

**A PARAMETRIC DESIGN TOOL TO SUPPORT CUSTOMIZED
ADAPTATIONS OF ASSISTIVE TECHNOLOGIES FOR PEOPLE
WITH HAND IMPAIRMENTS**

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**A PARAMETRIC DESIGN TOOL TO SUPPORT CUSTOMIZED
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LIST OF SYMBOLS AND ABBREVIATIONS

AT/ATs	Assistive technology / Assistive technologies
ADL	Activities of daily living
CAD	Computer-aided design
DASH form	Disability of the Arm, Shoulder, and Hand form
OT/OTs	Occupational therapist / Occupational therapists
MMT	Manual Muscle Strength Testing
PEO	Person-environment-occupation
3D	Three-dimensional

SUMMARY

This thesis aims to explore the feasibility of a proof-of-concept parametric software that empowers occupational therapists (OTs) in fabricating customized adaptations of assistive technologies (ATs) to effectively address the distinctive requirements of individuals with hand impairments. The platform enables OTs to modify pre-designed models of utensil grips, serving as examples of ATs, based on individuals' hand assessments and anthropometric data. We conducted observations and interviews to gain insights into the AT adaptation processes by OTs for individuals with hand impairments. Subsequently, using an iterative design process, we created an interface prototype that allows for customized adaptations of ATs and invited an OT to participate in the preliminary testing of the prototype. Furthermore, a usability test was carried out with OTs to achieve a comprehensive appraisal of the parametric design tool's practical application and to obtain insights to the physical ATs for the hand that were generated. Lastly, we provide an outline of the design requirements for parametric modeling tools that support OTs and other clinicians to design customized ATs for individuals with limited hand dexterity.

CHAPTER 1. INTRODUCTION

1.1 Hand-related Assistive Technologies and Adaptations

Assistive technologies (ATs) enable individuals with disabilities to participate in activities of daily living (ADL) that would otherwise be unattainable for them (Anson, 2018). In individuals with hand impairments, reduced hand mobility and grip strength, attributed to aging and various pathologies, can have a detrimental impact on the performance of ADL, ultimately restricting personal independence (Brand & Hollister, 1999). Hands play a critical role in a wide range of daily activities, encompassing simple object manipulation to intricate motor tasks such as grasping, writing, eating, and dressing.

Assistive devices enhance the motor functions of the user (Roda-Sales, 2019). Therefore, to mitigate the negative impacts of hand impairments, OTs frequently prescribe AT to enhance hand mobility or prevent further damage caused by compensatory body movements (McDonald et al., 2016). ATs can be acquired either through commercial off-the-shelf solutions or by tailoring them to cater to specific individual requirements (Smith et al., 2018). However, purchasing off-the-shelf ATs presents a significant challenge when it comes to finding devices that meet the personal needs of users (Scherer & Craddock, 2002). To address this issue, OTs may refer to databases such as EASTIN (Andrich, 2011), Walmart, or Amazon to locate commercially available devices. Nevertheless, it is crucial to recognize that mass-produced assistive devices are primarily designed to meet the needs of the general population and may not be suitable for individuals with specific and unique requirements (Giesbrecht, 2013) (Aflatoony & Kolarić, 2022). In addition, the abandonment rate of ATs and the reasons behind such abandonment are crucial factors that

OTs need to evaluate when considering the appropriateness of a particular device. Common reasons for abandonment include poor fit and inadequate functional requirements (Cruz et al., 2016).

OTs often employ various materials such as foam, tape, Velcro, cardboard, string, thermoplastic, and sponge to customize off-the-shelf or everyday objects, aiming to improve the fit and enhance usability for individuals with specific needs (Hammell & Iwama, 2012). These materials are particularly useful for quickly modifying mass-produced ATs as they are readily available and do not require OTs to acquire new skill sets (Aflatoony & Shenai, 2021). For instance, foam and sponge are affordable and readily available materials. Their stretchability enables them to be fitted onto various grips, but they are not washable. Thermoplastic is a suitable material for rapid prototyping and customization, offering an optimal fit for the user's hand. However, it is not resilient to high temperatures and can be relatively more expensive compared to other materials.

1.2 3D Printing Technology

To enhance the durability and extend the lifespan of augmented ATs, the emergence of affordable 3D printing technology offers a promising avenue for rapidly fabricating a wide range of adaptations (Chen et al., 2016) (Buehler, Easley, et al., 2015). These 3D printed adaptations are known to be more durable, functional, and aesthetically pleasing compared to traditional field-modified products (Campbell et al., 2007) (Gao et al., 2015). Moreover, 3D printing technology eliminates the requirement for tooling, thereby making the rapid prototyping process more cost-effective (Hunzeker & Ozelie, 2021) and time-efficient compared to traditional manufacturing methods. This is particularly beneficial for

producing low-volume, highly customized parts that offer equivalent functionality (Conner et al., 2014). Furthermore, ATs produced through 3D printing can be further customized to meet specific user requirements. This is achieved by employing a heat gun to soften the material, thus rendering it malleable, smooth, and capable of being reshaped, or by utilizing a 3D pen to append additional elements or contours to the existing printed structures (Takahashi & Kim, 2019). For the purpose of fabricating an object via 3D printer necessitates the development of a corresponding 3D digital model.

1.3 Digital Fabrication

Regarding the fabrication of 3D objects, there are multiple methodologies that provide possible solutions of this process. One approach is to generate 3D models through the use of a 3D scanner to directly scan the real-world objects. Nevertheless, the precision of the 3D scanning process and the repetition of the scanning process in order to obtain a noise-reduced model may impact the efficacy of developing adaptations. Furthermore, the post-scan alteration of objects within the computer continues to present challenges for individuals with limited experience. A solution that integrates two-dimensional shape scanning, manual sketching, and machining tools (CNC) exists to enable the modification of physical items (Follmer et al., 2010), but it is constrained to planar surfaces and only suitable for subtractive manufacture.

Another approach is using professional Computer-Aided Design (CAD) software for the digital generation of 3D models. However, many 3D design and fabrication tools are costly and difficult for inexperienced users to navigate. Popular CAD tools such as AutoCAD or SolidWorks often come with a steep learning curve, which can pose a

challenge for OTs to overcome (Carrington et al., 2015). On the other hand, while individuals may find certain free pre-designed ATs available for free on online communities such as Thingiverse (Hurst & Kane, 2013) (Buehler, Branham, et al., 2015), the limited selection of models does not encompass the full range of ATs needed to meet everyone's specific requirements. Additionally, even after downloading these models, OTs still need to acquire the necessary CAD skills to make further adaptations to the designs. Despite these challenges, studies have shown that OTs generally have a positive attitude towards adopting 3D printing technology in the process of creating ATs (Slegers et al., 2022).

The objective in the development of such software is to simplify the complexity inherent in the design process for therapists (Buehler et al., 2014). Therefore, to better support OTs in AT adaptation, it is crucial for CAD tools to align with OT clinical practice (Hofmann et al., 2019). CAD tools used by OTs in their typical operations should be highly specialized and require dedicated interactive operators. These operators should encompass specific features that are relevant to OTs' tasks, including custom expansion, custom extension, augmentation, mounting, and grasping/holding (Aflatoony & Shenai, 2021). Moreover, in the software, the parametric field and labels need to utilize terminology more aligned with OT jargon, to avoid the confusions caused by CAD-related vocabulary (Buehler et al., 2016). By incorporating these specialized operators, the design and modification process for OTs can be streamlined. An ideal platform for this purpose should also possess an intuitive user interface, consolidating the various aforementioned operators.

CHAPTER 2. METHODOLGY

2.1 Observation

We employed observation as one of the research methods to initiate the study. The observation study took place over a duration of four hours at a local upper extremity occupational therapy clinic, allowing us to make firsthand observations of three OTs in their work environments. The primary goal of the observation sessions was to gain a holistic understanding of the AT adaptation processes, including clinical examinations. During the observation sessions, OTs demonstrated the use of various tools to measure hand strength and other relevant parameters. These measurements provided valuable information about the overall functionality of the upper limbs, allowing the therapists to assess the strength and capabilities of the hands, wrist, and arms. These tools included a goniometer for measuring range of motion, a dynamometer for quantifying grip strength, and a pinch gauge for assessing pinch strength (see **Figure 1**). Additionally, OTs typically employed the Disability of the Arm, Shoulder, and Hand form (DASH form) in conjunction with these tools to comprehensively evaluate the mobility of a person's upper limbs. OTs also shared examples of adapted grips and the materials they utilize when creating handheld ATs (see Figure 2).



Figure 1 - Goniometer, dynamometer, and pinch gauge tools for hand measurements.



Figure 2 - Examples of DIY handheld ATs created by OTs. Foam tubes and thermoplastics are commonly used materials for quick adaptations.

2.2 First Prototype Iteration

We developed the parametric design tool using two software components: Grasshopper and Human UI. Grasshopper is a parametric modeling tool that operates in conjunction with Rhinoceros, while Human UI is an interface paradigm specifically designed to customize the user interface of Grasshopper. In the initial iteration of the tool (see Figure 3), we created two types of add-on grips: a round smooth grip and a round grip with a straight-line textured surface. The interface of this iteration presents a comprehensive list of adjustable elements, encompassing outside dimensions such as diameter and height, as well as inside connecting channel dimensions. In the case of the round straight-line textured grip, we also included additional adjustable components, such

as the number of teeth, teeth length, and teeth chamfer degree, in addition to the parameters mentioned earlier.

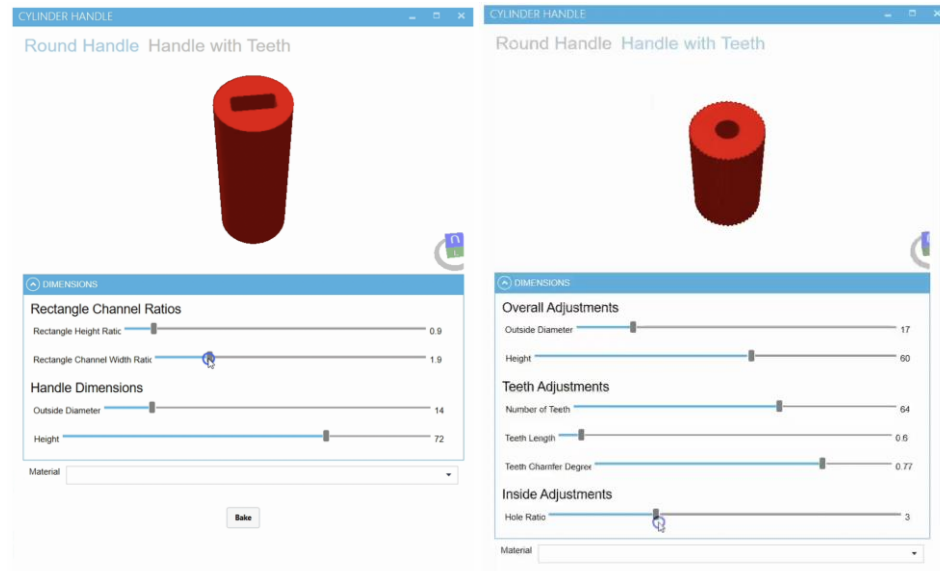


Figure 3 – The first prototype iteration.

2.3 Interview

The primary objective of the interview was to gain insight into how OTs adapt ATs or everyday items for individuals with limited hand dexterity. Additionally, through the interview, our aim was to develop a comprehensive understanding of the assessment process conducted by OTs during client interactions and how this data influences the selection of ATs. We also sought their perspective on the design of the two presented grips, namely the round smooth grip and the round straight-line textured grip, as well as the preliminary interface design. We selected grips as they were identified as a sample of adaptations with the highest perceived need by OTs. The interview study comprised a sample size of five participants, identified as OT1, OT2, OT3, OT4, and OT5 throughout the subsequent sections. Each interview lasted between 30 to 70 minutes, with an average

duration of 50 minutes. An affinity diagram was employed to systematically organize and analyze the information obtained from the interviews. The collected data was categorized into two primary themes: (1) OT's client assessment process and data processing, (2) OT's approaches to assistive technology design and adaptation, and (3) OTs' recommendations for grip and interface designs.

2.3.1 *OT's Assessment Process and Data Processing*

2.3.1.1 The methods used by OT to evaluate the hand mobility of users

OTs utilized various tools to assess different dimensions of hand mobility. OT1, OT2, OT3, and OT5 acknowledged the usage of a goniometer to measure the range of motion, a dynamometer to examine grip strength, a pinch gauge to assess pinch strength, and tape or soft tape for measuring hand width or length. Additionally, OTs sometimes employ a simple method of tracing customers' hands on paper for documentation purposes, as expressed by OT2: *"We don't use anything very high tech... a lot of times it is just tracing the hand on a piece of paper."* Furthermore, OT2 emphasized the significance of evaluating sensory capabilities for hand function, stating, *"We might be looking at their sensation cause that might be important with the hand function. Can they tell [perceive] hot and cold [temperatures] and those sorts of things?"* There are additional methods that could be employed to assist OTs in comprehensively analyzing the upper extremity situations of their clients. As suggested by OT1, the *"9-hole peg test"* can be used as a standardized test for assessing finger dexterity. In addition, surveys can be conducted with clients, involving task or subtask completion as part of the assessment process. OT1 expressed this by stating,

“There could be a survey and having individuals complete different whatever their task or subtask is as part of that test.”

2.3.1.2 Data Acquisition, Analysis, and Visualization

The specific data collection methods and information storage practices varied among different clinics. According to OT2, “most places have now transitioned to electronic documentation, so whatever they input into their system for the evaluation is what they'll use. However, the same information is typically collected in slightly different forms.” In the context of hand measurements, these forms are referred to as the Certified Hand Therapist Form, as mentioned by OT3.

After collecting the necessary information for evaluating hand mobility, OT1 offered important insights into the interpretation of this data. Regarding range of motion, OT1 explained, *“There are established norms for range of motion, for example, shoulder flexion is typically 180 degrees. So that's one set of things that I basically used that information to judge where my patient is to help [and] set a goal for them to work on [improving] their range of motion.”* Similarly, when analyzing strength testing results, OT1 explained, *“For me, Manual Muscle Strength Testing (MMT) involves assessing the patient's strength and then referencing normative data based on age and gender. This helps me interpret the results and make sense of the information gathered.”* These normative data often serve as both reference and documentation for OTs. Furthermore, OT3 highlighted, *“there's even psychological thing [factor] ...some people are a little self-conscious of an adaptive device that they're gonna use, maybe in a social setting like a workplace.”*

Consequently, the prescription of assistive devices by OTs is influenced by a combination of normative data collected and the preferences expressed by the users themselves.

2.3.2 *OT's Approaches to Assistive Technology Design and Adaptation*

2.3.2.1 Design Scope

When designing ATs, two distinct approaches are considered: universal design and specialized design. This conclusion draws from OT3 perspective, who stated: “... *the difference between a OT practice as 'person' approach vs. a 'population' approach.*” When the AT is intended for use by multiple individuals, anthropometry principles, as established in static anthropometric estimate tables, are applied. OT3 supports this approach, stating, “*usually with population approach you use more of a universal design so that it's inclusive for everybody to use.*” Furthermore, OT3 mentioned, “*Ergonomics is a staple practice domain for OTs, and when it comes to assistive technology, we usually apply anthropometry principles when the AT is being used by multiple individuals, such as classroom AT or workplace AT. There are 'static' anthropometric estimate tables for the hand available if needed.*”

On the other hand, when the AT is designed or modified exclusively for one individual, OTs adopt an “*ergonomics for one*” approach, incorporating the person-environment-occupation (PEO) model to guide the development of an appropriate AT solution. As OT3 affirmed: “*Ergonomics for one usually follows the model called PEO while making ATs.*” In the context of the design of adapted grips in this study, OT3 categorizes it under universal design, indicating that the utilization of anthropometric tables

would be more suitable. OT3 stated: *“I would say yours is more for a bigger population, one grip could fit different groups of people, so it is more universal.”*

2.3.2.2 Material

Foam tubes are commonly used as a versatile material for adaptations, as acknowledged by OT2: “foam tubing can sometimes be used for a variety of things. Like if we need it for a utensil for eating or a toothbrush. It is also available in different diameters and can be easily cut to accommodate specific length.” However, the use of foam presents certain limitations, as pointed out by OT3: “the bad part with the foam is...hard to wash and can't be really sterilized.” This drawback significantly contributes to the abandonment rate of ATs that incorporate foam as a material. Alternatively, thermoplastic is also considered a practical material for modifying ATs. Nonetheless, as pointed out by OT2 *“3D printing would probably still be preferable because it is also less expensive. You buy it in like these big sheet and you know a sheet would cost a lot more than making a device with a 3D printer.”* Additionally, the iterative nature of AT modification often requires repeated adjustments. Notably, 3D printed models offer the advantage of adjustability through methods such as heat gun shrinking, bending, or extending. These methods are already familiar to OTs in their professional practice, allowing them to make precise adjustments to the 3D printed models. Consequently, 3D printing presents a more efficient, cost-effective, and easily modifiable solution for OTs when adapting ATs.

2.3.2.3 Cost and Time Effectiveness

OTs demonstrate a strong aptitude for balancing cost and time efficiency in their practice, considering the regulations and reimbursement constraints they face. As OT4

highlighted, “*OTs in clinical practice are heavily regulated by reimbursement.*” The prevailing practice, as stated by OT4, is to recommend off-the-shelf ATs that closely align with clients' needs: “*if you were in the hospital setting or home health where most of your clients are reimbursed by Medicare or private insurance, OTs are not really reimbursed for any extra time taken to do precise measurements, design and modify ATs. In these settings, recommending off-the-shelf ATs that are the closest fit to their needs is by far most common.*” Therefore, ensuring the provision of effective off-the-shelf ATs remains crucial, especially in settings where reimbursement constraints and time limitations may limit the ability to provide customized solutions.

To avoid wasting time and resources on acquiring unsuitable ATs, OT2 suggested initially adopting a trial-and-error approach when exploring different options. As OT2 explained, this involves trying out various devices and tools to assess their suitability. Some clinics provide a range of different items for customers to test, especially for smaller devices used for eating or other specific tasks. However, in the current market, off-the-shelf ATs are primarily available in three standard sizes: small, medium, and large. Therefore, OTs often need to modify these ATs to ensure a better fit for their clients. As OT3 pointed out, “*OTs are pretty good at taking a universal design and modifying that.*”

2.3.3 *OTs' Recommendations for Grip and Interface Designs*

2.3.3.1 Grip Design

OTs approach to designing adapted grips took into account various pathologies and utilization scenarios. For individuals with arthritis, OT4 recommended the use of utensils that minimize the need for extensive gripping. These utensils often feature thicker grips

and padding. As OT4 explained, “*We would recommend using utensils that don't require as much gripping, such as those with thicker grips, padding, or allow stabilization in some other ways.*” When addressing the needs of individuals with Parkinson's disease, OT5 suggested the use of weighted utensils, as “*the weight helps a lot of patients who have Parkinson's.*” To accommodate individuals with limited grip strength, OT3 suggested a grip design featuring flared ends. This design helps prevent the hand from sliding off the foam onto the spoon and improves grip. As described by OT3, “*Each end of the grip had a flare, flared out the end of it, so that some people, whose hand ends up sliding off the foam onto the spoon because they didn't have a very good grip, would have a better grip. And when they put it in their mouth, their hands [wouldn't] slid forward.*”

In addition, OT3 suggested incorporating teeth on the grip to provide sensory feedback for individuals who struggle with grip control. However, OT3 acknowledged that using teeth texture on the grip for feeding purposes raises hygienic concerns: “*The teeth, if included, can give them that sensory feedback, and they can feel it better than a smooth grip. But they're going to be using this for feeding, for eating. So if they get mashed potatoes or gravy on it. You know, whoever cleans it is going to have to dig out the food [particles] from those teeth.*” Moreover, for individuals with limited grip control, OT3 recommended incorporating finger grooves into the grip design. This allows each finger to fit into a specific groove, providing enhanced stability and control. As OT3 explained, “*some people don't have a lot of control with their grip, either from numbness and tingling or spasticity. If you put a finger groove in that, it'll help that person as each finger goes into the groove.*” Another solution suggested by OT3 is the use of a strap to secure the grip for individuals with weak grip strength. By tightening the strap over their fingers, the grip is prevented

from slipping off, ensuring a secure grip. OT3 further elaborated, "*You can tighten the strip over their fingers, and now it won't come off.*" For individuals who struggle with fully closing their fists, OT5 recommends the use of "*a U cuff grip*". This type of grip is specifically designed to accommodate their hand shape and abilities.

2.3.3.2 Interface Design

During the preliminary interview, OTs also provided suggestions for interface designs. They identified several essential features that should be incorporated into the software. OTs identified several essential features that should be incorporated into the software. According to OT2, "*the outside diameter is the most important, and the height, inside diameter are also important to have.*" Additionally, OT5 emphasized the need to "*specify the unit of measurements.*" OT5 also suggested implementing a slide scale, as it allows for easy visualization of the immediate effects. As stated by OT5, "*Having a slide scale is good because it is easy and I can see the effects of that right away.*"

When considering individuals with low vision, incorporating bright colors into the design of adapted grips can be advantageous. OT3 emphasized that using a bright color, such as yellow, can facilitate the identification and retrieval of utensils from storage: "*sometimes a bright color would make it easier for them to find them in the drawer where they keep their utensils.*"

CHAPTER 3. PROTOTYPE

We organized design requirements (see Figure 4) based on the feedback we received from OTs during the interview session and continued to refine the interface. The second prototype (see Figure 4) offers a wide range of grip types, adjustable dimensions, weight options, and material choices to cater to the diverse needs of individuals with hand impairments. The interface introduces four distinct grip types: bended grips, round cylindrical grips, polygon cylindrical grips, and oval cylindrical grips. Within each category, OTs have the flexibility to choose from three different grip options, taking into consideration the unique needs and preferences of their clients. These options include smooth grips, straight-line texture grips, and curvy texture grips. Our selection of these textures stems from previous interviews with OTs, who endorsed gear-like shapes in handle design for their sensory feedback. However, enhancements were made to address concerns about cleanliness, particularly for eating utensils. We refined the shape by smoothing edges and lessening depth. Additionally, we introduced a curvy texture as a novel option for sensory engagement, offering a more organic and distinct shape for user preference. This variety caters to individual personalities and desires for unique adaptive device designs, as noted by an OT regarding their clients' diverse preferences. Additionally, OTs have the flexibility to customize the surface color of each grip by selecting from a color swatch. To cater to clients with limited hand strength and mobility, OTs can choose from specialized grip variations, such as flared grips, grips with hooks, or flared grips with hooks. These variations help to enhance the hand mobility of patients.

Task example	Task component	UI element
Navigation of needed handle	Select by shape	Name button on the top bar
	Specification for specific pathology	Description
Customization	Color	Color swatch
	Designs of adaptive handles	Pull down menu
	Width/Diameter	Slider
	Height	Slider
	Inner width	Slider
	Inner thickness	Slider
	Weight	Multiple choices
Visualization	Material	Multiple choices
	Visualization of changes	Real-time and interactive display
Completion of design	Unit of measurement	Millimeter
	Generate the designed model	Button



Figure 4 - Design requirements were developed based on data gathered through interviews and translated into the second iteration of grips and interface design.

The dimension parameters are categorized into two sections: outside dimensions and inside dimensions. Within the outside dimension section, OTs can adjust the diameter and overall height of the grips. In the inside dimension section, they can modify the inner length and width according to specific requirements. The parameters are correlated to the dimensions OTs will measure before using this tool. The correlation of parameters is shown in Figure 5.



Figure 5 - The correlation between parameters and measurements. B - refers the measurement from the width of the proximal transverse palmar crease to that of the

distal palmar crease, and this dimension correlates to the “Height” parameter on the interface; C and D- refer to the measurement of gripping diameter, and these dimensions correlate to the “Diameter or Width 1/2” parameters on the interface; E - refers to the measurement for the width of the utensil grip, and this dimension correlates to the “Inner length” parameter on the interface; F - refers to the measurement for the thickness of the utensil grip, and this dimension correlates to the “Inner width” parameter on the interface.

Furthermore, the interface provides OTs with the option to choose the weight of the grips, offering three categories: light (~95g), medium (~180g), and heavy (~250g). This allows for customization based on the unique needs of their clients. Recognizing that OTs may not be familiar with 3D printing filaments, the interface simplifies material selection by offering two options: flexible and rigid materials. This ensures that OTs can confidently select the appropriate material based on their requirements. Additionally, the interface includes a text box on the bended grips and round cylindrical grips indicating compatibility for users with Parkinson's disease. However, it is important to ensure that the diameter of these grips does not exceed 20 millimeters (Ma et al., 2008).

The user flow chart (see Figure 6) illustrates the methodology employed by OTs using the parametric design tool to create customized handles. Initially, OTs gather measurements of the AT user's hand and utensil dimensions, serving as input parameters of handle size. Other parameters such as color, weight and material are then modified according to individual patient needs and health conditions. Upon finalizing the design, OTs click the 'bake' button on the interface to generate the handle model. Next, OTs will be able to save and download the model. The model is then fabricated using a 3D printer.

OTs proficient in 3D printing may opt to slice the model themselves using specialized software (we use Ultimaker-Cura), adjusting settings as needed. Conversely, those with limited access or expertise may seek assistance from technicians or outsource the task to a 3D printing service provider or DIY lab. The printer displays the estimated duration of the printing process. Upon completion, OTs can collect the finished adaptive device and proceed to evaluate its effectiveness with clients.

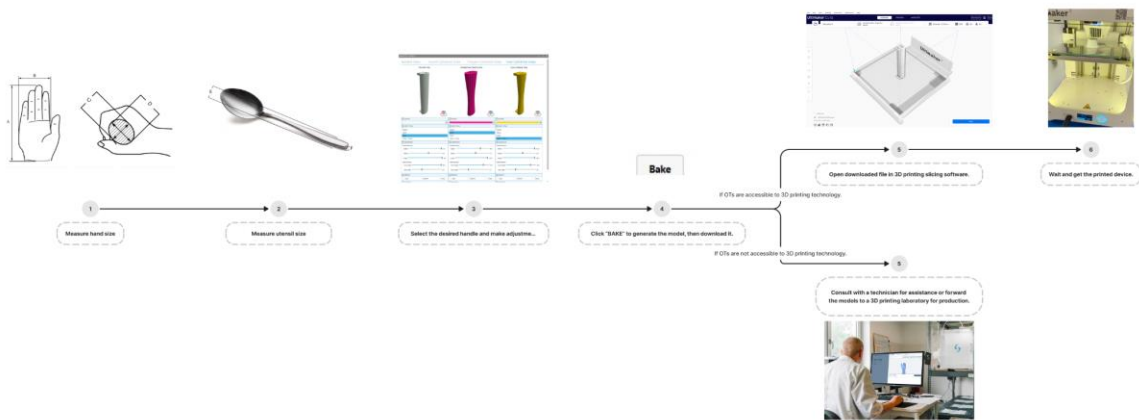


Figure 6 - The user flow chart illustrates the methodology employed by OTs using the parametric design tool to create customized handles.

CHAPTER 4. PILOT STUDY

During the evaluation of the second prototype, we conducted a 90-minute pilot study workshop with an OT to assess its functionality. The OT was initially given the opportunity to manipulate the tool, generating two distinct grips based on specific requirements. Valuable insights regarding the interface and physical grip design were subsequently provided by the OT. The researcher utilized a 3D printer to produce the two handles created by the OT (see Figure 7). The OT found this version of the prototype to be comprehensible, emphasizing that the tool's parameters aligned with the measurement process involved in creating ATs for their clients.



Figure 7 - The left image displays the outcome of the interface's manipulation of a grip by the OT, while the right image exhibits the printed grips attached to utensils.

CHAPTER 5. USABILITY TEST

5.1 Methodology

At this phase, we focused on evaluating the effectiveness and user-friendliness of the newly developed prototype as well as the physical devices. For this purpose, the 'think aloud' methodology in usability testing was employed to gauge the tool's applicability in the routine operations of OTs. This study involved 12 OTs (as identified as OT1-OT12 in the following sections) with experience in hand disabilities. The demographic information of OTs is listed in Table 1.

Table 1 - Demographic information about OTs who participated in this usability test.

Participant	Gender	Years as OT Professional	Education/certification
OT1	F	21	OTR/L
OT2	F	5	OTR/L
OT3	M	30	OTR/L
OT4	F	11	OTR/L
OT5	M	7	OTR/L
OT6	F	15	OTR/L
OT7	F	2	OTR/L
OT8	F	3	OTR/L
OT9	F	8	OTR/L
OT10	F	16	OTR/L
OT11	M	13	OTR/L
OT12	F	27	OTR/L

Note: OTR = current National Board for Certification in Occupational Therapy (NBCOT) certification. OTL = current state-issued professional licensure.

5.2 Procedures

The evaluative procedure was bifurcated into two distinct sessions. During the initial session, which lasted between 45 to 60 minutes, OTs had an opportunity to manipulate the

parametric design tool and develop a customized adaptive handle that suits the user's needs. As part of the preparation for this session, participants were required to complete a Hand Therapy Evaluation Profile. This profile encompasses a comprehensive range of user-specific details such as age, gender, medical pathologies, occupation, various assessments (strength, dexterity, range of motion, sensation), and precise hand measurements. The thoroughness of these profiles aimed to ensure the validity and accuracy of the subsequent device design process. The data garnered aligns with the information obtained throughout the OT evaluation process. These profiles served as a reference, guiding OTs in their creation of adaptive devices within the parametric design tool, with a keen consideration of the user's pathology, personal requirements, and hand dimensions derived from past patient cases. The patient's fundamental details outlined in Table 2.

Table 2 – Information of hand therapy evaluation profile

AT User	Gender	Age	Pathology/Diagnosis
U1	F	56	Stroke
U2	F	67	Parkinson
U3	F	50	Diabetic Neuropathy & Diabetic retinopathy
U4	M	55	Central cord Syndrome
U5	M	88	Neuropathy
U6	F	51	Post Stroke
U7	F	63	Stroke
U8	M	50	Spinal Cord Injury
U9	M	46	Muscle Weakness
U10	F	88	Arthristis
U11	F	71	Parkinson
U12	M	91	Neurological Deficits

Note: U1 to U12 is correlated to OT1 to OT12.

At the end of this session, a system usability scale (SUS) survey and a semi-structured interview were conducted to gather quantitative and qualitative feedback aimed at identifying and enhancing the parametric design tool's functionality and user experience.

This session was organized to accommodate either virtual or in-person attendance, contingent upon the availability of the OTs. Each session took between 37 and 75 with an average duration of 43 minutes. We recorded and transcribed their words during the session, and pictures were taken for their handle design on the interface. For virtual sessions, integration of TeamViewer and Microsoft Teams was implemented to facilitate remote access and interaction with the parametric design tool.

Following the first session, the adaptive devices conceptualized by the OTs were fabricated using a Fused Deposition Modeling (FDM) 3D printer, specifically Ultimaker 3/5S. These printed adaptive handles were provided to OTs for evaluation in the second session. The follow-up session (session 2) reconvened the participants from the prior session. During this session, OTs have the chance to try and evaluate the printed hand ATs. In this phase of the evaluation, each OT participated in a focused interview concerning the design and practicality of the adaptive devices. This session was designed to be more concise, with the duration of 15 to 20 minutes, with the average time of 17 minutes. Given the varying availability and preferences of the OTs, this session is structured to be conducted either remotely or face-to-face. It is acknowledged that assessing the tangible aspects of the adaptive device through a virtual platform may introduce certain constraints. In future studies, it is crucial to dispatch the handles to those OTs who were unable to participate in in-person meetings, thereby enabling a hands-on experience with the device. All the handles produced by 3D printers were demonstrated in Table 3. And the patients' information and handle details are listed in Table 4.

The two-tiered structure of this usability test was critical in not only gauging user interaction with the parametric design tool but also in assessing the practicality of the 3D

printed devices, thereby ensuring a comprehensive evaluation of the prototype from conceptualization to physical usability.

After the two sessions, affinity diagrams were employed to analyze the qualitative data (please see the APPENDIX A. Interview questions for usability test session 2).

Table 3 - Examples of 3D printed handles designed by OTs according to user profiles.

























Designed by	OT1	OT2	OT3	OT4	OT5	OT6	OT7	OT8	OT9	OT10	OT11	OT12
Handle												

Table 4 - Details of printed handles

Designed for	U1 - Stroke	U2 - Parkinson	U3 - Diabetic neuropathy	U4 - Central cord Syndrome	U5 - Neuropathy	U6 - Post Stroke	U7 - Stroke	U8 - Spinal Cord Injury	U9 - Muscle Weakness	U10 - Arthritis	U11 - Parkinson	U12 - Neurological Deficits
Handle with hand												
Handle types	Curvy texture round cylindrical grip + Hooks	Straight-line texture oval cylindrical grip	Curvy texture round cylindrical grip + Hooks + Flared	Straight-line texture round cylindrical grip	Smooth polygon cylindrical grip	Straight-line texture round cylindrical grip + Hooks + Flared	Straight-line texture oval cylindrical grip + Hooks	Smooth oval cylindrical grip + Hooks	Straight-line texture round cylindrical grip + Hooks + Flared	Straight-line texture bended grip + Hooks + Flared	Smooth oval cylindrical grip	Straight-line texture oval cylindrical grip + Hooks
Material	Rigid	Rigid	Flexible	Rigid	Rigid	Rigid	Rigid	Rigid	Flexible	Flexible	Flexible	Flexible
Weight	Medium	Heavy	Medium	Light	Light	Medium	Heavy	Light	Medium	Light	Heavy	Light

CHAPTER 6. USABILITY TEST RESULTS AND DISCUSSION OF FINDINGS

6.1 SUS Survey

The assessment of SUS survey results employs a specific computational methodology. This involves initially aggregating the individual contributions of each item's score, which vary between 0 and 4. For odd-numbered items (1, 3, 5, 7, 9), the contribution is calculated by subtracting one from the scale position. Conversely, for even-numbered items (2, 4, 6, 8, 10), the contribution is derived from subtracting the scale position from 5. The cumulative score is then multiplied by a factor of 2.5 to yield the overall SUS value. Refer to **Error! Reference source not found.** for detailed SUS scores of each study participant (Brooke, n.d.).

Upon computing the SUS scores for each participant, the mean score across 12 participants is found to be 78.96. Generally, scores exceeding 68 were considered as positive feedback. Consequently, a mean SUS score of 78.96 indicates that the users perceive the system as usable, intuitive, and satisfying, reflecting positively on the user experience.

Table 5 - SUS survey results.

	OT1 Score	OT2 Score	OT3 Score	OT4 Score	OT5 Score	OT6 Score	OT7 Score	OT8 Score	OT9 Score	OT10 Score	OT11 Score	OT12 Score
Q1	1	2	4	3	4	3	4	3	4	2	4	3
Q2	4	3	3	4	4	3	4	2	3	2	4	4

Q3	3	3	3	3	4	3	4	3	3	2	3	3
Q4	3	2	3	3	4	1	3	4	1	3	2	3
Q5	1	3	4	3	4	3	4	3	4	3	4	3
Q6	4	3	3	4	4	2	4	3	4	3	4	3
Q7	4	3	3	4	4	3	4	1	3	3	4	3
Q8	4	2	4	4	4	3	4	2	3	2	4	4
Q9	2	3	3	2	4	3	4	3	3	2	4	3
Q10	4	3	3	3	4	2	4	4	3	3	3	2
Sum Score	30	27	33	33	40	26	39	28	31	25	36	31
SUS Score	75	67.5	82.5	82.5	100	65	97.5	70	77.5	62.5	90	77.5
Avg. SUS Score			78.96									

6.2 Findings on the Parametric Design Tool

6.2.1 Usability and Functionality of the Tool

Following their experience with the software, 11 OTs confirmed this tool's usability from different aspects. OT4 provided the insight about this tool to meet his expectations: *“I think this tool meet my expectation. It seems like it would be easy to use if you had the dimensions just to input. [OT4]”*

OTs also gave considerable positive feedback on the utility and functionality of the parametric design tool in their professional activities. Highlighting its ease of use, OT7 and OT1 remarked, *“I found it pretty self explanatory... if it is for someone that would use this,*

I think they would probably intuitively understand the functions of it... It was pretty straightforward to use. [OT7]” and “I'd like that I was able to turn it like in all 3D shapes... pretty quick that you can learn... I just need to slide the slider... So I felt pretty OK with using it. [OT1]” Similarly, OT5, OT6, and OT10 endorsed its simplicity and efficiency with comments like “It's a pretty good design... It's very easy to use for me... [OT5]”, “This software is very easy to use... it is a mature and useful software. [OT6]”, and “I think it's pretty easy to use... from the types (handle) to the dimension to the weight to the material, that's pretty clear. [OT10]”

In evaluating the current prototype, which featured 48 different handle designs, 6 OTs acknowledged various aspects of the tool's functionality. OT5 and OT10 appreciated the variety and customization options: “*You had all different sizes and different materials to choose from making it much easier. [OT5]”, and “I see there's so many grips! I would be so excited to get to choose from these for her. [OT10]”*

The ability to alter colors and view these changes in real-time was highlighted by OT1, OT3, and OT8: “*I liked that I could change the color, and see the color changed on the screen. [OT1]”, “Having the option of changing colors is great, because some people may have low vision... [OT3]”, and “And the color thing is really cool too...for dementia you want to use colors like red ... grabs their attention. They need cues to eat like reminders to eat their food [OT8]”. The significance of real-time monitoring in 3D design was also emphasized by OT4 and OT10: “*Manipulate it like from a position standpoint. So that's actually cool and that would help like if I was actually fabricating something for sure [OT4]” and “Drag and zooming function is very cool. What a neat interface! [OT10]”**

Additionally, the ease of inputting precise measurements was mentioned: *“Double click the bar to type the number that's easier. [OT4]”* and *“I like that you can double click the slider to type in the number. [OT10]”*

OT1 also pointed out the tool's utility in aiding decision-making: *“You have a little line that says like this is more for Parkinson's maybe the cylindrical grasp that's helpful.”*

6.2.2 Usefulness and Uniqueness of the Tool

OTs believe this tool would be beneficial for their everyday practice, as OT3, OT7, and OT10 mentioned *“I love this. This is awesome. I can't wait to see this in my catalog. One day I'll be buying them, you know...”*, *“That's cool, I think in real life I would definitely use this.”*, and *“... this tool beyond my expectation... I love this idea and it is a need... How can we help you be more independent? That's our question for our client. And then we could say, here's another tool in our toolkit to help you do something better... And it was designed by your therapist and you. I think that. Is very valuable... definitely exceeds my expectations. I like it very much [OT10].”* OT10 also envisioned how this tool could be adapted to their everyday practice, *“I see that being a very positive way to build toward the future. And then the company itself could have it be part of our system we already use and it just be a built-in click on that link it takes because we're always connected to the internet wherever we are. This follows me everywhere. It knows where we are and it always has the internet. So you would click that link. While you're in with a client, yeah, select it, send it through. Just like the nursing order supplies, the therapist would order that one.”* OT6 broadens the application of this adaptive device, transitioning its use to a rehabilitative

context: *“You have the flexible material ... it is squishy, so patients can squeeze it several times a day for rehabilitation”.*

5 OTs emphasized the uniqueness of the tool in addressing current challenges in assistive device provision. OT5, OT6, OT8, and OT9 highlighted its customization and cost-effectiveness: *“So because it's a very customized design, it has a big benefit for all the patients ... We have so many special utensils in the market right now that are more like a standard size. So it's very hard to give a patient a try, but also very expensive if you purchase it ... if it doesn't work... you will return or you buy another one. So it's very costly, a lot of money and time. So a good thing for your design is ... it is pretty cheap ... so we can try another one and it's pretty quick [OT5]”*, *“So like what you're doing is cool because we basically gave a one size fits all...like this foam tubing and it really didn't fit all, but it's all we had ...[OT8] ”*, *“OT6: I think customization really differentiate your products from others, and that makes it unique on the market. [OT6]”* and *“You give me an opportunity to create a ... specialized handle just made for him... as opposed to buying a universal one from Amazon, which can be hard to adjust at times [OT9]”*. OT8 also noted the tool's potential for different user groups, particularly in pediatric settings: *“For instance, like this would be a good tool... they (pediatrics) can't use typical silverware... this will be a cool tool because those types of utensils are typically not anything like the radius of your typical utensil. [OT8]”* Moreover, OT11 suggested that involving clients in the design process using this tool could potentially decrease the abandonment rate of adaptive devices: *“I think this system is wonderful and fairly quick to create your device... You could do it right there with the client, involve them... they will be more welcoming to use the handle they designed. [OT11]”*

6.2.3 *Suggestions for Improvement*

6.2.3.1 Measuring Unit and Number Difference

During the first usability testing session, 9 OTs which are OT1, OT2, OT3, OT4, OT7, OT8, OT9, OT10, and OT12 suggested the importance of incorporating both imperial and metric systems in the measurement unit options, as the prototype was limited to millimeters. They expressed, “... *that would be very helpful if I can change the measuring unit because I can tell how many inches of the patient's hand approximately would be. But I can't do that conversion in my head for the millimeters [OT7]*” and “*I know that millimeters are probably the most accurate. So I understand using millimeters. However, I could see my coworkers being like why is this not inches. But to me, millimeters make sense [OT8]*”. Additionally, 7 OTs consist of OT4, OT5, OT6, OT7, OT8, OT9, and OT11 recommended adjustments in the precision of measurements. They advised that having a 0.1 millimeter difference is unnecessary for handle design, suggesting the use of whole numbers or half-millimeter increments: “*I think if you're already in millimeters at that point ... where you wouldn't have to split a millimeter down [OT11]*”, “*Sometimes with our patients, a small change does make a difference... at least .5 could make a difference [OT4]*”, and “*The millimeter I really did not think you need a decimal [OT9]*”.

6.2.3.2 Weight Selection

OTs frequently addressed the aspect of weight selection in the tool, which currently offers three categories: light, medium, and heavy. 4 OTs including OT1, OT5, OT7, and OT12 suggested that a slider scale indicating the specific weight in pounds would provide a more precise understanding of the handle's weight. They expressed, “*I do think slider*

scale instead of like option 1, 2 or 3 [OT12]” and “if they have tremors, I would likely lean towards medium or heavy, but it would be hard for me. I'm putting my own subjective thought on what I think heavy is versus medium, so maybe you could quantify it because we know pounds of pressure. [OT1]”

6.2.3.3 Navigation and Comparison

OT1, OT6, and OT7 identified areas for enhancement in terms of navigating and comparing different handle designs within the tool. They suggested improvements for a more streamlined selection process. OT1 proposed a more integrated comparison feature: *“If you had a Dropbox ... if you had only one screen and then you could choose and maybe you could pop up different ones... I could pull up the three, but at the end of the day I can only manipulate one at a time... in one screen then I would have a better rhyme or reason for why I picked this versus that one and be able to contrast them side by side. [OT1]”*

OT7 also indicated the potential confusion with the current tab layout and recommended a more consolidated approach: *“I think having the multiple tabs up top, even though I was able to navigate them, I could see how it would be a little bit confusing... if there is a way to consolidate it somehow or have a separate drop down... instead of having like all the tabs at top. [OT7]”*

6.2.3.4 Sense of Size

OT7, OT8, and OT9 provided suggestions to enhance the digital representation of handle sizes, solving the challenge of visualizing the actual dimensions in the design tool. They proposed practical solutions for a more accurate perception of size. OT7 suggested adding common objects for scale: *“... it is hard to See what the image would look like in*

real life... maybe even having a size comparison of a regular object next to it just so that somebody could conceptualize how big it is ... like even if there was a human hand or a banana or something next to it [OT7] ” OT8 recommended clarifying the correlation of design coordinates: *“Maybe like an example of where the X&Y are... Just give a correlation of a scale... or a map like a legend. [OT8]”* OT9 suggested incorporating diagrams for intuitive design input: *“Maybe that will make it easier to understand the term, like the diagram on the side... with some arrows pointing on the grips ... so it is easier for the OTs to put the number in there and to do it a little more accurately. [OT9]”*

6.2.3.5 Others

In the final segment of their feedback, OTs identified additional areas for improvement in the design tool. OT7 provided insights on the user interface and material selection process. She suggested enlarging the 3D viewport for better visualization and incorporating detailed descriptions for material options, noting the ambiguity in terms like 'flexible' or 'rigid': *“... for someone that's probably new to this system, I think they might appreciate like a larger view of the item.”* and *“explaining like what the material is ... because when it says flexible or rigid, I don't know like what necessarily they are talking about with flexible or rigid. [OT7]”* Furthermore, OT10 recommended adding another set of parameters to adjust the bending angle of grips, thereby increasing customization options: *“It would be great if the angle can be changed for the bended handle option. [OT10]”*

6.3 Findings on the Handle Design

6.3.1 *Advantages*

6.3.1.1 Velcro for Extra Support

5 OTs affirmed the utility of the adaptive handle designs offered by the software for hand AT users. OT1, OT3, OT5, OT8, and OT12 highlighted the significance of incorporating hooks on both ends of the handle for Velcro insertion, which is vital for their clients. They expressed their appreciation for this feature: “... *it hooks and Velcro around so that their hand stays in place. That's a neat design ... because their hands may fatigue or they can't hold on to it to grip it. So it gives an extra assist to be able to hold [OT1]*”, “*I have a patient and turns out I don't need the Velcro, the hooks can stay on, but I can take the Velcro straps out, have a little more versatility [OT3]*.”, “... *hook design...it's perfect for the patient who cannot make for full fist [OT5]*”, “*Velcro is always a great idea with somebody has neurological problems because like at any point, their nerves could just stop firing. [OT8]*” and “... *especially because you have the option for the hooks that allow the Velcro strapping, that's a really big deal [OT12]*”.

6.3.1.2 Inclusive Design

In addition, 3 OTs emphasized the inclusive design of the handles, expanding the adaptability and using scenarios to various utensils such as hair brushes, wheelchair locks, and toothbrushes. OT2, OT3, and OT11 observed: “*I think the handles, it's versatility can be used in multiple ways [OT2]*.”, “*I have enabled her to have two kinds of grips ... either end can be for different purposes, but you got one tool for both. It's more of a universal grip [OT3]*.”, and “*I like the design of this one and I feel like I could see it translating quickly to other self-care utensils or writing utensils, toothbrushes, things like that [OT11]*.”

6.3.1.3 Texture

6 OTs including OT1, OT2, OT4, OT7, OT8, and OT9 confirmed the effectiveness of the handle textures (smooth, straight-line texture, and curvy textured) included in the design. OT4, OT7, and OT9 specifically commented on the utilization of each texture: “*The curvy texture could help... with traction. [OT4]*”, “*I think the textures on here are pretty good. I think having smooth and having texture pretty much covers it. [OT7]*”, and “*Straight line texture here is good, it is not sliding easily. [OT9]*”

6.3.2 *Suggestions for Improvement*

3 OTs provided valuable suggestions to improve handle design in this parametric design tool. OT2 mentioned the idea of creating a foldable handle for enhanced portability, suggesting it be “... *foldable or just a little bit more compact...*”. OT7 recommended diversifying material options beyond the existing rigid and flexible categories: “*I feel like maybe having more material options might be helpful instead of just rigid and flexible*”. Though the printing material depends on the filament technology, this suggestion aligns with some possibilities afforded by various 3D printing technologies, such as using soft PLA or exploring other methods like Stereolithography (SLA) or metal 3D printing. Furthermore, OT9 suggested adding a dot texture to the handles, aiming to provide additional sensory input for users with diminished sensation, suggesting a design with “... *more little dots on the surface, so they have more sensory input.*”

6.4 **OTs’ Feedback on 3D Printing Technology**

6.4.1 *Efficiency*

In this session, 6 OTs expressed positive feedback on integrating 3D printing technology into their practice. OT2, OT3, OT4, and OT11 emphasized the cost-effectiveness of this approach. OT2 indicated the expense of conventional products: “... *it costs 15 to \$20 even for one spoon, that can be really expensive for a lot of patients, so I think 3D printing could lower the cost of producing such products for patients.*”, and OT4 noted the affordability of multiple versions: “*It's cheap. So you could get three or four different versions...*” Additionally, the time efficiency of 3D printing was deemed acceptable, with an average handle printing time of about 6 hours (calculated based on our 12 customized handles average printing time). OT5 and OT12 commented on the printing duration: “*I wait for couple hours and do not need to supervise the machine, at the end of the day, I will get the handles, so I think the time is not an issue*”, and “*I mean, they wait for weeks and weeks on a wheelchair cushion, so as long as they had it by their next session ...*”.

6.4.2 *Subsequent Customization*

Because prescribing ATs is a trial and error process, and the ease of making adjustments to 3D printed models, like surface smoothing or shape modification using heat guns. OT2 and OT11 shared their experiences with customization: “*we ... come up with some other sort of rigged modification. So I think we're pretty used to adjusting. I have a heat gun in my car when I go to the patient's home.*”, and “*OT have to really think outside the box ...*”. OT4 and OT10 suggested wrapping materials like neoprene and Dycem around the handles for enhanced effectiveness. Furthermore, OT5 pointed out the personalization aspect of 3D printed handles: “*Me or my patients can paint or draw something on the*

handle, that's good, make the handle more unique", illustrating the potential for individualization in assistive device design.

6.5 Findings on 3D Printed Physical Handle

7 OTs provided positive feedback on the practicality and utility of the handles they designed. OT5, OT8, and OT10 highlighted the handles' suitability for specific needs: *"because she had arthritis on the hand ... So she cannot make a full fist, so sometimes she could not hold a regular utensil. That's why this one perfectly matches her hand. And it has a hook, it makes gripping more secure, So I'm excited to try this one for her [OT5]"*, *"It turned out so good. It's cool because I've never seen one that big, and that's actually what people need. And I like that color, I think a guy would like black [OT8]"*, and *"The handle is very useful. I think this handle requires the user to deviate from typical routines involved in using a spoon. But it is in a good way. Because they cannot twist their wrist, so they have to do the compensation task. The most important thing is to improve their self-independence, to complete the task of feeding [OT10]"*. The designs were noted for enhancing user independence and facilitating ease of use.

OT3 emphasized the design's hygienic benefits: *"The handle looks so good, I want to try it with my clients. And it is very easy to clean, there are some off-shelf ATs, it has grooves, turns out there are many food residues in the grooves. So the hygiene is very important for eating utensil and your stuff, I can tell is easy to clean and the texture itself provides some sensory feedback as well. [OT3]"*, aligning with OT8's perspective on the importance of cleanliness: *"I feel like that cleanliness aspect would probably outweigh them self managing, cleanliness is the most important thing [OT8]"*.

Additionally, there were suggestions for improvement. OT7 proposed altering the inner design for more functional versatility: “*So I think even the inner design of it being a rectangle instead of like an Oval, I wonder also how functional that is, because not that many items that you grab do have like the perfect rectangular base. It's usually like a cylindrical handle [OT7]*”, while OT8 suggested enlarging the slot for the hooks: “*I am trying to think about maybe making that slot (hooks) a little bigger [OT8]*”, to provide more space for Velcro adjustments.

CHAPTER 7. DISCUSSION AND CONTRIBUTION

7.1 Parametric Modeling Software Supports the Design for One Approach

The specialized design approach in AT plays a pivotal role in catering to the unique requirements of individual users, distinctively diverging from universal design paradigms. Interviews with OTs revealed a prevalent trend of prescribing standard, off-the-shelf hand ATs due to budgetary constraints. These ATs are typically available in three sizes (small, medium, and large) and exemplify universal design, which seeks to create products and environments that are broadly accessible and usable, thus often reducing the necessity for customized solutions (Hitchcock & Stahl, 2003). However, the utilization of such universally designed ATs has led to high abandonment rates, primarily due to inadequate fit for individual body specifications (Petrie et al., 2018).

Previous research has demonstrated the restrictions of universal design in adaptive devices, including this handle created for specific conditions such as Parkinson's disease (Cavalcanti et al., 2020). While this device offers weight customization through the addition of water in their internal cavities, their fixed dimensions (diameter and length) still limit its functionality and inclusiveness.

In contrast, our design approach offers the adaptability to alter essential variables utilizing the expertise of OTs. This allows for the customization of handle designs to suit the unique pathologies, hand measurements, and particular requirements of each individual. Such an approach yields a personalized solution advantageous to both AT users and therapists.

Furthermore, though this software will require OT's professional knowledge on modifying the parameters, the design process has the ability to involve end users in co-designing their devices as annotated by OTs in user tests. Such collaborative engagement in the design phase has notable implications. It increases the users' interest in the device and reduces abandonment rates. Simultaneously, it promotes a more profound comprehension of their health status among end users (Aflatoony & Lee, 2020). This deeper participation is supported through specialized grip design processes and aligns with user-centered design principles, fostering a better connection between the user and the ATs.

7.2 Benefits of Incorporating 3D Printing Technology in OT's Practice

7.2.1 Cost and Time Effectiveness

The findings of our study indicate that the production cost of a single handle using 3D printing ranges from 1 to 5 dollars, depending on the material and weight. This cost is markedly lower than the expense incurred from procuring off-the-shelf ATs as stated by OTs. The affordability of 3D printing is further supported by the decreasing cost of 3D printers, making it feasible to acquire a suitable printer at a reasonable price. Our research also reveals that OTs are increasingly open to adopting 3D printing technology for AT device creation.

The process of prescribing and modifying ATs typically involves trial and error (Sabari et al., 2019). Previously, OTs would endure days or weeks waiting for devices, often returning them if they proved unsuitable, followed by purchasing and modifying alternative options. This iterative process could extend over several weeks. However, the integration of 3D printing technology using parametric modeling software can significantly

accelerates this cycle. If a handle requires redesign, a new, customized version can be produced swiftly and efficiently, streamlining the entire process, and markedly reducing waiting times.

Additionally, the enhanced durability of 3D printed adaptive devices, offers a more sustainable solution for OTs in designing AT solutions and for end users (Aflatoony et al., 2023). This durability not only optimizes the cost of replacing devices but also reduces the time involved in prescribing new ATs.

7.2.2 Allow for Customization and Further Modifications

Our study reveals that OTs may occasionally need to fine-tune the 3D printed handles to better suit individual needs if necessary. The nature of 3D printing materials is conducive to such adjustments, allowing OTs to utilize tools like heat guns or 3D pens for modifications. This flexibility is particularly advantageous as OTs are already well-versed in such modification processes.

Additionally, 3D printed objects offer further customization opportunities. As mentioned by OT5, patients and OTs can personalize the assistive devices by painting them in different colors or adding unique patterns. Aesthetic appeal is a crucial factor in the acceptance of ATs, alongside considerations of cost and functionality (De Jonge et al., 2016).

7.3 Parametric Modeling Software Facilitates Digital Fabrication

Prior research has focused on enhancing the digital production of customized adaptive devices using various methods. For example, studies involved creating eating ATs

and adaptations in AutoCAD, utilizing end-user's hand metrics, and employing 3D printing for manufacturing (Dos Santos et al., 2023). While this introduces digital production into the AT creation workflow, it relies on specialized software like AutoCAD, typically suited for trained technicians and professionals. This reliance presents a challenge for OTs to independently engage in the design process. Consequently, the gap between OTs' expertise and digital fabrication of ATs remained. Another study introduces integrating 3D scanning into the digital creation of hand assistive devices (Lee et al., 2019). The process begins with acquiring a 3D scan of the patient's hand, followed by employing Geomagic Freeform, a professional CAD design software, to construct the AT over the hand model. Nevertheless, the utilization of 3D scanners and advanced CAD software poses difficulties for OTs, and the complexity is further underscored by the 14-step procedure outlined in the article for fabricating a single assistive device.

In a closely related study, a parametric design program called GripFab was developed, enabling OTs to modify pre-designed adaptive grips for art supplies (Buehler et al., 2016). Though this software simplifies some degrees of the complex features of professional CAD tools, its user interface, limited features, and specific terminology do not correspond well with the needs, workflow, and vocabulary familiar to OTs, which constrained the using scenario.

Our platform introduces an innovative approach for incorporating digital fabrication into the routine creation of adaptive grips by OTs. It features ease of use, time efficiency, and compatibility with OT practices. OTs require none or minimal investment in training to utilize this tool effectively. Moreover, all the features are demonstrated by OTs to fit the basic needs of designing an adaptive handle. As OT1 noted, "*That (this tool)*

helps with the major areas, dimensions, weight, and material.” The design process can be completed swiftly, enhancing the tool's efficiency: the streamlined procedure, comprising merely 5 or 6 steps from initial design to the final production of the grip, significantly simplifies the overall fabrication workflow, contingent on the availability of a 3D printer.

7.4 Guideline for Designing Parametric Tool for OTs

Based on our iterative prototyping and research processes, we recommend the following set of design requirements for designing a parametric modeling tool and associated ATs (in this case grips) (see Table 6). Within the software interface, OTs have the capability to search for specific grips based on pathology or daily activities. Next, they can customize various parameters such as grip size, material, color, and weight, with instant feedback provided through the real-time display. Upon finalizing the design, OTs can proceed to download the file and utilize a 3D printer to generate physical models of the grips. The grip designs are informed by anthropometric tables (Tilley et al., 1993) and consider OT range of motion and strength norms. Furthermore, these design considerations are integrated within the size adjustment function of the software interface, ensuring a cohesive and comprehensive experience for OTs to adjust grips.

Table 6 - Design requirements for the parametric design tool of AT adaptation by OT.

	Design recommendation	Specifications of the feature/interaction
Parametric design tool	Search pre-designed grip	Facilitating the identification of appropriate grips based on distinct pathologies and the specific requirements of users.

	Comparison between grips	Providing an intuitively designed comparative analysis of grips enables OTs to make expedited, informed decisions.
	Customization	Enabling OTs to customize pre-designed adapted grips according to dimensions, materials, colors, and weights.
	Visualization	Enhancing a precise comprehension of size on the interface through the display of diagrams or the inclusion of a reference object for scale comparison enhances user clarity.
	Display	Offering an immediate and interactive real-time visual representation to promptly demonstrate any modifications enacted by OTs.
	Manufacture	Supplementary instructional documentations outlining the setup procedures for the 3D printer should be attached to the downloaded grip model file.
	User Interface	The interface design should demonstrate intuitiveness and harmonize with the OTs' professional workflows and vocabulary.
Grip design	Anthropometry	Incorporating static anthropometric data (Tilley et al., 1993) during the design process of the adapted grip.
	Ergonomics	The design process should thoroughly consider the diverse needs and pathologies of different users. Creating a user profile can support this process.
	Hygiene	Ease of cleaning is critical in the design of adapted grips for eating utensils.

CHAPTER 8. CONCLUSION AND FUTURE WORK

This study presents an innovative parametric design tool, developed for OTs to customize, and produce ATs for individuals with hand impairments. This tool, with its intuitive interface, empowers OTs to quickly and easily tailor ATs to the unique preferences, health conditions, and hand measurements of users. The significant contribution of this tool lies in its ability to offer personalized adaptive devices for those with hand impairments, enhancing their daily living experiences. Moreover, it streamlines the OTs' process of identifying and prescribing suitable ATs, substantially reducing the time and effort traditionally involved in a trial-and-error approach. The integration of 3D printing technology in this process further underscores the efficiency and cost-effectiveness of producing these adaptive devices.

We plan to iterate and refine the interface (parameters, measuring unit, navigation of needed devices, and comprehension of size) based on the study outcomes as well as integrate examples of adaptable handles or more complex ATs to further test the feasibility of the tool. And incorporate more patients to test out the physical device and gain their point of view of using the designed handles.

Moreover, while our software is designed for OTs, its scope could extend to a more universal framework to be usable for broader target users (e.g., AT specialists, patient's families, AT users and so on) by adjusting the parameters, layout, or indications on the interface. This concept aligns with studies on enhancing interface inclusivity through universal design principles (Sanford & Remillard, 2021). In that way, future studies with more individuals with disabilities and their family members or care givers are needed to

further test the interface and physical adaptive device to obtain holistic understandings. Another direction we envision is transitioning this tool to an online platform, which could further its reach, eliminating the necessity for OTs to download Grasshopper, thereby broadening accessibility. These two directions could be incorporated together, which will extend this tool's usability in larger scale.

Another approach involves engaging both patients and OTs in a co-design process. Initial findings suggest this collaborative approach could foster a deeper connection between the AT and its user, potentially reducing abandonment rates. And OT's professional knowledge in this process will ensure the effectiveness of designed device. Further research in this area could explore the impact of such co-design on user satisfaction and device usability.

In summary, we believe the implications of this tool extend beyond individual customization; it marks a progressive step in the field of rehabilitative technology, potentially transforming the landscape of assistive device provision. Its application could lead to more rapid, accurate, and patient-specific AT solutions, thereby improving the quality of life for individuals with hand impairments. This study not only demonstrates the utility and effectiveness of the parametric design tool but also underscores its potential as a pioneering solution in the realm of AT. We anticipate that such a tool can be utilized in rehabilitation centers, clinics, and homes to support AT design and adaptation, ultimately enhancing the quality of life for individuals with hand impairments.

APPENDIX A. INTERVIEW QUESTIONS FOR USABILITY TEST

SESSION 2

Q1. What is your opinion/concern of these ATs?

Q2: Do you think this adaptive device is useful for your client, and why?

Q3: And what improvements do you think can be made?

APPENDIX B. AFFINITY DIAGRAM OF USABILITY TEST

Usefulness - Parametric Design tool		Things could improve/suggestions - Interface		Things could improve/suggestions - Physical handles
OT1: It was simple to use because it wasn't a lot to mess with, you know, necessarily.	OT6: This software is very easy to use, you already thought about different scenarios of using and it's a mature and useful software.	OT10: I think it's a pretty easy to use like the step by step instruction or the way to the material, that's pretty clear.	OT7: Now the one aspect I thought it was sometimes a little hard to move or adjust the sliding bar for the radius and the length stuff.	OT9: It was basically a little, you know, I just a little. I saw somewhere in there where they could sort of not their thumbs there and then that caused it there didn't have a lot of good grip, you know, so it could kind of and it was more open kind of you changed or whatever.
OT2: The tool was able to handle the different sizes of the material and it was able to handle the different thicknesses of the material. It was able to handle the different thicknesses of the material and it was able to handle the different thicknesses of the material.	OT7: Um, I think it's pretty self as I found pretty self explanatory. If it's for someone that would use this, I think you know they would probably intuitively understand the functions and, and I didn't think it was really all that challenging.	OT8: I mean, you give me an opportunity to make like a little like a handle position, you know, like a quantified handle just inside the handle, which, as opposed to being like a traditional one from like Amazon, which can be hard to adjust at times. Yeah, this individuals need.	OT8: But I think that would be super important because right now we have like the weighted stuff. So for the people who, who has Parkinson, some people just get too heavy, like control really hold it so. So it would be better like to have a number to indicate how much weight it is.	OT10: So some of them wanted, like somehow it to be foldable or just a little bit more compact or that's why I sometimes like with the handles if they can like snap on or grip on to existing utensils.
OT3: That helps with the major areas, dimensions, weight and material.	OT7: That's cool, I think in real life I would definitely use this.	OT9: This tool is definitely will be beneficial for my everyday practice.	OT10: Yeah, I mean, it's nice that there's three options instead of just having light or heavy because I think that that gives you a little bit more idea of, you know, we don't want to be too light or too heavy. It would be nice to know how heavy it was then, it would be a good idea and I think it's being the 5 pounds then, it would be helpful to know that that would give you a little bit more of a sense of, but I think that's a helpful that there's at least three options like light, medium and heavy.	OT11: I think if you're already in millimeters at that point, yeah, you could go with, it's always okay that way, yeah, it's an idea that would make sense because it's still enough surface area to where you wouldn't have to split a millimeter down.
OT4: I love this. This is awesome. I can't wait to use this in my catalog. One day I'll be buying them, you know?	OT7: It was pretty straightforward to use.	OT9: This tool is definitely will be beneficial for my everyday practice.	OT10: Yeah, I mean, it's nice that there's three options instead of just having light or heavy because I think that that gives you a little bit more idea of, you know, we don't want to be too light or too heavy. It would be nice to know how heavy it was then, it would be a good idea and I think it's being the 5 pounds then, it would be helpful to know that that would give you a little bit more of a sense of, but I think that's a helpful that there's at least three options like light, medium and heavy.	OT12: So some of them wanted, like somehow it to be foldable or just a little bit more compact or that's why I sometimes like with the handles if they can like snap on or grip on to existing utensils.
OT5: I think this tool meet my expectation. It seems like it would be easy to use if you had the dimensions just to input.	OT8: For instance, for the handle, because I think you know they would probably intuitively understand the functions and, and I didn't think it was really all that challenging.	OT9: This tool is definitely will be beneficial for my everyday practice.	OT10: Yeah, I mean, it's nice that there's three options instead of just having light or heavy because I think that that gives you a little bit more idea of, you know, we don't want to be too light or too heavy. It would be nice to know how heavy it was then, it would be a good idea and I think it's being the 5 pounds then, it would be helpful to know that that would give you a little bit more of a sense of, but I think that's a helpful that there's at least three options like light, medium and heavy.	OT13: I think if you're already in millimeters at that point, yeah, you could go with, it's always okay that way, yeah, it's an idea that would make sense because it's still enough surface area to where you wouldn't have to split a millimeter down.
OT6: It's a pretty good design. That is perfect. It's very easy to use for me, so they put on design and you try, yeah.	OT8: So like what you're doing is cool because we basically give a size fit all. Um, I'm like this tubing and like it really didn't all, but it's all we had so.	OT9: This tool is definitely will be beneficial for my everyday practice.	OT10: Yeah, I mean, it's nice that there's three options instead of just having light or heavy because I think that that gives you a little bit more idea of, you know, we don't want to be too light or too heavy. It would be nice to know how heavy it was then, it would be a good idea and I think it's being the 5 pounds then, it would be helpful to know that that would give you a little bit more of a sense of, but I think that's a helpful that there's at least three options like light, medium and heavy.	OT14: I think if you're already in millimeters at that point, yeah, you could go with, it's always okay that way, yeah, it's an idea that would make sense because it's still enough surface area to where you wouldn't have to split a millimeter down.
OT7: I think customization really differentiate your products from others, and that makes it unique on the market.	OT8: Obviously I can't think of anything, so that must mean it's really great.	OT9: This tool is definitely will be beneficial for my everyday practice.	OT10: Yeah, I mean, it's nice that there's three options instead of just having light or heavy because I think that that gives you a little bit more idea of, you know, we don't want to be too light or too heavy. It would be nice to know how heavy it was then, it would be a good idea and I think it's being the 5 pounds then, it would be helpful to know that that would give you a little bit more of a sense of, but I think that's a helpful that there's at least three options like light, medium and heavy.	OT15: I think if you're already in millimeters at that point, yeah, you could go with, it's always okay that way, yeah, it's an idea that would make sense because it's still enough surface area to where you wouldn't have to split a millimeter down.

APPENDIX C. SUS SURVEY

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I think that I would like to use this system frequently.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I found the system unnecessarily complex.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I thought the system was easy to use.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I think that I would need the support of a technical person to be able to use this system.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I found the various functions in this system were well integrated.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I thought there was too much inconsistency in the system.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I would imagine that most people would learn to use this system very quickly.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I found the system very cumbersome to use.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I felt very confident using the system.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I needed to learn a lot of things before I could get going with this system.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

APPENDIX D. INTERVIEW QUESTIONS FOR USABILITY TEST

SESSION 1

Q1: How long have you been working as an OT, and what's your title?

Q2: Can you briefly describe the adaptive handle you created, and this handle is for what type of patient?

Q3: What things frustrate you while using this parametric design tool?

Q4: What concerns do you have while using this tool?

Q5: Does this tool meet your expectations or needs, and why?

Q6: Do you think if this tool would be beneficial for your practice?

Q7: What suggestions do you have about improving this computational tool?

APPENDIX E. HAND AT USER PROFILE FORM

AT User Profile Form

Please complete this form with your past patients in mind. This form will serve as a reference during the initial session, helping you create add-on handles (adaptive devices) in the computational tool for the user you've created in this form, considering their pathology, requirements, and hand dimensions. If you wish to generate additional add-on handles for different patient profiles, please duplicate this form as needed. Ensure you finish this form before the start of the first session and return the completed form to the researcher at the end of the session.

Patient age: _____

Gender: Male / Female

Diagnosis/Symptoms/Pathology:

Duration of symptoms/Date of injury: _____

Chief complaints: _____

Pain level: _____

Edema: _____

Patient roles and occupations

Work: _____

Retired: Yes / No

Marital status: Single / Married / Widowed

Lives with: _____

Hobbies: _____

Limitation with ADLs: _____

Limitation with IADLs: _____

Evaluation

Hand dominance: Right / Left

Brief description of strength assessment (dynamometer, lateral pinch, 3-chuck jaw pinch, MMT):

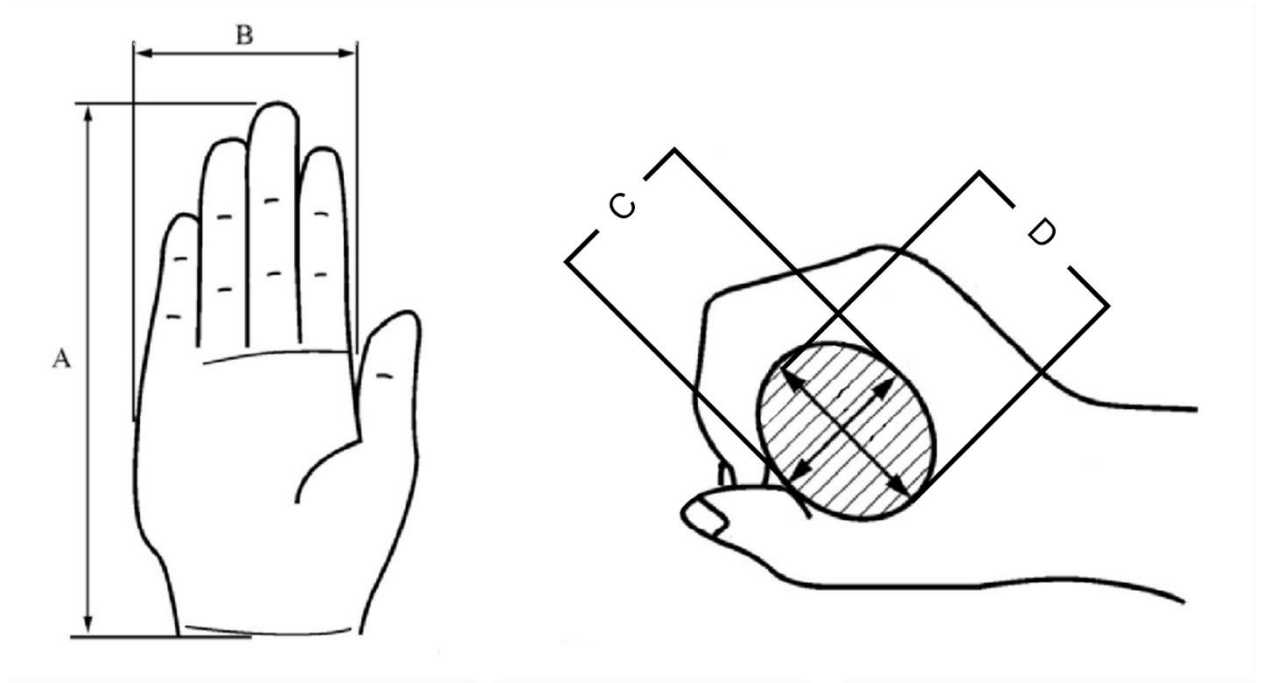
Brief description of dexterity assessment (9-hole-peg...):

Brief description about range of motion (shoulder, elbow, wrist, digits):

Brief description of patient's sensation condition:

DASH score: _____

Hand measurements: please fill in in millimeters (mm)



A: _____

B: _____

C: _____

D: _____

APPENDIX E. PRELIMINARY INTERVIEW STRUCTURE

Interview Structure:

1. Consent Form and Questions
2. Brief Introduction to study
3. Previous experience:
 - a. How long have you been working as an OT?
 - b. Could you please share some examples of the adaptations you made to everyday items or existing AT to help people with hand impairments if possible, and please explain how it will help?
 - c. Could you please indicate what activities of daily living (ADLs) or postures that are relied on hand dexterities (e.g. lifting, rotating, cutting, holding...) require more adaptations for people with hand impairment. (6 grasp patterns)
 - d. What are the major differences you think of making adaptations for people with hand limitations compares to other body limitations? (Things or processes needed to pay attention on while designing assistive technologies for people living with hand impairments)
4. Opinions of first iteration of the parametric design tool (Show a brief video demonstration of the first prototype I made):
 - a. Do you have any comments, recommendations or concerns you want to share about the computational tool I designed?
 - i. Pros and cons

ii. Helpful or not

iii. Concerns

5. What tools you will use to make accurate anthropometric measurements for people with functional limitations? And how you will use these tools? (Please feel free to share the tools you have if possible)
6. What are the things frustrated you while making measurements for people with functional limitations?
7. What are the materials you use to create adaptations of everyday items or existing ATs?
8. Have you ever used a 3D printer as a useful tool for making adaptations before
 - a. If yes, please indicate how a 3D printer has helped you in your work?
9. What is your opinion of using 3D printer to make adaptations of everyday items or existing ATs?
 - a. Pros and cons
 - b. Helpful or not
 - c. Concerns

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