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PAPER

Development and Pilot Implementation of a 3D Printed Prototype for Surgical Education and Preoperative Planning in Blount's Disease

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ABSTRACT

Blount's disease is a complex pediatric orthopedic disorder characterized by progressive tibial deformities, necessitating precise surgical planning. Traditional imaging techniques often fail to provide a comprehensive assessment. This study explores the role of 3D printed anatomical prototypes in enhancing surgical planning and medical training, particularly within the Jordanian Royal Medical Services. This study focuses on a 12-year-old patient with a severe multiplanar tibial deformity. A 3D prototype of the patient's tibia and fibula was generated using CT scan data, segmented via 3D Slicer software, and printed using a Formlabs Form 3BL SLA 3D printer. The printed prototype was utilized in a pediatric orthopedic workshop attended by over 30 surgeons. Seven surgeons responded to the post-workshop survey. The qualitative assessment showed that all participants found the 3D prototype beneficial for understanding anatomical deformities, enhancing surgical preparedness, and improving procedural accuracy. However, challenges such as cost, material rigidity, and production time were noted as barriers to widespread adoption. Future research should focus on optimizing material properties and reducing costs to facilitate broader implementation in surgical education and planning in Jordan.

KEYWORDS

3D printing, surgical education, preoperative planning, Blount's disease, orthopedic surgery

1 INTRODUCTION

There is an increasing interest in utilizing technological advancements to improve patient safety and care in Jordan [1], [2], [3]. One area where this is becoming increasingly evident is in orthopedics and biomedical engineering—two interconnected disciplines that are working closely together to enhance patient outcomes, especially in complex procedures such as deformity correction [4],

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[5], [6], [7], [8]. Advances in medical imaging technologies, along with the development of sophisticated computer programming and software, have paved the way for more effective preoperative planning in orthopedic procedures [9], [10]. One of the most significant innovations in this field is the ability to generate 3D digital prototypes, which offer a detailed and accurate representation of a patient's anatomy [11]. The rise of 3D printing has further expanded the scope of these technologies, allowing for the creation of physical prototypes that can be utilized for surgical planning, training, and education of orthopedic surgeons [9], [12], [13], [14].

Blount's disease, a pediatric orthopedic disorder characterized by abnormal tibial growth leading to progressive deformities, serves as an exemplary case in which these technological advancements can make a significant impact [15], [16]. This condition is particularly prevalent in children and adolescents, especially those who are obese or exposed to excessive mechanical stress during their growth periods [17]. The patient highlighted in this study is a 12-year-old boy diagnosed with a complex multiplanar deformity of both the tibia and fibula, including Varus angulation, flexion, and internal rotation. The complexity of this presentation necessitates precise and individualized surgical intervention, making accurate preoperative planning critical to achieving optimal outcomes.

However, traditional diagnostic methods and surgical planning tools often fail to provide a comprehensive understanding of such complex cases. This study investigates the potential of advanced 3D modeling and printing technologies to address the limitations of conventional methods in managing Blount's disease. The study focuses on two primary objectives: first, to enhance the training of orthopedic surgeons by providing an interactive and physical tool for better visualization of these deformities, and second, to support surgeons in gaining a more accurate understanding of the patient's unique condition, which can lead to more informed decision-making and precise surgical execution. While 3D printing has been explored in surgical applications globally, its clinical utilization in Jordan remains limited. This study bridges that gap by providing practical evidence on the effectiveness of 3D printed prototypes as a novel tool for orthopedic training and preoperative planning. By integrating advanced 3D printing technology into the local medical system, this study paves the way for a shift in surgical education and patient-specific treatment strategies, setting a foundation for wider adoption of personalized, technology-driven medical solutions in Jordan's healthcare sector [18], [19].

2 METHODOLOGY

2.1 Presentation of case

An overweight 12-year-old male, weighing 110 kg, presented with a progressive bilateral genu Varus deformity, which was more pronounced on the left side. The deformity had been worsening over the past two years, and the patient exhibited a noticeable Varus thrust during ambulation. On clinical examination, the left lower limb demonstrated Varus angulation, flexion contracture, and internal rotation deformity, consistent with adolescent Blount's disease (see Figure 1).

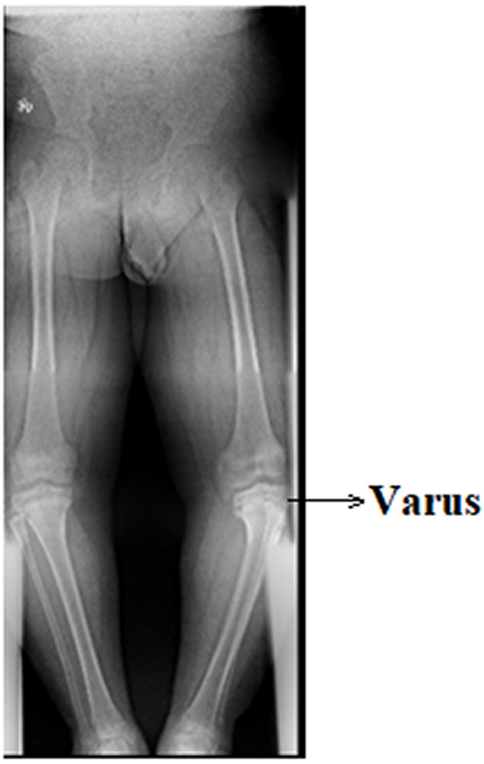

Fig. 1. X-ray showing bilateral genu Varus deformity in a 12-year-old male (110 kg), more pronounced on the left, consistent with adolescent Blount's disease

To accurately assess the severity and plan for surgical correction, a series of imaging studies were performed. Standing anteroposterior (AP) and lateral radiographs of the lower limbs revealed characteristic signs of Blount's disease. Long-film X-rays were obtained to evaluate overall limb alignment and mechanical axis deviation, while a CT scan provided a detailed three-dimensional assessment of the bony architecture. Additionally, 3D printing technology was employed to create an anatomical prototype of the deformity, enabling precise preoperative planning. Based on these findings, a diagnosis of adolescent Blount's disease with progressive left-sided Varus deformity was confirmed. Given the severity of the condition, surgical intervention was planned, involving a proximal tibial osteotomy of the left leg and gradual correction using a Taylor Spatial Frame (TSF) to achieve proper limb realignment.

Due to the complexity of Blount's disease and its associated deformities, 3D modeling and printing played an important role in this case. The primary objectives of this approach were first, to provide orthopedic surgeons with a training tool to better understand and manage deformities associated with the disease, and second, to enhance preoperative planning by offering a detailed visualization of the patient's specific condition before surgery.

2.2 Image segmentation

The methodology began with performing a CT scan of the patient, and the images were obtained in DICOM format. These CT images were imported and loaded using the open-source software 3D Slicer [20], [21]. Upon uploading the DICOM images into 3D Slicer, the software automatically displayed the anatomical structures in three orthogonal planes: axial (red window), sagittal (yellow window), and coronal (green window). The coronal plane was selected as the primary viewing plane, as it provided an optimal view of the anatomical structures of interest—specifically, the tibia and fibula. The Segment Editor module was activated to segment the bones of interest. This module offers a range of tools for both semi-automated and manual segmentation. The thresholding technique was used for segmentation. By hovering over individual pixel values in the 2D images and scrolling through the slices, the Hounsfield Unit (HU) range was identified. The lower threshold was set at 120 HU and the upper threshold at 1100 HU, ensuring that only the relevant bony tissues—namely the tibia and fibula—were selected (see Figure 2).

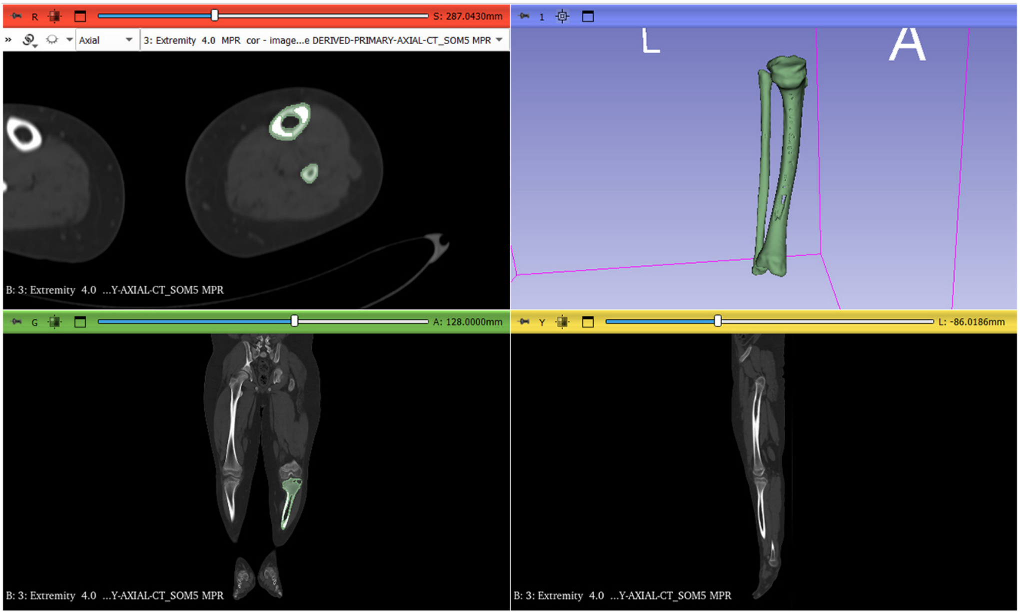

Fig. 2. DICOM image visualization and bone segmentation in 3D slicer using thresholding technique

These values effectively distinguished the bones from surrounding soft tissues and other anatomical structures, as illustrated in Figure 3. The relevant regions corresponding to the bones of interest (the tibia and fibula) were identified in each image slice. The segmented images were then compiled to construct a 3D prototype of the tibia and fibula, allowing for full volumetric visualization.

To refine the prototype, the Scissors Tool was used to remove any unwanted tissues and organs, particularly adjacent bony structures not part of the tibia or fibula, leaving only the bones of interest. The Paint Tool was employed to manually segment any missing parts, especially in areas such as the condylar region where gaps or holes were present. Finally, smoothing tools such as Fill Gaps and Median were applied to close small discontinuities and improve the overall quality of the segmentation.

The complete segmentation workflow is summarized in Table 1, outlining each key step from data acquisition to 3D prototype export. The entire process, including segmentation and subsequent refinement of the 3D prototype, required approximately 30 minutes, indicating its potential for practical integration into routine preoperative planning workflows.

Table 1. Segmentation steps for the tibia and fibula prototype

Step 1	Acquire a standard, anonymized CT scan of the patient in DICOM format.
Step 2	Load the CT images into 3D Slicer.
Step 3	Choose the coronal view for optimal visualization of the tibia and fibula.
Step 4	Open the Segment Editor module to begin segmentation of the bones.
Step 5	Use the Thresholding Tool to define the Hounsfield Unit (HU) range (120–1100 HU) to isolate the tibia and fibula.
Step 6	Use the Scissors Tool to remove unwanted structures, the Paint Tool to fill missing parts (e.g., in the condylar region), and smoothing tools like Fill Gaps and Median to enhance segmentation quality.
Step 7	Review the 3D prototype for completeness and accuracy.
Step 8	Export the finalized 3D prototype as an STL file for 3D printing.

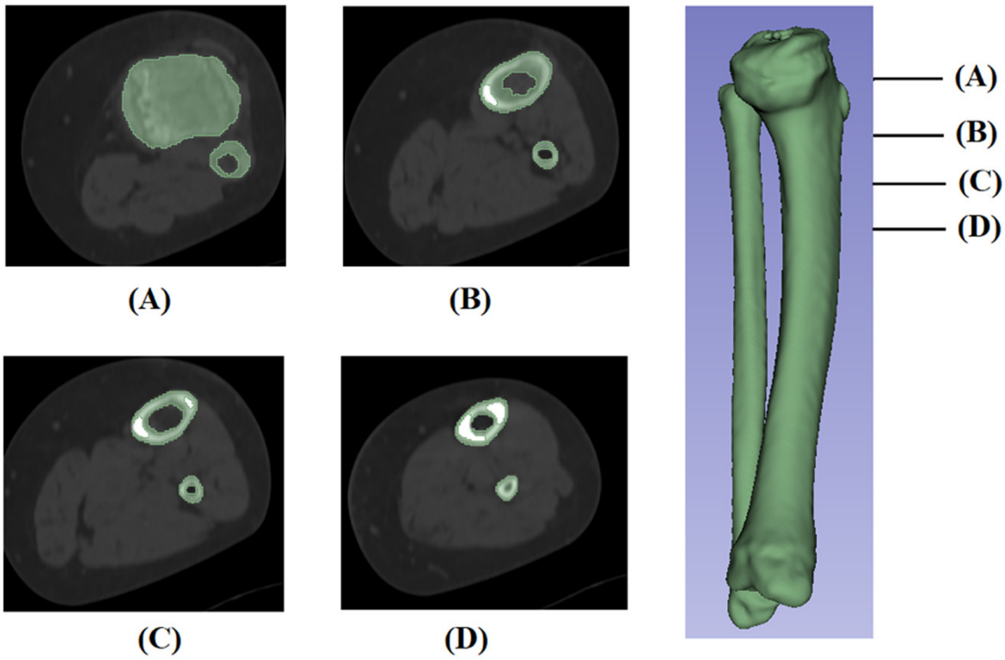

Fig. 3. Axial views of the segmented tibia and fibula at different levels from top to bottom (A–D), along with the corresponding 3D prototype created in 3D Slicer

2.3 3D printing

The steps involved in 3D printing the tibia and fibula prototype are summarized in Table 2. The process began with exporting the digital prototype from 3D Slicer as an STL file. This file was then processed and prepared using PreForm v3.45 slicing software, where necessary adjustments were made before printing. The Formlabs Form 3BL SLA 3D printer was used for fabrication, offering high precision and reliability. The prototype was oriented as shown in Figure 4, and support structures were auto-generated by the slicer, incorporating a raft with a touchpoint size of 0.3 mm and a touchpoint density of 1. Printing settings included a layer height of 0.1 mm, ensuring a balance between detail and print time.

Table 2. 3D printing steps for tibia and fibula prototype

Step 1: Exporting	The digital prototype of the tibia and fibula was exported from 3D Slicer as an STL file.
Step 2: Slicing Preparation	The STL file was imported into PreForm v3.45, where adjustments were made for 3D printing.
Step 3: Support Generation	Support structures were auto-generated, including a raft with a 0.3 mm touchpoint size and a touchpoint density of 1.
Step 4: Printing Settings	Layer height was set to 0.1 mm for a balance between detail and print time.
Step 6: Printing	The model was printed using the Formlabs Form 3BL SLA 3D printer.
Step 5: Post-Processing	The printed prototype was washed using 99% IPA, following Formlabs' standard washing procedures.

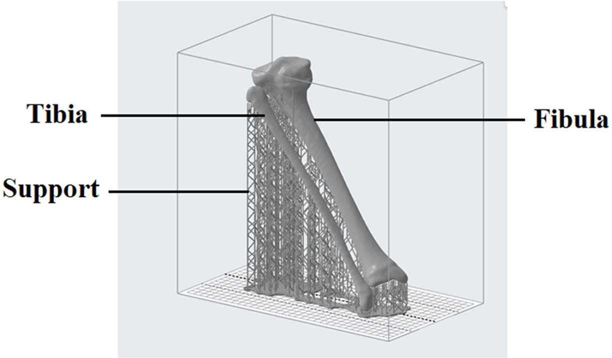

Fig. 4. The prototype orientation with auto-generated supports, including a raft, a 0.3 mm touchpoint size, and a touchpoint density of 1

The printing process lasted 22 hours, consuming 410 mL of Formlabs General Purpose Grey Resin v4. After printing, the prototype was washed using IPA 99% concentration alcohol following Formlabs' standard washing guidelines. Figure 5A illustrates the digital representation of the tibia and fibula, while Figures 5B and 6 display the final 3D printed tibia-fibula.

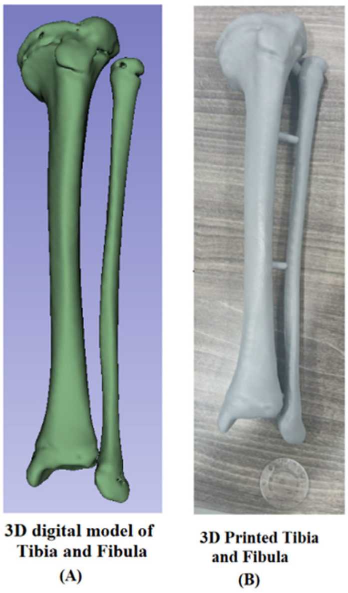

Fig. 5. (A) Digital 3D prototype of the tibia and fibula (B) 3D printed prototype of the tibia and fibula

Fig. 6. A 3D printed prototype produced with the Form 3BL SLA 3D printer

2.4 Usage in the TSF in the pediatric orthopedics workshop

A total of four tibia and fibula prototypes were printed, and they were presented in a workshop for orthopedic surgeons (focused on TSF in pediatric orthopedics). Over 30 orthopedic surgeons with varying levels of experience, ranging from residents to specialists and consultants, attended the workshop to enhance their knowledge on Blount's disease. The 3D printed prototype enabled the surgical team to closely examine the patient's anatomy and clearly visualize the complex deformities, including Varus angulation, flexion, and internal rotation. These multiplanar deformities, often challenging to fully assess through standard imaging alone, were more comprehensively understood through the physical model. By providing a tangible and detailed representation, the 3D printed model allowed the surgeons to study the compound deformities with greater precision and depth, significantly enhancing preoperative planning and enabling a more efficient and targeted surgical approach.

After the workshop, a questionnaire was distributed to gather feedback from the participating orthopedic surgeons regarding their experiences with the 3D prototype during both the workshop and the surgery. The feedback helped evaluate the usefulness of the 3D prototype in teaching, educational purposes, and surgical planning. The survey was developed based on a review of relevant literature [12], [15], [16], [17], [22] and refined through expert input from two senior orthopedic surgeons to ensure its content validity. Additionally, the questionnaire was piloted with two orthopedic residents to assess the clarity and relevance of the items, allowing for necessary adjustments prior to its final administration.

The feedback was critical in assessing how effectively the 3D prototype could assist in understanding complex deformities and improving preoperative planning, as well as in enhancing the overall learning experience for the surgeons.

3 RESULTS

The survey aimed to explore the benefits and challenges of using the 3D printed prototype of the tibia and fibula for teaching and surgical planning in orthopedics.

Seven experts in the field responded to various questions. Three respondents were specialists with over 10 years of experience, two had less than five years of experience, and two had between 5–10 years of experience.

Regarding the participants' previous experience with using 3D printing for surgical planning, none of them had utilized this technology before. Instead, they relied on other established methods. Three participants had employed CT scans with 3D reconstructions for planning surgeries, while two used traditional X-rays. Additionally, one participant had experience with advanced surgical planning tools such as Bone ninja, OrthoView, or TraumaCad (see Figure 7). However, after working with the 3D printed prototype, all participants agreed that the most significant advantages were improved surgical planning and a better understanding of the anatomical deformities. Furthermore, six participants highlighted the ability to practice and rehearse the surgical procedure before the actual operation as a valuable benefit, enhancing their preparedness and confidence in executing the surgery effectively (see Figure 8).

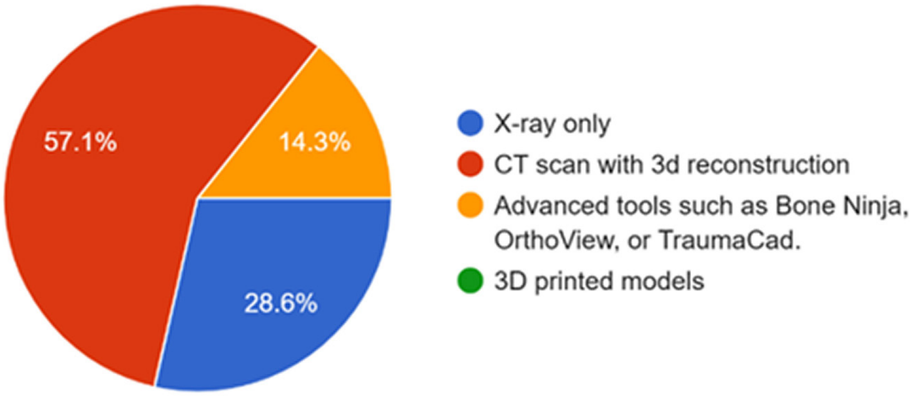

Fig. 7. The techniques currently used for surgical planning by the surgeons who participated in the survey

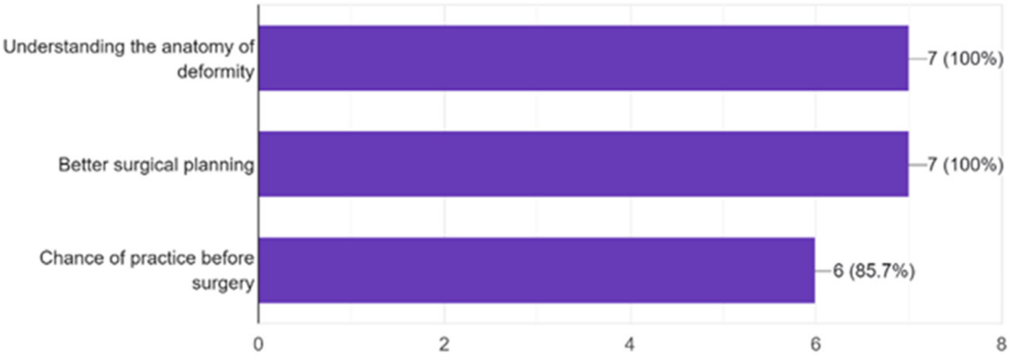

Fig. 8. Benefits of using the 3D printed prototype of the tibia and fibula during the workshop and prior to surgery

When questioned about the challenges associated with 3D printing, all participants pointed to cost as a primary concern ($170 per prototype). They emphasized that incorporating this technology into surgical planning would inevitably increase the overall expenses of medical treatment, which could be a barrier for some patients or healthcare systems. Additionally, three participants identified the quality of the printed prototypes as a significant challenge. Specifically, they noted that the material used for the prints was quite rigid, which made performing osteotomy procedures and drilling difficult. This posed an issue for accurate simulations and preparation for surgery.

Furthermore, two participants expressed concern about the time required to produce a 3D printed prototype. In certain cases, patients could not afford to wait for the prototype to be printed, especially if time-sensitive decisions needed to be made, which could delay or complicate the surgical planning process (see Figure 9).

While these responses provide valuable qualitative insights into the perceived utility of 3D printed prototypes for surgical planning and educational purposes, the limited sample size (n = 7) represents a clear limitation of the study. This limitation should be carefully considered when interpreting the findings, as it may affect the generalizability of the results.

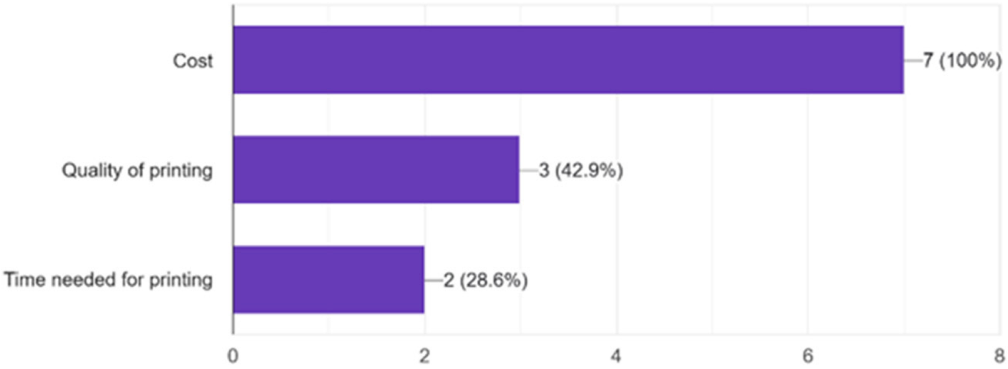

Fig. 9. Challenges associated with using the 3D printed prototype of the tibia and fibula during the workshop and prior to surgery

4 DISCUSSION

This study conducted among orthopedic specialists shows the benefits and challenges of utilizing 3D printed prototypes of the tibia and fibula for surgical planning and educational purposes. It aims to promote the clinical adoption of 3D printing and facilitate broader acceptance among surgeons in Jordanian healthcare settings. One of the key findings was the recognition of the enhanced ability for surgical planning and a deeper understanding of anatomical deformities. All participants, after engaging with the 3D printed prototype, reported that it improved their preparedness for surgery. Specifically, the ability to physically interact with the prototype allowed for a better understanding of the deformities, which traditional methods, such as CT scans or X-rays, often fail to provide. This aligns with previous studies highlighting that 3D printed prototypes enable a more comprehensive visualization of complex anatomical structures, facilitating precise surgical planning [23], [24], [25]. Additionally, six out of seven participants emphasized the value of practicing the surgical procedure beforehand, which contributed significantly to their confidence and readiness. This finding supports the growing recognition that preoperative rehearsal using patient-specific 3D printed prototypes can mitigate intraoperative complications and shorten surgery time, ultimately improving patient outcomes [25], [26].

While the benefits were evident, several challenges were highlighted, particularly regarding the costs associated with 3D printing. All participants identified cost as a major barrier, a concern that is consistent with the literature, which frequently cites the high expense of producing 3D printed prototypes as a significant hurdle for widespread adoption in healthcare [27], [28]. The increased cost could potentially limit access to 3D printing technology in resource-limited settings, creating disparities in the availability of advanced surgical planning tools.

In addition to cost, three participants raised concerns about the quality of the printed prototypes. The rigid nature of the materials used made certain procedures, such as osteotomy or drilling, more difficult to simulate accurately. This limitation in the material's flexibility may impede the full utility of 3D printed prototypes for complex surgical preparations. Such challenges underscore the ongoing need for improvements in 3D printing materials that can better replicate the mechanical properties of bone tissue and allow for more realistic simulations [29].

Another challenge pointed out by two respondents was the time required to produce the 3D printed prototypes. In time-sensitive surgical cases, waiting for the prototype could delay the surgical planning process, potentially leading to adverse outcomes. While this challenge may be mitigated with advancements in 3D printing technology and faster production times, it remains a practical concern for clinicians in urgent or emergency situations.

Despite these challenges, the overwhelming consensus among participants was that the advantages of 3D printing in orthopedic surgical planning outweigh the current limitations. However, to fully integrate 3D printing into clinical practice, solutions must be developed to address concerns related to cost, material quality, and production time.

The present study offers important quantitative insights into the application of 3D printed prototypes for surgical planning and educational purposes. Nevertheless, the limited sample size ($n = 7$) constitutes a notable constraint, potentially affecting the generalizability of the findings. This limitation underscores the importance of engaging a larger and more heterogeneous group of participants in future investigations at our institution. Expanding the sample size in subsequent studies will be crucial to strengthening the validity of the results and facilitating wider clinical implementation.

Future research in Jordan, particularly within the Jordanian Royal Medical Services, should expand the scope of 3D printing applications to other medical fields, such as cardiac and neurosurgery, to further explore its potential in improving surgical precision and patient outcomes and to promote its clinical adoption.

5 CONCLUSIONS

In conclusion, while the 3D printed prototype of the tibia and fibula presents clear advantages in surgical planning and teaching, the barriers of cost, material quality, and time constraints must be carefully considered to optimize its integration into clinical practice. Moreover, the clinical adoption of 3D printing technology is both feasible and promising, with growing interest among various specialties within the Jordanian Royal Medical Services in utilizing 3D printed prototypes for medical training and preoperative planning.

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