued)

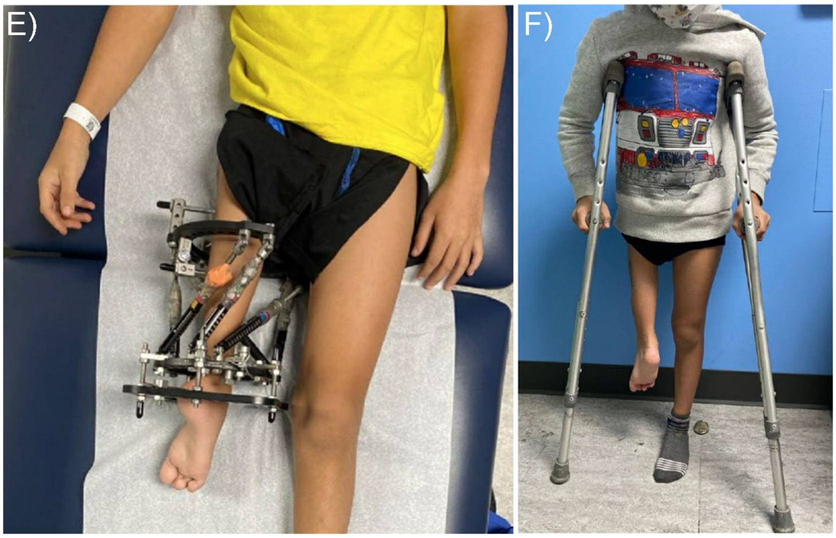
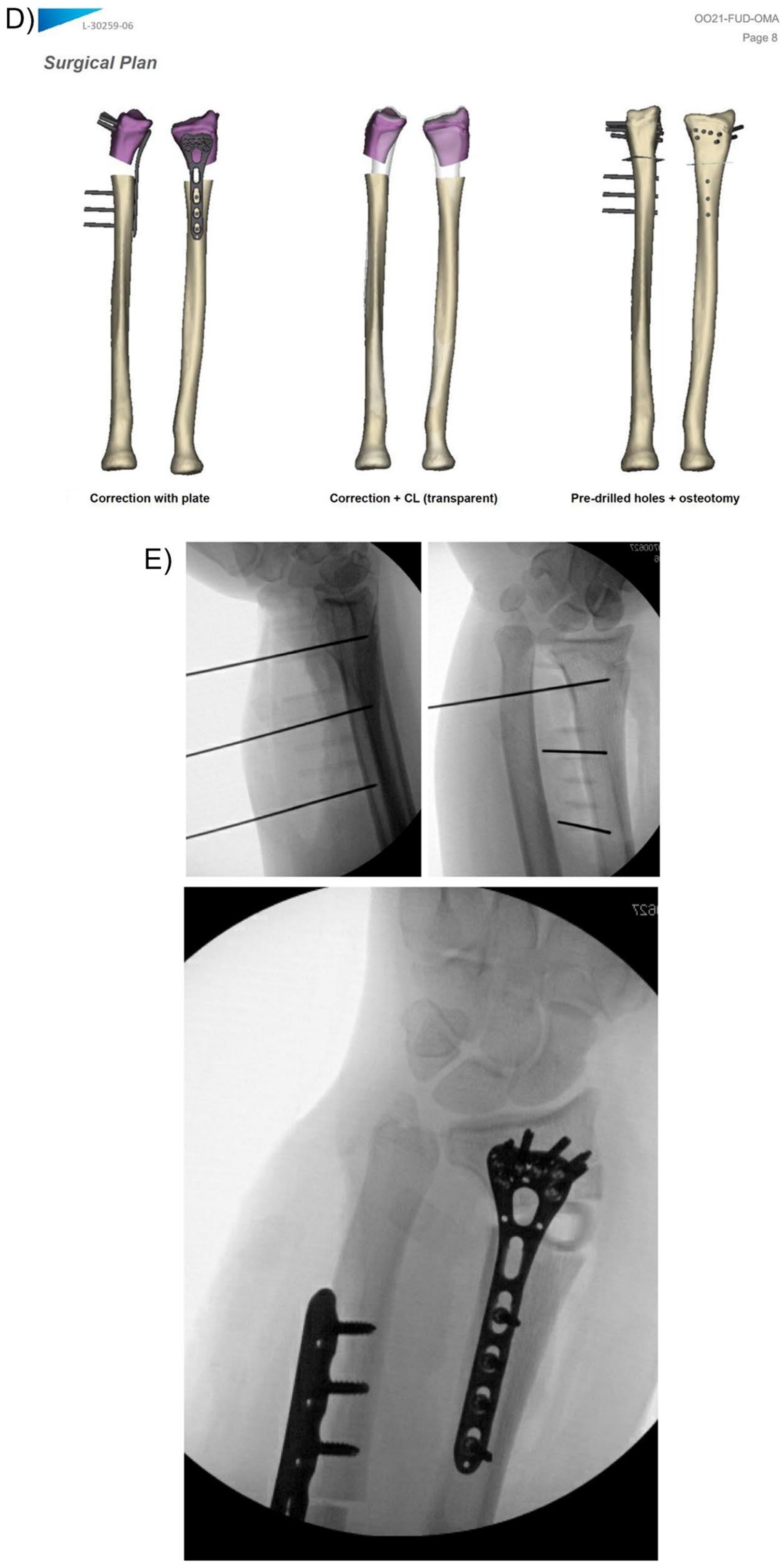


Fig. 3 Fourteen-year-old male with distal radius malunion after sustaining a distal forearm injury treated in a cast. (**A**) Preoperative clinical range of motion examination of the left upper extremity demonstrates distal ulnar prominence, decreased ulnar deviation, and decreased wrist flexion. (**B**) Preoperative radiographs of the wrist (AP/lateral) demonstrating increased dorsal tilt, loss of radial height, and ulnar-positive variance. (**C**) Life-size 3D-printed models based on CT scans of the patient's operative left radius and ulna (blue and green) with the normal right radius and ulna (maroon and red) for comparison. (**D**) Preoperative surgical plan based on 3D-guided patient-specific osteotomy guides. (**E**) Intraoperative fluoroscopy documenting the use of patient-specific guides to achieve precise osteotomy. (**F**) Early post-operative radiograph of the forearm demonstrating improved osseous alignment with opening wedge osteotomy of the radius and closing wedge osteotomy of the ulna. The ulnar fragment was used as an autograft for the radius. (**G**) Eight-month post-operative radiographs demonstrating maintained osseous alignment and healing. (**H**) Post-operative clinical examination demonstrates improved forearm and wrist range of motion

Fig. 3 (continued)



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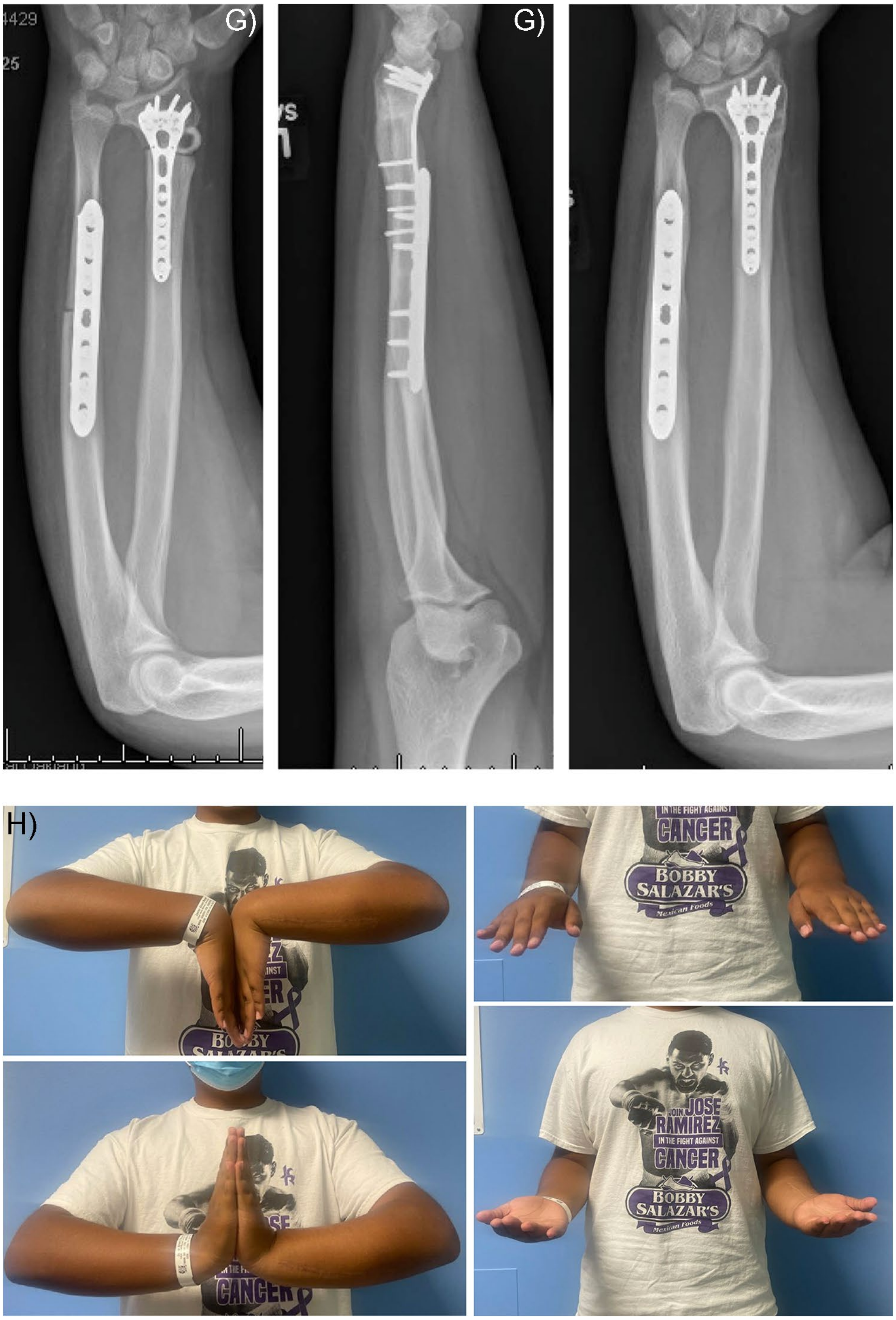

Fig. 3 (continued)

Compliance with Ethical Standards

Conflict of Interest Wei Wu, Samir Sabharwal, Michael Bunker, and Sanjeev Sabharwal declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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