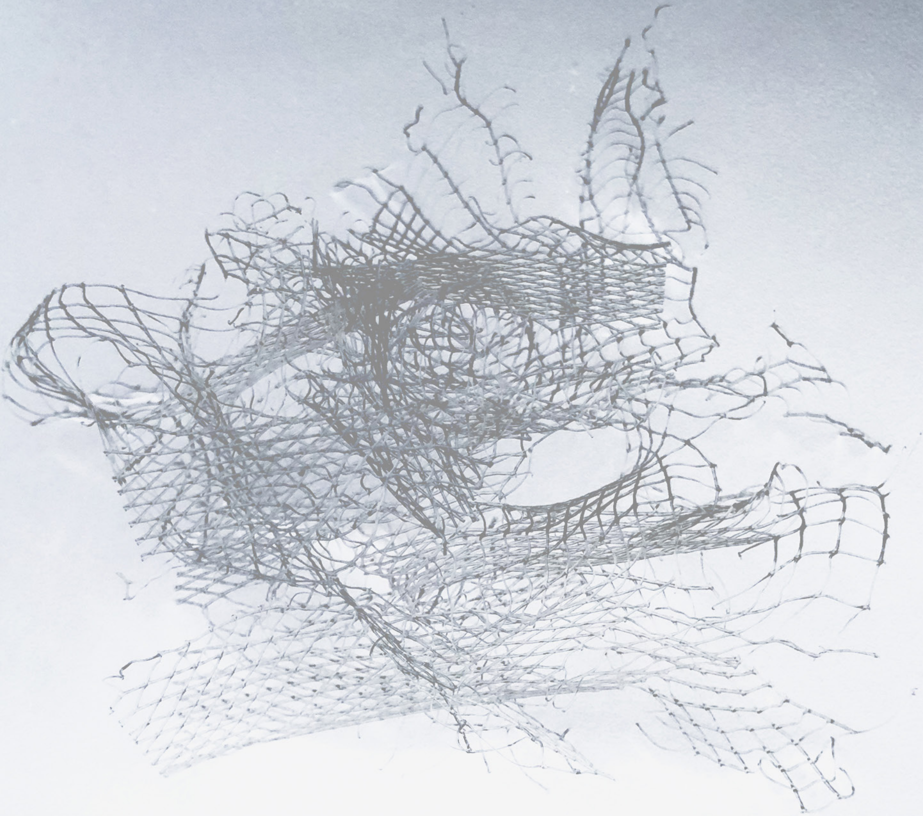

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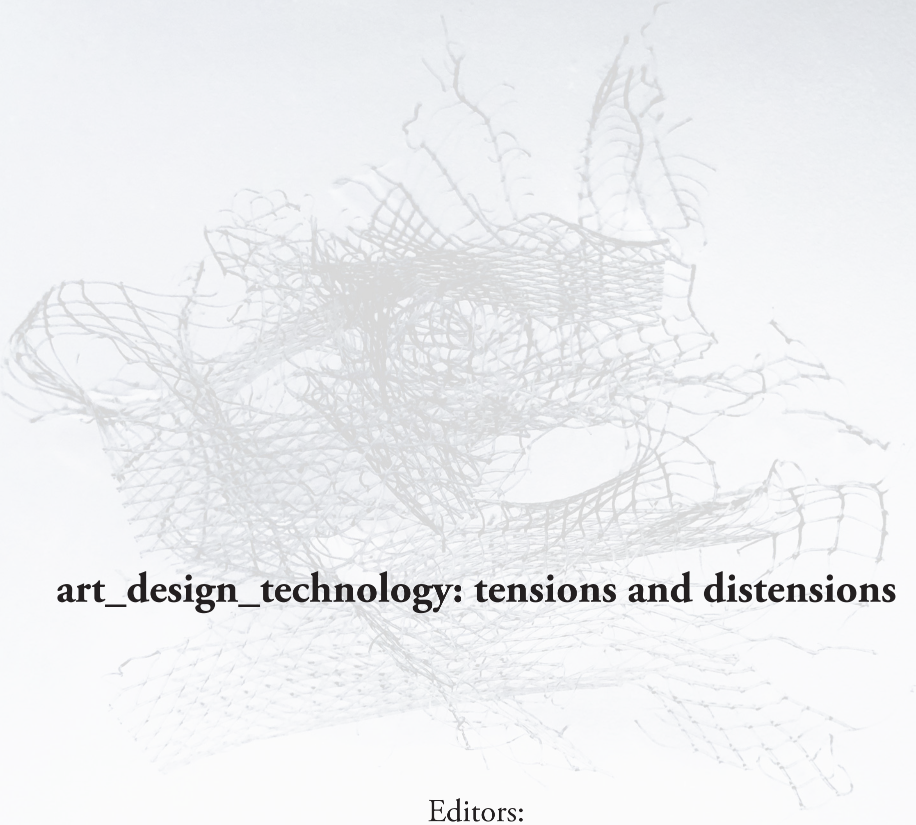

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CHAPTER 8

3D SCANNING, PARAMETRIC DESIGN, AND DIGITAL FABRICATION IN THE CONTEXT OF ASSISTIVE PRODUCT DEVELOPMENT

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Abstract

This chapter discusses how 3D scanning, parametric design, and digital fabrication enhance the development of assistive products. These technologies allow, respectively: greater adaptation of devices to the user's body; dynamic exploration of different shapes through parameter variation; and the incorporation of aesthetic demands such as color, detail, and specific materials. First, we will examine the potential of 3D scanning, parametric design, and digital fabrication. Next, we will present three examples of assistive products that employ these digital technologies, entirely or to a significant degree, in the creative processes. This will demonstrate how these methods contribute to the creation of individualized and unique products. Finally, we will analyze a specific case study, highlighting how the application of these technologies and their resulting uniqueness can increase the user's self-esteem.

1. Introduction

Digital technologies provide greater flexibility in the production of objects, differentiating them from those created through large-scale manufacturing of identical products, made using molds. In such mass production, the goal is to supply a generalized need without accounting for the unique characteristics of individual human beings, instead addressing the average requirements of most people. Those who do not fit this standardized profile must adapt to participate as active and functional members of society (Hawkins, 2022, p. 9).

However, this reality has changed significantly due to technological advancements that enable adaptive production and product customization for everyone. This can occur through the user's selection and combination of project components or through personalization that incorporates specific material details into the product.

Assistive technologies are particularly well-suited to this context within the healthcare field. Each person has or is going to have distinct physical and functional limitations, and these technologies prioritize the development of products tailored to individual needs. This new perspective on assistive technologies considers not only the functional aspect but also the sociocultural context experienced by the user. As a result, everyone's body is seen as unique rather than an average of a desired standard.

Individuals with visual, auditory, or motor impairments who are supported by such assistive technologies do not need to adapt to interact with these devices. On the contrary, their preferences and needs serve as the guidelines for creating the object, which can then be customized and/or personalized.

2. Potentialities of 3d digitization, parametric design, and digital fabrication

Digital technologies enhance the processes of designing and producing artifacts. In addition to enabling the creation of virtual objects that are mathematically defined and manipulable through algorithms, these technologies establish a direct correlation between what can be digitally created and what can be physically constructed. Conversely, they also incorporate the possibility of translating physical objects into virtual objects through digitization, allowing everyday three-dimensional objects to exist as models within a computer.

In this context, digital fabrication processes mediate the flow of information between digital and physical media. As Kolarevic (2003, p. 33) suggests, "constructability" is a direct function of "computability." Consequently, the steps involved in the information flow can begin with the dimensional capture of a physical three-dimensional object, ensuring the representation of its geometry in the virtual plane. This capture enables manipulation of the virtual model through various algorithms, such as parametric design systems. Such manipulation may result in alterations to the object's original shape and/or its subsequent materialization in the physical medium, facilitated by different digital fabrication technologies.

As proposed by Moles (1990, p. 112), it is possible to achieve a "singularized multiplicity" of products, characterized by their distinctiveness, through the use of various algorithms whose variations derive directly from their numerical properties. The object is established as the result of algorithmic manipulations which, when adjusted, allow creators to generate multiple distinct objects that are nonetheless similar in their structure. These variations yield unique representations and materializations tailored to the specific needs and preferences of users.

Considering the aforementioned potential of digital technologies, we will now present three stages involved in the design and materialization of assistive products. When employed together, these stages broaden the possibilities for customizing and/or personalizing such devices. They are: 3D digitization, parametric design, and digital fabrication utilizing additive manufacturing. These technological procedures result, respectively, in the capture of dimensional data from a physical artifact—or even a person—into the digital realm; the manipulation of the virtual model's geometry through computational systems employing parametric equations; and the physical materialization of the model.

Objects are, essentially, numerical descriptions defined by topologies and geometries, which can be physically represented or three-dimensionally printed to meet the individual needs of each user. The information thus flows between the physical and digital realms in a process that is not necessarily unilateral.

2.1. 3D Digitization

The process of translating physical objects into the digital realm is the reverse of computer-assisted digital manufacturing. From any physical object, it is possible to generate a digital representation of its geometry, a process commonly referred to as reverse engineering. In this context, scanning technologies create highly accurate 3D models of pre-existing objects.

An example of this technique can be found in the project developed for the Pinacoteca of the State of São Paulo, as described by Celani et al. (2008, pp. 231-232). In this project, the redesign of part of the museum's permanent collection was requested, which involved digitizing 3D pieces from the collection. According to the authors, geometric models of real-world objects could be obtained manually, semi-automatically, or automatically. In the manual method, the user measures the real-world object with a measuring device and transfers the values into CAD software to produce a geometric model. In contrast, the automatic and semi-automatic methods perform both measurement and 3D modeling with minimal or no user intervention, making them significantly faster, especially for complex surfaces.

By associating the concept of reverse engineering with augmented sculpting, Adzhiev, Comninos, and Pasko (2003, p. 211) emphasize the importance of this creative approach as a process that can start from the digitization of a physical object. Once existing as a digital model, the object can be manipulated and, eventually, manufactured into a new, distinct 3D object.

New visual configurations can be realized through different creative pathways. As Kolarevic (2003, pp. 31-33) suggests, translational approaches stand out, moving either from the physical to the digital or from the digital to the physical.

Alencastro et al. (2019), building on Pavlidis et al. (2007), consider 3D digitization as composed of three stages: a) preparation, which defines the technique, methodology, scanning location, and safety planning; b) digital acquisition, which refers to the data capture of the object's surface; c) processing, which involves the modeling phase of the object, determined by different processes.

According to Celani and Cancherini (2009), 3D digitization techniques can be divided into two main groups based on the technology used: contact and non-contact 3D digitization techniques. Rocha (2017, p. 22) points out that the creation of 3D models using the non-contact method is advantageous, as it allows visualization of the object from different angles and provides simultaneous virtual access to the representation for multiple users.

In this context, the most common methods are laser scanning, structured light, and photogrammetry. The triangulation method uses an infrared laser beam that, when it contacts the object's surface, is distorted and captured by a camera. By triangulating the scanned object, the camera, and the laser, the original shape of the scanned element can be mapped. This type of technology can be employed in fixed platforms with rotating bases or manually, with the scanner moved around the object, person, or environment being scanned. The structured light method uses a video projector to cast distributed sequences of patterns onto the object's surface. A camera captures the patterns deformed by the surface, enabling the calculation of the positions of the points that make up the object's topography. Photogrammetry, the most accessible and popular method, is based on the successive capture of images at regular distances around an object, using a dedicated camera or a mobile phone camera. The technique relates a set of sequentially captured images around an object, utilizing the principle of stereoscopy[1]. Specific software interprets these images and reconstructs the 3D model. The sequential grouping of these images to create the three-dimensional object is ensured by the richness of detail in both the photographed object and the background in which it is positioned. Elements such as colors, textures, and shadows play an important role in the grouping and mapping of the set (Bernier, Luyt, Reinhard, 2015, pp. 26–29).

3D scanning, therefore, allows that dimensional or anatomical data of an object or person can be accurately captured to serve as the basis for bespoke customization processes, such as the creation of assistive devices. The geometric structure of the object or the user's body is digitally transposed and made available for subsequent manipulations.

In the case of parametric design, algorithms are used to create complex and personalized products or structures. This process provides a set of parameters or variables used to generate a unique solution.

Assuming the digitized model maintains precision in relation to the physical object or anatomy to be represented, 3D scanning becomes an essential tool for capturing and mapping the physical elements in the digital realm. It is the most accurate way to digitally reproduce the geometry of human anatomy. This involves digitally representing a physical model using various 3D scanning devices. The accuracy of the object's representation may vary depending on the scanning device used.

Once scanned, the three-dimensional object is represented as a digital model on a computer using spatial coordinates: x (width), y (depth), and

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[1] According to Siscoutto (2018) et al., three-dimensional (or stereoscopic) vision results from "…the brain's interpretation of the two two-dimensional images captured by each eye from its perspective, along with visual accommodation information about the degree of visual convergence and divergence."

z (height). In the virtual space, the object is described through numerical data, which can undergo parametric manipulations and restructurings. Visualization occurs through techniques that transform the data stored in the machine's memory into images displayed on the two-dimensional support of the screen.

2.2. Parametric Design

New imaging technologies involve sophisticated programs for scanning, processing, and three-dimensional modeling, which are becoming increasingly accessible and commonplace. These systems incorporate programming and data parameterization to achieve precise and personalized results.

Parametric design functions as an algorithmic system oriented toward problem-solving. It is based on translating relationships between internal and external variables and establishing correspondences between design elements and their parameters (Assasi, 2019). A parametric project is a technological tool that uses algorithms to conceive and subsequently produce complex and personalized products or structures. These algorithms rely on a set of parameters and variables to generate a unique solution.

According to Casini (2022, p. 299), parametric design can be defined as a process based on an algorithmic approach that expresses parameters and rules to define, encode, and clarify the relationship between the designer's intent and the design response. For this author, parametric design primarily involves describing and creating geometry flexibly by linking decision variables and constraints (parameters), which establish interdependencies between objects and define their transformational behavior.

The notion of parametrics used to describe three-dimensional models in mathematics has been investigated since the end of the 19th century. However, it was not until the late 20th century that Ivan Sutherland created Sketchpad—without directly using the term parametric—a digital interactive model capable of accelerating the calculation of parametric equations.

In 1982, AutoCAD was launched; however, its parametric functionality was only added in the AutoCAD 2010 version. The first commercially popular parametric engineering software was Pro/ENGINEER, released in 1988 and created by Samuel Geisberg. In 1993, many of the parametric features of Pro/ENGINEER were introduced into CATIA v4 by Dassault Systèmes.

It was only in the 2000s that parametric software, such as ArchiCAD and Revit, became commercially available. The parametric equations used in Revit were embedded in the user interface and were limited. However, scripting interfaces enabled parametric modeling in projects. These interfaces and the available programming languages gained popularity, especially when visual programming packages became available, allowing for the creation of complex equations and algorithms using the parameters of CAD or BIM software. In the first 20 years of the 21st century, 3D modeling programs based on parametric equations, such as 3D Studio Max, Maya, and Rhino, have been widely used in architecture. Parametric visual programming packages were developed for these programs, such as Rhino Grasshopper 3D, Maya Embedded Language (MEL), and Max Creation Graph (Assasi, 2019).

In parametric design, equations are used to describe the relationships between objects, defining associative and linked geometry. This establishes interdependencies between objects, with their behaviors defined during transformations. These interdependencies become the structural and organizing principles for generating and transforming geometry. How these are structured and reconfigured depends largely on the designer's skill in accurately creating these relationships (Kolarevic, 2008, p. 121).

In essence, parametric design aims to overcome the limitations resulting from the independent nature of design elements in conventional computer-assisted drawings. It is based on defining the relationships between elements, whether simple or grouped, and how these relationships are organized and controlled (Casini, 2022, p. 299).

Kolarevic (2008, p. 122) emphasizes that the potential of parametric design lies in the designer's ability to effectively edit the nuances of the underlying parametric generative system. This ability requires expertise and skill, as the designer must intuitively know which small quantitative changes can produce qualitatively different results.

Instead of designing a single solution, the designer now creates a multidimensional design space. Each dimension represents one of the critical parameters exposed by the parametric model, which varies according to the design situation (Casini, 2022, p. 300).

2.3. Digital Fabrication

It is now possible for an object to transition between the physical and digital environments (and vice versa), according to the project's requirements and the inventor's subjectivity.

In conventional manufacturing processes, many steps are performed manually or with the aid of non-automated machines. In digitally controlled processes, however, most steps can be automated. Automated manufacturing processes offer an alternative for materializing virtual models of varying complexities, enabling the production of prototypes and final objects.

This automation began with machines performing subtractive manufacturing, such as computer numerical control (CNC) lathes and milling machines. These machines were large and expensive, making them accessible only to large industries. Recently, additive manufacturing machines, employing more affordable technologies, have been introduced to a broader audience.

In general, the automated process is divided into five stages (Celani, 2009, p. 167). The first stage defines the proposed model, considering its objective, scale, and configuration. The second stage includes the definition of the production techniques and materials. The third stage refers to the preparation of files to produce the model. The fourth stage is related to part production of the parts of the model. And in the fifth stage, the assembly of the parts and the finishing takes place. The three intermediate stages differentiate digital processes from manual or non-automated ones. However, the final stage (assembly and finishing) is common to both.

Digital computation and fabrication use CAD (Computer-Aided Design) and CAM (Computer-Aided Manufacturing) technologies to transform virtual models into physical objects. In other words, a virtual model made of bits is encoded by computer software and processed by a digital fabrication machine, which decodes these electronic impulses and materializes them into the realm of atoms. One of the most remarkable features of digital fabrication is its ability to transform highly complex virtual models into physical solids.

Using CNC (Computer Numerically Controlled) machines, it is possible to reproduce objects using various materials and techniques. Automated production processes are subdivided into three main methods: a) additive process (also known as 3D printing or rapid prototyping), that builds three-dimensional objects by depositing successive layers of material; b) subtractive process, that removes specific volumes of solid materials through machining, utilizing multiple axes; c) laser cutting process, that cuts thin materials (such as paper and fabric) or thicker materials (such as wood and acrylic).

Given the specificity of each digital manufacturing technology, it becomes essential to become familiar with and understand them. Kolarevic (2008, p.123) emphasizes that the design process should be based on the capabilities of the machines. A thorough understanding of techniques and materials necessarily implies the selection of the appropriate technology, as each project "chooses" its specific type of production. Thus, it is the designer's responsibility to integrate this knowledge to establish an intrinsic and interdependent relationship between the conceptualization and the execution of the object—that is, its materialization.

3. The creation of assistive products: some examples

The term "assistive technology" refers to technology designed for use in devices or products aimed at enhancing, maintaining, or improving the functional abilities of individuals with disabilities or reduced mobility. However, as previously mentioned, we understand that the design of assistive technology can also address gaps in user satisfaction and needs. This outcome can be achieved if the creation process involves collaborative work between the team and the user, prioritizing the use of the aforementioned digital technologies to expand customization and/or personalization possibilities.

When utilized in an interconnected manner, digital technologies enable the production of personalized and tailor-made devices that meet the preferences and needs of everyone. The creation of assistive products has been significantly transformed by the ability to obtain precise anatomical measurements of an individual, dynamic exploration of shapes by varying parameters, and digital fabrication of objects to meet specific demands.

In this section, we present examples of assistive products that illustrate how the use of 3D scanning, parametric design, and/or digital manufacturing facilitates the customization and/or personalization of these objects, emphasizing the principle that the user is a decision-making agent in the design process. Subsequently, examples will be provided in three areas: visual impairment, hearing impairment, and motor impairment.

Among existing assistive products for low vision, eyeglasses are the most explored from an aesthetic perspective (Pullin, 2009). Many fashion brands invest in various frame models, elevating eyeglasses to the category of accessories. Despite the variety of frame models, they are rarely personalized to fit the facial measurements of everyone.

The project by Bertol et al. (2010) investigates the personalization of eyeglass frames that are aesthetically and ergonomically adapted to the individual measurements of the user. Using 3D scanning, anthropometric data of the user's face—such as measurements of the nasal, ocular, and facial regions—were obtained to create an accurate facial virtual model. This facial model was imported in 3D modeling software, enabling a matrix frame design, developed using parametric design, to be adapted to the user's measurements. The parameters of the design, including lens and temple measurements, were adjusted to fit the individual's facial shape while adhering to ergonomic requirements based on the proportions of eyeglass frames as defined by ISO 8624 standards. Once the frame design was finalized, the production phase began, with the frame being machined using a CNC milling machine.

In the context of assistive products available on the market for hearing, invisibility is a key design premise. The miniaturization of technology has enabled the reduction in the size of devices. However, it is worth noting that the smaller the device, the greater the loss in performance (Pullin, 2009; Profita et al., 2018). However, in opposition to invisibility, there are some user groups have created online forums to share personalization proposals for their own hearing aids. These proposals include different colors and visual elements, giving visibility to the devices and elevating them to the status of fashion accessories (Profita et al., 2018).

In this context, the OH behind-the-ear hearing aid, designed by Cunha (2017), proposes customization to counter the trend of hearing aid invisibility. The new product has a functional part in the shape of a flat cylinder, located in exposed areas of the ear, and it can be customized through interchangeable rings with different finishings that cover the functional part of the device. The device is intended to symbolize an accessory rather than being hidden as a medical item. The designer's proposal is for the hearing aid to allow the user to exercise his/her right to choose by using the product as a form of self-expression. Using universal anthropometric measurements, the hearing aid was modeled in parametric design software. For the final prototype, an additive manufacturing technique was used, specifically Fused Deposition Modeling (FDM)[2].

In the category of assistive products designed for the loss of upper and/or lower limbs, there is currently a gap in the availability of prostheses that foster a strong sense of identification between the user and the device. The prosthesis models available on the market largely prioritizes mechanical features, focusing on meeting functional requirements for restoring lost movement. Generally speaking, insufficient attention is paid to the aesthetic qualities of prosthetics, which may lead users to abandon these devices.

The Swedish researcher Anders Lindén Døviken, in partnership with Norsk Teknisk Ortopedi (NTO), developed a customized surface for an upper-limb myoelectric prosthesis, with the active participation of the user (Døviken & Wallerud, 2023). The project considered the preferences of the user, who was born with a congenital upper-limb disability. It incorporated the user's conceptual suggestion to represent human anatomy on the prosthesis. The surface of the prosthesis was designed to simulate the visual characteristics of muscles distributed along the forearm region.

To build the prototype of the prosthetic surface, a 3D scan was performed on a plaster mold of the user's residual limb. Subsequently, a surface was modeled in parametric design software, encompassing both the area occupied by the scanned residual limb and the prosthesis's internal electronic components. Textures were applied to simulate muscles, adhering to the user's proposed design. Once the digital model of the surface was finalized, it proceeded to the fabrication stage using 3D printing with PLA (polylactic acid), employing fused deposition modeling (FDM) technology.

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[2] In this manufacturing process, each cross-sectional layer is created by melting a filament, which solidifies upon cooling.

After printing, the piece underwent several finishing steps to mitigate the "layered lines" characteristic typical of the printing process. A spray coating was applied to fill the originally printed surface, which was then sanded and received a base layer of red paint. Over this base layer, acrylic paint was manually applied to simulate the muscular coverage of the forearm. The final prototype pleased the user, meeting their desire for a prosthesis that closely resembled their measurements and anatomical visual references.

These projects demonstrate how 3D scanning, parametric design, and digital fabrication technologies enhance the interaction between producers and users. They highlight how the potential of digital technologies makes products more suitable and tailored to users, ensuring aesthetic value and promoting pleasure and well-being.

4. Case study

Motivated by the high number of lower-limb amputations annually in the United States, industrial designer William Root developed the EXO Prosthetic Leg[3]. This prosthesis partially restores the lost limb's functionality and helps rebuild the user's self-esteem.

The design of the prosthetic aims to adapt it to the user's body anatomy by combining 3D scanning, advanced 3D modeling software, and 3D printing, simplifying the production steps for limb prosthetics. Traditional production processes require multiple molds, workshops equipped with expensive machinery, and highly trained technicians. This significantly increases the final cost, making the product less accessible and limiting the range of available models. Root simplified the production to just three stages, making it more precise, less expensive, personalized, and better suited to the user's anatomy.

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[3] Its name references the exoskeleton, an external bone structure that provides support. Information about the "EXO Prosthetic Leg" is available at: https://willrootdesign.com/exo-prosthetic-leg. Accessed on: October 7th, 2024.

In producing the EXO Prosthetic Leg, the first step was capturing the user's anatomical measurements. A contact 3D scanner[4] was used to create an accurate digital model of the patient's residual limb and the intact limb on the opposite side of the amputation. Based on the scan of the intact limb, anatomical measurements were referenced for constructing the prosthetic. For scanning the residual limb, a technology called FitSocket, developed by the MIT Biomechatronics Lab, was used. This technology captured the properties of the user's leg tissue, ensuring a better fit between the residual limb and the prosthetic socket.

The second step combined the geometries obtained from scanning the residual limb and the intact limb into a parametric mesh model using 3D modeling software. This precise virtual model, which replicated the user's lost lower limb, was digitally adapted to integrate a structure that allowed for the attachment of the prosthetic's functional mechanisms. Using the parametric tools of the 3D modeling software, the prosthetic's external mesh was designed with a personalizable perforated surface pattern. By making the prosthetic hollow internally and perforated externally, its weight was reduced. The patterns covering the structure can be personalized, allowing the user to identify with their prosthetic.

The third step involved materializing the finalized virtual models from the modeling phase using additive digital manufacturing methods. Components of the prosthetic, such as the leg socket, calf, and foot, were 3D printed using the Selective Laser Sintering (SLS) technique[5]. After printing the prosthetic parts, assembly was completed using connectors that joined the structural elements to the functional mechanisms of the prosthetic.

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[4] The scanner used in the EXO Prosthetic Leg project is a contact scanner model, which employs a digital or manual probe; these are slower and more costly. By contrast, the 3D scanners discussed in section 2.1 of this chapter are more accessible and do not require direct contact with the object, as they use lasers and/or structured light.

[5] In this method, the laser fuses metal particles to form the final titanium piece, ensuring durability, lightness, and biocompatibility.

The final prosthetic limb was produced through an automated process that not only ensured anatomical precision concerning the lost limb but also reduced the prosthetic's cost and enabled user personalization. This case study demonstrates that, in the context of assistive products, there is an effective integration of 3D scanning, parametric design, and digital fabrication technologies. The continuous feedback between the physical and digital realms ensures a creative dynamic, allowing for constant revisions and adaptations throughout the project.

Moreover, these technologies guarantee a better fit of the prosthetic to the user's body, and by varying the external mesh parameters, they allow for the incorporation of user-specific features. This project exemplifies a successful balance between functionality and aesthetics. The possibility of customization and personalization contributes to increased self-confidence and self-esteem, fostering a sense of belonging between the user and the product. Beyond being functional instruments, prostheses created with these technologies promote greater social acceptance for their users.

5. Final considerations

3D scanning, parametric design, and digital fabrication enhance the creation of assistive products, making them more bespoke and appealing to individuals with hearing, visual, or motor impairments. These technologies allow users to be at the center of the design process, manage it, and incorporate their dimensional data. A good integration of users with assistive devices ensures greater comfort during use, improves physical adaptation, and minimizes the chances of abandonment of the device. In addition to their functionality, these devices promote greater social acceptance of individuals with disabilities within their sociocultural contexts, consequently increasing their self-esteem.

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