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RESEARCH ON THE DESIGN AND MANUFACTURING OF AN UPPER-LIMB PROSTHESIS BY FUSED DEPOSITION MODELLING

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Abstract: *This paper presents a finite element analysis (FEA) performed with the aim of evaluating the mechanical behaviour of upper-limb prostheses manufactured by Fused Deposition Modelling (FDM) using two distinct printing materials: Polylactic Acid (PLA) and Polyethylene Terephthalate Glycol (PET-G). The prosthetic parts were tailored to meet the specific needs of individual patients, reflecting the trend in the design of personalized medical devices. The FEA approach employed in this study offers valuable information about the structural integrity and performance of prosthetic devices, ensuring their safety and functionality in real-world applications. The results of this analysis contribute to the advancement of prosthetic design and fabrication techniques, offering patients improved mobility and quality of life.*
Key words: *finite element analysis, fused deposition modelling, upper limb prosthesis, PET-G, PLA*

1. INTRODUCTION

The domain of conceiving and producing prosthetic hands has undergone a paradigm shift, driven by a convergence of cutting-edge technologies and innovative approaches that have ushered in an era of unprecedented customization and cost-effectiveness. In recent years, 3D printing technologies have revolutionized prosthetic design and production [1]. Fused Deposition Modelling (FDM) has particularly emerged as a game-changing technique for crafting prosthetic components with high accuracy and speed [2,3]. Its ability to create patient-specific solutions with intricate geometries has not only expanded design possibilities but also reduced costs, making advanced prosthetic care more accessible to people [4]. Materials selection has long been a critical aspect of prosthetic design. This paper takes an in-depth look at PET-G and PLA as prime candidates [5]. PET-G combines the mechanical strength of traditional thermoplastics with the printability and chemical resistance of PET-G, making it a compelling choice for prosthetic applications. PLA derived from renewable resources is characterised by biocompatibility and ease of printing [6,7]. The main purpose of this research consists in applying the finite element analysis (FEA) to comprehensively assess the mechanical characteristics of prosthetic devices. FEA enables the estimation of critical parameters such as stress distribution, and deformation under diverse loading scenarios of the considered materials in accordance with the design structure of the prosthesis [8-10]. By subjecting PET-G and PLA prosthetic components to FEA, the research presented in this paper aims at establishing their mechanical strength in view of optimizing the design of products for maximum performance and patient satisfaction.

2. MAIN CONCEPT OF UPPER-LIMB PROSTHESIS

The model presented in Fig. 1 is a mechanical prosthesis that can be produced by 3D printing. This model has been designed to be compatible with personal means of conveyance (e.g., bicycles or scooters) for a specific patient. The prosthesis is part of an AutoMedPrint system described in previous studies realized at Poznan University of Technology [11,12]. This prosthesis is intended to function as a

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mechanical apparatus and is tailored to suit the anatomical parameters of a particular patient resulted from measurements made by 3D scanning. The main purpose of the prosthesis is to help a patient having a transhumeral amputation. Additionally, it might be a viable solution for patients with short forearm stumps.

The prosthetic device can be produced by 3D printing from a wide range of materials. PLA and PET-G are highly recommended due to their well-documented compatibility with the human skin. Specifically, PLA is deemed suitable for paediatric applications, while more robust materials like PET-G are recommended to be used for adult patients. Alternately, ABS and other materials may be considered, under the condition that there is no direct skin contact (e.g., when employing foam) or if sterilization is conducted both prior to and after their use.

The design of the customizable prosthesis model was parametrically realized relying on the anatomical parameters of the patient. The prosthesis was further on fashioned with reference to a healthy limb since there was a significant size disproportion in the residual amputated limb.

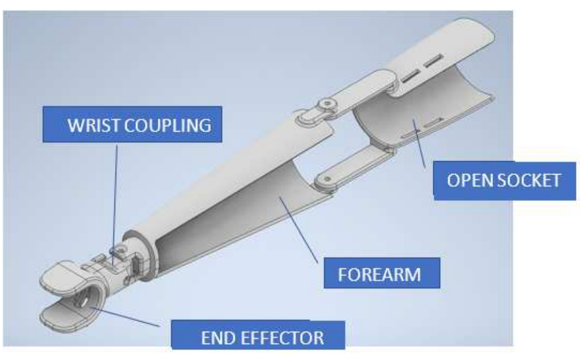


Fig. 1. Upper limb prosthesis – main components

As one may notice in Fig. 1, the main components of the prosthesis are the socket (stump part) with elbow coupling, the forearm, the wrist coupling (consisting in four parts), and the end effector.

The 3D model in Fig. 1 was elaborated with Autodesk Inventor. Users must not directly modify the dimensional parameters of the prosthesis. Instead, the customization is done by means of an Excel spreadsheet storing the parametrization (as shown in Fig. 2).

This spreadsheet serves as a user interface intended for data entry. It includes guiding and illustrations for helping the user to prepare a parametric design that fits the needs of a specific patient.

name	dimension	unit	
X1	110	mm	hand length "a"
X2	112	mm	don't change
X3	78	mm	don't change
X4	70	mm	don't change
promien_wew_C	17	mm	handle radius, don't change
wymiar_b	160	mm	forearm length (healthy limb)
wymiar_c	100	mm	arm length (stump)
wymiar_d1	70	mm	arm section 1 - bbox size y
wymiar_d2	60	mm	arm section 1 - bbox size x
wymiar_e1	60	mm	arm section 2 - bbox size y
wymiar_e2	60	mm	arm section 2 - bbox size x
wymiar_f1	60	mm	arm section 3 - bbox size y
wymiar_f2	55	mm	arm section 3 - bbox size x
odsunięcie	23	mm	offset value at the elbow

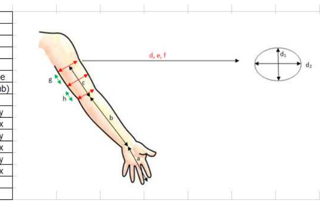


Fig. 2. Excel spreadsheet – upper limb prosthesis

Upon inputting parameters, the model automatically redesigns itself, as shown in Fig. 3. After updates and error checking, the model is saved externally as “*.step” or “*.stl” files for future use.

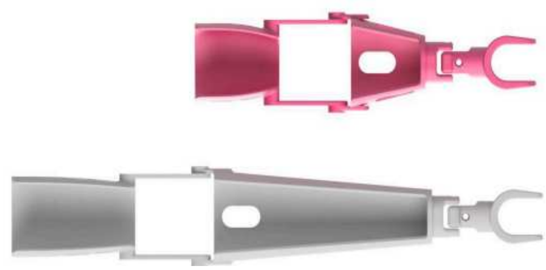
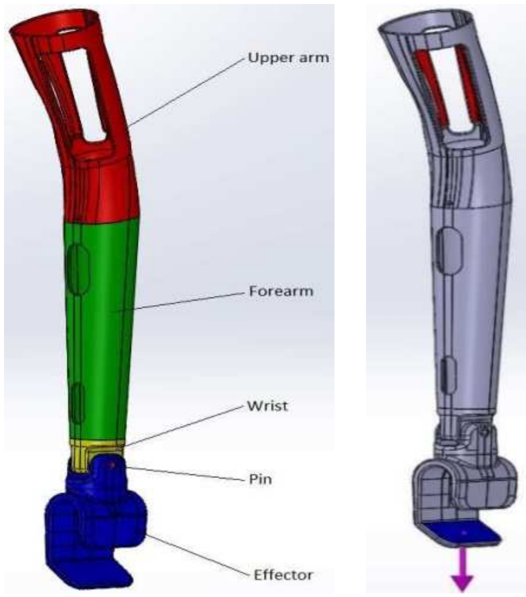


Fig. 3. Update of model with different patient data

3. FINITE ELEMENT ANALISYS PERFORMED FOR ASSSESSING THE MECHANICAL STRENGTH OF THE PROSTHESIS

The primary aim of the finite element analysis was to assess the strength characteristics of an enhanced bicycle prosthesis designed for adult users (Fig. 4, a). The analysis was made by simulating a distal tensile test. The principle of the test is presented in Fig. 4, b. As one may notice, the prosthesis is subjected to a distal traction. The load is applied to the effector (at the level of the blue region shown in Fig. 4, b), being gradually increased from zero to 750 N. During the tensile test, the inner surfaces of the upper arm are firmly attached to a rigid support that perfectly fits their configuration (see the red regions in Fig. 4, b).

The following hypotheses were adopted for preparing the finite element model of the tensile test:



a b

Fig. 4. 3D model of the upper-limb prosthesis (a) and principle of the distal tensile test (b)

• All the prosthesis components are made of PET-G exhibiting an isotropic linear elastic behaviour. Table 1 lists the physical and mechanical parameters of this material that are relevant for the simulation of the tensile test.
• All the prosthesis components are bonded together along their contact surfaces.

Table 1

Physical and mechanical parameters of PET-G [13]

Density ρ	1270 kg/m^3
Elastic modulus E	1660 MPa
Poisson's ratio ν	0.419
Yield strength Y	30.3 MPa

The finite element model of the tensile test was prepared with SOLIDWORKS Simulation in the following sequence of steps:

a) Assigning the PET-G material properties to the prosthesis components

b) Defining a bonded contact interaction between the prosthesis components

c) Imposing a full locking kinematic constraint on the inner surfaces of the upper arm (as shown in Fig. 5)

d) Defining a unit downward vertical force applied to the effector (as shown in Fig. 5). The actual values for this force were later specified as load cases (see step (f) below)

e) Specifying the average size of the finite elements and generating the mesh

f) Defining the actual values of the downward vertical force applied to the effector as load cases: 150 N (load case 1), 300 N (load case 2), 450 N (load case 3), 600 N (load case 4), and 750 N (load case 5).

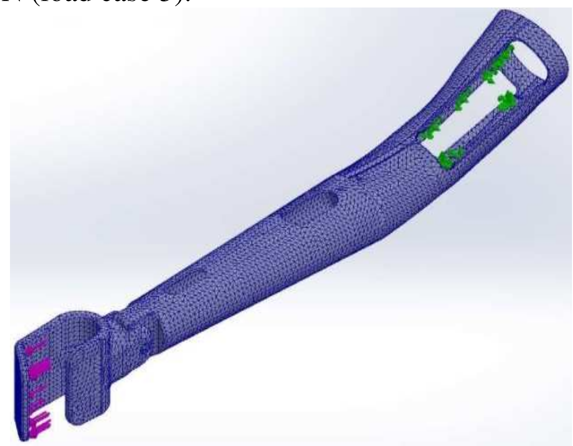


Fig. 5. Finite element model of the distal tensile test used for assessing the mechanical strength of the bicycle prosthesis

Fig. 6 shows the most significant result of the finite element analysis namely, the distribution of the von Mises equivalent stress in the bicycle prosthesis as predicted by SOLIDWORKS Simulation for the fifth load case (traction force of 750 N).

Fig. 7 illustrates the relationship between the maximum equivalent stress ($\sigma_{eq,max}$) and the traction force (F) associated to different load cases. The data plotted in the diagram were extracted from the numerical results of the finite element analysis.

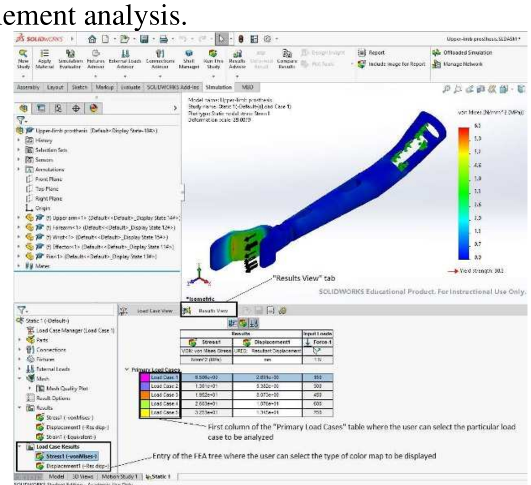


Fig. 6. Distribution of the von Mises equivalent stress in the bicycle prosthesis for the fifth load case (traction force of 750 N)

The diagram in Fig. 7 allows formulating the following conclusions:

a) The mechanical response of the bicycle prosthesis is well approximated by the linear regression $\sigma_{eq,max} = 4.337 \cdot 10^{-2} \cdot F$ (see the black path in Fig. 7).
b) This regression can be used to determine the traction force F_{cr} at which the maximum von Mises equivalent stress reaches the yield strength of the PET-G material (30.3 MPa – see Table 1): F_{cr} = 698.64 N.

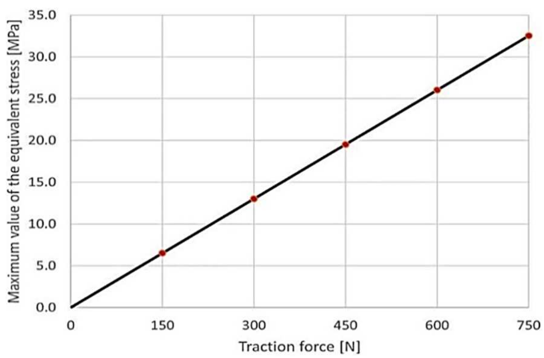


Fig. 7. Maximum values of the von Mises equivalent stress corresponding to various traction forces: red dots – numerical results provided by SOLIDWORKS Simulation; black path – approximation of the numerical results by a linear regression

4. MANUFACTURING THE UPPER-LIMB PROSTHESIS BY FDM

The components of the bicycle prosthesis were manufactured by Fused Deposition Modelling (FDM). This procedure offered versatility in terms of compatible machines and materials. Prusa i3 MK2 machines were used for manufacturing the components (Fig. 8). The Prusa Slicer software (Fig. 9) was also used for programming the printers and setting their parameters.

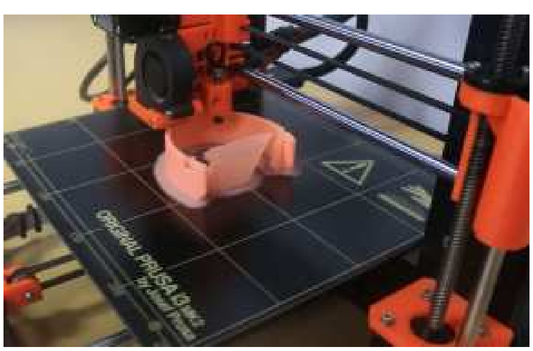


Fig. 8. 3D Printing the prosthesis components on the Prusa FDM machine

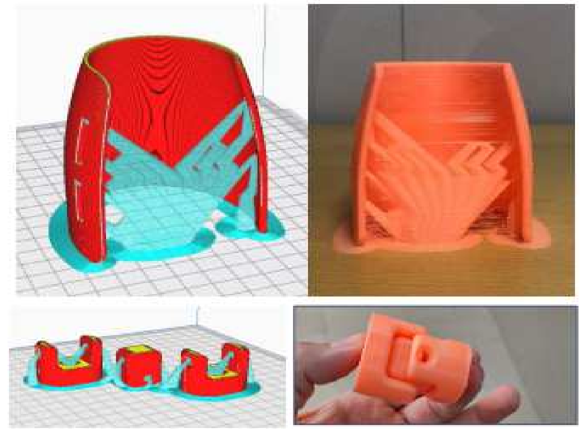


Fig. 9. Prusa Slicer software used for preparing the 3D printing process

Besides the components manufactured on Prusa i3 MK2 machines, a few others were printed from PLA using FlashForge Creator Pro machines (Fig. 10).

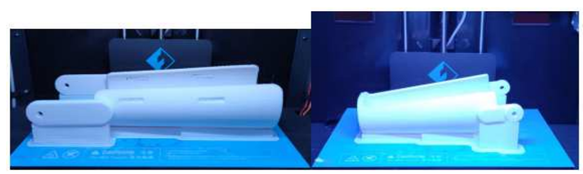


Fig. 10. Components of the upper-limb prosthesis (socket and forearm) manufactured on FlashForge Creator Pro machines

Standard settings were used for the parameters of the 3D printing process: 30% infill, 0.2 ÷ 0.3 mm layer thickness, and maximization of the velocity for the specific material in use. The recommendations provided by the machine manufacturer were used for establishing the temperature regime of the 3D printing process.

Under the conditions mentioned above, an upper-limb prosthesis was manufactured in a single day using four 3D printing machines. This time consumption includes the postprocessing steps (e.g., mechanical removal of support structures, and manual grinding and polishing of the components to eliminate sharp edges or other imperfections of the printed components).

The postprocessing steps were followed by the assemblage of the prosthesis using standard nuts and bolts. Fig. 11 shows examples of upper-limb prostheses having shapes and dimensions customized for different patients (child and mature person, respectively).

Fig. 11. Upper-limb prosthesis customized for different patients – child and mature person, respectively [14]

5. CONCLUSIONS

The results of the finite element analysis and the experiments presented in this paper prove that Fused Deposition Modelling (FDM) is a viable and cost-effective procedure for manufacturing upper-limb prostheses made of PET-G and PLA. By using the numerical simulation of a distal tensile test, the authors have established the level of the traction load at which the maximum value of the von Mises equivalent stress occurring in the prosthesis reaches the yield strength of the PET-G material. From this point of view, finite element analysis is a powerful tool that can be used by designers to evaluate the mechanical strength of medical devices.

The authors intend to focus their future research on investigating the usage of new materials for manufacturing prosthetic devices by 3D printing, customization of such devices in accordance with the anatomical parameters of the patients and optimizing the parameters of the 3D printing process. These tasks are subordinated to the need of enhancing the quality of life for individuals requiring prosthetic solutions.

ACKNOWLEDGMENT

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CERCETĂRI PRIVIND PROIECTAREA ŞI FABRICAŢIA UNEI PROTEZE A MEMBRULUI SUPERIOR PRIN DEPUNERE DE MATERIAL PLASTIC TOPIT

Rezumat: Această lucrare prezintă o analiză cu elemente finite efectuată cu scopul de a evalua comportarea mecanică a unei proteze de membru superior realizată prin depunere de material topit (FDM) folosind fie acid polilatic (PLA), fie polietilen tereftalat glicol (PET-G). Componentele protezei au fost ajustate pentru a fi compatibile cu nevoile specifice ale pacientului, reflectând tendințele actuale din domeniul proiectării dispozitivelor medicale. Abordarea cu elemente finite din acest studiu oferă informații valoroase cu privire la integritatea structurală și performanțele dispozitivelor medicale, asigurând siguranța și funcționalitatea lor în aplicații. Rezultatele analizei contribuie la progresul proiectării și fabricației protezelor, asigurându-le pacienților o mobilitate mai bună și condiții de viață îmbunătățite.

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