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Optimizing Mechanical Design for an Additively Manufactured Prosthetic Leg

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Abstract

The study discussed in this paper focuses on additive manufacturing (AM) of intricate geometrically structured components of a prosthetic leg. The objective is to optimize the original design to reduce the need for support structures while maximizing stiffness and reducing weight. Making a prosthetic leg lighter can improve the mobility of a person and reduce the energy required to climb stairs, enhancing their quality of life and independence. Traditional manufacturing methods, such as injection molding and computerized numerical control (CNC) machining, have limitations in terms of design flexibility. The study used Selective Laser Melting (SLM) technology with 316L-A stainless steel powder. The optimization process focused on the knee, upper leg, lower leg, hydraulic, and oil support system. The workflow procedure for additive manufacturing was discussed. Overall, the study successfully reduced the weight of the prosthetic leg by 50% from the original model.

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1. Introduction

Additive manufacturing (AM), also described as three-dimensional printing (3DP) technology, is used to manufacture products from digital 3D-model data, i.e., computer-aided design (CAD) files, by the addition of material one layer at a time [1]. With the use of computer-aided design data and a sophisticated layer-based manufacturing technique called additive manufacturing, patients' specific prostheses and orthoses may be manufactured without the need for part-dependent equipment. Today, it has been demonstrated that the application of additive manufacturing techniques helps to expedite, streamline, and enhance the quality of customized products in the prosthetics industry [2], [3], [4]. According to Lindberg et al. [5], for many years additive manufacturing (AM) has been used to create prototypes, but it is currently being utilized more often to create final products. The capability to produce geometries that were previously impractical or impractical when utilizing subtractive manufacturing, as well as the ease of customization, are two advantages of additive manufacturing. Aryal and Pun [6] mentioned that the use of additive manufacturing in the prosthetic industry minimizes the number of manufacturing stages. However, it should be mentioned that Additive Manufacturing technology has several downsides. For example, in the current study, selective laser melting was utilized, and this technique has size limitations that depend on equipment. Parts created with AM techniques frequently have a coarse surface finish look. The cost of AM equipment and material powder is considered an expensive investment, as is post-processing if necessary [7].

The primary objective of above-the-knee prostheses is to reestablish the mobility of individuals with amputations, playing a vital role in their rehabilitation journey by replacing the missing lower limb, whether in part or entirely, with an artificial counterpart. Over time, the evolution of prosthetic technology has yielded increasingly advanced mechanisms and structures [8]. While prosthetic innovations have expanded the range of components and mechanisms available, they have yet to fully address the persistent gait irregularities in above-the-knee amputees. The overarching aim of prosthetics remains the restoration of amputees' ability to engage in daily activities comfortably, naturally, and efficiently, hinging on the fundamental criteria of comfort, functionality, and aesthetics. Achieving these objectives proves challenging as these aspects are intricately interconnected. Lower limb prostheses are categorized by height, primarily as transfemoral (upper leg) and transtibial (lower leg) prostheses, each composed of distinct components. This discussion focuses on transfemoral prostheses, specifically designed for upper leg amputations [8].

This article is organized into several sections. The second section introduces additive manufacturing (AM), the technology used in this research, along with design for additive manufacturing (DfAM) and topology optimization techniques. Section 3 outlines the primary objective, initial design iterations, alternative configurations for the prosthetic leg, and the last version (original design) prior to being optimized. Section 4 covers the materials and methods used, including the redesign process, topology optimization workflow, and 3D printing workflow. The results and discussion are presented in section 5, while section 6 offers conclusions.

2. Additive Manufacturing (AM)

Additive manufacturing utilizes a CAD file to create an STL file. The CAD drawing is transformed into triangles and divided into slices that represent each layer of the object to be printed. In the preceding section, it was noted that additive manufacturing operates on the fundamental concept of adding material in layers, where each layer corresponds to a thin segment of the initial computer-aided design [9], [10]. Topology optimization (TO), which automatically generates an optimum design, allows for the methodical use of AM's capabilities [11]. Additive manufacturing (AM) technology is viewed as a versatile manufacturing process with significant promise for significant advancements in the production of medical equipment and instruments, orthoses prostheses, medical models, inert implants, and biomanufacturing [12]. Powder bed fusion (PBF) is a technique of additive manufacturing that involves the use of lasers or electron beams to melt and combine powdered materials. This process includes spreading a layer of powdered material on top of the previous layer. The PBF technique includes three different

methods, known as Selective Laser Sintering, Selective Laser Melting, and Electron Beam Melting [13]. In this paper, we will briefly discuss the technology used in this study.

2.1. Powder Bed Fusion (PBF) technologies

This process involves the use of a laser or electron beam to selectively melt metal powder layer-by-layer to create the final part. There are two types of PBF technologies: Selective laser melting (SLM) and electron beam melting (EBM). SLM uses a laser to melt the metal powder, while EBM uses an electron beam. Both technologies can create highly complex and precise parts with excellent mechanical properties [10]. The entire process of sintering/melting is conducted in an inert atmosphere using argon or nitrogen, depending on the type of material being printed. These methods require support (of the same material as the component) to minimize molten material collapse on overhanging surfaces, dissipate heat, and prevent deformities. During the stage of preprocessing, supports can be generated and customized to meet the needs of the component, and they must be removed mechanically during the postprocessing phase. Depending on the requirements, the component may be subjected to postprocessing procedures such as shot peening, polishing, and machining once the support has been removed [14].

2.2. Selective laser melting (SLM)

Selective laser melting (SLM) employs a laser beam to combine metal powders by melting them. The process involves placing a thin layer of powder on a substrate plate or the previously deposited layer, and then selectively melting and fusing the powder particles with the laser beam, based on instructions from the CAD data [15], [16]. This method can be utilized to create intricate geometry that is both stronger and lighter without wasting a significant amount of material (see Fig.1). As a result of these benefits, SLM technology has become more popular and has been incorporated into major manufacturing industries, such as aerospace, medical implants, and automobiles [17]. A PrimaSharp250 printer was utilized in the current investigation.

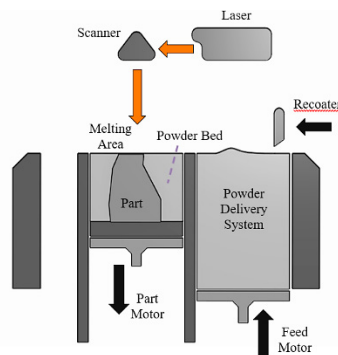


Fig. 1. Typical selective laser melting (SLM) process.

2.3. Design for additive manufacturing (DfAM)

Design for Additive Manufacturing (DfAM) is a methodology that aims to optimize product design by considering the intricacies of the manufacturing process and the advantages of using additive manufacturing (AM) throughout the product's lifecycle [18]. Furthermore, to create designs for additive manufacturing (DfAM), engineers must utilize a variety of software tools [19]. Ponche et al. [19] proposed a three-step DfAM methodology that considers the manufacturing process details and physical phenomena to achieve the desired part functionality. First, identify the important surfaces of the part and position them in a way that ensures the selected AM process can meet their accuracy

and surface finish requirements while also considering the overall cost and time of fabrication [19]. Second, create the ideal part shape, while considering the manufacturing process and material, with a preference for using topology optimization [20], [23]. Topology optimization is a valuable computational strategy that is used during the design process to determine the best layout based on functional needs, with the important addition of using multi-material structures [24], [25]. The last and third step is to improve the manufacturing process plan and tool paths to achieve the desired mechanical properties, functionality, and cost and time targets [20].

2.4. Topology optimization method

Design optimization requires considering all manufacturing steps leading to the final product. AM has limitations such as overhang angle restrictions and the need to prevent fragile features that could cause overheating or warping. Milling can remove support structures, but minimizing their use reduces build time and material consumption. Sufficient material is necessary for attaching components at interface locations. Ignoring these practical considerations during optimization leads to subpar designs requiring modifications and adding unnecessary design time [11]. Topology optimization works by eliminating any part of the structure that does not contribute to its strength, using internal strain energy density distributions [26]. Topology optimization is specifically utilized during the planning stage of this project. When creating topology-optimized structures, engineers can utilize AM to overcome the constraints of traditional manufacturing methods and focus on designing structures that are both lightweight and high-performing. As a result, topology optimization is a powerful technique for producing additively manufactured goods that feature creative configurations and low weight [27], [28].

3. Objective and background

3.1. Objective

The objective of the investigation was to utilize the process of additive manufacturing, commonly known as 3D printing, in order to produce a prosthetic leg, with the intention of enhancing the functionality and efficiency of prosthetics. The new prototype active prosthesis is exposed to additional forces of 3000 N, acting at an angle of 10 to 30 degrees in relation to the vertical plane, which is achieved by linear actuators in the area of the knee joint and a slightly smaller force in the area of the ankle joint. It also has a newly designed ankle joint that allows the foot to rotate up to 30 degrees. For the above reasons, it is necessary to create a prototype that will enable checking the functionality of the prosthesis. For this reason, a prototype prosthesis was made of wood. After using 3D printers through the KnowHUB project, we 3D printed a prosthesis made of Acrylonitrile butadiene styrene (ABS) and Polylactic acid (PLA) materials. The lower leg was divided into two parts and later connected by gluing. The lower leg was divided into two parts and subsequently joined together by means of gluing. Following a functionality check, certain defects were observed, leading to a redesign of the prosthesis, and printing it from PLA to ABS material.

3.2. Early versions

Initial prosthesis iterations were adaptations of the Endolite model, enhanced with hydraulic linear actuators and corresponding connectors. The initial version incorporated a single knee actuator, but it proved inadequate for stair ascent. A subsequent version featured two actuators - one in the knee and another in the ankle - yielding positive experimental outcomes. The third iteration introduced a hydraulic mobile unit with a backpack-mounted battery drive. Above-the-knee prostheses aim for aesthetic similarity to a healthy limb and are predominantly crafted from carbon in modern production (see Fig.2).

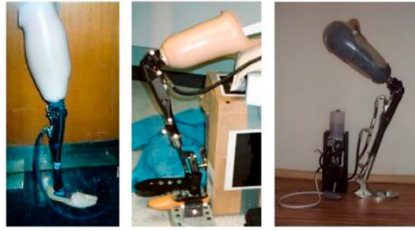


Fig. 2. Earlier versions of the prosthesis.

3.3. Alternative configurations

After the analysis, serially produced hydraulic cylinders were ordered. These cylinders were found to possess dimensions larger than the available space within the Endolite prosthesis, leading to the decision to develop our own above-the-knee prosthesis. Fig. 3 displays the various versions of the prosthesis, including a) the wooden version, b) the PLA version, and c) the ABS version. Prototyping with wood, PLA, and ABS materials was a way to test different options, ensuring the best fit, comfort, and performance for prosthetic configurations before final production.

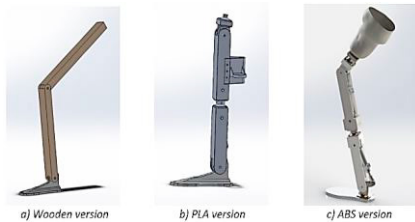


Fig. 3. Alternative versions of the prosthesis.

3.4. Original design concept

A visual representation of the prosthetic leg components is shown in Fig. 4. The original parts were obtained from the University of Mostar as STEP files, and it's important to note that the original design has not been commercialized. While redesigning the components, the screw holes were kept in their original location and size, and areas were left open to enable the hydraulic mechanism to move freely. Fig. 4 displays the parts that required alterations in the prosthetic leg.

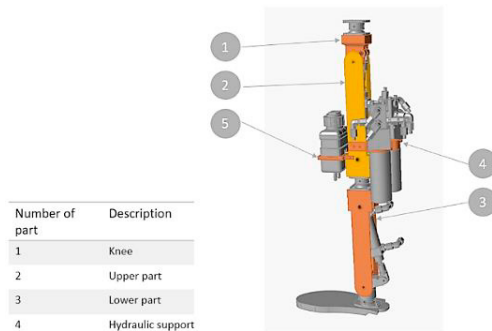


Fig. 4. Description of the five components comprising the original configuration of the prosthetic leg.

4. Material and methods

4.1. Material

The careful selection of materials is crucial for ensuring that a component is capable of enduring applied loads and displaying minimal levels of deformation [29]. Metal implants produced via 3D printing techniques typically exhibit finer grain structures, resulting in superior mechanical properties [30]. The material used in this work was MetcoAdd 316L-A stainless steel gas atomized provided by Oerlikon Metco. 316L stainless steel powder was selected for 3D printing prosthetic legs because of its exceptional corrosion resistance, strength, biocompatibility, and customization capabilities, improving prosthetic durability and user experience. Table 1 shows the chemical composition of 316L stainless steel powder.

Table 1. Chemical composition of 316L stainless steel powder [31].

		Weight Percent (wt. %)					
	Fe	Cr	Ni	Mo	Mn	C	Other
MetcoAdd 316L	Balance	17.4	11.2	2.6	1.5	<0.02	<1.0

4.2. Re-design objective

The CAD models produced by the University of Mostar required the modification of five components to make them suitable for additive manufacturing. To reduce the weight of each component, topology optimization was employed. To ensure functionality and safety, the part was constrained during the optimization process. The primary constraint was the stiffness of the part, and to maintain it, the maximum displacement along the component's axis was limited.

4.3. Topology optimization workflow

Topology optimization is a method for creating a component or system that meets certain criteria and limitations while achieving optimal performance. Engineers can utilize Altair Inspire software as a user-friendly tool for conducting topology optimization. The software workflow consists of a series of steps, including 3D CAD modeling was carried out using SolidWorks, while topology optimization was solved using Altair Inspire. The optimization process started by defining the design space, which needed to be maximized while minimizing interference with other components and joint rotation. The non-design space, such as connections to bearings and bolts, was also defined, where optimization was not performed. A FE model was introduced for optimization, with material properties and boundary conditions, including external load, applied. Design parameters were set, including design variables, objective function, constraints, and the minimum or maximum size of the structure. Preprocessing was followed by an optimization process that aimed to determine the optimal structure while satisfying the constraints. Minimizing the need for support structures was crucial in the optimization process due to the printing direction being a constraint (see Fig.5).



Fig. 5. The latest active prosthetic model can endure 3000 N forces at 10–30-degree angles.

It features new ankle joints that rotate 30 degrees.

This is because using less material and requiring less post-processing were both important considerations. Iterations were performed until the performance met the objective function. The optimized shape was then designed using the optimization results, and the optimized model was verified by FE analysis (see Fig. 6). The chosen result was adjusted manually to eliminate any irregularities in the model and make the surface smoother.

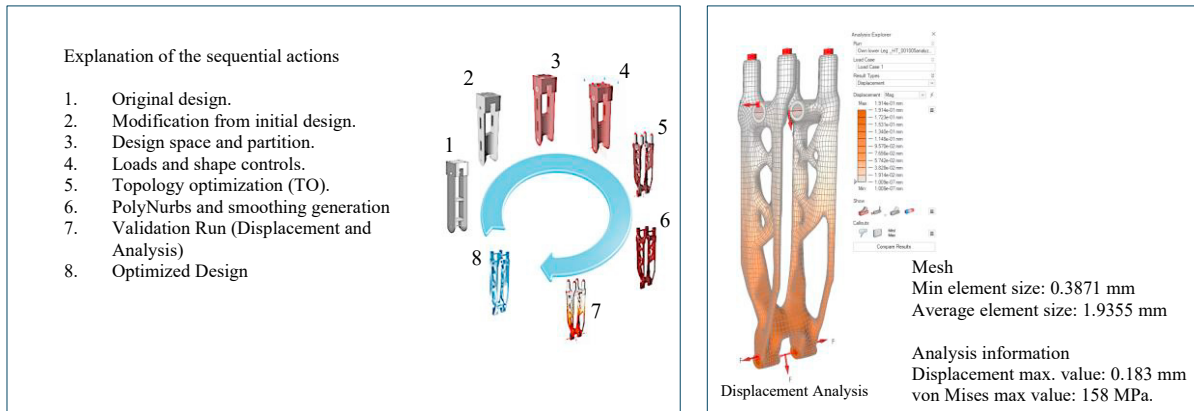


Figure 6. Workflow of topology optimization for lower leg component (left).

Topology optimization result, minimum thickness: 6mm, maximum thickness: 12 mm. Simulation, maximum displacement: 0.183 mm (right).

4.4. Metal 3D printing workflow

Selective Laser Melting (SLM) is an additive manufacturing (AM) technique that uses a high-power laser to selectively melt and fuse successive layers of powdered material to build up a three-dimensional object. Metal additive manufacturing (MAM) using the Primasharp250 printer involves a specific workflow. This process involves several steps to ensure the successful fabrication of metal parts. The workflow for all the components started with a redesign phase to prepare the initial CAD files for Additive Manufacturing (AM). After importing the original CAD files in STEP format, the files were prepared for topology optimization.

In this study, the applied force was 3000N at an angle of 30 degrees and other design constraints. After the topology optimization, the next step was to export the files in STL format, which is a common file format used for 3D printing. The exported files were then prepared for 3D printing using software such as Materialise Magics and EPHatch. Materialise Magics was used for support generation and determining the printing orientation, while EPHatch was used for setting the printing path and slicing the files (see Fig. 7).

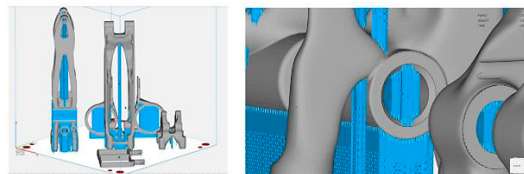


Fig. 7. The process of getting the parts ready in Materialise Magics involved performing topology optimization to reduce the need for support structures (as shown in the left image). The support structures themselves were designed with teeth and perforations to facilitate their removal, as seen in the right image.

To be compatible with the PrimaSharp250, the format of the model should be readable, such as STL for the supports

and EBI for the components. The excess humidity was removed from the powder by preheating it to 80°C before loading it manually into the build chamber of the PrimaSharp250. Table 2 describes the production parameters.

Table 2. Production and laser parameters from the Prima250 printer.

Production parameters	
Layer height	30 μm
Scanning strategy	Paintbrush scanning
Substrate temperature	60°C
Hatching distance	0,12 mm
Scan speed	800 mm/s
Volumetric Energy Density (VED)	83,33 J/mm ³
Oxygen percentage	< 4000 %/ppm
Process Time	75.5 hours
Laser parameters	
Laser power	240 W
Spot size	70 μm

Upon completion of the printing process, the object was extracted from the building chamber and any excess powder was cleaned off. The support structures were detached manually before the parts were taken out or separated from the base plate with the aid of a VASKI cutting machine. Finally, all the components necessitated supplementary post-processing, including polishing by hand, and shot peening to enhance the quality of the surface. Fig. 8 illustrates the metal 3D printing workflow.

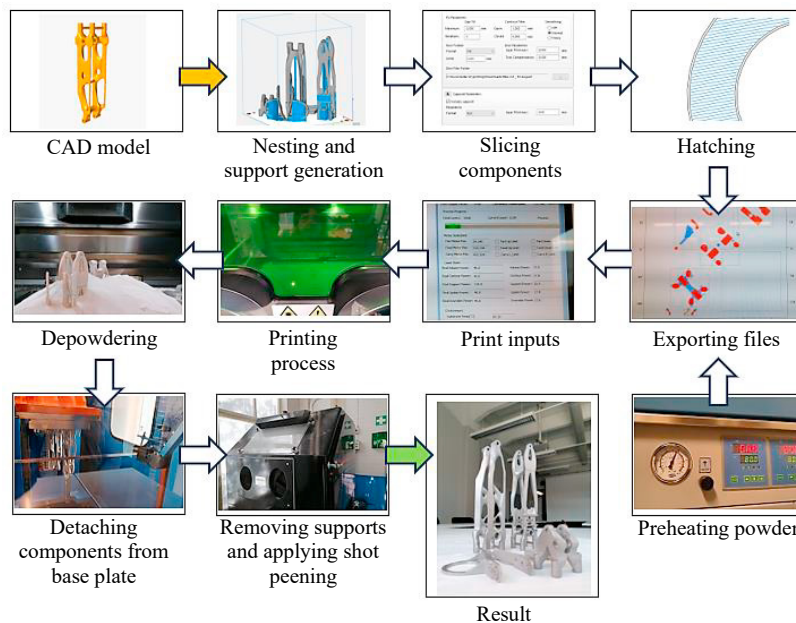


Figure 8. Metal 3D printing workflow.

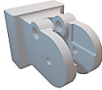




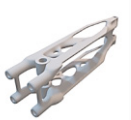


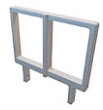

5. Results

5.1 Final version

According to the research findings, additive manufacturing (AM) has the potential to create intricate and optimized

parts, but there are certain obstacles associated with this technique. These impediments include difficulties with design and support generation, which are vital for generating topology-optimized parts that can be printed. To ensure successful metal 3D printing, designers should strive to produce CAD models/topology-optimized parts that require minimal support during printing and post-processing. Such an approach will facilitate a more adaptable AM workflow and allow the production of functional parts that can be installed directly upon printing. In addition to design issues, the investigation emphasizes the significance of support structure and generation, as they can impact the internal stress, cracking, and deformation of the final product. Furthermore, the orientation of the part during printing is a crucial factor in determining the success of the print (see Fig. 9).

Figure 9. Original components vs. optimized components from the prosthetic leg.

Original Part	Optimized Part
Knee component	
	
Weight: 0.781 kgs	Weight: 0.312 kgs
Upper leg component	
	
Weight: 1.902 kgs	Weight: 0.798 kgs
Lower leg component	
	
Weight: 2.271 kgs	Weight: 0.861 kgs
Hydraulic support component	
	
Weight: 0.255 kgs	Weight: 0.184 kgs
Oil support component	
	
Weight: 0.114 kgs	Weight: 0.075 kgs

5.2 Discussions

The findings of this research are relevant to the utilization of additive manufacturing (AM) technologies in

optimization strategies. Through the application of topology optimization, the overall mass of all components was reduced by 50% (Fig. 10). The findings of this research have significant implications for the application of additive manufacturing (AM) technologies in optimization strategies, particularly in the field of prosthetics. This reduction in mass is crucial not only for improving the mobility and comfort of prosthetic users but also for minimizing material usage and weight, which can lead to cost savings and a more sustainable approach to prosthetic manufacturing.

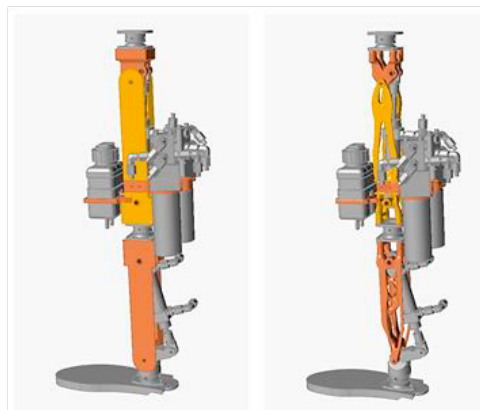


Fig. 10. Assembly comparison made in 316L ss. Original components, total weight: 5.323 kgs (left figure). Optimized components, total weight: 2.230 kgs (right figure).

6. Conclusions

6.1 Conclusions

This research has shown that additive manufacturing (AM) technologies, when combined with topology optimization, can significantly reduce the mass of components. This optimization process ensures that the final design meets performance and strength requirements while minimizing material usage and weight. Component simulation after topology optimization confirmed displacement remained below 0.2 mm, with easily removable support structures. These findings highlight the potential for innovation in prosthetics, offering personalized designs with precision. As technology advances, we can expect further improvements in prosthetic limb construction. Additionally, optimizing the hydraulic system configuration could potentially reduce mass by up to 25%.

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