3D printing application for orthopedic pediatric surgery – a systematic review

Danilo Calderone, Giuseppe Cesarelli, Carlo Ricciardi and Francesco Amato
Department of Electrical Engineering and Information Technology, University of Naples Federico II, Naples, Italy, and
Fabrizio Clemente
Institute of Crystallography, National Research Council, URT c/o AORN Santobono-Pausilipon, Naples, Italy

Abstract

Purpose – This paper aims to present a systematic review of the latest scientific literature, in the context of pediatric orthopedics, on the development by additive manufacturing of anatomical models, orthoses, surgical guides and prostheses and their clinical applications.

Design/methodology/approach – Following the current guidelines for systematic reviews, three databases (Elsevier Scopus®, Clarivate Web of Science™ and USA National Library of Medicine PubMed®) were screened using a representative query to find pertinent documents within the timeframe 2016–2023. Among the information, collected across the reviewed documents, the work focused on the 3D printing workflow involving acquisition, elaboration and fabrication stages.

Findings – Following the inclusion and exclusion criteria, the authors found 20 studies that fitted the defined criteria. The reviewed studies mostly highlighted the positive impact of additive manufacturing in pediatric orthopedic surgery, particularly in orthotic applications where lightweight, ventilated and cost-effective 3D-printed devices demonstrate efficacy comparable to traditional methods, but also underlined the limitations such as printing errors and high printing times. Among the reviewed studies, material extrusion was the most chosen 3D printing technology to manufacture the typical device, particularly with acrylonitrile butadiene styrene.

Originality/value – To the best of the authors' knowledge, this is the first systematic review which annotates, from a more engineering point of view, the latest literature on the admittance of the clinical application of additive manufacturing (and its effects) within typical pediatric orthopedic treatments workflows.

Keywords Literature review, Additive manufacturing, Pediatric orthopedics

Paper type Literature review

1. Introduction

Three-dimensional (3D) printing technology, also known as additive manufacturing, has rapidly developed in the past years, allowing the creation of complex 3D objects starting from digital models by adding material (powder, metal or plastic) layer by layer on a printing bed. The strengthening of 3D printing technology has revolutionized various industries because of its low cost and high treatment personalization, including the medical field; in this last sector, additive manufacturing was proposed as an possible innovation in a wide variety of specialties, such as neurosurgery (Abranches *et al.*, 2022; Formisano *et al.*, 2021), maxillofacial surgery (Kamio and Onda, 2022; Khorsandi *et al.*, 2021), cardiothoracic surgery (Kappanayil *et al.*, 2017; Lau *et al.*, 2018) and orthopedic surgery (Formisano *et al.*, 2021; Iuppariello *et al.*, 2024; Tack *et al.*, 2016). In this field, 3D printing technologies are used, each with its own characteristics and specific applications, such as:

- *Material extrusion:* also indicated as fused deposition modeling (FDM), this technology is very common and uses the deposition of melted filament material layer by layer to create 3D objects. FDM printers are used for the fabrication of anatomical models, surgical guides and prototypes of medical devices. Its use in medicine is largely discussed in literature, mainly because of its low-cost fabrication and easy use (Pirozzi *et al.*, 2020; Quodbach *et al.*, 2022; Sharma *et al.*, 2020).

The current issue and full text archive of this journal is available on Emerald Insight at: **https://www.emerald.com/insight/1355-2546.htm**

Rapid Prototyping Journal
30/11 (2024) 276–288
Emerald Publishing Limited [ISSN 1355-2546]
[DOI 10.1108/RPJ-05-2024-0222]

Special thanks are due to collegues from AORN Santobono Pausilipon (both MD and biomedical engineers) and Fondazione Santobono Pausilipon for their interest in 3D printing application for orthopedic pediatric surgery that has permitted the development of a research line in wich this paper has been developed.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

Authors contributions: Francesco Amato and Fabrizio Clemente have contributed equally to this work.

Received 21 May 2024
Revised 26 July 2024
Accepted 8 August 2024

- *Vat photopolymerization:* also indicated as stereolithography (SLA), this technology uses a photosensitive resin that is solidified layer by layer using an ultraviolet laser. SLA offers high precision and the ability to manufacture detailed models, and it is often used for the fabrication of small-sized anatomical models or surgical guides for surgical and training purposes (Nguyen *et al.*, 2023; Sharma and Goel, 2018).
- *Powder bed fusion:* also indicated as selective laser sintering (SLS), this technology uses a laser to melt and solidify metal or plastic powders, creating 3D objects. It is used for the fabrication of customized prosthetics and implants, such as cranial prostheses or artificial joints (Fina *et al.*, 2017; Nguyen *et al.*, 2023).

3D printing technology has played a crucial role in medical education and research. In fact, the capability of fabricating anatomical models faithful to the medical images used for the generation, which could be computed tomography (CT) or magnetic resonance imaging (MRI), provides an invaluable resource for training surgeons and medical students and improves surgical planning, allowing for hands-on practice and a deeper understanding of complex anatomical structures. Furthermore, the capabilities of 3D printing allow surgeons to practice complex surgical procedures before operating on the patient, improving precision and minimizing potential risks (Formisano *et al.*, 2021; Grillo *et al.*, 2018; Lau *et al.*, 2018).

The potential of 3D printing technology has also revolutionized the field of prosthetics and orthosis. Traditional manufacturing techniques often involve labor-intensive and time-consuming processes, making custom devices costly and inaccessible for many patients. 3D printing, instead, allows for the rapid production of personalized prosthetic limbs and orthotic devices, significantly reducing costs and increasing accessibility. In addition, the customized designs can be easily modified and adjusted, improving comfort and functionality for individuals with limb differences or orthopedic conditions (Silva *et al.*, 2022; Ten Kate *et al.*, 2017).

The advantages of 3D printing technology applications also apply to the orthopedic pediatric surgery field (Goetstouwers *et al.*, 2022). The applications mentioned above, such as anatomical models for surgical planning and orthoses for limb correction, gained more advantages from 3D printing technology when treating pediatric patients; this is due to a necessity of high adaptation to their clinical needs (Frizziero *et al.*, 2019; Martelli *et al.*, 2016). Applications, advantages and clinical outcomes of 3D-printed devices in pediatric orthopedic field are well presented in literature (Martelli *et al.*, 2016; Tserovski *et al.*, 2019); however, the current scientific literature lacks of systematic reviews on this particular topic. In this regard, the objective of this systematic review is to investigate the applications of 3D printing in pediatric orthopedic surgery discussed in literature following PRISMA guidelines, focusing the attention on the fabrication workflow of the 3D-printed devices and on the outcomes obtained from their use.

2. Materials and methods

2.1 Research methods

The systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Scopus, PubMed and Web of Science (WoS) databases were selected for article research, which was focused on the admittance of the clinical application of additive manufacturing (and its effects) within typical pediatric orthopedic treatments workflows. The research was done combining keywords such as: "3D printing" or "Additive Manufacturing" or "3DP" or "Three-dimensional Printing," "children" or "pediatric" or "paediatric" and "orthopedics" or "orthopaedics." Search was limited by including only English scientific articles, conference papers and case report from 2016 until 2023. Automation tools were used to remove articles that did not fit the type and language criteria.

2.2 Inclusion and exclusion criteria

As the scope of this systematic review was to evaluate the efficacy of 3D printing technology applications on pediatric orthopedic treatments, the focus of the reviewed studies had to be on the use 3D printing devices for surgical planning, prostheses, surgical guides and orthoses for the orthopedic treatment of pediatric patients. Manuscripts focusing on other technologies, such as virtual 3D applications, or focusing on the treatment of pathologies where the figure of the orthopedic is accompanied by other medical figures (i.e. neurosurgeons), such as bone tumor treatment, spinal surgery treatment, skull surgery treatment, were excluded. Moreover, studies whose focus is different from the patient treatment and its clinical outcome, such as the evaluation of costs to fabricate medical 3D-printed devices, and studies out of scope of this review (i.e. absence of patient data in the study), also were excluded.

2.3 Article screening

Research articles selected using the criteria mentioned above were successively screened. Screening was carried out by extracting meaningful data such as:

- article goal;
- 3D printing technology application type (i.e. anatomical model, surgical guide, etc.);
- number of pediatric patients included in the study;
- treated pathology;
- 3D printing technology type (i.e. FDM, SLS, SLA, etc.);
- 3D printer used;
- printing material;
- total number of devices printed;
- presence of printing parameters in manuscript;
- printing time; and
- clinical outcome.

Data were tabled using Microsoft Excel (Microsoft Corporation®, 2018). Data were selected to focus this review on the treated pathologies with the use of 3D printing and its efficacy in the treatment.

3. Results

A total of 135 published manuscripts were identified on the three databases (109 from Scopus, nine from PubMed and 17 from WoS). From these 135 records, nine duplicate records from PubMed, and 14 duplicate records from WoS were removed, and 25 records were removed from automation tools for undesired format (14 records) and other languages other than English (11 records). The 87 remaining records were screened following the eligibility criteria (inclusion and exclusion criteria) mentioned above (Figure 1).

Due to unavailability of retrieval, three articles were excluded from this review. Finally, a total of 20 articles were included in review (see Table 1). Out of the 20 manuscripts, the majority, namely, 6/20 (30.00%), were published during the period from 2021 to 2022. The research included a total of 12 research articles, seven case reports and one conference paper. The mean age of pediatric patients examined by the reviewed studies is 8.62 years old (y.o.). Few studies do not focus only on pediatric patients but extend the work also to adults. FDM was the technology with the highest occurrence in the manuscripts (11 of them, 55.00%), while the SLA and SLS were being used in only respectively one and three manuscripts (5.00% and 15.00%). In the remaining manuscripts, the 3D printing technology was not specified (25.00%).

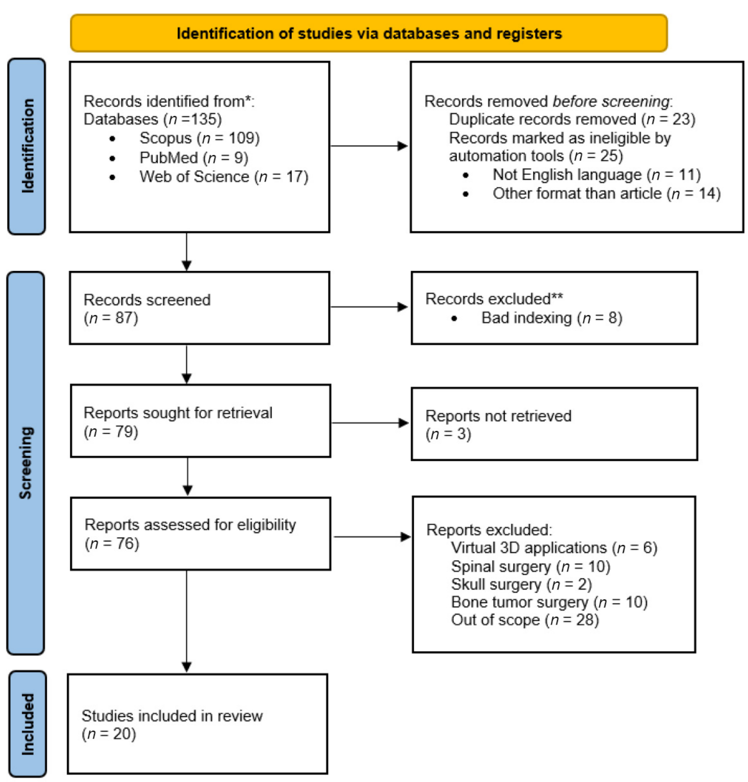
The applications of 3D printing technology in medicine found in the manuscripts were gathered in the following paragraph into four main application types (Table 1):

1. *Anatomical models:* 3D-printed devices, which mimicked anatomy of patient used for preoperative planning and surgical simulation. Six manuscripts are part of this subsection.
2. *Surgical guides:* 3D-printed devices used for assisting surgeons and clinicians in performing precise and accurate surgical interventions. Six manuscripts are part of this subsection.
3. *Orthoses:* 3D-printed devices commonly used for immobilization of fractured or deformed limbs. Seven manuscripts are part of this subsection.
4. *Prosthesis:* 3D-printed devices used for substitution of a partially missing limb. One manuscript is part of this subsection.

3.1 3D-printed anatomical models

3D-printed anatomical models are 3D representations of specific body parts that are used for educational, instructional, research and diagnostic purposes. 3D-printed anatomical models in orthopedics have become invaluable tools, because surgeons are able to perform more accurate preoperative plannings and simulations of complex surgical operations. The work proposed by authors in (Chen *et al.*, 2021) focused on the evaluation of the effect of surgical planning using patient-specific 3D-printed anatomical models on the treatment of severe postburn ankle contracture (SPAC) with external fixators, by comparing quantitative measurements obtained from surgery (such as operation duration, blood loss and hospital stay) with the ones obtained from a control group. A total of ten patients were involved, with five of them treated with the use of a 3D-printed anatomical model and five of them treated with standard procedures (even if not all the patients recruited for this study are pediatric patients, these are anyway present in both groups). In this study, anatomical models were fabricated from CT images of ankle and foot from patients with 0.6 slice thickness and the software Materialise Interactive Medical Image Control System (MIMICS from Materialise,

Figure 1 PRISMA flow diagram of the selected records



Source: Figure by authors

Rapid Prototyping Journal
Volume 30 · Number 11 · 2024 · 276–288

Table 1 Preliminary data of the articles included in the review

Authors	Year	Title	Application type	No. of patients	Mean age of patients (y.o.)
Chen *et al.*	2021	3D-printed models improve surgical planning for correction of severe postburn ankle contracture with an external fixator	Anatomical models	10	Not specified
Lam *et al.*	2021	Office 3D-printing in paediatric orthopaedics: The orthopaedic surgeon's guide	Anatomical models	4	13
Wei *et al.*	2019	Anatomic three-dimensional model-assisted surgical planning for treatment of pediatric hip dislocation due to osteomyelitis	Anatomical models	1	4
Jin *et al.*	2022	Genetic analysis combined with 3D-printing assistant surgery in diagnosis and treatment for an X-linked hypophosphatemia patient	Anatomical models	1	12
Frizziero *et al.*	2020	Computer-Aided Surgical Simulation for Correcting Complex Limb Deformities in Children	Anatomical models	5	10
Holt *et al.*	2017	Rapid Prototyping 3D Model in Treatment of Pediatric Hip Dysplasia: A Case Report	Anatomical models	1	10
Mazy *et al.*	2020	Orthopaedic support with 3D printing in children: Marketing effect or solution of the future?	Orthoses	19	7.9
Kuhl *et al.*	2020	Clubfoot kickbar: Development of an improved brace for use following correction of clubfoot	Orthoses	4	< 2
Deckers *et al.*	2018	Development and clinical evaluation of laser-sintered ankle foot orthoses	Orthoses	7	Not specified
Katt *et al.*	2021	The use of 3D printed customized casts in children with upper extremity fractures: A report of two cases	Orthoses	2	4.5
Lazzeri *et al.*	2022	3D-Printed Patient-Specific Casts for the Distal Radius in Children: Outcome and Pre-Market Survey	Orthoses	10	8.9
Chen *et al.*	2020	Application of 3D-Printed Orthopedic Cast for the Treatment of Forearm Fractures: Finite Element Analysis and Comparative Clinical Assessment	Orthoses	60	Not specified
Guida *et al.*	2019	An alternative to plaster cast treatment in a pediatric trauma center using the CAD/CAM technology to manufacture customized three-dimensional-printed orthoses in a totally hospital context: A feasibility study	Orthoses	18	11.9
Hu *et al.*	2020	Clinical application of individualized 3D-printed navigation template to children with cubitus varus deformity	Surgical guides	35	7.5
Alessandri *et al.*	2022	Virtual Surgical Planning, 3D-Printing and Customized Bone Allograft for Acute Correction of Severe Genu Varum in Children	Surgical guides	1	7
Fürnstahl *et al.*	2020	Computer-assisted femoral head reduction osteotomies: an approach for anatomic reconstruction of severely deformed Legg-Calvé-Perthes hips. A pilot study of six patients	Surgical guides	6	14
Menozzi *et al.*	2023	Side-to-Side Flipping Wedge Osteotomy: Virtual Surgical Planning Suggested an Innovative One-Stage Procedure for Aligning Both Knees in "Windswept Deformity"	Surgical guides	1	15
Sun *et al.*	2023	Application of 3D-printed osteotomy guide plates in proximal femoral osteotomy for DDH in children: a retrospective study	Surgical guides	36	4.48
Trisolino *et al.*	2023	Virtual Surgical Planning and Patient-Specific Instruments for Correcting Lower Limb Deformities in Pediatric Patients: Preliminary Results from the In-Office 3D Printing Point of Care	Surgical guides	29	11.6
Xu *et al.*	2017	Three-dimensional-printed upper limb prosthesis for a child with traumatic amputation of right wrist	Prostheses	1	8

Notes: 3D = three-dimensional; CAD/CAM = computed-aided design/computer-aided manufacturing; DDH = developmental dysplasia of the hip; y.o. = years old
Source: Table by authors

Rapid Prototyping Journal
Volume 30 · Number 11 · 2024 · 276–288

Leuven, Belgium) was used to create the 3D digital model. Digital models were then printed with the SLA Printer iSLA880 (ZRapid Tech, Beijing, China) using photosensitive resin [as in Figure 2(a)]. The 3D-printed model was successively used for preoperative planning and surgical simulation by determining the drilling locations and assembling the external fixators. The study showed how the use 3D-printed anatomical models significantly shortened the surgery duration and improved the patient–surgeon communication; this last aspect come to light since the innovative workflow reached higher scores of patient satisfaction in comparison with the control group. Differently, significant differences in blood loss or hospital stays were not reported (Chen *et al.*, 2021).

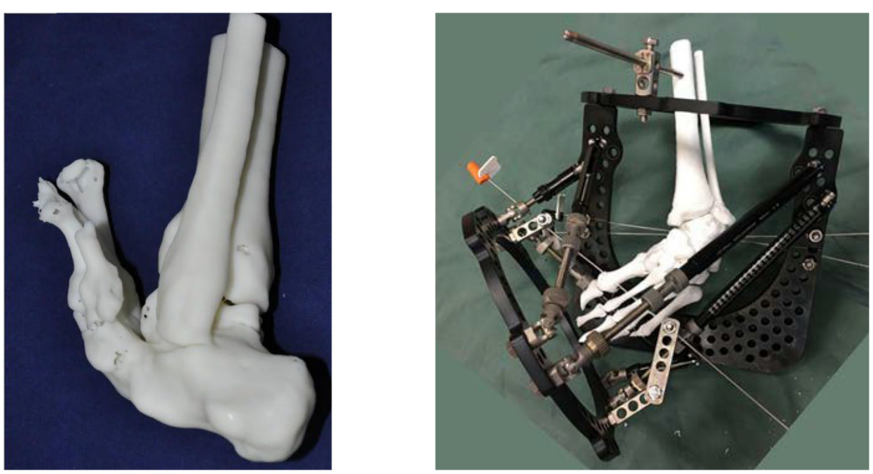
Similar findings can be found in the study proposed by authors in (Lam *et al.*, 2021), which presents four clinical cases in which 3D-printed surgical models were used by the surgical team. In this case, patients suffered from different pathologies, but all of them were treated by orthopedic surgeons. 3D anatomical models were printed in this case with an FDM Ultimaker® printer using polylactic acid (PLA) as printing material [see Figure 2(b)]. The printing of the models took a mean time of 36.2 ± 19.8 h. For each case, the anatomical model was used for surgical simulation, reducing, on the one hand, intraoperative damage and, on the other hand, improving clinical outcome, decreasing the operation time, the blood loss and the radiation exposure. Similarly to the previous study (Chen *et al.*, 2021), the use of anatomical models improved communication with patients and, in this last case, even cost efficiency of the whole process. Nevertheless, the authors highlighted few limits of this technology, such as model dimensions, which in some cases are bigger than maximum build size of the 3D printer and require further elaboration to print the model successfully, and a non-faithful tactical feel due to the difference of density between cortical bone, well mimicked by the model, and cancellous bone, which is hard to mimic by only using FDM printing (Lam *et al.*, 2021).

Another example of the promising use of 3D-printed anatomical models is that of the authors in Wei *et al.* (2020), which presented the use of a 3D-printed bone model for the treatment of a 4 y.o. patient suffering from post-osteomyelitis deformity. The 3D-printed model was used to simulate the Pemberton osteotomy of the right hip and the derotation osteotomy of the right femur, so as to determine the correct osteotomy sites. Osteotomies were simulated on the anatomical model and showed a good bone coverage of the acetabulum and the potential restoration of the length of the femur. Authors' results from physical functionality and radiological findings after one-year follow-up suggested how 3D-printed models have enhanced postoperative outcomes (Wei *et al.*, 2020).

Always focusing on improving osteotomies, the case report proposed by authors in Jin *et al.* (2022) focuses on the application of 3D-printed anatomical model to help the surgeon to visualize and plan the left femur corrective osteotomy of a 12 y.o. patient affected by X-linked hypophosphatemia. A model in PLA was 3D-printed to verify cutting angle and positions of the corrective osteotomy. Successively, the model was used to perform a surgical simulation. After the operation, the patient's 35-degree left genu varum was repaired, and the left leg was then fixed using an Ilizarov external fixator. Briefly, the authors concluded that the appearance of the surgically intervened leg was satisfactory for the surgeons, but the long-term effect needed further follow-up observations.

The study proposed by the authors in Frizziero *et al.* (2021), even if concentrates on the usefulness of virtual surgical planning, even proposes 3D-printed anatomical models of the clinical cases presented, which in this case are limb deformities. For five patients (mean age 10 y.o.), surgery was simulated using a low-cost computer-aided surgical simulation (CASS) system, and digital anatomical models were successively printed using FDM technology ("EZT3D model T1" 3D printer) with PLA as printing material. Operations were carried

Figure 2 Examples of 3D-printed anatomical models from (a) Chen *et al.* (2021) and (b) Lam *et al.* (2021)



(a) (b)

Sources: Image (a) courtesy of Chen *et al.*, (2021(2021) ©[2021] Springer Nature. Image (b) courtesy of Lam *et al.*, (2021(2021) under the terms of the Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by-nc-nd/4.0/)

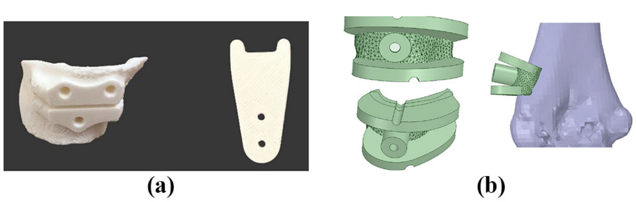
out successfully using CASS process in combination with 3D-printed models of patients' bone.

Finally, the last work of this subsection (Holt *et al.*, 2017) deals with the clinical case of a 10 y.o. female with left acetabular dysplasia and chronic hip instability who underwent a periacetabular osteotomy. For this patient, the 3D-printed model of hip bones was fabricated using FDM ("Makerbot Replicator" 3D printer) with acrylonitrile butadiene styrene (ABS) as printing material. The model was used by surgeons to better understand the patient's anatomy, to counsel the family about the clinical problem and the surgical procedure, as well as to plan the surgical technique. In particular, planned osteotomies were simulated on the model and the osteotomy fragment was rotated into a position that best stabilized the hip. Surgery had positive outcome, with the patient demonstrating complete radiographic healing by ten months. Similarly to several of the previous cited works, the authors highlighted the importance of the 3D-printed model to better understand the case and to improve physicians-parents communication.

3.2 3D-printed surgical guides

3D-printed models have significantly advanced the field of orthopedics by providing orthopedic surgeons with powerful patient-specific tools for surgical planning, custom implant design and patient communication. The capability of performing precise cuts during the surgery allows the surgeon to obtain a series of advantages. The authors in Alessandri *et al.* (2022) used two surgical guides for the treatment of severe genu varum in a 7 y.o. patient. The entire surgical operation, which was planned to be a double elevating osteotomy, was first simulated in a virtual environment, where the wedges of bone to be cut were measured. Successively, two surgical guides were printed to allow surgeon to precisely cut the bone in the desired position and a personalized bone graft from a donor was obtained for the elevation of the bone. The design of the surgical guides was based on the correction planned in virtual surgical planning. In particular, two guides were printed: the first one to perform a distal osteotomy, the second one to perform a proximal osteotomy. Both the guides were printed using PLA (FiloAlfa PLA) through the FDM technology (Anycubic Delta Predator 3D printer), as in Figure 3(a). After printing the surgical guides and obtaining the bone graft, the surgery was carried out by performing an osteotomy on both tibias and, in this scenario, the cutting guides were used to perform the cut as planned in virtual surgical planning stage. To evaluate the

Figure 3 Examples of 3D-printed anatomical models from (a) Alessandri *et al.* (2022) and (b) Hu *et al.* (2020)



Sources: Images (a) and (b) courtesy, respectively, of Alessandri *et al.*, (2022(2022) and Hu *et al.*, (2020(2020) under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/)

correction, pre- and post-operative radiographical measurements were made. The surgery was performed successfully, accurately replicating the planned surgery at the time of the operation by using the patient-specific cutting guides, obtaining saves in cost and time (Alessandri *et al.*, 2022).

Authors in Hu *et al.* (2020) explored the advantages of using 3D-printed surgical guides for assisting the corrective treatment of children with cubitus varus deformity. For this study, 35 patients with a mean age of 7.5 y.o. and affected by cubitus varus deformity were enrolled and divided in two groups; namely, 16 patients were treated using 3D-printed surgical guides, and 19 patients followed standard clinical course. For the 3D printing group, surgical guides were designed basing on the two planned osteotomies on the distal end of humerus. The angle formed from the crossing of the two cutting planes was at the base of the surgical guide dimensioning. Furthermore, the guide form was personalized to accurately reproduce the bone anatomy for correct positioning during the surgery. The designed surgical guide was printed using medical PLA [as in Figure 3(b)]. Provided that the surgical guides fabricated reproduced successfully bone anatomy of the 16 patients and the surgical operation was carried out successfully for all the patients from both groups, clinical parameters – such as operation time, post-operative appearance, carrying angles (before-after), maximum elbow motion (degrees) and Bellemone criteria – were measured and statistical analysis was performed to examine the differences between the two groups (statistical significance set at $p > 0.05$). The numerical and statistical results highlighted a significant diminution of the operation time ($p < 0.001$) and a significantly smaller post-operative difference between affected side and healthy side for patients who were treated with the surgical guide (Hu *et al.*, 2020).

A similar study was carried out by the authors in Sun *et al.* (2023), who compared the application benefits of proximal femoral osteotomy between 3D-printed guide assisted and traditional surgical operation in 36 pediatric patients affected by DDH. For the comparison, patients were divided into two groups: the guide plate group, composed by 16 patients, and the traditional group, composed by 20 patients. For the first group, a navigation template was designed for each patient to facilitate the femoral osteotomy. The device was designed starting from the surgical simulation performed using CT images, where the osteotomy angles were defined. Mimics 21.0 and 3-Matic software (Materialise, Leuven, Belgium) were used by the authors for the segmentation of the bone and the digital planning of the surgery. 3D printing of the digital model of the navigation template was commissioned from third party. After the surgery, X-rays were used to assess the postoperative femoral angles. A statistical analysis was carried out for the evaluation of differences between the measured data of the two groups with significance at $p < 0.05$. Results highlighted significant differences in particular for the X-ray fluoroscopy times, operation time and intraoperative blood loss. No differences between the two groups emerged when comparing the postoperative angles, enforcing the identical clinical outcome independently from the strategy used.

Authors in Trisolino *et al.* (2023) evaluated the advantages and challenges in using virtual surgical planning and 3D-printed patient-specific surgical guides for treating lower limb deformities in 29 pediatric patients (mean age of 11.4). To evaluate the differences between the same surgery using traditional strategies, 16 procedures were performed using only virtual surgical planning, and 23 were performed using both virtual surgical planning and surgical guides, for a total of 39 bone segment correction to evaluate. The workflow followed by authors started from acquisition of CT scans of both limbs, which are successively segmented using Mimics 25.0 (Materialise, Leuven, Belgium). Digital models of patients' limbs in standard triangulation language (STL) format were obtained, and with it, the surgical procedure is virtually simulated. In the simulation, angular corrections are performed for the repositioning of the limb, and two surgical guides are created. Surgical guides were designed considering size, position and shape of the used instruments for cutting and for immobilization. Surgical guides were then 3D-printed using high-temperature PLA using FDM 3D printing technology. Results presented in the study highlighted how surgeries aided by the 3D-printed devices were notably shorter, averaging 125 min, compared to those with traditional approach, averaging at 170 min. This resulted in a time savings of approximately 45 min representing about 26% of the total surgical time. The average fluoroscopy shots needed without surgical guides were meanly 29, compared to the meanly 16 shots with the 3D-printed device, resulting in a mean difference of meanly 13 shots.

Another work combining virtual surgical planning and surgical guides was proposed by the authors in Menozzi *et al.* (2023), where surgical guides, in combination with virtual surgical planning, are used to ensure precise correction in surgery and to determine the appropriate size, positioning and orientation of the screw plates in a 15 y.o. patient, affected by knee windswept deformity, treated with a single-stage acute correction with bilateral osteotomy. The 3D digital model of pelvis and feet was obtained from the segmentation of the CT scan. Once the 3D digital models of the lower limbs were obtained, angular corrections of both limbs were planned virtually, and a total of four surgical guides were designed for immobilization and cutting of the bone: three for the right femur and one for the left femur. 3D printing of the surgical guides was carried out by using an FDM 3D printer (Qidi I-Mate S). Printing material was not specified by the authors. After the surgery, radiographs showed complete bone healing of the osteotomies. Authors highlighted how the use of surgical guides resulted in significant savings in surgical time and blood loss and eliminated the need for high-quality intraoperative radiographs. Additionally, authors observed that surgical simulation, planning and 3D printing could reduce the steep learning curve required for performing similar interventions.

Finally, the last eligible contribution retrieved by the authors in Fürnstahl *et al.* (2020) reports the results following the treatment of six patients using the combination of computer simulation for preoperative planning and additive manufacturing for the fabrication of patient-specific surgical guides. After the planning of the surgery using CASS software, a patient-specific surgical guide was designed to aid surgeons in replicating the virtual simulation of the corrective osteotomy performed. The guide was designed to have two cutting slits for the surgical cut of the bone (following the planned the surgery) and medial lateral hooks and two drill sleeves to better stabilize the device on the bone during surgery. The evaluation of surgery clinical outcome was measured by comparing clinical parameters of the bone, such as femur head diameter and sphericity index. After the surgery, the authors underlined a slight improvement of clinical parameters, compared with similar others from literature (based on procedures without the use of 3D-printed devices). The authors underlined the importance of surgical guide positioning for the success of surgery. For three patients out of six, complications not related to the computer simulation and the surgical guide were reported. Malposition of the surgical guide occurred in one patient out of six. This led authors to a slight re-design of the surgical guide.

3.3 3D-printed orthoses

3D-printed orthoses have proven to be a valid substitute of traditional casts for the treatment of limb fractures or deformities, thanks to the high customizability and comfort that the former ones have shown. Scientific literature already proved the effectiveness of this technology in many cases. For instance, the authors in Lazzeri *et al.* (2022) fabricated patient-specific 3D-printed casts to treat buckle fractures of the distal radius in children, a typical fracture in such a age bracket. The study included a total of ten pediatric patients, with a mean age of 8.9 y.o., for which an orthosis for limb immobilization was fabricated starting from 3D reconstruction of the patient fractured limb, whose virtual data were acquired using an optical scanner. The design of the orthoses was performed using a software designed by the authors (T3DDY-Oplà) within Siemens NX modeling environment, in which two shells for each orthosis were generated. Once the design stage was completed, the shells were printed using the FDM 3D printer Stratasys F370 using ABS as printing material [see Figure 4(b)]. The shells were positioned on patients' fractured arm using three plastic ties. Patient's fracture clinical conditions and cast conditions were evaluated after 3, 7 and 21 days after the first application. For each follow-up, patients were requested to report the primary outcomes of general comfort, efficacy of contention and mechanical integrity. A questionnaire was administered to both children and parents to furtherly evaluate the general comfort of the orthoses. Concurrently, the secondary outcome of the study was the practicability of the supply chain (briefly, several management factors, e.g. manufacturing time and price, for the whole process were investigated). The results from questionnaires indicated overall positive feedback, although comfort was low initially,

Figure 4 Examples of 3D-printed orthoses from (a) Katt *et al.* (2020) and (b) Lazzeri *et al.* (2022)

(a) (b)

Sources: Images (a) and (b) courtesy of, respectively, Katt *et al.*, (2020(2020) and Lazzeri *et al.*, (2022(2022) under the terms of the Creative Commons Attribution-NonCommercial 3.0 Unported License (https://creativecommons.org/licenses/by-nc/3 0/deed.en) and Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/)

reflecting the natural healing process. The study also highlighted fast manufacturing (within 24 h), the orthosis fabrication was cheap, and the absence of deformation of the device after its use (the authors compared the 3D model before and after use by performing a finite element analysis) (Lazzeri *et al.*, 2022).

Similar findings could be found in the study proposed by authors in Katt *et al.* (2020), which focuses on the evaluation of the benefits achieved after the application of 3D-printed customized casts in two patients affected by upper extremity fractures. For both patients, after an initial clinical evaluation in which the fracture of the upper limb was found, the arm was scanned using a 3D scanner to obtain a 3D digital model. Subsequently, the personalized casts were 3D printed in PLA, and the process required 6–7 h to complete [see Figure 4(a)]. Casts were then applied on the fractured arm for both patients after two days from the fabrication so as to limit the swelling from the fracture. On follow-up evaluation, both patients were asymptomatic and re-acquired normal function and movement. The study highlighted, compared to standard casts, a greater breathability of the 3D-printed casts and a reduction of skin irritation (Katt *et al.*, 2020).

The work proposed by authors in Mazy *et al.* (2020) focuses on the advantages and disadvantages resulting in the use of 3D-printed casts for the treatment of both fractures and deformities of 19 pediatric patients (with a mean age of 7.9 y.o.). The patients suffered from different pathologies: eight of them had a forearm fracture, three of them had an elbow fracture, seven of them suffered from clubfoot and one patient suffered from Sinding–Larsen syndrome. First, for each patient, a restraint was designed considering the virtual data obtained scanning the fractured limb (using a dimensional infrared scanner), data which were then further elaborated on a CAD software, also with the aid of an algorithm. Then, the personalized orthopedic restrain fabrication was carried out using a polyolefin filament on a FDM 3D printer (the fabrication time for each cast lasted from 5 to 15 h). The evaluation was carried out using two questionnaires, one for the doctor, and the other for the patient. The feedback obtained highlighted, aside from the therapeutic effectiveness, the recyclability, lightness, ventilation, hydro-compatibility and radio-transparence of the casts. The authors also underlined the limitations related to the fabrication phases, in particular the high printing time, printing errors, size of the cast depending on the building plate dimensions of the printer (Mazy *et al.*, 2020).

Similar to the previously presented work, the study carried out by authors in Kuhl *et al.* (2020) focuses on the design and test of a 3D-printed orthosis for the correction of clubfoot using Ponseti method in four pediatric patients (mean age < 2 y.o.) with the aim of allowing patients' mobility so as to, in turn, increasing the comfort for both patient and parents. The Ponseti method device is formed by a bar (kick-bar) that connects patients' feet, keeping in this way the desired posture while allowing the patient to move its feet in an up-and-down motion. From a manufacturing point of view, the device was fabricated by FDM ("Markforged Mark II 3D" printer) using ONYX filament (a filament characterized by the combination of nylon and carbon fibers). The results from the application of the orthoses on the four patients highlighted an initial positive opinion from parents, because the children maintained the desired posture also while moving. Furthermore, the low manufacturing costs and, also, the easy use of the device were underlined (Kuhl *et al.*, 2020).

The authors in Deckers *et al.* (2018) proposed the development of an ankle foot orthosis by using SLS 3D printing technology aiming at comparing the mechanical and clinical performances of the 3D-printed devices with traditionally manufactured orthosis. In this study, seven patients (three children and four adults) suffering from different pathologies (trauma, neuro-muscular disorder, cerebral palsy) were selected. For these patients, ankle foot orthoses were prescribed to support weak muscles and reduce spastic movements. The design of the device was carried out starting from 3D reconstruction of patients' leg obtained using a 3D scanner. Then, the digital reconstructions were corrected using a specialized orthopedic software (Rodin 4D). Operatively, for each patient, two orthoses were fabricated: one through standard workflow (milling out of wood and then vacuum thermoforming), while the second one using SLS technology. The 3D-printed orthosis was first designed on CAD environment ("Rhinoceros," Robert McNeel and Associates) and then printed in SLS using polyamide 12. The clinical trial for both devices lasted six weeks, in which patients walked on both laser-sintered and traditionally manufactured devices. Albeit the casts could be effectively fabricated, the mechanical performances reported from the authors highlighted a need for improvement for the 3D-printed orthoses, which proved poor mechanical resistance under daily use conditions (Deckers *et al.*, 2018).

On this topic, a detailed study was described by authors in Chen *et al.* (2020). In particular, the authors investigated the mechanical characteristics of a cast-wrapped fractured forearm using finite element analysis for the simulation of 3D-printed device stress distribution; simultaneously, Chen *et al.* also performed a clinical comparative study of the fabricated 3D-printed orthopedic cast with same devices manufactured with traditional methodologies. Particularly, the comparative study was carried out on a total of 60 patients, with age ranging from 5 to 76 y.o., randomly and divided into three groups from 20 patients each: Group A, which used 3D-printed casts, Group B, which used plaster casts, and Group C, which used splint fixations. To manufacture the cast, first, the images of both the fractured and the non-injured limb (this useful for the plaster cast) were obtained using a CT system. Successively, the digital model of the cast was designed basing on the fractured limb and then printed using SLS 3D printer "EOS P395" using PA2200 Polyamide. To collect data about the performance of the 3D-printed cast, two questionnaires were designed for the evaluation of clinical efficacy and patient satisfaction, which were proposed to the surgeon and for each patient enrolled, respectively, after six weeks of cast use. To properly analyze survey data, statistical analysis using the ANOVA statistical test with Bonferroni *post hoc* comparisons was carried out (significance for $p < 0.05$). The results presented by the authors were mostly positive, in particular the total score of the clinical efficacy assessment and the fineness rate of the functional evaluation showed significantly superior outcomes in Group A compared to the other two groups.

Finally, the last eligible contribution retrieved is the one proposed by the authors in Guida *et al.* (2019). The aim of the authors was to verify whether it has been possible to use 3D-printed personalized orthoses for children who presents at the trauma center's emergency room for the treatment of distal composed fractures of the forearm (torus, greenstick and unicortical). A total of 18 patients with mean age of 11.9 y.o. were enrolled for the study. For all of them, 3D reconstruction of fractured limb was performed by using a 3D laser scanner. Successively, the orthosis was designed in a CAD environment ("Rhinoceros" v5.0 Robert McNeel and Associates). Then, 3D printing was carried out using FDM technology with reinforced ABS (Zortrax Z-UltraT), where the printing time stated by the authors was from 10 h to 12 h. An evaluation of patient satisfaction in using the 3D-printed device was carried out using questionnaires administered to patients before and after the immobilization. From a clinical point of view, the authors reported that the mean immobilization time was 28 days, no major and minor complications occurred in orthoses use, bone healing was reported to be successful in all patients, even if one case of orthosis breakage from fall was reported. The scores of questionnaires before and after the treatment were analyzed using the Wilcoxon test: the findings highlighted a significant difference in all scores, specifically in pain and functionality ones. Moreover, the mean overall satisfaction score was 4/5, aspect which further highlighted the effectiveness of the 3D-printed casts, also thanks to the skin ventilation and lightness properties, which improved patients' comfort (Guida *et al.*, 2019), as already evidenced by other works cited in this section.

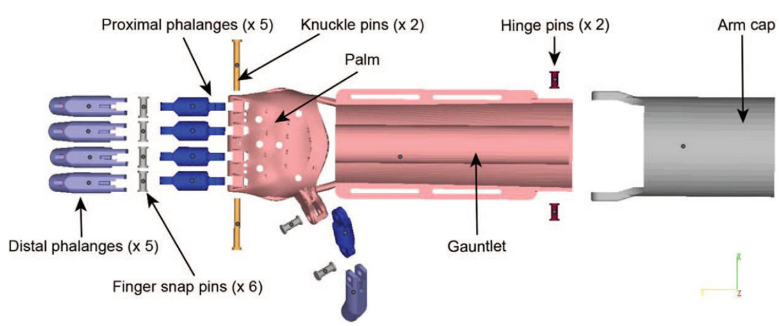
3.4 3D-printed prostheses

The application of 3D printing for the fabrication of prostheses is less explored with respect to the other presented applications, but it has opened new possibilities in the design and fabrication of prosthetics, offering more customized, lightweight and economic solutions to improve the quality of life of patients. In this field, Xu *et al.* (2017) have proposed in their work a case of use of 3D-printed prosthesis in a pediatric patient of 8 y.o. after the traumatic wrist amputation. For the fabrication of the prosthesis, the authors started from the scanning of the arm. Subsequently, the scanned data were elaborated using Slic3r, in which the distal phalanges, proximal phalanges, finger snap pins, knuckle pins, palm, gauntlet (forearm), hinge pins and arm cap were designed (see Figure 5). The device was then printed in less than 8 h though an FDM 3D printer ("FlashForge Creator Pro," Zhejiang, China), using ABS as printing material. Once complete, the device was then assembled using nylon strings and medical foam. Once the device was printed and installed, a rehabilitation program was applied for training the patient in the prosthesis use. After one and three months, the device function was evaluated by the Children Amputee Prosthetics Projects score, used for evaluating the performance of daily behaviors. The results highlighted a relevant improvement of the score comparing Month 1 and Month 3 evaluations, finding positive feedback from the patient in completing daily activities. The authors also highlighted the affordability and customizability of the device (Xu *et al.*, 2017).

4. Discussion

The findings deducible from the reviewed articles (presented also in Table 2) underline the general positive impact of 3D printing in medicine (and, as focus of this review, in the orthopedic pediatric surgery field), independently from the approach used. The most used application found is 3D-printed orthoses (41.17%, 7 articles), which can easily substitute in many cases the traditional devices used to immobilize limbs. In this case, the analyzed articles mostly focused, more than on the efficacy of the 3D-printed device (which is in any case proven to be positive), on its durability throughout daily activities. The results presented show that these devices are a valid substitute to standard casting, thanks to advantages such as lightweight, comfort, ventilation and low costs related to their fabrication (Chen *et al.*, 2020; Guida *et al.*, 2019; Mazy *et al.*, 2020; Katt *et al.*, 2020; Lazzeri *et al.*, 2022). FDM printing using ABS as printing material is preferred, thanks to the low-cost and high efficiency of both/either the FDM technology and ABS, as confirmed by many works in the literature that presented a workflow for 3D printing of orthoses (Frizziero *et al.*, 2021; Pirozzi *et al.*, 2020; Quodbach *et al.*, 2022). Other 3D printing technologies have been also explored, such as SLS, although these still needs further research, in particular on the durability of the fabricated devices (Deckers *et al.*, 2018). Together with FDM, the SLA technology has been also preferred in the case of the manufacturing of anatomical models, allowing the fabrication of high resolution models of patients' region of interest starting from medical images collected during standard clinical treatment. The reviewed articles on this topic highlighted the reduction of surgical time as the main improvement obtained using the anatomical models in clinical treatment, typically thanks to a better understanding of the case

Figure 5 Example of 3D-printed anatomical models from Xu *et al.* (2017)



Sources: Figure courtesy of Xu *et al*., (2017)(2017) ©[2017] Wolters Kluwer Health

Table 2 Relevant findings on the fabrication workflow of reviewed studies.

Authors	Application type	Material	3D printer technology	Printer	No. of model printed	Printing parameters	Printing time
Chen *et al.* (2021)	Anatomical models	Photosensitive resin	SLA	iSLA880	1	Yes	Not specified
Lam *et al.* (2021)	Anatomical models	PLA	FDM	Ultimaker 3 Extended	1 per patient	Yes	From 23 h to 65.41 h
Wei *et al.* (2020)	Anatomical models	Not specified	Not specified	Not specified	1	No	Not specified
Jin *et al.*(2022)	Anatomical models	PLA	Not specified	Not specified	1 per patient	No	Not specified
Frizziero *et al.* (2021)	Anatomical models	PLA	FDM	EZT3D model T1	1 per patient	No	Not specified
Holt *et al.* (2017)	Anatomical models	ABS	FDM	Makerbot Replicator	1 per patient	No	Not specified
Mazy *et al.* (2020)	Orthoses	Polyolefin	FDM	Not specified	1 per patient	No	5–15 h
Kuhl *et al.* (2020)	Orthoses	Nylon and carbon fiber filament	FDM	Markforged Mark II	1 per patient	Yes	Not specified
Deckers *et al.* (2018)	Orthoses	Polyamide 12	SLS	EOS LS	1 per patient (20)	No	Not specified
Katt *et al.* (2020)	Orthoses	PLA	Not specified	Not specified	1 per patient	No	6–7 h
Lazzeri *et al.* (2022)	Orthoses	ABS	FDM	Stratasys F370	1	No	Not specified
Chen *et al.* (2020)	Orthoses	P2200 Polyamide	SLS	EOS LS P395	1 per patient	No	Not specified
Guida *et al.* (2019)	Orthoses	Reinforced ABS	FDM	Not specified	2 cutting guides	No	10–12 h
Hu *et al.* (2020)	Surgical guides	ABS	FDM	FlashForge Creator Pro	1 per patient	No	< 8 h
Alessandri *et al.* (2022)	Surgical guides	PLA	Not specified	Not specified	1	No	Not specified
Fürnstahl *et al.* (2020)	Surgical guides	PLA	FDM	Delta Anycubic Predator	1 per patient	Yes	Not specified
Menozzi *et al.* (2023)	Surgical guides	Not specified	FDM	Qidi I-Mate S	1	No	Not specified
Sun *et al.* (2023)	Surgical guides	Not specified	Not specified	Not specified	1 per patient	No	Not specified
Trisolino *et al.* (2023)	Surgical guides	PLA	FDM	Not specified	2 per patient	No	Not specified
Xu *et al.* (2017)	Prostheses	P2200 Polyamide	SLS	EOS LS P395	1	No	Not specified

Notes: ABS = acrylonitrile butadiene styrene; FDM: fused deposition modeling; PLA = Polylactic acid; SLA= stereolithography; SLS = selective laser sintering
Source: Table by authors

(Chen *et al.*, 2021; Holt *et al.*, 2017; Lam *et al.*, 2021). Other works also underlined an improvement of the communication with patients or their caregiver (Chen *et al.*, 2021; Jin *et al.*, 2022; Lam *et al.*, 2021). Anatomical models are, moreover, easily combined with surgical guides, also thanks to their low demanding fabrication process in terms of printing time and material needed. Surgical guides, as highlighted by the retrieved articles, are an efficient way to reproduce steps done in the virtual surgical simulation to reduce the surgical time and improve the surgical operation itself (Frizziero *et al.*, 2021; Hu *et al.*, 2020). Finally, the 3D printing technology also has revealing to be useful in the prosthetic field, because it has given patients the opportunity to obtain low-cost and easily rebuildable prostheses, which can be easily compared to the traditional ones in terms of efficiency (Xu *et al.*, 2017).

The 3D printing workflow, despite being different depending on the application of the technology, follows some key steps, which are all validated from the reviewed works: the "Acquisition" stage, required to achieve of the digital volume of patient's region of interest, "Elaboration," during which the digital 3D model is designed to be ready for the "Fabrication" phase, where the materials and the printing parameters are chosen and the manufacturing of the model is completed. These steps are also confirmed by similar works in literature (Formisano *et al.*, 2021; Iuppariello *et al.*, 2024).

The implementation of these 3D-printed devices in standard clinical treatments is still under development, because this aim is still hindered by some limits related to the fabrication (as part of the reviewed articles highlighted), such as the printing dimension limit, printing errors (which forces the re-printing of the model) and a typically high printing time (Deckers *et al.*, 2018) respect to clinicians needs. For this last reason, these conditions in the typical scenario do not meet the needs of clinicians, who, in fact, still either prefer or are compelled to adhere to standard procedures for patient treatment; however, workflow optimizations can be carried out (and will still be needed) for the purpose of reducing printing time and minimizing the possibility of printing errors (Calderone *et al.*, 2023; Ravi and Chen, 2021; Wu, 2018).

Following the limitations highlighted, the future direction of the research of 3D printing technology in the medical field will be likely to focus on enhancing its capabilities, expanding the applications and addressing current limitations, specifically by improving the fabrication phase by implementing new materials with superior mechanical properties and by improving the printing resolution, for the purpose of manufacturing more accurate and personalized devices. Furthermore, also, the combination of 3D printing with 3D virtual surgical planning and virtual surgery simulation has demonstrated to be effective, as some of the reviewed articles have already shown (Alessandri *et al.*, 2022; Hu *et al.*, 2020; Sun *et al.*, 2023; Trisolino *et al.*, 2023), leading to new strategies for helping surgeons in patients' treatment.

5. Conclusions

In conclusion, the positive outcomes found across various studies underscore the promising trajectory of the 3D printing technology in reshaping the landscape of pediatric orthopedics, offering personalized and effective solutions for patient care. As advancements continue, further research and optimization efforts will contribute to realize the full potential of 3D printing in pediatric orthopedic treatments, fostering a new era of innovation and improved patient outcomes.

References

Abranches, G.D.P., Silva, A.C.F.D., Dering, L.M., Scremin, L.G., Pedro, M.K.F. and Leal, A.G. (2022), "Application of Three-Dimensional printed tractography in neurosurgical planning: a systematic review", *Jbnc - Jornal Brasileiro DE Neurocirurgia*, Vol. 33 No. 4, pp. 463-471, doi: 10.22290/jbnc.2022.330410.

Alessandri, G., Frizziero, L., Santi, G.M., Liverani, A., Dallari, D., Vivarelli, L., Di Gennaro, G.L., Antonioli, D., Menozzi, G.C., Depaoli, A., Rocca, G. and Trisolino, G. (2022), "Virtual surgical planning, 3D-Printing and customized bone allograft for acute correction of severe Genu Varum in children", *Journal of Personalized Medicine*, Vol. 12 No. 12, p. 2051, doi: 10.3390/jpm12122051.

Calderone, D., Cesarelli, G., Cesarelli, M., Iuppariello, L., Guida, P., Casaburi, A., Romano, G., Amato, F. and Clemente, F. (2023), "Optimization of 3D fused deposition modeling printing process for the manufacturing of devices for medical use", *Presented at the 2023 IEEE International Conference on Metrology for eXtended Reality, Artificial Intelligence and Neural Engineering (MetroXRAINE)*, IEEE, *Milano*, pp. 484-489, doi: 10.1109/MetroXRAINE58569.2023.10405691.

Chen, Y., Lin, H., Yu, Q., Zhang, X., Wang, D., Shi, L., Huang, W. and Zhong, S. (2020), "Application of 3D-Printed orthopedic cast for the treatment of forearm fractures: finite element analysis and comparative clinical assessment", *BioMed Research International*, Vol. 2020, pp. 1-12, doi: 10.1155/2020/9569530.

Chen, Y., Niu, Z., Jiang, W., Tao, R., Lei, Y., Guo, L., Zhang, K., Xia, W., Song, B., Huang, L., Zhang, Q. and Han, Y. (2021), "3D-printed models improve surgical planning for correction of severe postburn ankle contracture with an external fixator", *Journal of Zhejiang University-SCIENCE B*, Vol. 22 No. 10, pp. 866-875, doi: 10.1631/jzus.B2000576.

Deckers, J.P., Vermandel, M., Geldhof, J., Vasiliauskaite, E., Forward, M. and Plasschaert, F. (2018), "Development and clinical evaluation of laser-sintered ankle foot orthoses", *Plastics, Rubber and Composites*, Vol. 47 No. 1, pp. 42-46, doi: 10.1080/14658011.2017.1413760.

Fina, F., Goyanes, A., Gaisford, S. and Basit, A.W. (2017), "Selective laser sintering (SLS) 3D printing of medicines", *International Journal of Pharmaceutics*, Vol. 529 Nos 1/2, pp. 285-293, doi: 10.1016/j.ijpharm.2017.06.082.

Formisano, M., Iuppariello, L., Casaburi, A., Guida, P. and Clemente, F. (2021), "An industrial oriented workflow for 3D printed, patient specific orthopedic cast", *SN Applied Sciences*, Vol. 3 No. 11, p. 830, doi: 10.1007/s42452-021-04816-w.

Formisano, M., Iuppariello, L., Mirone, G., Cinalli, G., Casaburi, A., Guida, P. and Clemente, F. (2021), "3D printed anatomical model for surgical planning: a pediatric hospital experience", *Presented at the 2021 International Conference on e-Health and Bioengineering (EHB)*, IEEE, *Iasi*, pp. 1-4, doi: 10.1109/EHB52898.2021.9657653.

Frizziero, L., Santi, G.M., Leon-Cardenas, C., Donnici, G., Liverani, A., Papaleo, P., Napolitano, F., Pagliari, C., Di

Gennaro, G.L., Stallone, S., Stilli, S., Trisolino, G. and Zarantonello, P. (2021), "In-House, fast FDM prototyping of a custom cutting guide for a Lower-Risk pediatric femoral osteotomy", *Bioengineering*, Vol. 8 No. 6, p. 71, doi: 10.3390/bioengineering8060071.

Frizziero, L., Santi, G.M., Liverani, A., Giuseppetti, V., Trisolino, G., Maredi, E. and Stilli, S. (2019), "Paediatric orthopaedic surgery with 3D printing: improvements and cost reduction", *Symmetry*, Vol. 11 No. 10, p. 1317, doi: 10.3390/sym11101317.

Fürnstahl, P., Casari, F.A., Ackermann, J., Marcon, M., Leunig, M. and Ganz, R. (2020), "Computer-assisted femoral head reduction osteotomies: an approach for anatomic reconstruction of severely deformed Legg-Calvé-Perthes hips. A pilot study of six patients", *BMC Musculoskeletal Disorders*, Vol. 21 No. 1, p. 759, doi: 10.1186/s12891-020-03789-y.

Goetstouwers, S., Kempink, D., The, B., Eygendaal, D., Van Oirschot, B. and Van Bergen, C.J. (2022), "Three-dimensional printing in paediatric orthopaedic surgery", *World Journal of Orthopedics*, Vol. 13 No. 1, pp. 1-10, doi: 10.5312/wjo.v13.i1.1.

Grillo, F.W., Souza, V.H., Matsuda, R.H., Rondinoni, C., Pavan, T.Z., Baffa, O., Machado, H.R. and Carneiro, A.A.O. (2018), "Patient-specific neurosurgical phantom: assessment of visual quality, accuracy, and scaling effects", *3D Printing in Medicine*, Vol. 4 No. 1, p. 3, doi: 10.1186/s41205-018-0025-8.

Guida, P., Casaburi, A., Busiello, T., Lamberti, D., Sorrentino, A., Iuppariello, L., D'Albore, M., Colella, F. and Clemente, F. (2019), "An alternative to plaster cast treatment in a pediatric trauma center using the CAD/CAM technology to manufacture customized three-dimensional-printed orthoses in a totally hospital context: a feasibility study", *Journal of Pediatric Orthopaedics B*, Vol. 28 No. 3, pp. 248-255, doi: 10.1097/BPB.0000000000000589.

Holt, A.M., Starosolski, Z., Kan, J.H. and Rosenfeld, S.B. (2017), "Rapid prototyping 3D model in treatment of pediatric hip dysplasia", *The Iowa Orthopaedic Journal*, Vol. 37, p. 157.

Hu, X., Zhong, M., Lou, Y., Xu, P., Jiang, B., Mao, F., Chen, D. and Zheng, P. (2020), "Clinical application of individualized 3D-printed navigation template to children with cubitus varus deformity", *Journal of Orthopaedic Surgery and Research*, Vol. 15 No. 1, p. 111, doi: 10.1186/s13018-020-01615-8.

Iuppariello, L., Calderone, D., Casaburi, A., Romano, G., Guida, P. and Clemente, F. (2024), "Use of three-dimensional printing technology for supporting the hip reconstruction surgery in paediatric patients", *SN Applied Sciences*, Vol. 6 No. 44, doi: 10.1007/s42452-024-05644-4.

Jin, J., Zhang, L., Guo, S., Tang, K., Zeng, L., Xiang, R. and Liang, J. (2022), "Genetic analysis combined with 3D-printing assistant surgery in diagnosis and treatment for an X-linked hypophosphatemia patient", *Journal of Clinical Laboratory Analysis*, Vol. 36 No. 3, p. e24243, doi: 10.1002/jcla.24243.

Kamio, T. and Onda, T. (2022), "Fused deposition modeling 3D printing in oral and maxillofacial surgery: problems and solutions", *Cureus*, doi: 10.7759/cureus.28906.

Kappanayil, M., Koneti, N., Kannan, R., Kottayil, B. and Kumar, K. (2017), "Three-dimensional-printed cardiac prototypes aid surgical decision-making and preoperative planning in selected cases of complex congenital heart diseases: early experience and proof of concept in a resource-limited environment", *Annals of Pediatric Cardiology*, Vol. 10 No. 2, p. 117, doi: 10.4103/apc.APC_149_16.

Katt, B., Imbergamo, C., Seigerman, D., Rivlin, M. and Beredjiklian, P.K. (2020), "The use of 3D printed customized casts in children with upper extremity fractures: a report of two cases", *The Archives of Bone and Joint Surgery*, doi: 10.22038/abjs.2020.47722.2342.

Khorsandi, D., Fahimipour, A., Abasian, P., Saber, S.S., Seyedi, M., Ghanavati, S., Ahmad, A., De Stephanis, A.A., Taghavinezhaddilami, F., Leonova, A., Mohammadinejad, R., Shabani, M., Mazzolai, B., Mattoli, V., Tay, F.R. and Makvandi, P. (2021), "3D and 4D printing in dentistry and maxillofacial surgery: printing techniques, materials, and applications", *Acta Biomaterialia*, Vol. 122, pp. 26-49, doi: 10.1016/j.actbio.2020.12.044.

Kuhl, S., Cook, T.M., Morcuende, J. and Grosland, N. (2020), "Clubfoot kickbar: development of an improved brace for use following correction of clubfoot", 2020 Design of Medical Devices Conference, presented at the 2020 Design of Medical Devices Conference, American Society of Mechanical Engineers, *Minneapolis*, p. V001T03A001, doi: 10.1115/DMD2020-9043.

Lam, K.Y., Mark, C.W.M. and Yee, S.Y. (2021), "Office 3D-printing in paediatric orthopaedics: the orthopaedic surgeon's guide", *Translational Pediatrics*, Vol. 10 No. 3, pp. 474-484, doi: 10.21037/tp-20-236.

Lau, I.W.W., Liu, D., Xu, L., Fan, Z. and Sun, Z. (2018), "Clinical value of patient-specific three-dimensional printing of congenital heart disease: quantitative and qualitative assessments", *S.PLOS One*, Vol. 13 No. 3, p. e0194333, doi: 10.1371/journal.pone.0194333.

Lazzeri, S., Talanti, E., Basciano, S., Barbato, R., Fontanelli, F., Uccheddu, F., Servi, M., Volpe, Y., Vagnoli, L., Amore, E., Marzola, A., McGreevy, K.S. and Carfagni, M. (2022), "3D-printed patient-specific casts for the distal radius in children: outcome and pre-market survey", *Materials*, Vol. 15 No. 8, p. 2863, doi: 10.3390/ma15082863.

Martelli, N., Serrano, C., van den Brink, H., Pineau, J., Prognon, P., Borget, I. and El Batti, S. (2016), "Advantages and disadvantages of 3-dimensional printing in surgery: a systematic review", *Surgery*, Vol. 159 No. 6, pp. 1485-1500, doi: 10.1016/j.surg.2015.12.017.

Mazy, D., Elbaum, R., Beckers, G., Matriche, C. and Vannieuwenhove, O. (2020), "Orthopaedic support with 3D printing in children: marketing effect or solution of the future", *Acta Orthop. Belg*, Vol. 86, pp. 378-382, doi: https://doi.org/10.1016/j.sintl.2021.100117.

Menozzi, G.C., Depaoli, A., Ramella, M., Alessandri, G., Frizziero, L., Liverani, A., Rocca, G. and Trisolino, G. (2023), "Side-to-side flipping wedge osteotomy: virtual surgical planning suggested an innovative one-stage procedure for aligning both knees in 'Windswept deformity'", *Journal of Personalized Medicine*, Vol. 13 No. 11, p. 1538, doi: 10.3390/jpm13111538.

Nguyen, P., Stanislaus, I., McGahon, C., Pattabathula, K., Bryant, S., Pinto, N., Jenkins, J. and Meinert, C. (2023), "Quality assurance in 3D-printing: a dimensional accuracy study of patient-specific 3D-printed vascular anatomical models", *Frontiers in Medical Technology*, Vol. 5, p. 1097850, doi: 10.3389/fmedt.2023.1097850.

Pirozzi, M.A., Andreozzi, E., Magliulo, M., Gargiulo, P., Cesarelli, M. and Alfano, B. (2020), "Automated design of efficient supports in FDM 3D printing of anatomical phantoms", in Henriques, J., Neves, N. and De Carvalho, P. (Eds), *XV Mediterranean Conference on Medical and Biological Engineering and Computing – MEDICON 2019*, Vol. 76 Springer International Publishing, Cham, pp. 292-300, doi: 10.1007/978-3-030-31635-8_35.

Quodbach, J., Bogdahn, M., Breitkreutz, J., Chamberlain, R., Eggenreich, K., Elia, A.G., Gottschalk, N., Gunkel-Grabole, G., Hoffmann, L., Kapote, D., Kipping, T., Klinken, S., Loose, F., Marquetant, T., Windolf, H., Geißler, S. and Spitz, T. (2022), "Quality of FDM 3D printed medicines for pediatrics: considerations for formulation development, filament extrusion, printing process and printer design", *Therapeutic Innovation & Regulatory Science*, Vol. 56 No. 6, pp. 910-928, doi: 10.1007/s43441-021-00354-0.

Ravi, P. and Chen, V.C.P. (2021), "A focused simulation-based optimization of print time and material usage with respect to orientation, layer height and support settings for multi-pathological anatomical models in inverted vat photopolymerization 3D printing", *3D Printing in Medicine*, Vol. 7 No. 1, p. 23, doi: 10.1186/s41205-021-00112-w.

Sharma, S. and Goel, S.A. (2018), "3D printing and its future in medical world", *Journal of Medical Research and Innovation*, p. e000141, doi: 10.15419/jmri.141.

Sharma, N., Honigmann, P., Cao, S. and Thieringer, F. (2020), "Dimensional characteristics of FDM 3D printed PEEK implant for craniofacial reconstructions", *Transactions on Additive Manufacturing Meets Medicine*, *Transactions on Additive Manufacturing Meets Medicine*, Vol. 2 No. 1, doi: 10.18416/AMMM.2020.2009011. p. (2020): Trans AMMM.

Silva, A.T.D., Lages, A.S., Silveira, J.V.B.D., Esteves, G.R.P., Bispo, B.C., Santos, N.A., Kunkel, M.E. and Rodrigues, M.A.B. (2022), "Development and customization of a Dennis Brown orthosis prototype produced from anthropometric measurements by additive manufacturing", in Bastos-Filho, T.F., de Oliveira Caldeira, E.M. and Frizera-Neto, A. (Eds), *XXVII Brazilian Congress on Biomedical Engineering*, Springer International Publishing, Cham,Vol. 83, pp. 465-470, doi: 10.1007/978-3-030-70601-2_72.

Sun, J., Mu, Y., Cui, Y., Qu, J. and Lian, F. (2023), "Application of 3D-printed osteotomy guide plates in proximal femoral osteotomy for DDH in children: a retrospective study", *Journal of Orthopaedic Surgery and Research*, Vol. 18 No. 1, p. 315, doi: 10.1186/s13018-023-03801-w.

Tack, P., Victor, J., Gemmel, P. and Annemans, L. (2016), "3D-printing techniques in a medical setting: a systematic literature review", *BioMedical Engineering OnLine*, Vol. 15 No. 1, p. 115, doi: 10.1186/s12938-016-0236-4.

Ten Kate, J., Smit, G. and Breedveld, P. (2017), "3D-printed upper limb prostheses: a review", *Disability and Rehabilitation. Assistive Technology*, Vol. 12 No. 3, pp. 300-314, doi: 10.1080/17483107.2016.1253117.

Trisolino, G., Depaoli, A., Menozzi, G.C., Lerma, L., Di Gennaro, M., Quinto, C., Vivarelli, L., Dallari, D. and Rocca, G. (2023), "Virtual surgical planning and patient-specific instruments for correcting lower limb deformities in pediatric patients: preliminary results from the in-office 3D printing point of care", *Journal of Personalized Medicine*, Vol. 13 No. 12, p. 1664, doi: 10.3390/jpm13121664.

Tserovski, S., Georgieva, S., Simeonov, R., Bigdeli, A., Röttinger, H. and Kinov, P. (2019), "Advantages and disadvantages of 3D printing for pre-operative planning of revision hip surgery", *Journal of Surgical Case Reports*, Vol. 2019 No. 7, p. 214, doi: 10.1093/jscr/rjz214.

Wei, Y.-P., Lai, Y.-C. and Chang, W.-N. (2020), "Anatomic three-dimensional model-assisted surgical planning for treatment of pediatric hip dislocation due to osteomyelitis", *Journal of International Medical Research*, Vol. 48 No. 2, p. 30006051985428, doi: 10.1177/0300060519854288.

Wu, J. (2018), "Study on optimization of 3D printing parameters", *IOP Conference Series: Materials Science and Engineering*, Vol. 392, p. 62050, doi: 10.1088/1757-899X/392/6/062050.

Xu, G., Gao, L., Tao, K., Wan, S., Lin, Y., Xiong, A., Kang, B. and Zeng, H. (2017), "Three-dimensional-printed upper limb prosthesis for a child with traumatic amputation of right wrist: a case report", *Medicine*, Vol. 96 No. 52, p. e9426, doi: 10.1097/MD.0000000000009426.

Corresponding author

Giuseppe Cesarelli can be contacted at: giuseppe.cesarelli@unina.it