

RESEARCH ON 3D DESIGN OF A CUSTOMIZED BIOMECHANICAL PROSTHESIS FOR THE UPPER LIMB (FOREARM)

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Abstract: *This paper analyzes the computer-aided design (CAD) process applied to the realization of a personalized biomechanical forearm prosthesis. The goal is to restore the functionality of the upper limb through a device anatomically and biomechanically adapted to the individual needs of the patient. The paper covers the essential stages of the CAD methodology, from the collection of anthropometric data and 3D scanning, to the modeling of parts, kinematic simulation and finite element analysis (FEA).*

The importance of customization, structural optimization and integration of functional components (mechanical and electronic) in the context of a modern prosthesis is highlighted. Virtual simulations allow for design validation before manufacturing, ensuring a balance between performance, comfort and durability. Case studies and simulation examples confirm the technical feasibility of such an additively manufactured prosthesis (e.g. 3D printing), demonstrating the potential of this type of approach for future prosthetic solutions.

Key words: CAD modeling, forearm prosthesis, 3D scanning, biomechanical analysis, FEA

1. INTRODUCTION

Upper limb prosthetics aim to restore the function of a lost arm while maintaining comfort and ease of use. The design of the prosthesis must be adapted to the level of amputation (e.g. transradial, elbow disarticulation), and prostheses are classified into four types: passive, body-powered, externally powered (myoelectric), and hybrid. Regardless of the type, all include components such as: socket, fixation system, joints, control, and end pieces.

Biomechanical design involves integrating knowledge of the anatomy and natural movements of the upper limb into mechanical design. A forearm prosthesis generally includes a wrist joint and a functional hand. Actuation systems (mechanical or electrical) transmit movement to the fingers, allowing the user to perform functional gestures. The design aims to provide the necessary forces (e.g. for gripping), reduce weight, and align correctly with the body to increase comfort and naturalness of movement.

2. BIOMECHANICAL PRINCIPLES OF UPPER LIMB PROSTHESES

Upper limb prosthetics aim to mechanically and functionally mimic the human arm, which has multiple degrees of freedom (DOF). The forearm prosthesis should allow for finger movement and, if possible, hand orientation. Types of prostheses include: passive, body-powered, myoelectric, and hybrid, each with a customized socket for fixation and pressure dispersion on the abutment.

A critical aspect is biomechanical alignment: the prosthetic components must be positioned correctly relative to the natural joints to allow natural movement and avoid overstressing the abutment. Weight must also be reduced and centered close to the body to prevent fatigue.

The forces transmitted by the prosthesis during use must be analyzed and maintained below the strength limits of the materials, according to international standards (e.g. ISO 22523). These require durability and safety in daily use.

Figure 1 presents the biomechanical analysis of force transmission in a forearm prosthesis.

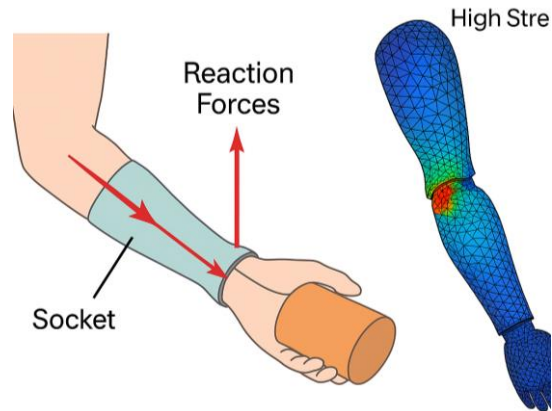


Figure 1: Biomechanical analysis of force transmission in a forearm prosthesis

Customization of the prosthesis is essential: each patient has a unique anatomy. 3D scanning of the healthy abutment or arm allows the creation of a precise shape, ensuring comfort and aesthetic and functional integration.

The principle of personalization is essential in prosthetic design, as each patient has a unique anatomy. Standard prostheses rarely fit perfectly, so personalized design is based on capturing the shape of the healthy limb or abutment. Through 3D scanning and reverse engineering techniques, an accurate digital model is obtained, which allows the prosthesis to be contoured for anatomical fit, high comfort and, if necessary, a realistic appearance.

3. COMPUTER-AIDED DESIGN (CAD) METHODOLOGY

Designing a custom biomechanical prosthesis involves several steps, using CAD software such as Autodesk Inventor. The process begins with **the collection of medical and anthropometric data** : abutment dimensions (via measurements or 3D scanning), the patient's mobility and functional needs. The opposing limb is also analyzed to ensure symmetry. The 3D scan provides an accurate digital model, useful in defining the contour of the prosthesis. Figure 2 shows an example of the use of 3D scanning in the personalized design of a hand prosthesis.

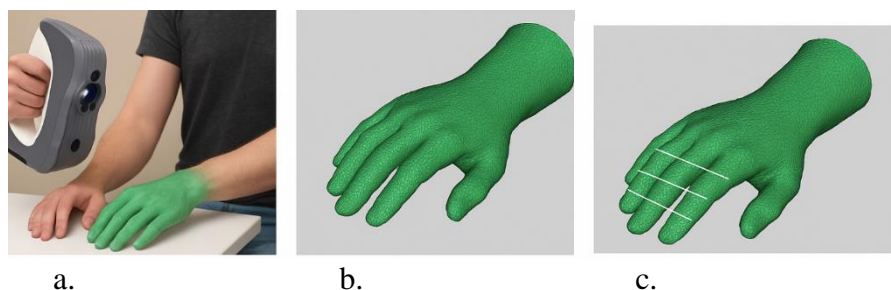


Figure 2: Example of using 3D scanning in the custom design of a hand prosthesis: (a) capturing the shape of the arm with a 3D scanner; (b) digital model of the hand surface obtained by scanning; (c) measuring characteristic dimensions (finger sections) on the 3D model to guide the design of the prosthesis.

The second stage is the design concept, based on functional requirements (e.g. finger mobility, joint type). The mechanical architecture and the type of actuation (wired or myoelectric) are decided. Preliminary sketches and CAD models are used to verify the geometric feasibility of the components.

In the 3D modeling stage, the individual parts of the prosthesis are created in CAD software, such as Autodesk Inventor, using parametric modeling to facilitate adjustments. Components such as the socket, forearm structure, joints, palm, fingers, and connecting elements are modeled separately. The scanned surface of the abutment can be imported to create a perfectly adapted internal coupling. Tolerances, minimum thicknesses, and 3D printing compatibility are taken into account.

After modeling, virtual assembly follows: the parts are positioned together and interferences are checked. Through kinematic analysis, finger and joint movements are simulated to evaluate range of motion, speed and acceleration. If problems arise (e.g. collisions or incomplete movements), changes are made to the design. Figure 3 shows the detailed 3D modeling of a forearm prosthesis in CAD software.

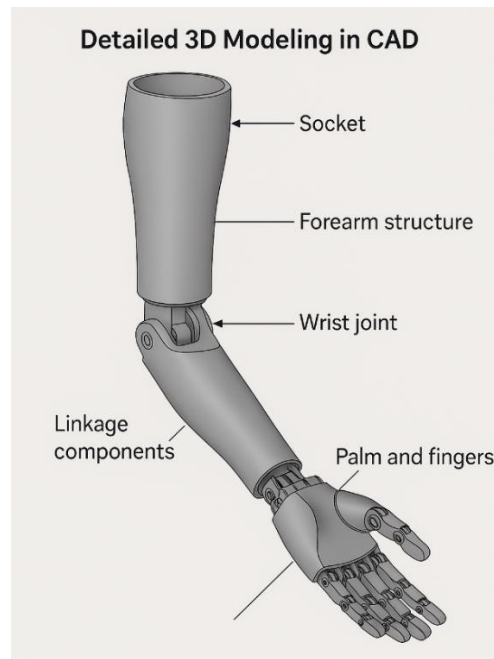


Figure 3: Detailed 3D modeling of a forearm prosthesis in CAD software

Digitally generated technical illustration, representing the individual parts of a customized biomechanical prosthesis: (a) socket adapted to the abutment, (b) forearm structure, (c) wrist joint, (d) palm and fingers, and (e) connecting components.

Prosthetic design is an iterative process, in which the model is adjusted based on simulations. Volumes can be reduced to reduce weight, add stiffening ribs in stressed areas, or improve ergonomics. Techniques such as topology optimization and generative design allow for lightweight yet strong structures suitable for 3D printing.

In the case of myoelectric prostheses, the CAD model must integrate electronic components – sensors, micromotors, batteries. These are modeled or imported and embedded

in the assembly, checking the space and fixation. At the end of this stage, a complete 3D model is obtained, ready for simulation and manufacturing.

4. FUNCTIONAL SIMULATIONS AND ANALYSES OF THE PROSTHESIS IN THE VIRTUAL ENVIRONMENT

Before finalizing the design, CAE simulations are essential to verify mobility (kinematic analysis) and mechanical strength (FEA analysis). Kinematic analysis allows the evaluation of finger flexion as a function of cable travel or motor rotation and verifies that the hand closure is complete. Forces in the mechanisms can also be calculated to verify the effort required by the motors or the user.

FEA analysis involves applying real forces to the discretized model to observe the distribution of stresses and strains. Scenarios such as resting on the palm or gripping objects are simulated. Areas of high stress may require optimization. Studies show that materials such as PETG provide adequate resistance to these stresses, confirming the viability of the design. Figure 4 shows the kinematic and static analysis of the closure mechanism of a prosthetic hand.

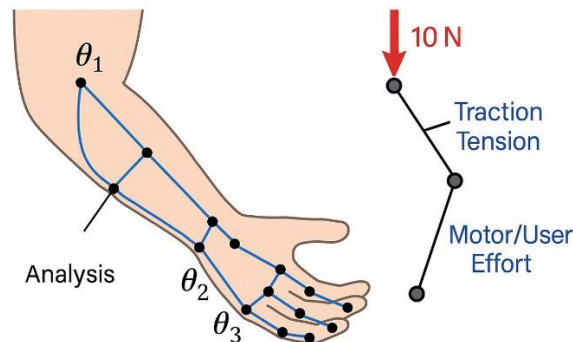


Figure 4: Kinematic and static analysis of the closure mechanism of a hand prosthesis

The technical diagram highlights the movement trajectories of the phalanges during flexion, depending on the traction cable travel or motor rotation. The flexion angles, the forces applied to the fingertips (e.g. 10 N) and the tensions developed in the cables are indicated, useful for functional validation of the biomechanical design.

Figure 5 shows the finite element analysis (FEA) of a biomechanical forearm prosthesis.

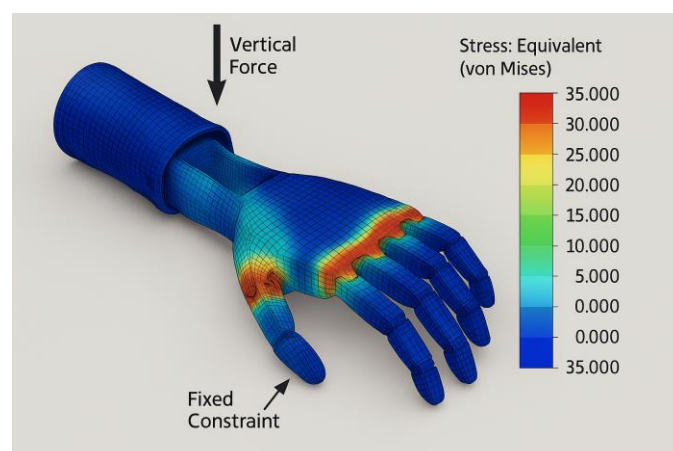


Figure 5: Finite Element Analysis (FEA) of a biomechanical forearm prosthesis

The image highlights the distribution of equivalent stresses (Von Mises) in the prosthesis structure, as a result of applying external forces – such as resting on the palm of the hand or gripping an object.

In addition to static analyses, fatigue simulations can be performed to estimate the durability of the prosthesis over repeated use. These are useful for plastics that are sensitive to repeated cycles. Thermal simulations can also be performed, especially for motorized components, although this is minimal for external prostheses.

Some teams also simulate the interaction of the prosthesis with the human body, analyzing the pressure distribution at the socket. Detailed models (possibly obtained through CT/MRI scans) can highlight the need for inner padding or geometric adjustments for comfort. CAD programs can generate visual reports (e.g. colored stress maps), useful in technical documentation.

5. CONCLUSIONS

Following the computer-aided design process and functional simulations, conclusions can be drawn regarding the technical feasibility of the proposed prosthesis. In general, if the CAD model and analyses show that the prosthesis:

- Satisfactorily mimics functional movements (e.g. performs the main types of grip – spherical, cylindrical, tweezers – necessary for daily activities) and has sufficient degrees of freedom,
- It has a resistant structure (without areas where stresses exceed the limits of the chosen material, or where deformation would prevent operation),
- It fits anatomically (both in terms of overall dimensions compared to the opposing limb and in terms of the interior of the socket adapted to the abutment),
- Fits within weight and volume constraints,
- Allows integration the necessary components (if it has motors, batteries – there is space and access),

then the design can be considered technically feasible. Recent case studies show that CAD-designed and additively manufactured (3D printed) upper limb prostheses can achieve good mechanical performance. For example, a prosthetic hand printed from nylon (PA12) and PETG components has been shown to withstand typical stresses, provided that rigorous design and testing procedures are followed.

Of course, the technical feasibility on the computer must be confirmed in practice. The next step after the virtual design would be to manufacture a physical prototype (by 3D printing the components or CNC machining, depending on the materials chosen) and test it on the bench and possibly with the user. In this scenario, the goal is not to make a physical prototype, but the technical analysis suggests what *would work* and what problems might arise. For example, if the simulations indicate critical areas, the designer can strengthen them before manufacturing, increasing the chances of the prototype's success.

An advantage of the CAD methodology is the possibility of rapid iteration: if an FEA analysis shows that a finger would break under a certain load, the design can be modified (increased thickness, different material) and re-engineered immediately, saving time and costs compared to the traditional “trial and error” method on physical prototypes. Thus, the virtual final product – the personalized biomechanical prosthesis – comes out optimized and ready for manufacturing.

In conclusion, designing a personalized forearm prosthesis using CAD simulations is a technically feasible approach, which allows to anticipate the performance of the prosthesis and

adjust it before investing in physical prototyping. By applying biomechanical principles and using modern engineering tools (3D scanning, parametric modeling, finite element analysis), *tailor-made* prostheses for the patient can be obtained, with a high level of accuracy and functionality. The feasibility is supported by numerous studies – from complex mechatronic prostheses made entirely by digital modeling to simpler e-NABLE solutions made of plastic – which demonstrate that, as long as the design meets the requirements of strength and ergonomics, the prosthesis can be manufactured and used successfully. In the next stage (second paper), we will analyze how 3D printing technology influences the actual realization of the prostheses and what are the challenges to overcome in order to translate such a design into practice.

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