On the Use of 3D Modeling, Reconstruction and Printing Techniques for the Development of an Ankle Bone Prosthesis

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Abstract. This paper presents the design and manufacturing of a personalized ankle prosthesis tailored to meet the diverse treatment needs of individuals with ankle disorders. The proposed approach integrates advanced 3D modeling and printing techniques to develop custom-made implants that optimize mobility, functionality, and patient comfort. By leveraging 3D printing technology, biocompatible and durable materials are utilized to create implants that closely match the unique anatomical structure of each patient's joint. This personalized approach aims to enhance orthopedic treatments by reducing anesthesia time, minimizing post-operative complications, and improving overall patient care. The study highlights the potential of personalized prosthetic solutions in advancing orthopedic medicine and improving the quality of life for affected individuals.

Keywords: 3D Modeling · 3D Printing · 3D Reconstruction · Arthrodesis · Ankle Prosthesis · Talocrural · Subtalar · Total Ankle Arthroplasty

1 Introduction

The human foot, with its 26 bones, 33 joints, 107 ligaments, and 19 muscles, is a masterpiece of natural biomechanical engineering. In other words, it represents a true feat of biological engineering. The ankle, a ginglymo-pivot type synovial joint, connects the foot to the leg and plays a crucial role in locomotion. It enables essential movements such as walking, running, jumping, and changing direction. Composed of a complex set of anatomical structures, this sophisticated joint ensures both stability and agility through harmonious cooperation between its components, such as bones, ligaments, and tendons. Unfortunately, these joints are susceptible to a range of disorders and diseases, including osteoarthritis, autoimmune diseases like Rheumatoid Arthritis (RA), and sometimes bone tumors. Often, these conditions lead to major joint damage when they progress to advanced stages. In severe cases, the joint may become immobilized. To address

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these issues, the two main surgical treatment options for degenerative ankle disease are arthrodesis and total ankle arthroplasty. The first, historically the most widespread, is often seen as the gold standard. It is applicable to most patients and is considered reliable based on favorable medium-term results. However, ankle arthrodesis has an irreversible nature at least with current validated knowledge. It places high demands on the neighboring joints, which may lead to early degeneration, and the long-term results are questioned. These factors have led to the search for an alternative to arthrodesis, namely total ankle arthroplasty. This technique has long suffered from a poor reputation due to disappointing results and sometimes severe failures following the implantation of the first ankle prostheses in the 1970s. These first-generation implants used the concept of an inverted hip prosthesis, which was quickly abandoned due to significant complications. Practices such as the use of cement and disregard for the ankle's anatomy in prosthesis design were contentious and have fortunately been discarded. However, analyzing these early failures provided valuable lessons regarding implant design and patient selection. As a result, current "second-generation" prostheses have led to promising short- and medium-term results. Consequently, total ankle arthroplasty is gradually becoming a viable surgical option, challenging the notion of the "gold standard" applied to arthrodesis in the treatment of degenerative ankle disease.

This research introduces a fully open-source and reproducible pipeline for the personalized design of an ankle bone prosthesis. Unlike prior works focused on generic or commercially dependent solutions, our study integrates patient-specific 3D imaging data with widely accessible tools such as 3D Slicer, Meshmixer, and Blender to create a three-part prosthetic implant (tibial, talar, and polyethylene bearing components). The novelty lies in demonstrating the feasibility of low-cost, anatomically accurate prototypes suitable for preclinical trials and educational applications. This approach holds promise for future adoption in resource-constrained healthcare environments.

The rest of the paper is organized as follows. Section 2 describes the medical background of the anatomy and the pathologies of the ankles. Section 3 introduces related work. In Section 4, we summarize the used software and data. Section 5 presents 3D reconstruction, modeling, and printing of the implant. In section 6, we discuss the advantages and the strengths of our work. Finally, we conclude the paper in Section 7.

2 Medical Background

2.1 Ankle anatomy

The ankle joint is a complex structure that provides both stability and mobility to the foot. It consists of three primary bones, the tibia, which supports the body's weight; the fibula, aiding lateral stability; and the talus (or astragalus), which transmits forces between the leg and foot Figure 1. These bones are connected by ligaments, which prevent excessive movement that could lead to injuries. The lateral ligaments, including the anterior talofibular ligament

(ATFL), posterior talofibular ligament (PTFL), and calcaneofibular ligament (CFL), provide lateral stability and prevent excessive foot inversion and eversion [9]. The deltoid ligaments, located on the inner side, are thicker and more resistant, consisting of the anterior tibiotalar ligament (ATTL), posterior tibiotalar ligament (PTTL), tibionavicular ligament (TNL), and tibiocalcaneal ligament (TCL), which collectively prevent excessive eversion [9].

Several tendons facilitate ankle movement. The fibular tendons, located on the lateral side, include the long fibular and short fibular tendons, which contribute to foot eversion, dorsiflexion, and weight distribution. The Achilles tendon, the strongest tendon in the body, connects the calf muscles to the calcaneus, enabling plantar flexion vital for walking and running [6]. The tibial tendons, both anterior and posterior, play key roles in dorsiflexion and maintaining the foot's arch, crucial for posture and movement. The ankle joint comprises two main articulations. The talocrural joint, a hinge-type synovial joint, connects the tibia, fibula, and talus, allowing foot flexion and extension, similar to the elbow or finger joints [4]. The subtalar joint, located between the talus and calcaneus, allows foot inversion and eversion, vital for balance and walking [1].

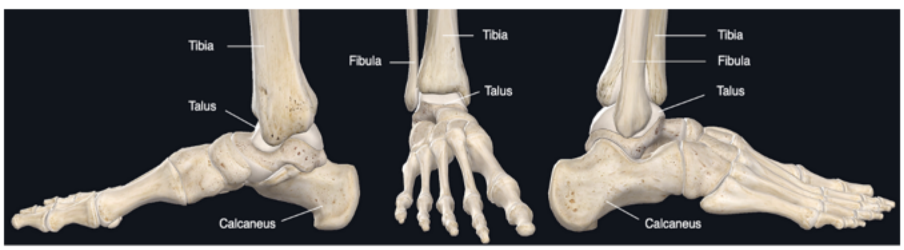


Fig. 1. Foot bones anatomy.

2.2 Ankle pathologies

The ankle is highly susceptible to various pathologies, including rheumatoid arthritis (RA) and osteoarthritis (OA). Arthritis refers to an inflammatory condition that affects one or more joints, while osteoarthritis is a degenerative disease that progressively damages the joint cartilage [3]. OA is classified into different types, including post-traumatic osteoarthritis, which results from previous joint injuries, metabolic osteoarthritis, associated with conditions like obesity and diabetes, and age-related osteoarthritis, which typically manifests after the age of 40-50 [11]. Contrary to earlier beliefs that OA only affects cartilage, it is now understood to involve all joint structures, including the articular cartilage, which absorbs shocks, the synovial membrane, which produces lubricating fluid, and the subchondral bone, which supports the joint surfaces. In addition to osteoarthritis, other inflammatory joint disorders, such as rheumatoid arthritis, neurological arthropathies, hemophilia-related joint disease, hemochromatosis, and certain tumors, can also affect the ankle. To address severe osteoarthritis of the ankle, implants are increasingly used to restore joint function and improve patients' quality of life. Our project focuses specifically on the application of ankle implants to provide effective solutions for patients suffering from degenerative ankle conditions.

3 Related Work

3D printing technologies are making their way into the field of medical prosthetics. Recently, a network of passionate volunteers created an open-access platform, e-NABLE'S, to develop customized prosthetic finger and hand kits [7]. Moreover, research conducted by Ayman and his collaborators [5] has helped further understand the potential of 3D printing. In his clinical report, he describes how he designed a hollow obturator prosthesis using computer-aided design (CAD) software, which was then 3D printed in resin with a dental 3D printer for an 82-year-old partially edentulous patient with a significant palatal defect. Additionally, American physicians [14] have successfully created tracheal implants and custom-made stents using 3D-printed bioresorbable polyester for treating children with severe bronchotracheomalacia. The first child to receive such an implant is now three years old, and the stent is in the process of resorption without any adverse effects. Subsequently, Morrison RJ et al. presented an illustrative application of these technologies by exploring the case of a fetus [12] with a mass that could compress its airways. This condition was not treated through emergency surgery, as it posed a high iatrogenic risk for both the mother and the child. Instead, the fetus received a facial implant created using 3D printing.

From this point, a groundbreaking methodology proposed by Jack Evill et al. led to the development of a 3D-printed cast named Cortex [22]. The design procedure is simple: the injured limb is scanned to precisely determine its shape. Once scanned, the cast is 3D printed in nylon with exact and accurate dimensions of the arm. Meanwhile, in collaboration with Stanford University and the Children's Hospital of Oakland, the American firm 3D Systems [2] introduced a new type of customized 3D-printed brace, developed using selective laser sintering (SLS), for the treatment of scoliosis patients. After being digitized through a pilot program called Bespoke Braces, the brace is adjusted via computer modeling to gradually straighten the spine and is ultimately 3D printed using SLS technology. In conclusion, research conducted by Xu and his collaborators [13] highlights the revolutionary potential of 3D printing in bone surgery. By describing the complex process they used to reconstruct bone defects with customized 3D-printed prostheses following the resection of a giant cell tumor in the metacarpal bone, the researchers provide valuable insights into the various stages of this innovative procedure, from preoperative planning and imaging to virtual modeling and the 3D printing process itself.

Recent literature highlights the emergence of 3D-printed orthopedic solutions. Xu et al. [13] reconstructed a metacarpal defect using a custom titanium implant, reporting successful post-operative integration. However, they note limitations in cost and accessibility of metal printing. Similarly, Jamayet et al. [5] developed a digital workflow for maxillofacial obturators, yet relied on expensive dental resin printers. These examples demonstrate the utility of 3D printing in personalized medicine, while also showing a gap in open-source and cost-conscious workflows—addressed by our study.

4 Materials and Methods

Several software tools play a critical role in the workflow of 3D modeling and printing, each designed with specific features that cater to a range of professional and academic applications. These tools support processes from the initial acquisition and processing of imaging data to the final stages of model optimization and physical printing.

3D Slicer is a free, open-source platform that has become a cornerstone in the medical imaging community. It supports a wide array of functions such as visualization, preprocessing, segmentation, and quantitative analysis of volumetric medical data. Its robust plugin architecture and support for DICOM standards make it particularly valuable in clinical and research settings for handling MRI, CT, and PET scan data. It also includes advanced modules for 3D reconstruction, allowing users to generate detailed anatomical models that can be used for diagnosis, surgical planning, or educational purposes.

Autodesk Meshmixer, on the other hand, serves as a highly flexible tool for refining 3D models. Especially useful in the post-processing phase of 3D design, Meshmixer provides functionalities such as mesh repair, hole filling, surface smoothing, and support structure generation, making it ideal for preparing models for 3D printing. Its intuitive interface and adaptive sculpting tools also make it accessible for both professionals and hobbyists.

Blender is a powerful, open-source 3D creation suite that excels in detailed modeling, texturing, and rendering. Although widely recognized in the animation, gaming, and film industries, Blender is increasingly used in scientific visualization and biomedical modeling due to its precision and versatility. Its non-destructive editing workflow, combined with scripting support via Python, allows for a high degree of customization, making it suitable for complex object creation and simulation.

In the domain of medical imaging, Materialise Mimics stands out as a specialized software solution for transforming 2D radiological data—primarily CT and MRI scans—into highly accurate 3D anatomical models. It is especially valuable in clinical environments for applications such as surgical planning, prosthesis design, and the development of patient-specific implants. Mimics offers powerful segmentation algorithms and integrates well with engineering tools for finite element analysis and CAD modeling.

SolidWorks, a widely used computer-aided design (CAD) software, is particularly relevant in engineering and biomedical device design. Its parametric modeling capabilities enable the precise construction of mechanical parts and anatomical structures, making it ideal for designing implants, prosthetics, and medical instruments. The software also includes simulation tools for stress testing and mechanical analysis, which are critical in evaluating the functionality of devices before manufacturing.

TableEDU 4.0 by Anatomage provides a different yet complementary approach by serving as an interactive, educational tool. Designed for anatomy and medical education, it allows users to virtually dissect highly detailed 3D models of the human body. It includes segmentation tools, 3D visualizations of various physiological systems, and integration with medical imaging data, making it a valuable asset in both classroom and clinical training environments.

Finally, the 3D Volumic Stream 30 Ultra is a high-performance desktop 3D printer known for its exceptional speed, precision, and material compatibility. It supports a wide temperature range, enabling the use of various filament types, including high-strength, biocompatible, and flexible materials. Its high-resolution printing capabilities make it suitable for producing detailed anatomical models, custom surgical guides, and engineering prototypes. This printer is well-suited for applications requiring rapid prototyping and reliable output quality, bridging the gap between digital modeling and tangible product realization [10].

5 Experimental Results

5.1 Hindfoot Segmentation

Segmentation involves dividing a 3D imaging volume into several distinct subsets based on predefined criteria. The goal is to isolate and identify specific elements of interest within a complex scene. In our case, this process mainly helped us select the bones of interest, including the tibia, talus, and fibula. To achieve this, the use of 3D Slicer software and the Anatomage Table present in the simulation center was invaluable, as both tools feature segmentation capabilities, which were crucial for the 3D reconstruction. Figure 2 below demonstrates the effectiveness of these two software tools during our work. Screenshots were taken to illustrate the segmentation results achieved by each, providing a precise visual comparison. Each software has its unique set of strengths and weaknesses, which we will explore in detail. This in-depth analysis aims to highlight their key advantages, particularly in terms of ease of use and the richness of available tools, while also considering their potential limitations, which may make their use challenging in certain cases. 3D Slicer is a free, open-source software that stands out as a versatile platform for 3D imaging and analysis, primarily in the medical field. The choice of this software is mainly due to the wide range of tools it offers users. Additionally, its ability to quickly read DICOM files is an asset. However, it is important to note that 3D Slicer may have relatively long execution and display times, sometimes taking 2 to 3 hours to process and display the area of interest. Despite this, as a reliable tool in the medical imaging and 3D reconstruction field, 3D Slicer generally provides satisfactory results. While the Anatomage Table Edu 4.0 excels in 3D reconstruction capabilities, particularly for the hindfoot, it is worth noting that it does not allow for exporting reconstructed models in an STL format compatible with 3D printing. Nevertheless, as shown in Figure 2, it provides impressive results in 3D reconstruction of the foot, carefully replicating intricate anatomical details. Beyond its advantages, it was also useful for measuring the length and width of the bones, ensuring that the prosthesis would fit perfectly with the patient's bones once printed.

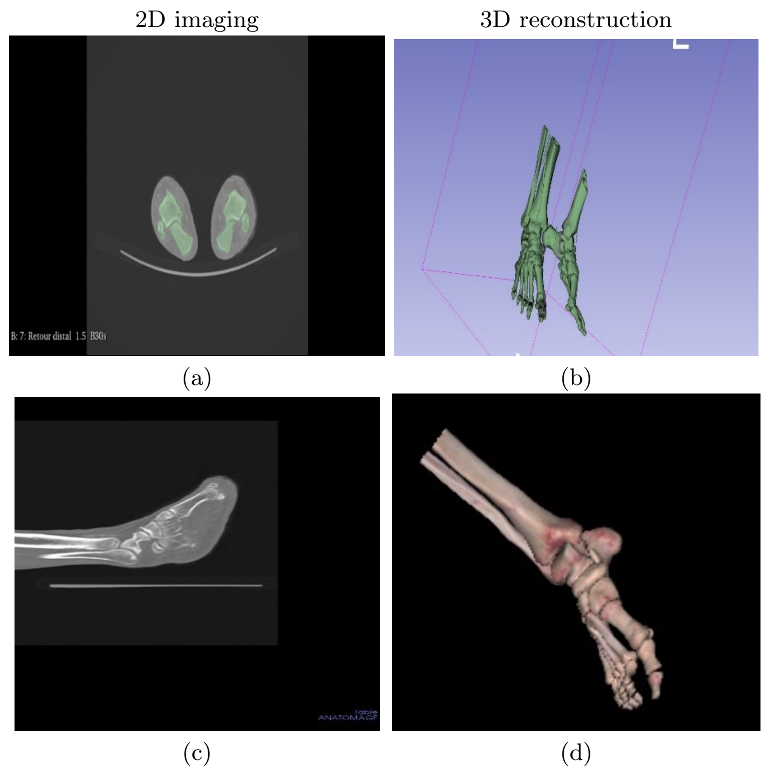


Fig. 2. 3D reconstruction results on both 3D Slicer ((a) and (b)) and TableEDU 4.0 software ((c) and (d))

5.2 3D reconstruction of bones

3D reconstruction, as its name suggests, involves creating three-dimensional representations of objects or scenes from 2D data. Recently, it has become a groundbreaking tool in the medical field, changing how doctors diagnose, plan surgeries, and conduct research by enabling the visualization of human anatomy with unmatched precision and realism. In the context of this paper, 3D reconstruction of the patient's arthritic bones is a critical step for the progression of the research. This phase requires exceptional attention to detail and precision, which was achieved with the use of 3D Slicer software. The first essential step in this process was to load the DICOM files using the "ADD DATA" tool. While the opening of the DICOM files went smoothly, it's worth noting that it took between 30 to 45 minutes for the initial 2D images to appear from various viewpoints (Fig. 3). This delay can be easily attributed to the substantial number of images in the patient's file, ranging from 1,000 to 2,000 images. Next comes the role of

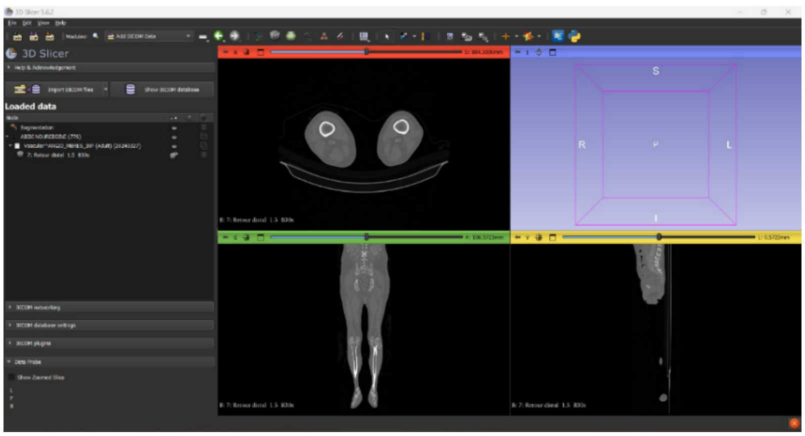


Fig. 3. Overview of 2D images in the 3D Slicer software.

segmentation, a crucial step that began with the meticulous segmentation of the foot, allowing for the careful isolation of the bones of interest, particularly the talus, tibia, and fibula of the patient. The "SEGMENT EDITOR" option provides the user with segmentation tools, notably the Threshold function. Unlike other segmentation functions such as PAINT, MASK VOLUME, and GROW FROM SEEDS, Threshold allows for quick and precise detection of bony volumes in 3D. Its simple working mode involves coloring the desired volumes, making it an efficient tool for this task.

Once the detection process is complete, the "SHOW 3D" function allows for instant visualization of the selected area in 3D. However, the initial display of the 3D images may require some loading time. For precise cutting, the "SCISSORS" option enables the user to carefully trim the desired bony area to be visualized, thus eliminating the need to display the entire body of the patient. This offers enhanced control over the visualization and simplifies the analysis of specific bony structures (Fig. 4).

5.3 3D printing of bones

The 3D printing technology of the Volumic Stream Ultra 3D allows for the faithful reproduction of the complex structure of bones, capturing even the smallest anatomical details, relies on the extrusion of thermoplastic filaments, specifically

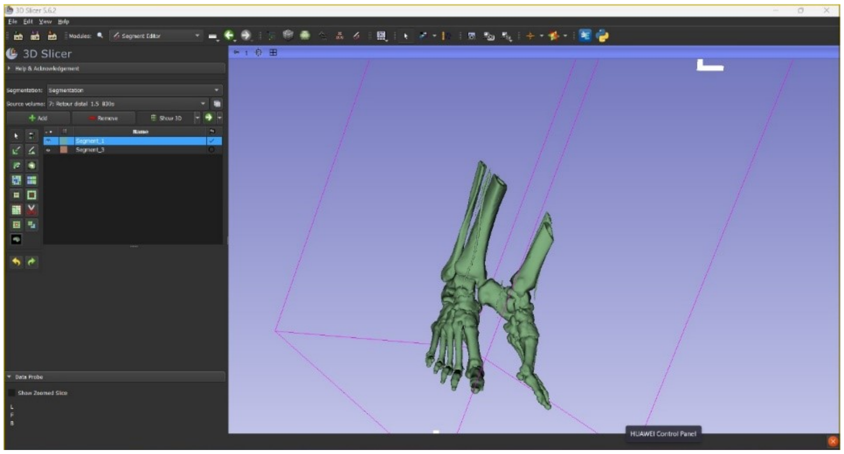


Fig. 4. 3D Reconstruction of the patient's bones.

PLA. In this case, the filament is heated to high temperatures in the printer's nozzle and then deposited layer by layer onto the print bed. It cools and solidifies instantly, forming the bone model with remarkable precision of 15 microns on the X and Y axes, and 1 micron on the Z axis. This process is repeated layer by layer until the bone model is completed. The printing of the patient's tibia and talus took a total of 6 hours (Fig. 5 and 6).

Fig. 5. 3D Printing of the Tibia and Talus of the actual patient with gray PLA using the Volumic Stream 3D Ultra.

5.4 3D modeling of the implant

After segmenting the patient's bones using 3D Slicer, MESHMIXER was used to repair mesh errors, check model integrity, and optimize 3D print orientation.

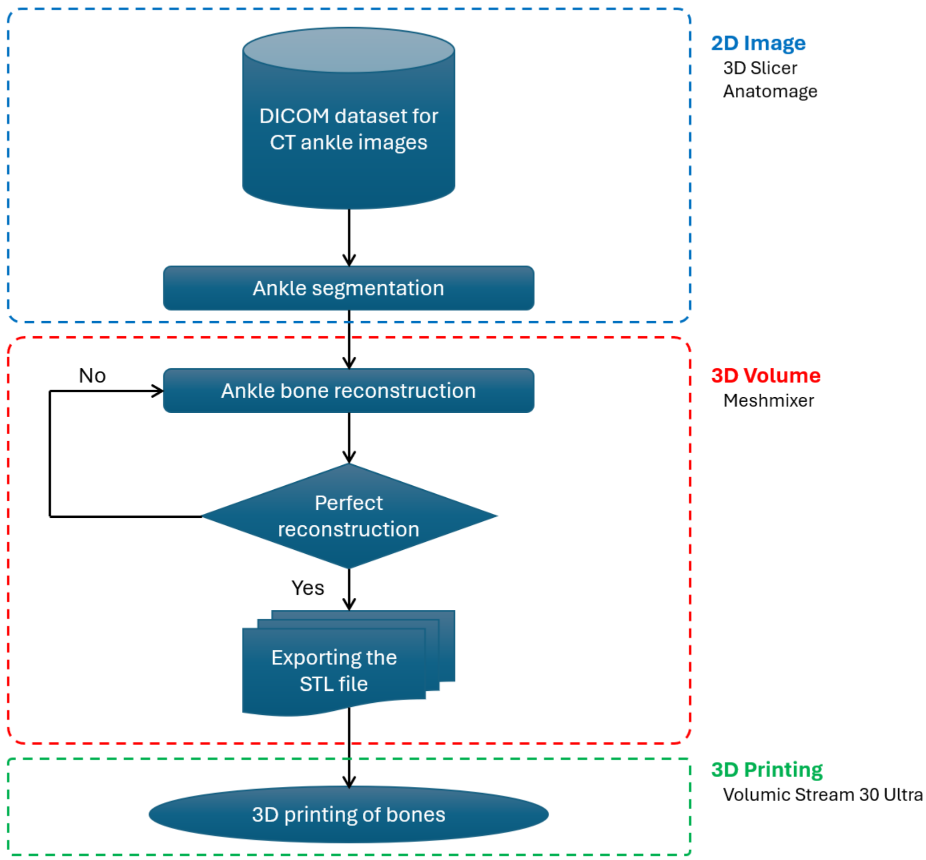
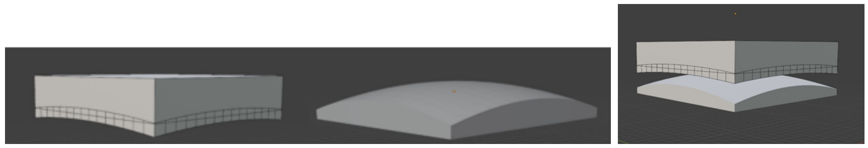


Fig. 6. Overview of the steps for creating the patient's bones.

Next, Blender was chosen to create a precise 3D model of the ankle prosthesis. The "OBJECT MODE" allowed access to the "MESH" option, followed by the "MATH FUNCTIONS" and "Z MATH SURFACE" to create the talar piece with a curved surface. The tibial piece, being flat, was modeled using the "EXTRUDE REGION" function on the Z-axis. For the bearing, a similar process was followed, ensuring it matched the tibial piece's size and axis. Finally, the parts were joined to form a three-piece prosthesis, designed to replicate the natural ankle joint, offering better movement control, stability, and reduced wear (Fig. 7).

5.5 3D printing of the implant

The creation of the ankle prosthesis involved advanced 3D printing technology, resulting in a prosthesis composed of two parts: a tibial implant for the lower tibia and a talar implant for the upper talus. These custom-designed components, created using Blender software, were engineered to connect the replaced



(a) (b)

Fig. 7. (a) Final design of the prosthesis components 3D modeling. (b) Front view of the prosthesis designed using Blender software.

bones and facilitate movement. The challenge arose in replicating the cartilage, a crucial task due to the need for a "bearing" component, typically made of polyethylene, which mimics natural cartilage. This bearing allows the tibial and talar components to move smoothly over one another. To replicate this, a concave object was designed to fit perfectly with the talar piece. Once assembled, the prosthesis allowed for movements such as flexion, extension, inversion, and eversion, closely mimicking the natural ankle joint. The 3D printing of the prosthesis took 45 minutes. PLA (Polylactic Acid), a bio-based plastic made from renewable resources like corn starch or sugarcane molasses, was used for the implant. PLA is ideal for 3D printing due to its ease of use, low printing temperature, and minimal risk of warping. It's available in various colors and finishes, allowing for customization. For our work, red PLA was used for the prosthesis and gray PLA for the bones (Fig. 8). PLA's biocompatibility, ease of printing, and mechanical properties make it an excellent material choice for the prosthesis.

Table 1 presents the distinct components of the ankle prosthesis, each accompanied by an illustrative image for immediate visual identification of the component, along with a detailed description explaining the specific functions and role of each component in the prosthesis.

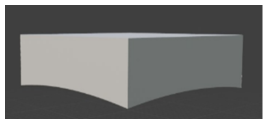
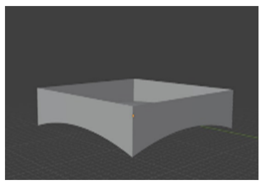
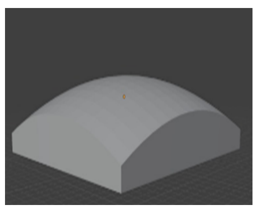
6 Discussion

3D Slicer is an essential software in the field of 3D printing, particularly for designing ankle prostheses. This open-source tool offers powerful and versatile features that facilitate every step of the process, from design to final printing. Its advanced segmentation tools allow precise editing of complex 3D models, ensuring a perfect fit for the patient's anatomy. Additionally, 3D Slicer enables users to visualize the 3D model from different angles, providing a clear representation before printing. It also supports various 3D file formats, such as STL, ensuring compatibility with 3D printers. Meshmixer proved to be an invaluable tool for modifying our implant. Its comprehensive toolkit allowed for precise and flexible adjustments. Features such as sculpting, merging, and mesh editing enabled us to refine the implant with high anatomical accuracy. Blender played a crucial role in developing our ankle prosthesis. Its user-friendly interface made it easy to use, even for beginners. The intuitive tools and logical workflow allowed for a smooth learning curve and efficient implementation. Moreover, Blender's

Fig. 8. 3D printing of the prosthesis with red PLA.

widespread popularity has led to a wealth of online tutorials, which greatly facilitated our mastery of the software. In conclusion, choosing open-source software proved to be a successful strategy, extending beyond cost savings. While proprietary solutions like Materialise Mimics or SolidWorks may offer faster workflows, open-source tools provide a viable alternative for ambitious projects without compromising quality. This approach demonstrated that high-quality, innovative projects can be achieved using free and evolving software, overcoming financial barriers while maintaining efficiency and precision. During initial experiments with Blender, combined with scientific research, literature reviews, and analysis of existing ankle prostheses, a novel concept was developed. The prosthesis was designed with only two components: a tibial implant inserted into the lower part of the tibia and a talar implant inserted into the upper part of the talus. The primary function of these components was to connect the bone structures. To limit the sliding of the talar component, research led to the exploration of adding supports to the tibial piece. These supports, acting as brakes, were intended to optimize the control of the prosthetic ankle joint's movement. However, significant challenges were encountered. The first issue was related to the 3D printer. Despite being able to read the STL file of the two prosthetic

Table 1. Implant components.

Component	Image	Functionality
Tibial Implant		The tibial implant has a flat shape that fits the lower surface of the tibia. This implant replaces the damaged articular surface of the lower end of the tibia, providing a stable base for articulation with the talar implant.
Pad		The pad is an essential component of the ankle prosthesis since the tibial part and the talar part are not a direct translation of the parts themselves, but rather a controlled sliding of the pad which ensures a durable and comfortable fluid articulation of the prosthetic ankle.
Talar Implant		The talar implant has been carefully designed to faithfully replicate the structural and functional aspects of the patient's talus. Its complex structure is reflected in its design, ensuring ideal force distribution and efficient movement. Maintaining the complex mechanical interactions of this part allows for a smooth transfer of the natural bone to the implant.

components using Simplify3D, the printer failed to detect the curved supports of the tibial implant during printing. These supports were crucial for minimizing excessive movement of the talar component. Additionally, the initial two-piece design (tibial and talar implants) proved insufficient based on further research. A polyethylene bearing was found to be essential, serving as an interface that enables smooth and controlled movement between the two components. It was observed that neither the tibial nor the talar component moves directly; instead, the bearing slides between them. This element plays a crucial role in protecting the metallic implants and is vital for the proper function of the ankle joint. In terms of biocompatibility, a rigid metal prosthesis alone would not adequately replicate the natural mobility of the ankle joint, potentially restricting movement and compromising patient comfort. Moreover, direct contact between metal and bone was found to increase the risk of infection, leading to complications such as pain, implant instability, and the potential need for surgical revision. Lastly, cylindrical shapes were initially incorporated at the implant ends to strengthen the connection between the patient's bones (tibia and talus) and the prosthesis. However, this approach was ultimately abandoned. During surgery, the surgeon removes the damaged portion of the tibia using a cutting guide to create space for the tibial implant, which remains fixed. As a result, integrating these cylindrical shapes was deemed unnecessary and was excluded from the final design.

6.1 Clinical Limitations and Risks

Although PLA (polylactic acid) was used to prototype the prosthesis, it is not considered suitable for permanent implantation due to its biodegradability and low fatigue resistance. Clinical-grade implants require materials such as titanium alloys, cobalt-chromium, or UHMWPE, which are biocompatible and meet ISO 10993 and ASTM F2026 standards [8]. Additionally, no clinical trials or orthopedic professional consultations were conducted for this work. Risks include mechanical failure, wear debris generation, inflammation, and infection if such materials were to be implanted. Thus, this study must be interpreted as an engineering prototype and not a validated medical solution.

7 Conclusion and Perspectives

An in-depth study on the fabrication of customized ankle joint implants using 3D printing has yielded promising results. The primary objective of this research was to enhance patients' quality of life by providing an implant tailored to their specific needs, particularly for those suffering from osteoarthritis, which was the most extensively studied condition in this project. The potential of 3D modeling and printing tools in the medical field has been demonstrated. The "3D Slicer" CAD software was utilized to accurately replicate the anatomical structure of the foot. Subsequently, "Blender" was employed to design a customized ankle prosthesis, ensuring a precise fit and optimal functionality for each patient. The decision to use free and open-source software aimed to highlight that promising results in personalized prosthesis design can be achieved even with simple tools. This approach allows various joint pathologies to be addressed and individualized solutions to be offered to each patient. Despite the enthusiasm surrounding this project, a major limitation must be acknowledged: the difficulty in accessing certain essential biomaterials. Titanium, cobalt, and polyethylene—critical materials for prosthesis fabrication—are currently scarce and difficult to obtain. For this reason, the focus was placed on developing a functional prototype from the outset. This prototype will allow the concept and functionality of the prosthesis to be validated through rigorous clinical testing. Once validated, further refinements can be made using more advanced materials that better meet industrial requirements. The revolutionary potential of 3D modeling and printing in the medical field has been demonstrated through the design of a customized and unconstrained ankle prosthesis. This implant enables the full range of motion of a natural ankle joint, allowing the patient to perform flexion, extension, abduction, and adduction. By achieving this, a significant step toward more individualized and effective medicine has been taken. This innovation adapts to the specific needs of each patient, significantly improving their quality of life.

Furthermore, this advancement paves the way for promising new perspectives in healthcare, encouraging further innovation and research, with the potential for even more significant breakthroughs in the future.

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