

Parametric Design of Custom Prosthetic Limbs Covers Using 3D Body Scanning and Algorithmic Modeling for Additive Manufacturing

Mohammad Saeid HOSEINI ^{1*}, Khashayar HOJJATI EMAMI ^{1#}, Mahdi MALEKKHOUYAN ^{2§}

¹ Industrial Design Department, Iran University of Art, Tehran, Iran;

² Najaf Abad Azad university, Isfahan, Iran

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Abstract

Prosthetic limbs personalization has been revolutionized by the development of digital fabrication and computational design; yet, aesthetic features of prosthetic limbs are still mostly neglected. Based on an analysis of anatomical scanning accuracy and algorithmic modeling techniques, this article presents a complete generative design workflow for custom limb prosthetic covers. Captured 3D high-resolution surface data is imported into Rhinoceros where Grasshopper scripts create adaptive shell geometries guided by curvature, ventilation, pattern density, and symbolic motifs. A user-friendly interface enables individuals to incorporate cultural and personal preferences from decorative patterns to functional perforations supporting an iterative and collaborative design process. The digital models are tuned for several additive manufacturing techniques and materials to guarantee compatibility across prototyping methods. To validate the workflow, a series of functional prototypes were fabricated and evaluated through user centered testing. Usability testing was conducted with one participant using a lower limb prosthetic, who engaged in the design customization process and provided feedback through structured interviews and a Likert scale survey. Results indicated increased user satisfaction, perceived identity alignment, and a greater willingness to wear the device in social settings. Qualitative feedback emphasized the emotional value of symbolic motifs and lightweight ventilation features. By merging technical precision with expressive customization, this framework establishes a new paradigm for human centered, aesthetically enriched prosthetic solutions.

Keywords: Prosthetic Limbs, 3D Scanning, Additive Manufacturing, Generative Modeling, Personalization.

1. Introduction

Prosthetic devices have, for a long time, been merely functional, and their main goal has been to restore motor ability to individuals with limb amputation. However, recent advances in digital design and fabrication technologies have provided new possibilities for expanding the role of prostheses beyond mechanical performance; a role that now also includes self-expression, comfort, and user identity. In this context, parametric design and additive manufacturing (AM) have emerged as powerful tools for the development of highly customized prostheses with rich aesthetic aspects.

Traditional prosthetic covers have often been standardized and limited to a few stylistic options, establishing little relation with the individual's identity. This lack of personalization can lead to reduced psychological acceptance and user satisfaction, especially in social contexts. In contrast, the combination of 3D body scanning and computational modeling enables the design of covers that are anatomically precise, culturally compatible, and emotionally attractive, produced exclusively in accordance with individual needs.

Research has shown that individuals following lower-limb amputation due to trauma face significant psychological problems such as anger, reduced self-esteem, and the need for specialized psychological support; moreover, negative reactions from family and society to their physical appearance can make their adaptation process more difficult [5]. In addition, despite the functional benefits of lower-limb prostheses, many patients refrain from using them solely due to their undesirable appearance [2].

* Master graduate, Industrial Design Department, University of Art, Tehran, Iran;
Email: ms.hoseini@art.ac.ir, Mobile: +989121819819

Assistant Professor, Industrial Design Department, Faculty of Applied Arts,
University of Art, Tehran, Iran; Email: k.emami@art.ac.ir, Mobile: +98 912 578 7971

§ Bachelor student, Industrial Design Department, Najafabad Azad university, Isfahan, Iran;
Email: mahdimalekkhouyan@gmail.com, Mobile: +989134649650

Recent advances in digital technologies such as 3D printing and 3D scanning have transformed traditional workflows in the prosthetics and orthotics industry, enabling faster, more efficient, and more personalized production [11]. This article presents a novel workflow for the design and fabrication of customized prosthetic covers, which includes acquiring high-resolution 3D scans, generating adaptive geometries based on anatomical and aesthetic parameters through algorithmic modelling, and implementing them in the Rhinoceros and Grasshopper environment. This system features an interactive user interface that allows users to select and adjust characteristics such as surface patterns, perforation density, ventilation areas, and symbolic motifs.

The additive manufacturing process, in addition to reducing waste and costs, enables rapid prototyping and cost-effective customization [10]. The final digital models are also optimized for additive manufacturing to be both technically stable and aesthetically reflective of the user's design and identity. This approach, by combining technological precision and individual expression, supports human centred design and provides a fresh perspective on integrating prostheses into everyday life.

1.1. The Importance of Additive Manufacturing and Parametric Design

One of the key challenges in the field of bionic prostheses is the high cost of development and fabrication, which stems from the need for extensive human and material resources, and consequently prevents many patients from accessing rehabilitation services [8]. Despite the increasing integration of digital technologies in prosthetic design, there remain gaps in aesthetic customization, user participation, and manufacturability. Most studies have either focused on practical functions (such as socket attachment and structural durability) or on the technical aspects of 3D printing, while the emotional, cultural, and identity aspects of prosthetic covers have received less attention. Moreover, while parametric and algorithmic tools have been extensively explored in architecture and product design, their potential for creating customized aesthetic prostheses has not yet been fully exploited. Current research often also overlooks the development of accessible design interfaces—tools that could enable non-designers, particularly prosthesis users themselves, to meaningfully participate in the customization process. This study addresses these gaps and proposes an integrated workflow that combines body 3D scanning, parametric modeling, and additive manufacturing with a user-friendly interface, thereby allowing prosthetic users to actively shape both the functional and symbolic dimensions of their devices.

2. Background and Related Work

Traditionally, the evolution of prosthetic design has focused on restoring mechanical function, with less attention given to customization and aesthetic expression. Common prosthetic covers are often mass-produced and offer limited options in terms of form, style, or compatibility with individual needs. However, in recent years, digital technologies—particularly 3D scanning, parametric design, and additive manufacturing—have created transformative opportunities for customization in the prosthetics industry.

Examples of this transformation can be seen in recent studies. In one proposed process, a set of 3D scans of the lower leg, along with longitudinal and circumferential measurements, was collected, and ultimately, the design of a customized prosthetic cover was carried out using CAD software and scan data; this approach enables the production of covers that are precise and conform to the individual's anatomy [14]. Additionally, traditional molding methods are increasingly being replaced by digital workflows involving 3D scanning and CAD, allowing for rapid design iteration and better customization of prosthetic sockets [10].

On the other hand, 3D-printed prostheses, like other technologies, have also gone through the Hype Cycle; a proper understanding of their capabilities and limitations can help specialists apply this technology more effectively in orthotics and prosthetics [4]. In this regard, methods for geometric analysis of body surfaces, when converted into mathematical-logical definitions, offer greater efficiency and flexibility compared to statistical approaches or traditional molds in identifying landmark points [9].

Findings have shown that additive manufacturing can reduce the number of production sessions and the need for specialized personnel, while digital data storage saves space and facilitates reproduction [11]. Furthermore, 3D printing enables prostheses and their covers to be produced not only based on body dimensions but also through algorithmic modeling and parametric design—an approach that significantly enhances customization and design flexibility [12]. Studies have also shown that parametric

modeling in the CAD environment simplifies the design process, allowing even non-specialist users to produce customized orthoses and prostheses in a short time [10].

While the research by Stefanovic and colleagues, using 3D scanning of the healthy limb, CAD modeling, and additive manufacturing technology, provided an efficient framework for designing and producing customized prosthetic covers [14], the present article goes a step further by using algorithmic modeling and parametric design to automate and optimize the design process. Our proposed approach not only allows for sizing and customization similar to previous studies, but by using algorithmic design tools, the steps of prosthetic cover customization become more flexible and efficient. Thus, this research complements previous studies and advances their outcomes in terms of accelerating design, improving fit accuracy of covers, and developing diverse patterns for different users.

3. Methodology

Using a design-based action research method, this research explores the development and evaluation of a generative workflow for manufacturing customized prosthetic covers for the lower limb. The proposed approach integrates digital scanning, computational modeling, and additive manufacturing within a user-centered framework. The workflow consists of six primary phases: data acquisition, parametric design, interface development, print setup, prototype production, and evaluation with users.

3.1. Data Acquisition

High-resolution 3D scans of the user’s lower limb were performed using a structured light scanning system with sufficient accuracy. In (see Figure 1), several common devices accessible to users are introduced. Each scanning session lasted approximately 10 minutes, after which the mesh was corrected and refined in Rhinoceros 3D software, and then the data, along with the reference mesh, were imported into Rhinoceros 3D for cover modeling (see Figure 3). This process ensured precise surface geometry and reliable anatomical reference points, which were essential for fit and customization. In this study, a Creality brand 3D scanner with an accuracy of 0.1 mm was used (see Figure 2). According to recent studies, accuracy within this range is fully within the clinically acceptable limits and can be used for capturing the shape of residual limbs in prosthesis fabrication [1].

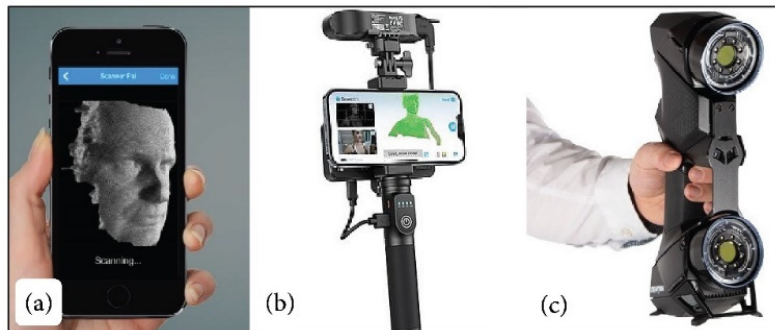
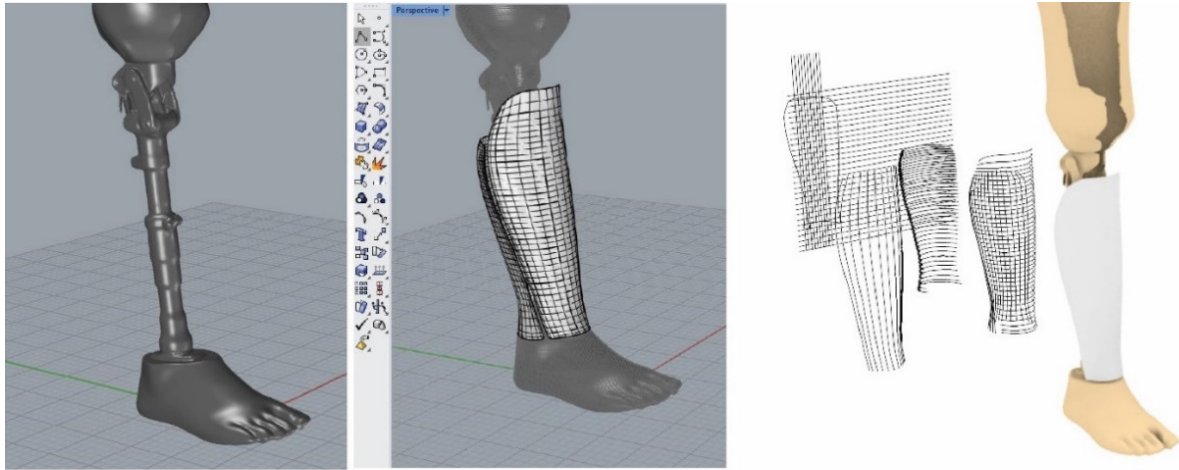


Fig. 1. (a) LiDAR sensor in mobile phones, low measurement accuracy; (b) 3D scanner with 0.1 mm measurement accuracy, medium range; (c) Industrial 3D scanner, high measurement accuracy and expensive.



Fig. 2. (a) Process of 3D scanning, involving acquisition of geometric dimensions and point cloud; (b) Final model obtained from the scan and its meshing.



A) Import a 3D scan file into Rhino. B) Generate the base reference mesh. C) Extracting and marking the reference points.

Fig. 3. Steps of processing the scanned file, extracting essential points, and deriving reference shells.

The reference shell is designed according to movement limitations within restricted angles (see Figure 4), and in this process, aspects such as the cover’s contact with the fixed and moving components of the prosthesis are checked. Then, the main shells are extracted according to the ergonomic form of the body (see Figure 5) and prepared to be completed in the algorithmic stage using various parameters.



Fig. 4. Examination of different prosthesis angles to identify movement limitations.

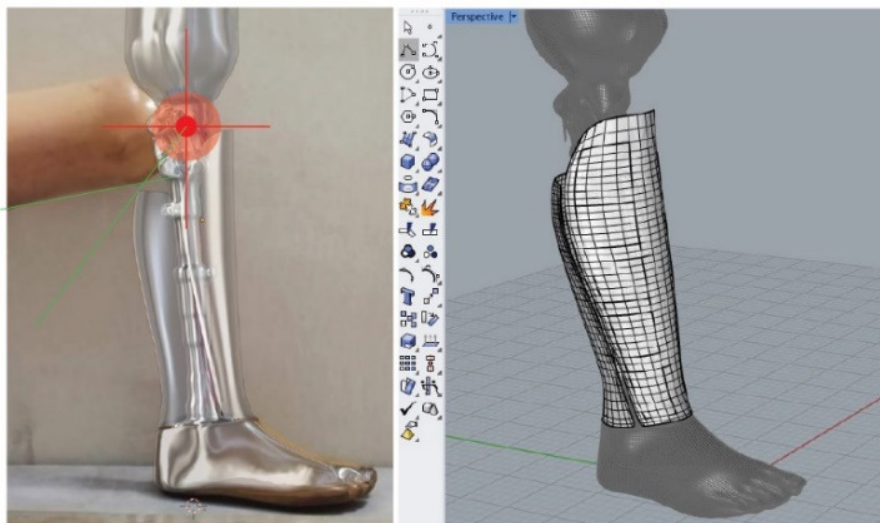


Fig. 5. Examination of different prosthesis angles to identify movement limitations.

3.2. Prototyping and User Evaluation

To validate the proposed workflow, a set of functional prototypes was fabricated and tested by a lower-limb prosthesis user who participated in the design during the customization process. User evaluation was conducted using a mixed-methods approach, including a semi-structured interview to collect qualitative feedback and a Likert-scale (1–5) questionnaire to record quantitative data. The criteria examined included overall satisfaction, comfort, identity alignment, and social acceptance. Due to time and resource limitations, the study was conducted with only one participant and is therefore considered a pilot study. The main goal of this stage was to assess feasibility and identify strengths and challenges of the proposed workflow. Future research with larger and more demographically and prosthesis-diverse samples will be planned to increase the generalizability of the results. These findings indicate the positive impact of integrating computational design, human centered principles, and additive manufacturing on the acceptance and social interaction of customized prostheses [8].

Table 1. User Evaluation Results (Pilot Study)

Evaluation Criteria	Score (1–5)	Feedback Summary
Satisfaction	5	Very satisfied with the personalization and fit.
Comfort	4	Lightweight design improved usability, minor pressure adjustments needed.
Identity Alignment	5	Symbolic motifs strongly reflected personal identity.
Social Acceptance	4.5	Reported greater willingness to use the prosthetic cover in public.
Overall Average	4.6	High satisfaction across all criteria.

3.3. Parametric Design and Algorithmic Modeling

The combination of bio-inspired algorithms with additive manufacturing capabilities enables the production of complex, efficient, and customized geometries—an approach that can be used both to enhance functionality and improve aesthetics [7]. Here, Grasshopper within Rhinoceros provides a unified framework for scanning, landmark recognition, measurement, and parametric modeling. Moreover, the automatic extraction of anthropometric points from 3D body scan data increases the speed and accuracy of the measurement process and improves the adaptability of digital design systems [9].

The integration of digital modeling, topology optimization, and the use of advanced materials in 3D printing has led to the development of lighter and stronger customized prostheses and covers; this approach can be considered a foundation for future parametric designs [12]. Within this framework, generative models in Grasshopper are developed based on a set of adjustable parameters including wall thickness, curvature response, shell depth, and variations in density in specific areas. This parametric structure allows rapid iteration and instant feedback, and by mapping parameters to anatomical features, a balance between ergonomic comfort, strength, and weight is achieved.

In this stage of the design process, various steps are precisely and parametrically implemented in Grasshopper software, as shown in (see Figure 6). First, in Step 1, the user’s 3D body scan file and base meshes, created based on prosthesis movement angles and motion limitations, are imported into the software. Then, in Step 2, this data is automatically aligned along the three main axes (XYZ) to ensure precise conformity with the individual’s anatomical structure. In Step 3, Pipe Clips are created, serving as the geometric foundation of the prosthesis. Subsequently, in Step 4, connectors and linking tubes are designed to create the internal structure and connect various prosthesis components. In Step 5, horizontal ribs are added to the prosthesis geometry to improve structural strength. In Step 6, vertical ribs are automatically generated for further reinforcement. In Step 7, all modifications are displayed as a preview so the user can observe and apply final adjustments, after which the STL file is generated for 3D printing. This parametric design process, using intelligent algorithms and adjustable settings, enables the fabrication of precise, durable, and customized prostheses.

Recent studies show that the application of biomimetic principles can lead to the design of structures with multifunctional mechanical properties inspired by nature. Specifically, the Voronoi tessellation method is considered an effective tool for reproducing irregular cellular geometries in algorithmic modeling. Controlling parameters such as cell gradients, the position of seed points, and member thickness in this method allows for the optimization of mechanical properties such as strength and structural flexibility [13].

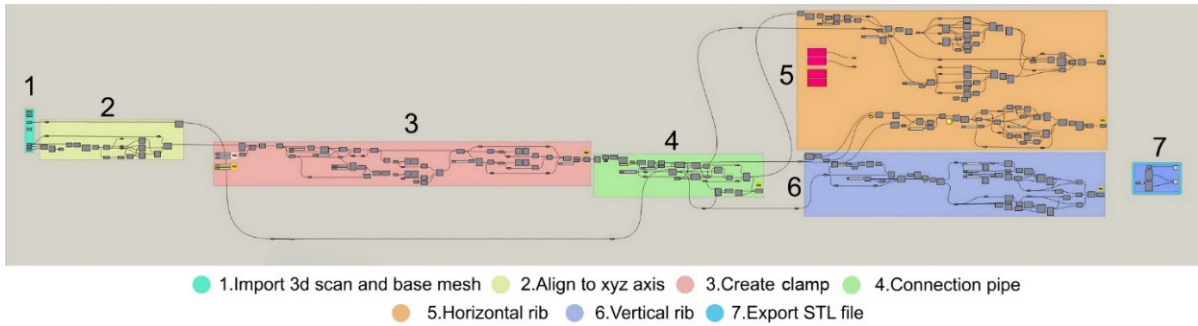


Fig. 6. Steps of the cover fabrication process carried out by algorithms in Grasshopper.

In this part of the design process, the ability exists to design various patterns for the prosthetic cover parametrically, enabling greater customization and precise adaptation to the individual user’s needs. In this study, three different types of patterns have been implemented: Geometric Pattern, Organic Pattern, and Crystalline Pattern. The Geometric Pattern is designed with precision and regular shapes, suitable for prostheses that require high structural strength. The Organic Pattern, with soft and curved lines, is designed to create covers with a more natural appearance and greater comfort. Finally, the Crystalline Pattern, with complex structures resembling natural crystals, provides distinctive aesthetic qualities in prostheses. These three types of patterns are fully adjustable, allowing the user to precisely customize the prosthesis design from both functional and aesthetic perspectives (see Figure 7).

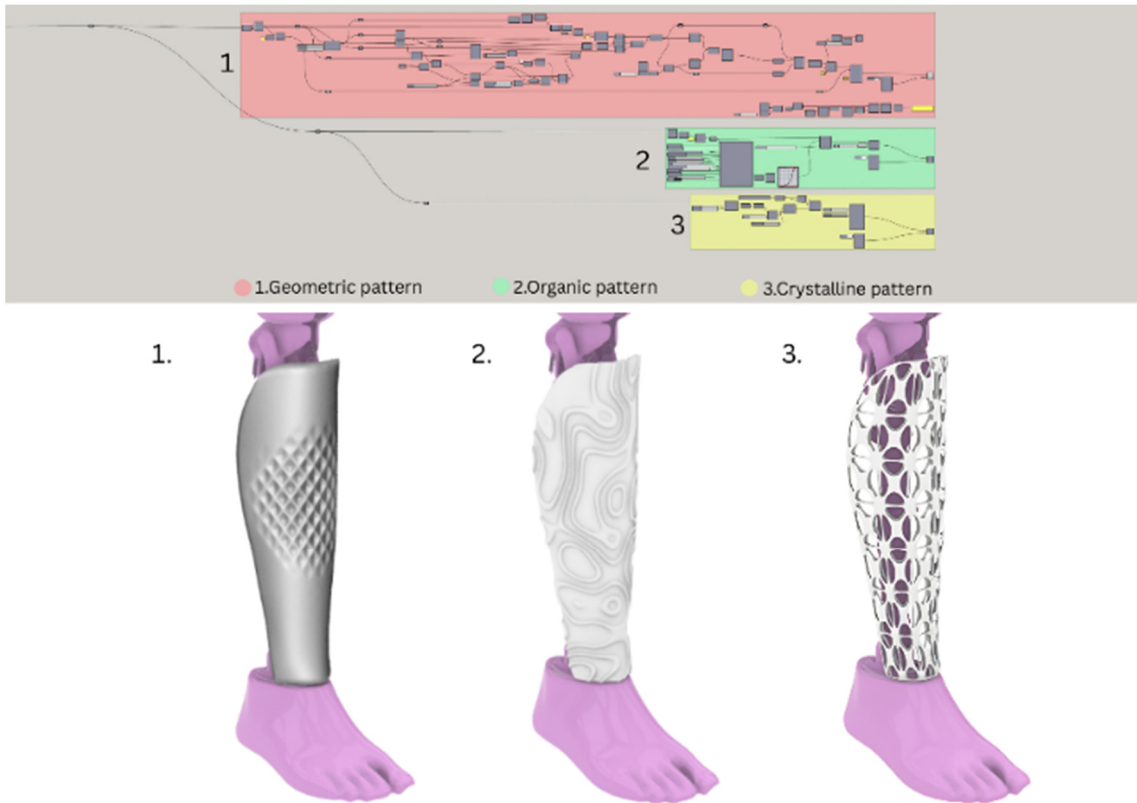


Fig. 7. Parametric patterns: 1 – Geometric pattern; 2 – Organic pattern; 3 – Crystalline pattern.

Finally, the core of the workflow was developed, where parametric definitions were designed to create shell geometries conforming to the lines and curvature of the scanned limb. In this process, parameters such as wall thickness, perforation density, decorative patterns, and ventilation areas were defined in the scripts, enabling dynamic adjustment and instant feedback.

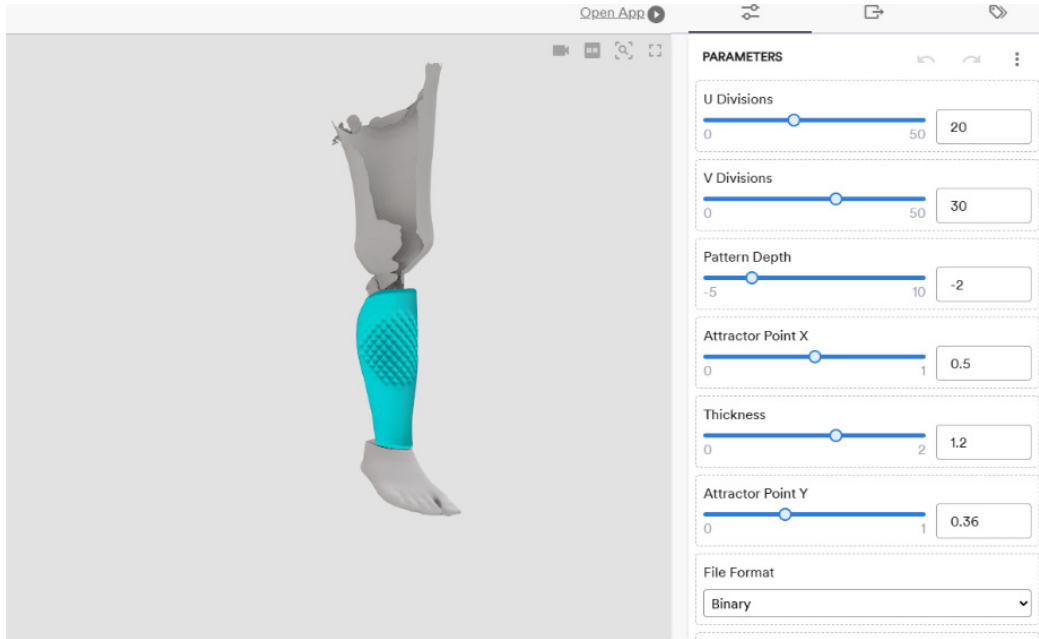


Fig. 8. An online version of the algorithm for easy use by users without knowledge of Grasshopper.

3.4. User Interface Development

By changing the parameters of u and v count, the density and distribution of the pattern can be adjusted, which helps modify the geometric shape of the diamond pattern. The higher the number of these parameters, the denser and more complex the pattern will become. On the other hand, the radius of the attractor point specifically helps adjust the range of indentation of the pattern and allows the user to change the depth and extent of the geometric variations on the prosthesis surface. This feature is particularly effective in creating three-dimensional and complex patterns that significantly affect the appearance and comfort of the prosthesis. Moreover, the depth of the pattern indentation directly influences the creation of fine details and three-dimensional variations of the pattern, which can enhance both the functional and aesthetic properties of the prosthesis. Additionally, adjusting the thickness contributes to the strength of the prosthesis. These adjustable features enable the user to fully adapt the prosthetic cover to their personal needs and preferences (see Figure 9).

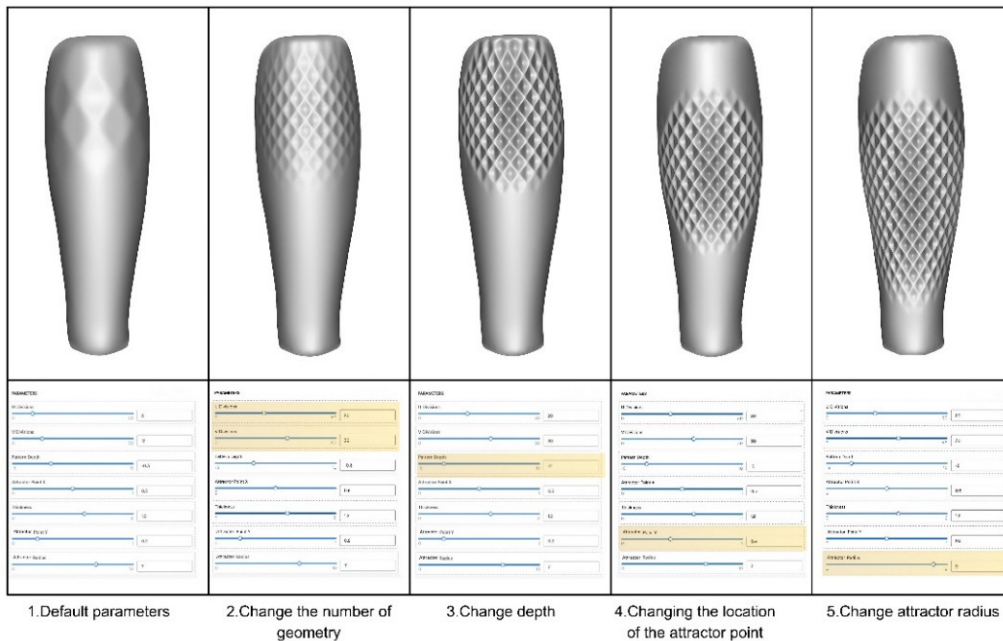


Fig. 9. Effect of parameter changes on the final output of the covers.

3.5. Quick and Easy Cover Attachment

Modification of socket geometry through the definition of design maps that control local fitting pressures and material stiffness can be performed automatically, enabling systematic optimization [6]. To increase ease of use, it was necessary to design a mechanism that was simple yet reliable, allowing users with different abilities to quickly and effortlessly attach the prosthetic cover while ensuring sufficient security against detachment during movement. For this purpose, the Pipe Clip connection system was used. These clips are reinforced with strengthening ribs and are automatically generated through parameters defined in Grasshopper software. By adjusting these parameters, it is possible to modify the technical specifications of the clips to meet the varying needs of users and prostheses. In addition, reinforcing ribs are also automatically created on the inner part of the cover to increase the strength and durability of the shell. This parametric approach not only simplified the design and fabrication process but also enabled adaptability to the diverse needs of users. The optimization process of the attachment mechanism is shown in (see Figure 10).

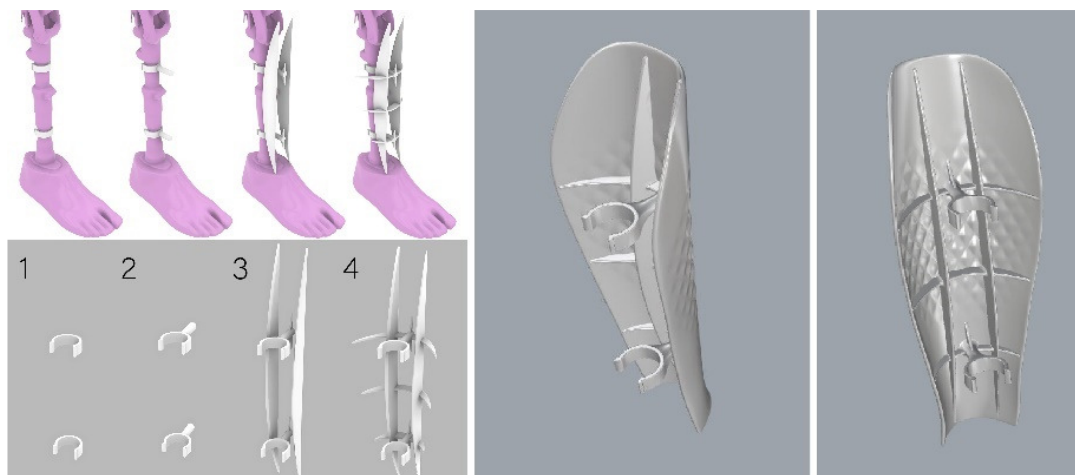


Fig. 10. Steps of creating ribs and Pipe Clamp connections adapted to the prosthesis scan file.

In the parametric design process of prosthetic covers, parameters such as Pipe Clip height, Pipe Clip thickness, Pipe Clip opening, connector tube diameter, horizontal and vertical rib height, and rib thickness are fully adjustable. These changes can be observed in real time and can be adapted to the user's 3D body scan file so that the prosthesis precisely conforms to individual needs and body anatomy, optimizing its performance and comfort.

3.6. Preparation for Additive Manufacturing

The digital models were exported in STL format and evaluated in slicing software for printing. Adjustments were made to ensure compatibility with FDM 3D printing technology. Factors such as support placement, print orientation, and material selection were considered with respect to strength, speed, and print quality.

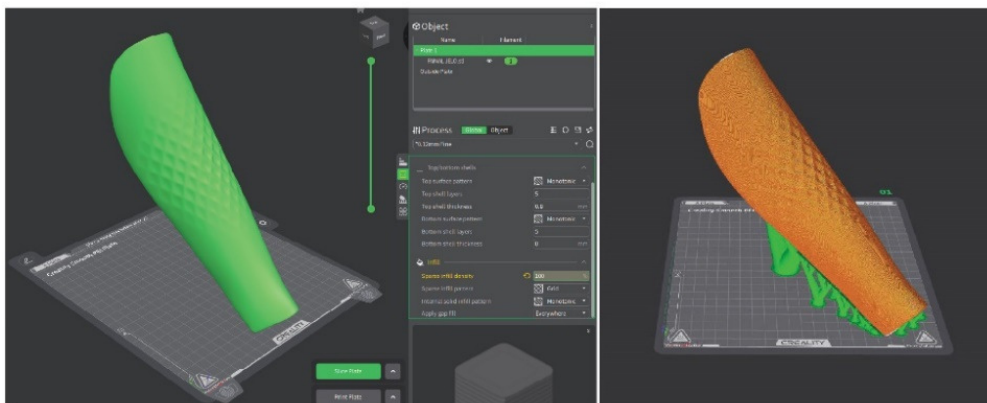


Fig. 11. Preparation and printing of the cover with a 3D printer.

3.7. Prototyping and User Evaluation

Prototypes were fabricated and re-tested by the prosthesis user. The assessment included a semi-structured interview and a Likert-scale questionnaire to collect qualitative and quantitative feedback regarding satisfaction, comfort, identity, and usability. These data were used to refine both the workflow and the design outputs.



Fig. 12. Steps of processing the scanned file and extracting essential points and reference shells.

4. Results

The output of the proposed workflow demonstrated that the integration of precise 3D scanning, parametric modeling, and additive manufacturing can lead to the production of customized prosthetic covers that are technically stable and aesthetically meaningful. The covers exhibited high conformity with the user's anatomical dimensions, which reduced pressure points and improved prosthesis fit (see Figure 13). Defining adjustable parameters such as thickness, density, and ventilation enabled instant modifications and rapid design iteration, and even in the prototypes, desirable fit quality and flexibility were achieved. Furthermore, the ability for aesthetic customization through symbolic and cultural patterns played an important role in enhancing personal identity and the emotional value of the prosthesis.



Fig. 13. Testing of 3D-printed prototypes and checking the dimensions and fitting of the cover with the prosthesis.

The developed workflow in Grasshopper, by providing a simple user interface, made the use of algorithms accessible to individuals with different levels of design knowledge. Technical components such as ribs, pipe clamp connections, and reinforcing details were also automatically generated, improving the accuracy and strength of the attachments. The final models were successfully produced using FDM 3D printers with PLA material, and they could also be adapted for SLA and SLS technologies to achieve higher surface quality and a wider variety of materials. Overall, FDM prints met the required standards in terms of dimensional accuracy and surface quality.

The pilot study with one user showed an overall satisfaction score of 4.6 out of 5. The highest scores were related to "fit and customization" and "identity alignment" (5/5), and the user reported a greater willingness to use the prosthesis in social settings (4.5/5).

5. Discussion

The findings of this study demonstrate that a parametric workflow integrating high-resolution 3D scanning, algorithmic modeling, and additive manufacturing can effectively bridge functional and aesthetic aspects of prosthetic cover design. Participants expressed high satisfaction with the ability to embed cultural and symbolic motifs, which enhanced both emotional value and social acceptance. These results are consistent with prior research emphasizing the role of personalization and psychological comfort in prosthetic adoption [5,8].

The incorporation of bioinspired modeling techniques, such as Voronoi tessellation and differential growth, not only improved ventilation and weight reduction but also aligned prosthetic appearance with natural geometries [7,13]. This resonates with earlier works that highlighted the structural and aesthetic potential of bioinspired algorithms in biomedical applications [6,7,13]. Moreover, the feasibility of polymer-based additive manufacturing for prosthetic components, previously validated in studies on orthotics and prosthetics [10,11,14], was confirmed in this research by successfully producing lightweight, durable, and customizable prototypes.

Importantly, this study advances beyond earlier approaches by shifting personalization from being primarily designer- or clinician-driven to a user-driven process. Unlike prior methods in which aesthetic customization was predefined or limited [3,4], the proposed workflow empowers end-users to directly adjust motifs, perforations, and structural patterns through an intuitive interface, fostering greater psychological ownership and identity alignment [5,8].

A more direct comparison with related work highlights the contribution of this study. For instance, Stefanovic et al. [14] proposed a framework for creating customized prosthetic covers using 3D scanning, CAD modeling, and additive manufacturing, which provided anatomically precise and functional results. However, their approach largely relied on manual CAD processes and lacked algorithmic adaptability or mechanisms for direct user participation. In contrast, the present study introduces parametric and algorithmic modeling in Grasshopper, enabling rapid iteration of designs, automatic generation of technical elements (e.g., ribs, clips), and integration of bioinspired and symbolic patterns. Furthermore, the inclusion of a user-friendly interface extends personalization from designers to end-users themselves, thus redefining the process as an interactive, participatory, and identity-oriented experience.

While promising, the workflow also faces notable challenges. The pilot validation involved only one participant, limiting generalizability. Broader evaluations with more diverse users are required to establish clinical reliability and usability. Additionally, the prototypes developed here were restricted to polymer-based materials, and future work should explore multi-material and bioresorbable options for enhanced durability and biocompatibility [10]. Technical barriers also remain, particularly in ensuring robust printability when scaling complex bioinspired geometries for daily use.

In summary, by building on previous foundations that demonstrated (i) the accuracy of scanning technologies [1,9], (ii) the role of algorithmic modeling in adaptive geometries [6,7,13], (iii) the feasibility of additive manufacturing for prosthetic applications [10,11,14], and (iv) the importance of psychological and cultural factors in prosthetic acceptance [5,8], this study contributes a distinctive advance:

- User-driven design participation through an interactive interface,
- Algorithmic customization that combines symbolic motifs with bioinspired structural patterns, and
- Seamless translation of personalized digital models into additively manufactured prototypes.

These contributions position the workflow not only as an incremental improvement but as a step toward human-centered, customizable, and clinically adaptable prosthetic design.

6. Conclusion

This research presented an integrated parametric approach to designing and fabricating personalized prosthetic limb covers, combining 3D body scanning, algorithmic design, and additive manufacturing techniques. The results demonstrated that combining technical precision with cultural and aesthetic personalization can move prosthetic devices beyond their purely functional role, transforming them into identity-driven and expressive products.

The pilot evaluation with one lower-limb prosthesis user yielded promising outcomes: high satisfaction (average score 4.6/5), strong identity alignment, and increased willingness to use the prosthesis in

social contexts. These findings highlight the potential of user-driven customization to enhance both psychological acceptance and social integration of prosthetic devices [5,8]. However, it must be emphasized that this study remains preliminary and is limited by the small sample size, short-term testing, and the use of polymer-based materials only [10,11,14].

Future research should broaden the evaluation by including larger and more diverse user groups, conducting long-term studies, and employing advanced materials such as multi-material and bioresorbable composites [10]. In addition, expanding algorithmic capabilities—such as real-time biomechanical feedback, automatic fit correction, and the development of more intuitive user interfaces—could further enhance accessibility and clinical applicability [6,7,9,13].

Overall, by emphasizing human-centered design and integrating computational adaptability with direct user participation, this research takes a step toward redefining the aesthetic and functional boundaries of prosthetic design. The preliminary framework provides a solid basis for future cross-disciplinary initiatives that seek to redefine prosthetics as not just medical aids but as individualized, empowering, and socially meaningful products.

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