Research on Customized Design Method of Rehabilitation Aids Based on Parametric Modelling

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Abstract. Explore a rapid design method for the customized appearance of rehabilitation aids to meet the needs of the disabled. Taking the main part of the lower leg prosthesis as an example, parameters are selected based on ergonomics and expert interviews. A parametric design solution is established in Rhino and Grasshopper. Leveraging their flexibility and real-time adjustability, this solution facilitates direct interaction between designers and users, providing a solution for co-creating personalized rehabilitation aids. Introducing a customized design method based on parametric modelling into the rehabilitation aids industry can meet diverse users' aesthetic and personalized needs, playing a crucial role in helping the disabled overcome psychological barriers and reintegrate into society.

Keywords- Parametric modelling, Prosthetic design, Customized design

1. Introduction

"Healthy China" has gradually become a national development strategy aimed at raising residents' awareness of health and improving their quality of life. Its rapid development has fully tapped into the inherent demand of the rehabilitation aids industry, driving the formation of a comprehensive elderly care service system covering the entire lifecycle of the elderly, disabled, and injured individuals [1].

The design of rehabilitation aids involves technological innovation, emotional care, and artistic metaphor, representing an integration of practicality and aesthetics in innovative designs for people's livelihood [2]. Nowadays, people-centric, customized innovative designs for rehabilitation aids have become a trend and focal point for the future development of the rehabilitation medicine industry.

2. Research Background

2.1. Background of prosthetic design

In the realm of prosthetics, medical device manufacturers typically design and manufacture products based on normative human ergonomic parameters, covering the 5th to 95th percentile of the population. While this approach satisfies the needs of the majority, it does not fully cater to individual users, leading to prolonged adjustment periods and adaptation. However, human-centric personalized design enterprises are relatively scarce globally. Those design studios face

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challenges such as high customization costs and extended timelines. For the average person with disabilities who has already invested significantly in healthcare, personalized designs that better suit individual needs can be considered a luxury. To address cost concerns, Scott Summit, chief designer at Bespoke, proposed the use of 3D printing technology for customizing rehabilitation aids for people with disabilities in 2010 [3]. Prosthetic design demonstrates new requirements compared to traditional ones: Increasing inclination towards personalized customization, improved breathability and lightweight products, products that align with public aesthetics and diverse functional requirements [4].

Currently, researchers such as Max Ortiz-Catalan from the MoReLife Biomechanics and Pain Research Centre in Sweden utilize neural-musculoskeletal interface technology clinically. In a patient with a below-elbow amputation, they implanted titanium into the radius and ulna marrow, achieve bidirectional communication between electrodes and prosthetics. Direct nerve stimulation induces phantom limb perception, overcoming discomfort and lack of control associated with traditional prosthetic [5]. This technology provides robust technical support for the customization of prosthetic.

2.2. Digital design trend

Digital design technology has improved traditional product development routes, made them more capable of capturing design intent and conveyed design information. Among them, parametric design is a generative design approach. It can leverage algorithms to rapidly complete a large number of design solutions in a short time [6]. The mainstream modelling software Rhino includes the parametric plugin Grasshopper. It can handle complex forms of curves and surfaces, modularize different algorithmic components, store the design process as operators on a computer for designers to use [7], also construct personal component modules using code to meet design requirements. Mature parametric design plugins provide a reliable experimental platform for research.

3. Design Case Parameter Selection Based on AHP

Taking the main part of the lower leg prosthesis in rehabilitation aids as an example, we use the Analytic Hierarchy Process, abbreviated as AHP, to construct a hierarchical analysis model of factors influencing the design of lower limb prostheses. This model helps guide the establishment of a digital platform.

3.1. Model construction and results

Conduct interviews with 20 design experts and prosthetic users. Based on the interview results, categorize the design into two main types: rehabilitative design which emphasizes simulating and reproducing the curves of the original limb, with the shape closely resembling the original limb. Divergent design, on the other hand, allows for free divergence in appearance based on numerical values of the original limb, resulting in a more distinctive shape. The designer summarizes and classifies various textures into four categories: Texture Mapping, Skeletal Structure, Dots and Curves, and Convex Carving. Using the information gathered from the interviews, construct a hierarchical analysis model for the design factors of lower leg prostheses, as shown in Figure 1.

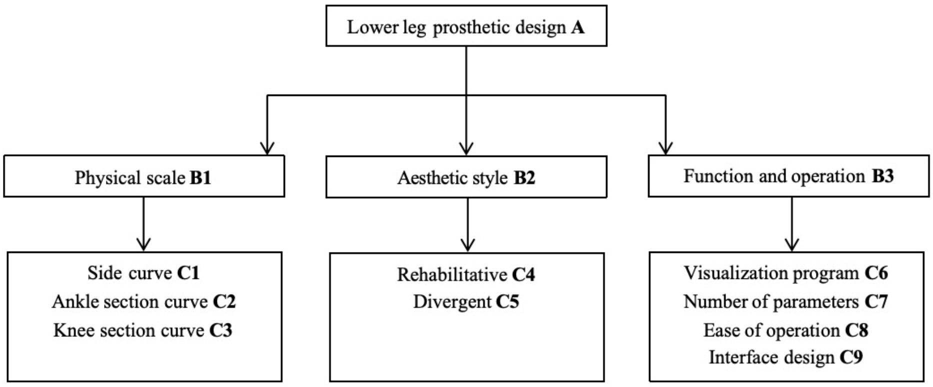

Figure 1. The hierarchical analysis model for the design factors of lower leg prostheses.

Compare the importance of different factors at the same level of the model in pairs, and perform hierarchical judgment and scoring. The final results are shown in the following table 1, for clear display, all data are rounded to five decimal places so the result of some sums is not 1.

Table 1. Calculation results of target weight of level C.

	C1	C2	C3	C4	C5	C6	C7	C8	C9
B1=0.5572	0.4941	0.3325	0.1735	-	-	-	-	-	-
B2=0.3204	-	-	-	0.3708	0.6292	-	-	-	-
B3=0.1223	-	-	-	-	-	0.4375	0.1875	0.3125	0.0625
W	0.2753	0.1852	0.0967	0.1188	0.2016	0.0535	0.0229	0.0382	0.0076

3.2. Consistency check

According to the judgment matrix and the weight vector W, the maximum eigenvalue is calculated as shown in equation (1).

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(AW_i)}{W_i} \tag{1}$$

A consistency check is performed on the weight vector W to ensure logical accuracy in expert evaluations and avoid inconsistencies. The consistency index (CI) is calculated as shown in equation (2), where a higher CI indicates greater inconsistency in the judgment matrix.

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{2}$$

The CI is compared with the random consistency index (RI), and the ratio CR is obtained. After verification, the 80 CR values for all four judgment matrices are less than 0.1, indicating good matrix consistency and passing the consistency check. Therefore, the logic of expert and user rating evaluations is deemed accurate.

4. Digital Design Platforms

Taking the lower leg prosthesis as a case in rehabilitation appliances, based on research and hierarchical analysis, we selected to construct four experimental platforms: Texture Mapping, Dots and Curves, Skeletal Structure and Convex Carving. The first and the second platforms belong to rehabilitative design, and the other two platforms belong to divergent design.

4.1. Algorithm selection

Utilizing the Grasshopper plugin embedded in Rhino, along with open-source community plugins such as Shapemap, Glasses, Ngon, etc., we created various design components for the battery assembly. The typical parts of components in four platforms are illustrated in the following figures 2 to 5.

Use the "Sweep2" command for a double rail sweep to generate a model shell that closely follows the original curvature of the lower leg.

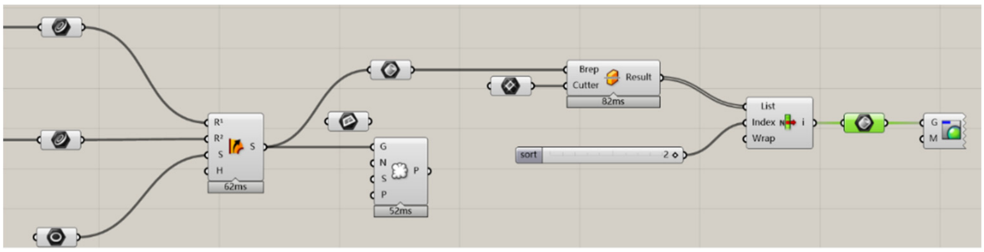

Figure 2. Important components of the original curvatures.

In the construction of the skeleton platform [8], the shape is transformed into a skeleton using TriRemesh. In the construction of the Dots and Curves platform, built-in elements such as curves and point grids are provided for selection. The built-in curves and dot matrices were input in the form of Python programs, as one of them is shown in the Figure 3.

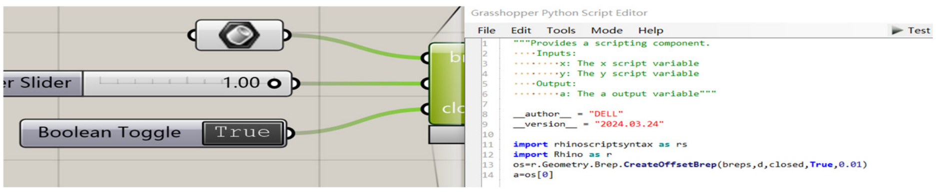

Figure 3. A python program which can generate rose curve as a decoration on the prosthesis.

In the construction of the Convex Carving platform, Rich Graph Mapper is used to simulate the original body curves. Using the Average component for averaging a set of points, and then creating smooth curves through operations like finding the nearest points on the curve. Through interpolation, estimating unknown points based on known points, drawing a smooth path for lofting.

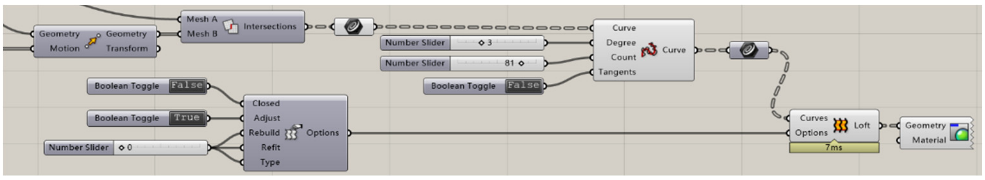

Figure 4. Important components of the Convex Carving platform.

Using Series component to generate a series of input values, these values are then input into the Remap Numbers component for initial mapping. Utilizing the Rich Graph Mapper component allows for a visual adjustment of the mapping curve. Finally, Loft is used to generate the required surfaces. Modifying the input parameters allows the generation of models with diverse calf dimensions and styles according to different users' needs, as shown in the Figure 5.

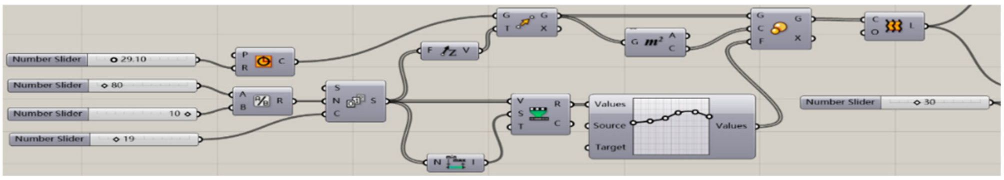

Figure 5. Important components of the Convex Carving platform.

4.2. Model display

Recruit four volunteers, match their individual styles with the styles of the prosthetic design platforms through communication, and take multi-angle photos of the lower legs of them, preserving limb dimension data. Simulating the shape of the calves for four participants, inputting parameters such as side curve points into the platforms. Through "Bake", parameters are converted into 3D models [9]. The first row from left to right shows the original models of the skeleton class and the texture class; the second row shows the original models of the dots and curves class and depiction class in Figure 6.

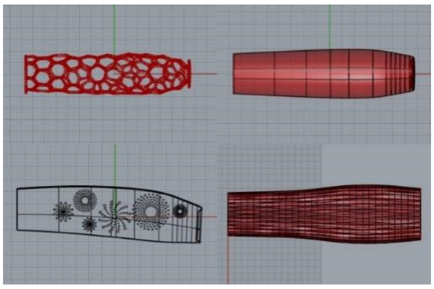

Figure 6. Models generated by four categories of digital design platforms.

4.3. Rendering effect image

Using the AIGC platform to generate simulated user image, perform human body modelling. Based on the data of the human body model, use the texture mapping platform to generate a prosthetic leg with restorative design. Choose any image, here using a tiger image as an example, select cylindrical mapping, adjust UV surfaces. Assign an aluminium alloy material to the model. Adjust the lighting conditions, simulate the environment [10]. Output the final design result, as shown in Figure 7.

Figure 7. The rendering effect image of the generated prosthetic shell in wear.

5. Design Method for Rehabilitation Aids

The traditional customization process of rehabilitation aids involves repeated sketching and communication before establishing 3D models for rendering and production. Both designers and users incur high time and resource costs in this approach. Although the traditional process prioritizes user-centric design, it's complex and involves a substantial workload [11]. To address these challenges, this design method with parameterization for prosthetic is proposed. This process, combined with advanced digital design tools, aims to enhance design efficiency, reduce workload, and achieve a higher level of personalization while ensuring a seamless nonlinear design process, as illustrated in Figure 8.

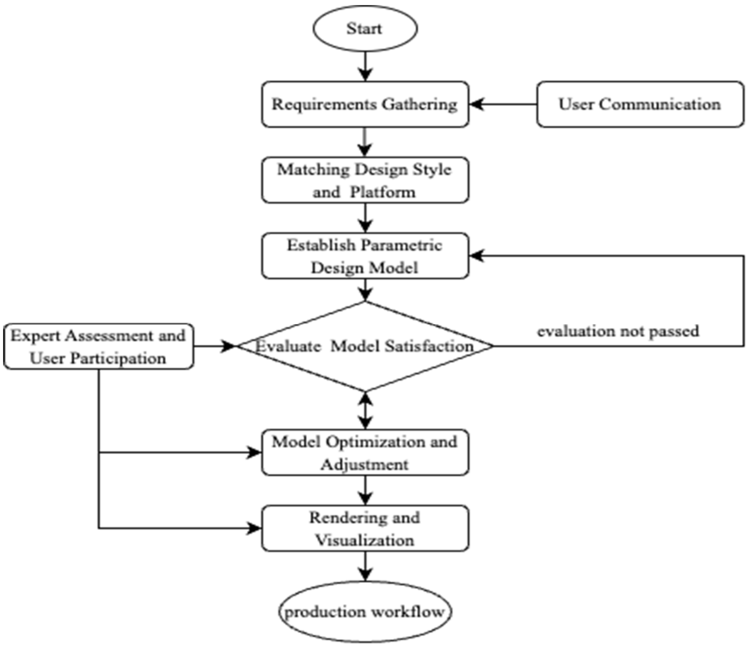

Figure 8. Workflow diagram for customized design of rehabilitation aids based on parametric modelling.

6. Evaluation of the Design Method

Invite nine design experts and one user to evaluate the digital design platforms, as shown in Figure 9. Ask design experts to become familiar with traditional modelling methods in Rhino of those 4 types and practice them. Provide three views of the lower leg and digital platform parameters. Ask the experts to perform both methods for the same object separately, timing each process, and rating on a 10-point scale after adjustments are made to the satisfaction of both methods.

Figure 9. Experimental scenarios of experts carried out two design approaches.

Analyse design factors that affect user experience, including the dissatisfied results after "Bake" lead to rework, understanding degree of provided data and errors in operation. The table 2 below shows the comparisons of two methods of design.

Table 2. The average evaluation results of design experts.

	Time(min)	Aesthetic	Ease of operation	User experience	User Satisfaction
Traditional method	27.9	9.7	6.8	7.9	8.7
New method	10.4	9.6	9.7	9.3	9.1

New design method has improved efficiency, offering more possibilities in a shorter time than the traditional design process and reducing communication time. Both methods exhibit similar performance at the aesthetic level, but there has been a significant improvement in user experience and user satisfaction.

7. Conclusion

The rapid design method for rehabilitation aids was validated through the construction of a digital platform and design practices. Using the Analytic Hierarchy Process, a parametric design target model for rehabilitation aids, taking the example of a lower leg prosthesis, was constructed. After expert and user ratings, data processing determined the experimental direction for parametric design. Four visually programmed experimental platforms, deemed comparably important, were evaluated, categorized, and built. Inputting user data into the program quickly generated four lower leg prosthesis model solutions. These generated solutions were imported into rendering software to produce the final product renderings.

7.1. Limitations and prospects

The introduction of parametric design into the field of prosthetics has yielded significant benefits but is accompanied by distinct limitations and challenges. Scalability in large-scale production stands out as a critical issue, as personalized designs may demand additional time and resources. Addressing this challenge involves implementing highly automated production processes, optimizing algorithms for enhanced efficiency, and adopting parallelization. Manufacturing feasibility poses another obstacle, especially when dealing with complex geometric shapes. To overcome this, exploring advanced manufacturing technologies such as 3D printing becomes imperative. Cost-effectiveness in parametric design signifies an initial investment in software, training, and equipment, which needs amortization through long-term use and strategies for large-scale production optimization. Additionally, technological accessibility is an issue addressed through training programs, user-friendly tools, and initiatives for widespread technology promotion.

7.2. Significance and impacts

Introducing customized design methods based on parametric modelling into the rehabilitation aids industry carries profound implications for the broader societal landscape. It not only helps them regain lost body contours but also provides a personalized form of expression. Compared to traditional design paths, the combined co-creation model of computer program creation and designer-user participation proved faster and more efficient, exploring various design possibilities in a short time, thereby enhancing the design efficiency of the non-linear design process for rehabilitation aids while retaining core elements for iteration. This goes beyond the mere provision of functional aids. It speaks to a fundamental shift in perspective and the acknowledgment of diversity in abilities. As we embrace and implement these advanced design methodologies, we actively contribute to dismantling barriers and fostering an environment where everyone, regardless of ability, feels seen, understood, and accommodated. In essence, the adoption of parametric modelling in rehabilitation aids design becomes a catalyst for a more empathetic future.

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