Designing the prosthetic appearance in virtual reality with the collaboration of participants and users

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Based on the approach of research through design, this research combines virtual reality (VR) and participatory design method to develop and customize the appearance of wearable assistive devices. It attempts to test the efficiency of developing designs with the help of VR, especially the collaborative capabilities with various participants and users without design background. The study cases are three wearable assistive device users (one shoulder amputation (AE) case and two hand deformity cases) at our partner institution, Disabled Reconstruction Center of Taipei Veterans General Hospital, with the design goal of helping them design prosthetic accessories. The research focuses on testing new design function in VR environment, the Collab feature of LandingPad in Gravity Sketch. During the studies, the designer discussed and modified the virtual model with stakeholders such as patients, medical and assistive device technicians, and the final design proposals were 3D printed and assembled with physical components. The research process was recorded both in real world and VR by means of audio and video. The experimental and interview results indicate that applying VR technology for wearable assistive device co-creation is beneficial for both the user participants and the prosthesis designers. Overall, this study developed a set of procedures for using VR to co-create assistive devices, explored assistive devices that were suitable for the study participants, and provided recommendations for designing VR user interfaces. In the future, we will further expand the scope of VR applications for designing assistive devices and examine more types of assistive devices and scenarios.

Keywords: virtual prototyping; participatory design; virtual reality; assistive devices design

1 Introduction

In Taiwan, the demand for assistive devices has increased yearly while the population continues to age. Such devices improve the self-care ability of users, reduce the burden on caregivers, and enhance the quality of life of individuals receiving and giving long-term care. However, because assistive device developers tend to emphasize functionality and comfort, the feelings of assistive device users are often neglected. This has led to users—particularly those in the younger age groups—refusing to use assistive devices because they think assistive devices look crude and unrefined.

In this study, prostheses that were aesthetically appealing to users were designed. Manufacturing factors, such as manufacturing time and material costs, and user customizability and aesthetic preferences were considered in the design process. A participatory design approach was adopted in which prosthesis users and medical professionals, who had limited or no design experience, participated in the design process. The design process was conducted in a virtual reality (VR) environment in which participants were able to inspect the devices and evaluate their feasibility, advantages, and disadvantages.

2 Literature review

2.1 Design methods for assistive device

Assistive devices cover a wide range of categories, including daily living, mobility, and medical aids. From a product design perspective, while broad definition of assistive design, such as wheelchairs, crutches, accessible tableware, etc., is designed to ensure that it can be used and experienced by "people of all ages and abilities" to the greatest extent with universal design principles (Story, 1998). However, personalized wearable assistive devices like prosthetics, which are designed to replace partially or entirely missing body parts, follow a different approach. Although they are divided by structure, prosthetic brackets, joints, etc., still mainly follow the principle of universal design, but the socket needs to fit perfectly on the patient's residual limb in order to maximize the function of the prosthetic. Due to the significant variations among individual cases and the higher requirements for comfort and functionality, universal design principles do not apply to sockets (Sugawara et al., 2018).

According to Newell et al. (2011), one of the reasons for the high abandonment rate of assistive devices is that the products have been designed only for functionality, which is possibly due to the fact that many assistive device developers do not interact or communicate with users and therefore do not adequately understand their target population.

Figliolia et al. (2020) collaborated with assistive device designers and rehabilitation professionals and produced three-dimensional (3D)-printed prosthetic upper limbs by using a user-centered design approach for users who had problems adapting to a standard prosthesis. Such an approach focuses on not only prosthesis functionality, comfort, and customizability but also aspects of user psychology to effectively lower the risk of product abandonment. Usability.gov (a website managed by the United States General Services Administration) states that the concept of user-centered design originates from design thinking and refers to considering, planning, and guiding the design and development of a product, system, or service from the angle of its users. The process of user-centered design involves the following steps: (1) identify needs, (2) specify the context of use, (3) specify requirements, (4) create design solutions, (5) evaluate designs, and (6) evaluate user satisfaction.

2.2 Application of VR in industrial design

VR involves the use of computer simulation to generate a 3D and highly realistic space that provides virtual sensory (visual, audio, and tactual) experiences. For example, wearing a head-mounted display enables the user to move about in a virtual environment, creating an intense immersive experience comparable to moving in the physical world. Krueger (1991) proposed that VR systems must have the following traits: immersion, interaction, and imagination. In the field of product design, VR is predominately applied in the simulation of product appearance, coloration (or lighting), and texture, or the visualization of a large object to examine its shape and proportions. The interactivity afforded by VR enables designers to identify and rectify errors and problems that are difficult to detect in design sketching before a product is substantialized, thereby averting unnecessary costs. This is a great advantage to the designing of large transportation equipment, such as motor vehicles.

According to Rendevski et al. (2022), existing VR equipment can be divided into two types: Tethered VR Headsets (High-End VR headsets, PC VR, Desktop VR) and Standalone VR headsets. The former type of VR device, apart from the VR headset and controller, includes a computer connected to the VR headset via USB or HDMI cable. The major advantages of this type of VR device are accurate motion detection, realistic visuals, and enhanced immersive experiences. However, its drawbacks include the need for a wired connection to a computer, which limits the user's range of movement, and the requirement for a high-performance desktop or laptop computer as an additional component. The existing Tethered VR Headsets include devices such as HTC Vive (2016) and Oculus Rift S (2019). The latter incorporates motion position detection, processor unit, display screen, data storage, and power supply in the VR headset, which does not need to be connected to a computer. The main advantage of this device is a reduction in mobility restrictions. However, the built-in CPU of VR has limited computing power, which may not be able to handle high-resolution visuals and complex 3D models effectively. Examples of such headsets include HTC Vive Focus (2018) and Oculus Quest series (2019~2022). With the advancement of chip technology, the resolution and clarity of newly launched Standalone VR headsets are mostly equivalent to or even surpass some models of Tethered VR Headsets. Therefore, under the incentives of low price and good mobility, most VR users will choose Standalone VR headsets (Ratushnyi, 2022).

Gravity Sketch, a software package developed in 2017, allows designers to create, import, and export 3D objects in a VR environment. Gravity Sketch generates strokes though an intuitive gestural interface, a process closely resembling that for normal two-dimensional (2D) design sketches. Gravity Sketch also provides functionality similar to that provided in 3D modeling software, such as the creation of curves, NURBS(non-uniform rational basis spline surfaces), sub-D(subdivision) surfaces, and control points, enabling the user to rapidly design a 3D object in the VR environment. Compared with experimental software, Gravity Sketch faces little restriction in the access to its full functionality (Lorusso et al., 2020), making it an ideal option for the preliminary exploration stage in 3D prototyping. The use of subdivision, which offers the user a high degree of freedom, enables the user to explore the suitability of a shape or exterior design in a manner close to kneading clay. Compared with conventional 2D drawings, this is an approach that can more easily inspire the imagination of designers. Presently, Gravity Sketch is widely used in the exterior design of transportation equipment. One example is Ford Motor Company, which uses Gravity Sketch to design cars that conform better to user experience. A notable feature of Gravity Sketch is the LandingPad Collab, which enables users from different geographic locations to meet in a virtual chatroom and engage in discussion, design development, and 3D model modification. Gravity Sketch has an intuitive interface that allows users with limited or no design experience to collaborate in product design with professional designers.

2.3 Participatory design and research through design

Participatory design refers to bringing users or stakeholders into the design process to ensure that the design outcome genuinely meets user needs. Participatory design is based on a user-oriented philosophy with a “with the user” approach rather than a “for the user” approach (Figure 1).

Participatory design can play a crucial role in navigating the uncertain early stages of the design process. That is, through participatory design, researchers may assist designers in product ideation and in turning ideas into concrete conceptual designs. Moreover, after a prototype is constructed from a conceptual design, the prototype can be further improved on the basis of user feedback before eventually becoming a finished product (Sanders & Stappers, 2008). Blackburn et al. (2018) reported that adequate patient and public involvement helped enhance overall research quality, improved researchers' understanding and insight, and promoted patients' self-value and confidence.

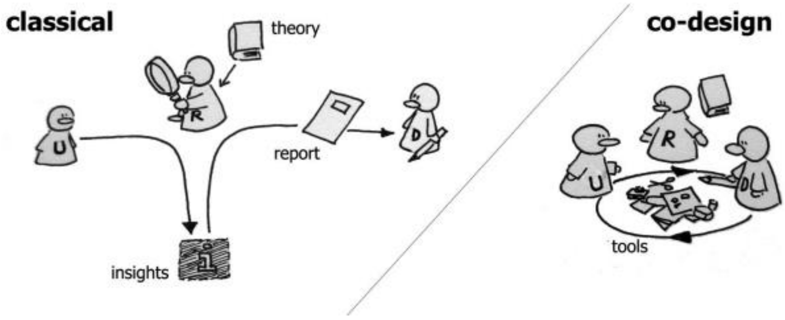


Figure 1. Comparison between user-centered design and participatory design. Source: Sanders and Stappers (2008)

Research through design (RtD) is a research approach that explores unknown territories and formulates new theories through design practices. By using a combination of iterative ideation and the creation of artifacts, RtD helps researchers gain more insight into a complex or ambiguous situation and identify potential patterns within it. In general, projects involving RtD do not restrict themselves to the aspects of human–computer interaction. Such projects also entail cross-disciplinary teams with members from a range of backgrounds, such as behavioral science, engineering, and design. A research team that practices RtD must apply professional knowledge and theories from multiple disciplines to solve complex, ill-defined issues, iterate through the design process, and refine their theories (Zimmerman et al., 2010). On the basis of a user-centered design approach, Giller et al. (1999) employed participatory design in a RtD project aiming to explore in-depth the online interactions of children aged 8–12 years.

3 Research method and process

This study adopted the RtD approach and drawing upon the process of participatory design described by Albouys-Perrois et al. (2018) for improving O&M tools for the visually impaired community. Modifications were made by incorporating the virtual collaboration platform LandingPad Collab in Gravity Sketch. The goal of this study was to enable prosthesis users, prosthesis technicians and designers to virtually collaborate in the design process of a prosthesis, as shown in Figure 2.

The study focuses on the collaborative outcomes between designers, individual cases, and assistive device experts, rather than emphasizing innovative structural designs. Therefore, the internal mechanisms of the assistive devices, such as joint components and sockets in prosthetics, primarily rely on existing fully developed prosthetic structures. Also, the research does not delve into ergonomics and medical aspects.

The collaborative experiments primarily focus on the use of VR devices and communication. Since the users of assistive devices belong to the vulnerable group and the possibility of having language and communication barriers, the study adopts purposive sampling, primarily recruiting individuals who have congenital developmental disorders or acquired amputations due to work-related injuries or illnesses. In addition, Biddiss and Chau (2007) found in their survey that the abandonment rates for upper limb prosthetics were 45% for children and 26% for adults. Similarly, Sugawara et al. (2018) reported in a recent study that the abandonment rate for assistive devices was around 30%. Among all types of assistive devices, the abandonment rate was highest for upper limb prosthetics (53.3%) followed by lower limb prosthetics (30.77%). Therefore, the study recruited individuals between the ages of 15 to 45, who are familiar with electronic products, and are users of upper limb prosthetics as the experimental subjects.

Figure 2. Co-creation of an assistive device through VR

Figure 3 presents the experimental procedures: (1) 3D scanning was used to collect the physical data of the users. (2) The designer conducted interviews and brainstorming sessions with users to understand their design needs, and recorded them in the form of hand-drawn sketches or reference images. (3) The designers input existing device structures and reference images into LandingPad Collab and designed the appearance of the prosthesis according to the user's needs. (4) The designers, users, and prosthesis technicians participated in a co-creation process by using LandingPad Collab. (5) The designed prosthesis was produced using 3D printing and then assembled. The co-creation process were recorded through audio and video for later analysis. At the conclusion of participatory design process, the prosthesis users and technicians were interviewed on a one-on-one basis, with interviews lasting for 10–20 min. The interviews focused on the following areas: (1) the experiences of the prosthesis users and technicians in terms of the participatory design process and the virtual chatroom interface and tools of Gravity Sketch, and (2) the differences between VR-based and conventional (reference pictures and freehand sketches) discussions in terms of the experiences and understanding gained through these methods from the perspectives of the prosthesis users and technicians. The interview contents are presented in Table 1 and Table 2.

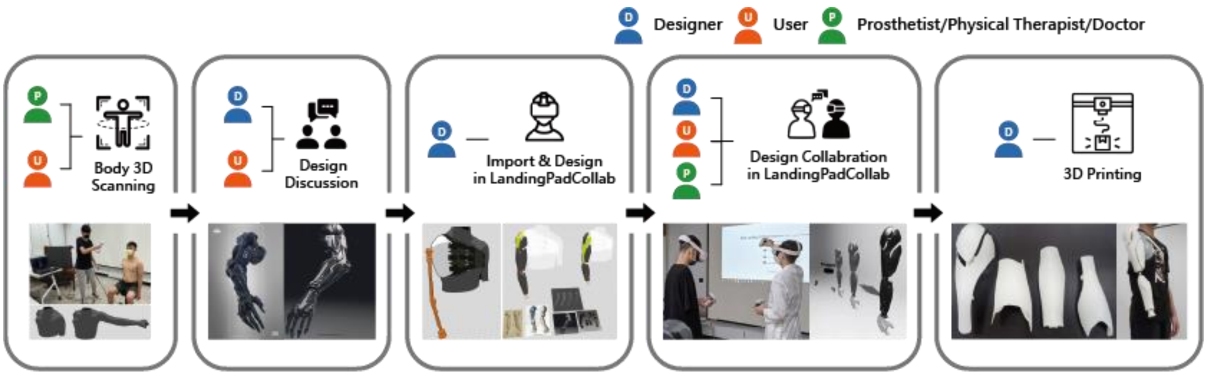


Figure 3. Creation of prosthesis through VR

Table 1 Interview contents for the users

1.	Did you encounter any problems while learning or using the VR equipment and the Gravity Sketch interface? What were the issues?
2.	Were you satisfied with the arrangement of the overall co-creation process? Are there any process that can be added, extended, or removed?
3.	Did you experience any difficulties or challenges in using toolbars during the process (e.g., drawing, detail indication, color changing), aside from the explanatory dialogues?
4.	If you were to compare the two (LandingPad Collab and 2D sketches/reference images), what are their respective strengths and weaknesses?
5.	Given that some functionalities require simultaneous operation with both hands (e.g., moving, zooming in/out the perspective and objects), was the interface and toolbars sufficient for one-handed operation? Or, which tools do you consider essential?
6.	What are your views on use of hand-drawn sketches and reference images (such as the way of discussions during the preliminary design)?
7.	What do you think about this service process and the use of VR?

Table 2 Interview contents for assistive device experts

Apart from questions 1 to 4 in Table 1, two additional questions are added for the interview with assistive device experts:	
5.	Based on your experience with assistive device manufacturing, what is your opinion on this service process and VR applications in assisting the users and the overall production process?
6.	Please compare the advantages and disadvantages of these two approaches in the production of prosthetic shell accessories: (A) practical handcrafting with subsequent testing and fine-tuning. (B) virtual modeling followed by discussion, modification, and 3D printing.

4 VR prosthesis design collaboration results

4.1 Co-creation processes

4.1.1 Cosmetic prosthetic shell for shoulder disarticulation amputee

Prosthetic upper limbs can be categorized into two major types: cosmetic prostheses without grabbing and holding functions, and functional prostheses that have built-in mechanisms and can perform grabbing and holding under the control of their wearers. User A was a shoulder disarticulation amputee and used a cosmetic prosthesis for aesthetic reasons. However, User A reported that he had stopped using the prosthesis because of its ungainly appearance, and an examination by the physical therapist revealed that User A had developed scoliosis. User A would be more likely to wear a prosthesis that was aesthetically appealing. To address this problem, the designer proposed the development of appealing accessories for the prosthesis. Figure 4 presents images of the co-creation process and the results. The images, from left to right, are the prosthesis originally designed for User A, preliminary design draft displayed in VR, co-creation process between User A and the designer, and the assembled prosthesis produced using 3D printing.

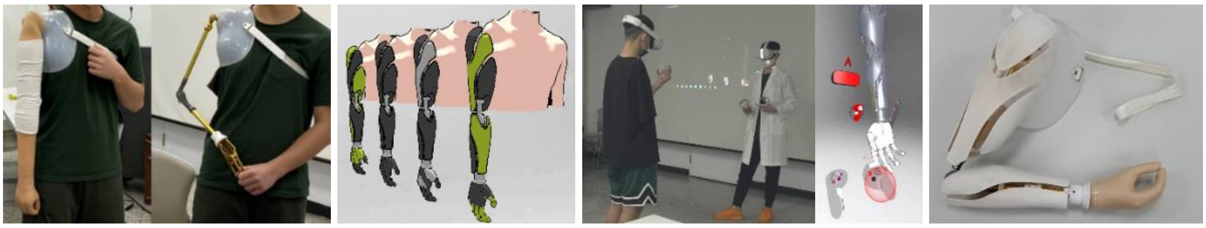


Figure 4. Images of the co-creation process and results for User A

4.1.2 Cosmetic prosthetic shell for below-elbow amputee

User B was a high school freshman whose right forearm below the elbow had been amputated due to a congenital condition. He had a functional below-elbow prosthesis but also wanted a cosmetic prosthesis. The functional prosthesis was for outside use, and the cosmetic prosthesis was intended for home use, to engage in cosplay, and to satisfy his mother's demand to get accustomed to wearing a prosthesis; grabbing and holding functions were not necessary because he would not perform such tasks with the cosmetic prosthesis. In terms of the exterior design, User B wanted the prosthesis to look like the forearm of Evangelion Unit-01, a mecha in his favorite Japanese anime, Neon Genesis Evangelion. Figure 5 presents images of the co-creation process and the results. The images, from left to right, are the affected joint and originally designed prosthesis of User B, a 2D sketch of the prosthesis design, the preliminary design draft displayed in VR, the co-creation between User B and the designer, and the prosthesis parts produced using 3D printing.

Figure 5. Images of the co-creation process and results for User B

4.1.3 Functional below-elbow prosthesis for exercise

User C, a computer engineer in his 30s, had congenital hand deformity and no experience with prostheses. User C worked out regularly but due to the different lengths of their left and right arms was unable to use equipment that required the use of both hands while maintaining a balance. Therefore, User C wanted a prosthesis to (1) rectify the difference in arm length and (2) enable him to perform grabbing by swinging his left wrist. Figure 6 presents images of the co-creation process and the results. The images, from left to right, are the affected joint of User C, a 2D sketch of the prosthesis design, the preliminary design draft displayed in VR, the co-creation between User C and the designer, and the assembled prosthesis produced through 3D printing.

Figure 6. Images of the co-creation process and results for User C

4.2 Interviews of prosthesis users and prosthesis technician

In this study, the use of 2D sketches in participatory design was deemed unfavorable because any ambiguities in the drawings and restrictions in viewing angles could hinder the participants from forming a 3D image in their minds, thereby impeding the communication and collaboration between the participants. VR-based tools were anticipated to effectively enhance design efficiency and quality. The interviews revealed the following findings:

1. During discussions, VR-based models enabled designers to quickly convey their ideas to chat participants without the need to present a mockup and enabled participants to quickly identify design problems or areas that did not meet their expectations.
   User B stated, "*Some details will differ from our expectations if the design is only based on verbal descriptions and 2D sketches. Using VR to communicate helps us view the object in full detail and therefore greatly reduces the expectation gap.* "
   User C stated, "*Although conventional discussion methods are convenient and we don't need to worry about problems such as the equipment or dizziness, VR is helpful because it lets us fully understand the actual situation and reduces the expectation gap*. "
   Expert A stated, "*If communication is purely based on verbal exchanges and sketches but doesn't include the physical product, users could easily have misconceptions about the product, which leads to expectation gap and disappointment. Gravity Sketch's 3D models enable users and technicians to both easily understand the situation.*"
2. Gravity Sketch was found to facilitate quick learning. The participants did not encounter notable problems in the learning and application stages and were able to quickly resolve problems in system control.
   User B stated, "*Because it was my first time using this equipment, it took some time to learn how to use it, but I didn't experience any major problems while using it.*"
   Expert A stated, "*I didn't have any problem learning how to use the equipment, but I sometimes forgot the locations and functions of certain buttons. However, I was able to use the equipment easily after a few reminders."*
3. In Gravity Sketch, basic tools were easy to learn, but advanced tools, such as free-form surfaces, required sufficient modeling and design knowledge and lengthy practice to master. The advanced tools were used primarily by the designers, but the system did not group tools according to their difficulty level. Consequently, the flow of the participatory design process was often interrupted by participants activating the wrong tools.
   User B stated, "*Sometimes I pressed the wrong button. The system lets me to return to the previous step, but it's a little inconvenient."*
4. Gravity Sketch was designed for use by individuals without hand impairments, but in this study, several users had hand impairments and could only use the tools that were grouped to one side of the interface. These users were unable to use the zooming function, which required

the use of two hands. The researchers made several attempts to modify the system interface into a form that was compatible with single-handed operation, including (a) setting the zoom ratio to 1:1 prior to participatory design and creating a spacious, obstacle-free space for the participants to move about freely, and (b) providing the one-handed users with the right-hand controller containing freehand drawing, object position editing toolbar, and some object modeling editing toolbar. The scenario of the co-creation between the one-handed user and the designer is presented in Figure 7. After the experiment, the participating users asserted that the interface met their needs. Being able to walk and move freely was highly intuitive, allowing the users to quickly adapt to the virtual environment.

User B stated, "*Compared with moving and turning the view angle by dragging the mouse, I prefer being able to move and observe on my own in a large space*."

User C stated, "*The advantage of VR is that it enables users to freely move and observe in a space. In the co-creation process, we were only co-creating a single product, so we might not fully notice this advantage. However, when users have to discuss about multiple objects, they will definitely notice that VR enables a more immersive experience.*"

Users could not zoom in or zoom out on their own; however, the designer could adjust the view for them. Therefore, the lack of this function did not affect the co-creation process.

User B stated, "*Although I couldn't do it on my own, the designer or someone else could help me with it.*"

User C stated, "*With the designer helping out, we successfully completed the discussion despite being unable to use certain functions*."

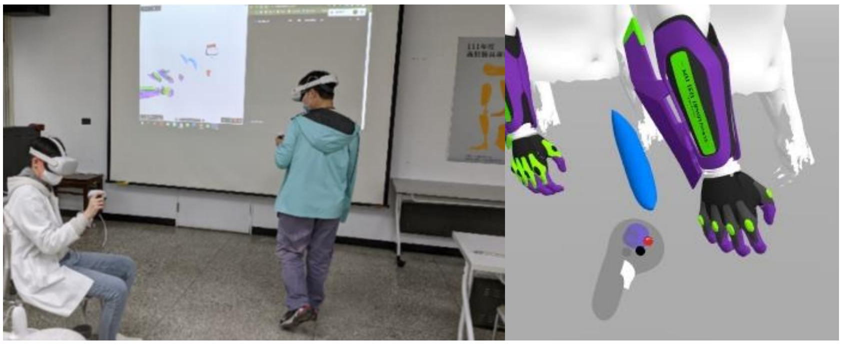


Figure 7. Co-creation between the designer and the one-handed user and the one-handed user's view in the VR environment

4.3 Observation and feedback from the designers

The designers not only completed the designs successfully, but also gave feedback and made recommendations during follow-up interviews. The feedback and suggestions are as follows:

1. Communication effectiveness was restricted by the fact that Gravity Sketch could not simulate the individual components of prostheses or their mechanical details. For example, on several occasions, the designers tried to describe the parts that made up the prosthesis or their mechanical actions by using abstract line drawings and verbal descriptions; however, this resulted in misunderstanding among participants.
2. In the participatory design process, the prosthesis users and technician primarily supplied ideas and the designers guided the design process and modified the virtual models. Therefore, they should be given different tool sets. In the future, software programs can offer a design

mode and a simplified support/discussion mode according to the scenario or role played by a user to reduce the risk of operator error.

3. Prosthesis users are likely to have impairments in one or both hands and require a drastically different system interface. Gravity Sketch should develop a mode specifically designed for users with hand impairments or weak grabbing strength.
4. At present, Gravity Sketch provides two co-creation platforms, namely Screen Collab for PC users and LandingPad Collab for VR users. The two platforms were tested and compared, and the results revealed that participants were better able to understand the design details and discuss with designers when using the VR platform. Consequently, the PC platform was less useful than the VR platform.

5 Discussion

5.1 VR design collaboration process

Comparing the experimental results and research hypothesis before the experiment revealed the following findings.

1. In this study, physicians were not invited to participate in the prosthesis co-creation process because physicians generally focus on medical treatment and patient evaluation, such as the reasons of amputation and causes of disease, whereas prosthesis testing is mostly handled by prosthetists and physical therapists. The experimental results also indicated that physical therapists and prosthetists might play similar roles in prosthesis design; in practice, prosthetic technicians frequently act as physical therapists when helping users select suitable protheses.
2. This study originally assumed that designers, prosthesis users, and prosthesis technicians would host discussions together in the same virtual space. However, implementation of the actual experiment revealed that the designer often had difficulty responding simultaneously to feedback from both the prosthesis user and prosthesis expert. In addition, most of the discussion was focused on prosthesis appearance and design, which was mainly based on the opinions of the user and required discussion between the designer and user. The prosthesis expert only needed to confirm the viability of the appearance design at the end of the co-creation process. Therefore, after discussion among the researchers and participants, the co-creation process was modified to involve multiple one-on-one discussion sessions arranged in a specific sequence, as the stage (2) shown in Figure 8.

According to the RtD process adopted in this study, an ideal and effective design process should constitute three stages: (1) Preceding operation, the prosthesis technician performs 3D scanning of the stump of the prosthesis user and sends the data to the designer for modeling. The designer and user engage in online or in-person discussions to determine design requirements using reference pictures and freehand sketches. The designer subsequently imports 3D models and design references into LandingPad Collab to develop preliminary 3D designs using Gravity Sketch. (2) VR-based participatory design, this stage involves a three-session participatory design approach. (A) The designer and user discuss the desired exterior design. (B) The designer and prosthesis expert examine the exterior design in terms of its structural rationality. (C) The designer and user finalize the exterior design. If a consensus is not reached in (C), the process restarts from (A), otherwise the process continues to the production stage. In (3) production stage, the designer exports the virtual model into

3D modeling software to repair the fracture surface(non-closed polysurface), splits the model into various components for printing, and converts the components into files ready to be sent to the 3D printer. Finally, the components of the prosthesis are 3D printed in photosensitive resin or high-strength nylon and then assembled.

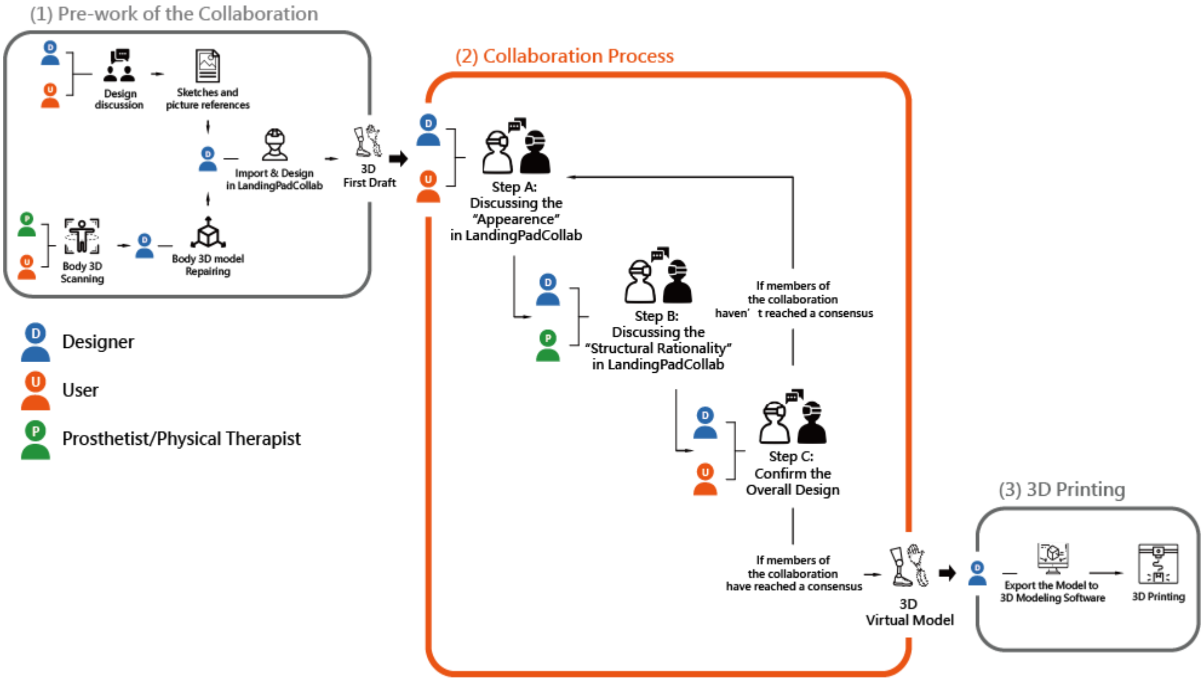


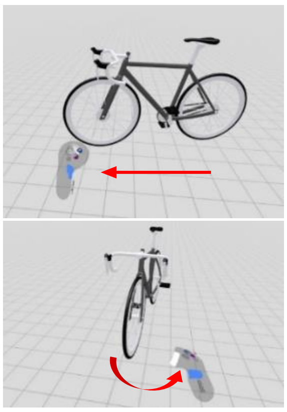
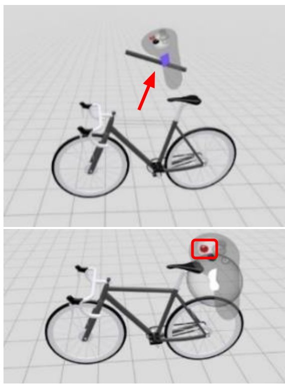
Figure 8. VR design collaboration process

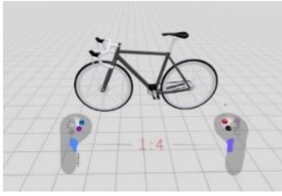
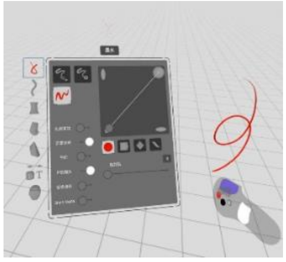
5.2 Co-creation toolbars for general and one-handed participants

5.2.1 Toolbar functions for general participants

During a prosthesis co-creation process in the VR environment, the main functions required by the prosthesis user and expert are those for making observations and providing feedback. To prevent the participants from selecting the wrong function during the co-creation process, this study simplified the existing toolbar of Gravity Sketch and compiled a list of functions suitable for general participants to help them quickly learn to use the co-creation platform. In Table 3, the co-creation process for a bicycle is presented as an example.

Table 3. Functions included in the toolbar suitable for general participants

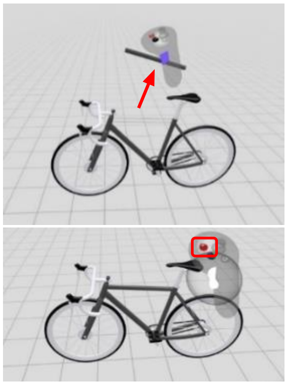
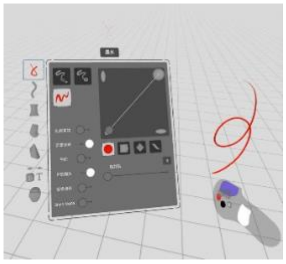
	View angle movement and rotation: Move the user window or adjust the view angle to observe the object from different directions.		Object movement and movement cancellation: Simulates the act of grabbing or placing an object.

	Scale: Zoom in or zoom out on the user window to view the overall shape or specific details of a 3D object.		Ink: Draw 3D lines in the virtual environment to facilitate conversations during co-creation.
	Passthrough mode: Turn on the sensors on the headset to view a virtual object in the real-world environment.		

5.2.2 Toolbar functions for one-handed participants

If a co-creation participant is one-handed (similar to those participated in this study), they should be provided with an ample space for movement (Figure 7) and a simpler toolbar than that designed for general participants. The functions should all be usable with a one-handed controller (Table 4).

Table 4. Functions included in the toolbar suitable for one-handed participants

	Object movement and movement cancellation: Simulates the act of grabbing or placing an object.		Ink: Draw 3D lines in the virtual environment to facilitate conversations during co-creation.
	Passthrough mode: Turn on the sensors on the headset to view a virtual object in the real-world environment.		

6 Conclusions

In this study, prosthesis designers, users, and technicians engaged in a participatory design process by operating a VR-based modeling software package to collaboratively design a prosthesis. The following conclusions are drawn according to observations during the participatory design process and the interview results:

1. The rapid 3D modeling facilitated by Gravity Sketch enables participants without design-related experience to quickly understand design proposals. Gravity Sketch also facilitates

timely correction of virtual models, saving time and money usually spent on remodeling. In addition, by using VR models and 3D printing technology, designers can overcome conventional prosthesis design by participating in co-creation with prosthesis users and technician to develop products with diverse appearances. This approach reduces the costs of prosthesis adjustment and overcomes the limitations of conventional prosthesis design procedures.

2. In the participatory design process, the basic tools of Gravity Sketch proved to be easy to learn for participants without VR experience. In addition, the novelty factor of VR encouraged the participation of the younger generation.
3. During the co-creation process, users can participate in the development process and contribute to the completion of their prosthesis. This enhances the user's sense of participation and their acceptance of the prosthesis, thereby indirectly increasing their confidence and intention to use the prosthesis and alleviating their emotional stress associated with wearing the prosthesis.
4. In addition to the complete mode for professional designers, Gravity Sketch should provide a simplified mode for users who have limited design experience and enable switching between the modes to facilitate co-creation among users of varying experience.

This study obtained preliminary research results regarding general and one-handed users of VR co-creation platforms. Future research projects will recruit users with more diverse prosthesis needs and increase the scope of co-creation platforms to the design of other functional assistive devices.

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