Helping Hands: Requirements for a Prototyping Methodology for Upper-limb Prosthetics Users

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ABSTRACT

This paper presents a case study of three participants with upper-limb amputations working with researchers to design prosthetic devices for specific tasks: playing the cello, operating a hand-cycle, and using a table knife. Our goal was to identify requirements for a design process that can engage the assistive technology user in rapidly prototyping assistive devices that fill needs not easily met by traditional assistive technology. Our study made use of 3D printing and other playful and practical prototyping materials. We discuss materials that support on-the-spot design and iteration, dimensions along which in-person iteration is most important (such as length and angle) and the value of a supportive social network for users who prototype their own assistive technology. From these findings we argue for the importance of extensions in supporting modularity, community engagement, and relatable prototyping materials in the iterative design of prosthetics.

Author Keywords
Assistive technology; design; disability; open-source; personal-scale fabrication; prototyping; 3D printing.

ACM Classification Keywords
K.4.2 [Computers and Society]: Social Issues – assistive technologies for persons with disabilities.

INTRODUCTION

Prosthetic limbs and assistive technology (AT) require customization and modification over time to effectively meet the needs of end users. Yet, this process is typically costly and, as a result, abandonment rates are very high [27]. Rapid prototyping technologies such as 3D printing have begun to alleviate this issue by making it possible to inexpensively, and iteratively create general AT designs [5] and prosthetics [36]. However for effective use, technology must be applied using design methods that support physical rapid prototyping and can accommodate the unique needs of a specific user [18,19]. While most research has focused on the tools for creating fitted assistive devices (*e.g.*, [12,14,37]), this paper focuses on the requirements of a design process that engages the user and designer in the rapid iterative prototyping of prosthetic devices.

In this paper, we report on three case studies where we experimented with materials and techniques for do-it-yourself (DIY) rapid prototyping of task specific variations of a prosthetic arm. Our emphasis here is on design of prosthetics, specifically iterative design, not prosthetics in general. The strengths and limitations of rapid prototyping technology are radically different than the resources used by traditional prosthetists. Therefore, many of their common practices are not applicable to this study. Thus, our work is unique in that we describe a multistage iterative, participatory design process. Another unique aspect of our work was its focus on areas where traditional AT failed participants. Thus, a standard survey for example of activities of daily living would not necessarily have uncovered the same range of things that simply asking participants to identify their greatest need.

Our findings include: three categories of tasks that prosthetics can support; *significant parameters* of these prosthetic systems (such as length and angle) that affect comfort and efficacy; playful and practical prototyping materials that can support immediate iteration; the influence of support networks on what is created; and participant experiences creating their own assistive technology.

Based on our study, we argue that a modular approach to prosthetic design needs to consider not only the *socket* and *end-effector* but also *extensions* that capture significant parameters. We also highlight the value of *relatable* prototyping materials for parameter capture. Our goal is to present resources and methods to strengthen the relationship between prosthetics users and both novice and professional designers, resulting in increased access to AT. Many of the approaches and requirements discussed in this paper may be generalized to a variety of design, DIY and rapid prototyping contexts.

BACKGROUND

The cost of a prosthetic arm can range from $4,000 to $100,000, depending on the location of the amputation and

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whether or not the device is body-powered or powered externally [29]. Despite the cost of obtaining a prosthetic, 56% of people with limb loss abandon their prosthetics over time [27]. Similar to other assistive technologies [10,26], the critical factors in abandonment for prosthetics users are: comfort, cost, and functionality [2,25]. In addition, state-of-the-art prosthetic devices may be unavailable to users because of the physiology of their amputation—for example, only 15% of prosthetic users have the amputation to support a myoelectric prosthetic [11,38]. Further, many of the most advanced prosthetics available are useless in harsh work environments where the device may be damaged [33].

Open source prosthetics and AT designs, spearheaded by communities such as E-Nable [36], have begun to address issues of cost and availability, by expanding customization and lowering the price of prosthetics. E-Nable's success is driven by its 3D printable hand designs and large community of dedicated makers [39].

A crucial aspect of prosthetic creation is making the socket (which goes around the residual limb) comfortable. The *socket* is the form-fitting attachment to the user. Traditionally, prosthetic designs use a relatively rough model of the residual limb though recent advances have allowed socket designs to model more subtle features such as pressure on bony protrusions [37]. Although *socket* fitting is traditionally done by a prosthetist, groups such as the Open Prosthetics Project[1] and E-nable [36] have begun to teach everyday people about this process. For example, E-nable gives advice about using Tracker [35] and Hand-o-Matic [9] to support fitting.

However, standard prosthetics do not have the same range of motion and sensitivity as a full hand. Thus, in addition to socket fit, special adaptations are needed for many tasks. For example, commercial adaptations are available for holding utensils, power tools, and sports equipment [22]. One of these adaptors can be seen in Figure 1; this violin bow adaptor has been used by one participant to play the cello. Recently the DIY community has taken up the challenge to expand the range of adaptations and lower their cost. Examples of DIY-produced adaptations include Lego attachments (right on the prosthetic) [7,32], Super Soaker attachment [7], utensil holder [7], violin bow holder [7,36] and trumpet holder [36]. In each case, these designs were driven by requests of children receiving the prosthetic, who often participated directly in the design process. For example the Super Hero Arm described in [7] was designed by a 9 year old and engineers at the 'Super Hero Cyborg Camp'. The designer-user relationships in these DIY design examples demonstrates a new interconnection between users with disabilities and their ecology of support [13].

Figure 1. A professionally designed Violin bow adaptor for a prosthetic.

Beyond prosthetics, 3D printing and rapid prototyping technology is applicable to a variety of AT devices.

Examples include tactile graphics for people with visual impairments [4,16] and orthotics for people with motor impairments [6]. More recently, Buehler *et al.* [5] demonstrated the wide variety of AT being shared on an online 3D modeling repository (Thingiverse.com). However, 3D printing currently depends on skilled use of advanced software. Recent advances in 3D printing have begun to reduce the expertise needed for tasks such as augmentation of existing objects [8,24]. We can expect to see further advances in DIY AT as this research begins to become broadly available.

DIY-AT has the potential to improve the relationship between users and assistive devices. Hurst and Tobias [17] demonstrated that user involvement in the design of AT can be empowering and results in higher adoption rates, while Hook *et al.* [15] propose that improved relationships between the maker communities and AT users would promote the design of DIY-AT. Access to online resources and communities has increased the number of partnerships between AT users and designers, and has thus increased the efficacy of existing devices [3].

In the broader context of DIY communities, social behavior among designers has a strong impact on the efficacy of produced designs. Torrey *et al.* discuss expert DIY designers communicate and their use of large online social networks to share and build upon each other's designs [31]. Kuznetsov and Paulos suggest that DIY designers often see their projects as extensions of the self [20]–this is especially true in the domain of prosthetics where this is no longer just analogy. Mellis and Buechley suggest that, as designs become more popular, personal fabrication becomes a social activity [23]. The growing social relevance of DIY communities may have a strong impact on the future of 3D printed prosthetics.

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Pseudonym	Gender	Age	Level of Amputation
Kevin	M	9	Below Elbow
Ellen	F	27	Below Wrist
Brett	M	47	Below Elbow

Table 1. Participant Demographics

To summarize, available commercial prosthetics do not fully meet the needs of many users. Further, when useful prosthetics are available, they are often prohibitively expensive and require assistance from professional designers. DIY-AT is increasingly useful and available, and a promising alternative.

CASE STUDIES

The goal of our work is to develop a deeper understanding of the requirements and practices used for end user involvement in rapidly prototyping task specific prosthetic devices. . Our focus was to explore the potential of 3D printing and other rapid prototyping technology for designing customized and nontraditional assistive devices. Since rich examples of DIY-AT are already appearing online, we chose to recruit and work with participants who were already engaged in designing and customizing their own assistive devices.

Method

We used a case study approach [34], which derives insights from a deep exploration of a few cases. We collected data through interviews, interaction with participants, and examination of existing artifacts. Over multiple unstructured interviews and design sessions, participants and researchers collaborated to develop and test multiple prototypes of a 3D printed prosthetic system that could be used to perform the selected task.

We recruited three participants with upper-limb amputations who already customized their assistive technologies. Participants were contacted *via* word of mouth and through local support groups for people with amputations. During *initial interviews* with each participant, we discussed their amputation and how it impacted the tasks they performed. Participants were asked to define a task that they struggled with or were unable to perform alone or with the help of traditional assistive devices.

We proceeded to develop a prosthetic for a participant selected task by conducting *design interviews* with participants where we worked together to design assistive prosthetic devices to support the selected task. Design interviews included prototyping sessions and testing. These sessions elucidated the users' needs and common significant parameters of the designs. Participants helped with ideation, made use of prototyping technologies (Lego, foam, *etc*.), and helped to define parameters of their prosthetics. Researchers were primarily responsible for all 3D modeling and printing models in between interviews.

When possible we incorporated practices from the AT community. Following recent advances in the DIY community [7,32], we approached our designs in a modular fashion, separating work on the *end-effector* (the task specific adaptation) from the *socket* (which must fit the user's residual limb). For socket design, we measured the residual limb at several standard locations. While scanning produces more exact molds of participant limbs, measurement was more supportive of rapid and simple modification. Measurement-based models are easy to adjust because new parameters could be inputted into a computer model. In contrast, each new scan requires that the model be painstakingly recreated, which is time consuming.

The emphasis of our research was the design process of users when creating assistive devices using rapid prototyping technology. Therefore testing of the devices was only done in a lab setting. Participants were allowed to take the devices home after the study ended, but no follow up data was collected.

Data Analysis

Interviews and notes were transcribed and then coded and organized using affinity diagramming, as described by Beyer and Holtzblatt [1], allowing researchers to derive common themes and design requirements. The first author did the coding and initial categorization into themes. This was discussed with other researchers and iterated on until consensus was reached.

RESULTS

Although the tasks participants described were varied in their requirements, we found common themes relating to the participants' needs (gripping, motor skills, two-handedness) and the prosthetics parameters (length, angle, rotation). Our themes also relate to the importance of the context of design, from the playful and practical value of rapid prototyping materials to the importance and impact of a network of helpers on participants' range of useful prosthetics.

Before presenting these general themes, we describe each individual participant and their task specific goals. Some participants mentioned multiple needs and our prototyping often went beyond a single task. In those cases, our work with the participant still focused on a single main prototyping goal.

Participant Overview

As described in Table 1, all three participants had congenital upper-limb amputations (two below the elbow and one below the wrist) and all three had some level of prior experience prototyping assistive devices to support specific tasks. Each participant cited different individuals that they had collaborated with to design these devices, including: family, friends, teachers, co-workers, and clinicians. Two participants had professional design experience and were able to engage in the design process using their expertise; the youngest participant (age 9) had less experience and was more engaged with the toys and play aspects of the design process. The tasks participants selected included: tasks that required gripping an object,

Figure 2. Kevin playing the cello using an old prosthetic. The prosthetic grips the cello bow loosely, making it difficult to hold the bow correctly.

tasks that required fine-motor skills, and tasks that required two-handedness or the use of both hands.

Kevin and Ellen are anonymized, however Brett asked us not to anonymize him. He works hard to educate others about prosthetics and we provide more details about him in the acknowledgements section of this paper.

Kevin's Cello Bow Holder

Kevin has a congenital amputation below his left elbow and has been using a passive prosthetic occasionally since he was five years old. However, he generally prefers to not use his prosthetic. On his right arm, he has an opposing thumb and single finger, which he can use to grip objects. We met with Kevin four times to work on a prosthetic that could hold a cello-bow. He had a current solution, which he was outgrowing: a prosthetic hand held permanently in a position to grab the bow. He can be seen playing with this prosthetic in Figure 2.

Initial designs for the cello-bow holder and socket were sourced from the 3D modeling repository Thingiverse. Kevin brought his cello with him to most sessions, so that we could test out designs. Socket fit and shoulder position (affected by length) were both issues of repeated concern. We used Legos to help Kevin iteratively adjust length. The length of the resulting Lego extension was measured and incorporated into a locking mechanism that allowed Kevin to detach his cello-bow from his fitted socket for storage.

An intermediate prototype shown in Figure 4.a, included a socket, a locking mechanism, and a cello-bow holder. The *key* to the locking mechanism was bolted to the end of the socket, and the *lock* was bolted to the cello-bow holder to create a complete system. However, the socket fit was not ideal, and the aesthetics were unappealing to Kevin. Figure 3 shows the final prototype, which addresses both problems. The gauntlet is taken from an E-Nable hand that is designed to be thermoformed and the end-effector is a combination of a design by an E-Nable volunteer and a bow holder we designed. This version lacks a lock and key, though Kevin would prefer we add one because the arm and bow combination does not fit in his cello case. Both were tested by Kevin on his cello during design sessions.

Figure 3. This shows the final version of Kevin's cello bow holder. The socket is thermoformed and the device is printedin Kevin's favorite color: red.

Ellen's Hand Cycle

Ellen is a PhD student researching applications of robotics in AT. As well as being a participant, Ellen contributed professional expertise as both a user and a colleague of many prosthetists. She has a congenital amputation of her left hand below the wrist with a partially formed thumb and partially functional wrist, but does not have a palm or fingers on this hand. She owns multiple passive, body-powered, and myoelectric prosthetics that she uses to perform specific tasks, such as soldering. Despite owning multiple prosthetics, Ellen prefers to use her residual limb whenever possible and finds prosthetics cumbersome and awkward. We met with Ellen five times to design a prosthetic adaptation for her hand-cycle—a bicycle that is powered by a hand crank. At the time, Ellen had adapted a rollerblade wrist guard and a bike handle to grip the hand-cycle. Ellen used the rollerblade guard to attach her hand to the handle, however, the guard was designed for a full hand and was not small enough or fitted to her residual limb, "*It's almost like I'd have to go down to a kid size. And that's not even quite right*" (Ellen, Interview 1).

Ellen identified the distance and angle from her wrist to the hand-cycle handle as significant parameters of her prosthetic. We adjusted these parameters by iteratively testing multiple angles and lengths using Styrofoam models. These models were attached to the hand-cycle and socket using zip ties and pipe cleaners, which Ellen found easy to adjust and move on her own. The prosthetic was modeled after the socket created for Kevin, and was adjusted to fit Ellen's limb measurements.

The final model, shown in Figure 4.b, consisted of two 3D printed components and hardware from her hand-cycle. The components included a form-fitting socket and an angled extension from her forearm, which were attached using a bolt taken from her original handguard design. The

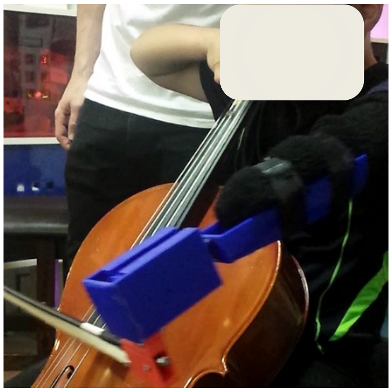

Figure 4.a. Kevin playing the cello with his prosthetic cello-bow holder.

Figure 4.b. Ellen riding a stationary hand-cycle with her final prosthetic hand-cycle attachment.

Figure 4.c. Brett slicing bread with his myoelectric arm and 3D printed knife holder.

extension was bolted to a quick-release mount on her hand-cycle. Using the stationary hand cycle in her home, Ellen was able to ride at various speeds for extended periods of time. This constituted the final testing phase of her device. During these exercises we were able to make final adjustments using the bolt. She kept the prosthetic device for personal use.

Brett's Knife Holder

Brett is an anesthesiology nurse with a congenital amputation directly below the elbow. He is an active prosthetic user and carries a passive prosthetic, two myoelectric prosthetics, and a body-powered prosthetic with him to work. His body-powered prosthetic includes a locking mechanism to which he can attach custom tools designed by his prosthetist. We met with Brett three times to develop an adaptation that would allow Brett to use a common table knife or steak knife to cut food or spread condiments. Although a table knife adaption was available from his prosthetist, he chose not to use it due to its prohibitive cost and cumbersome nature.

Because Brett extensively uses his prosthetics, we designed an augmentation for his prosthetics that would hold silverware in a comfortable position. The model holds a knife, whose handle is pressed into a hollowed rectangular prism lined with foam. Padding the inside of the prism allowed Brett to adjust the distance from the knife to his hand. He could adjust the angle he held the knife with the wrist rotators on his prosthetics.

Our final prototype had two variations—one attached to his myoelectric prosthetic, shown in Figure 4.c, while the other attached to his body-powered prosthetic. Both models used foam to grip the knife. The myoelectric grip design was created using the method described by Buehler *et al.* [6], while the body-powered model used the same knife holder as the myoelectric model and was attached to his prosthetic with a 3D printed version of the attachment mechanism designed by his prosthetist. Tests of the system were done by cutting bread and bagels, and then smearing them with peanut butter.

Grip: A Need for Custom End-effectors

Difficulties with gripping were identified by all three participants, each of the prototypes designed for participants addressed this impairment for specific tasks: Kevin needed a gripping adaptation for the cello-bow, Ellen required an adapted handle for her hand-cycle, and Brett requested an adaption for holding table knives.

Gripping impairment was task specific. For many tasks, handles must be designed to fit specific devices due to their unique shape or function, such as Ellen's specific requirements for hand-cycling or Kevin's cello bow. However, some tasks have similarities. Ellen and Brett requested *universal adaptors* that would adapt to typical handle sizes for tools such as: eating utensils, kitchen utensils, and tooth and hair brushes. These tools were common and each had similar cylindrical or rectangular handles. An adaptor such as Brett's foam-padded knife adapter should be able to support gripping of many such tools.

While each participant owned at least one prosthetic arm, only Brett regularly used his prosthetic to hold objects. However, Brett indicated that this is a difficult process since the myoelectric grip only pinched in one position, unlike a full hand which can produce innumerable gripping positions. Further exacerbating the problem, the electronic components in his myoelectric prosthetic functioned unreliably in certain conditions and would lock into place: "*given the high humidity, there is some moisture that has gotten down here so [my myoelectric prosthetic] not working*" (Brett, Interview 1).

When designing an assistive grip, it is important to consider how and when gripping stops. For the hand-cycle, grip should be secure but support an emergency release. Ellen explained that for her hand-cycle, "*I think we're going to want something that's as hard lockable as possible [so that the limb will not come loose while cycling]*" (Ellen, Interview 3), noting that both grip reliability and release are safety requirements for hand-cycling.

Another consideration for grips is the mechanical functions of a grip and action. For example, Kevin's cello-bow adaptation included a spring hinge system that helped support musical control. Similarly, it was important that Brett's prosthetic could rotate because cutting and spreading required two different knife angles.

Fine-motor Skills: Mapping Tools to the Residual Limb

Each participant found tasks that require fine-motor skills to be difficult or impossible. Many of these tasks require at least one motion that the participant was incapable of performing—for example, Kevin had no wrist to rotate his cello-bow properly while playing. Other tasks require the user to have control over a tool. Ellen mentioned having difficulty using her myoelectric prosthetic for soldering, and Brett required assistance from other nurses or specialized prosthetics to perform nursing tasks. As Brett summarized this common issue, "*There's always room and areas for improvement such as fine-motor skills,*" (Brett, Interview 1)

For tasks that required fine-motor skills, it was important that the prosthetic attachments mapped to the participant's mental image of their limb, as described by Ellen speaking about soldering: "*It wasn't, with my [myoelectric prosthetic]. Its somewhere out here [away from my wrist]. Which isn't mapped in my head*" (Ellen, Interview 1). As a result, Ellen had to focus all of her visual attention on the tip of the soldering iron, since she could not feel the relationship between the tip and the end of her residual limb. The inability for participants to relate motions of their residual limb to complex prosthetic devices limited prosthetic use in tasks that required fine-motor skills and was a source of frustration. Ellen resolved the problem by using a hand splint, "*I was using that splint to keep [the soldering iron] stable… I knew where it was.*" (Ellen, Interview 1).

Two-Handedness and the Impact of Physiology

Unlike one-handed tasks, tasks that require both hands must consider the relationship between the limbs. For example, Kevin's cello was sized for a child of his height with full arm length. His shorter residual limb (with an above-wrist amputation) could not reach the bridge of the cello. Similarly, Brett owns a myoelectric prosthetic that mirrors his full limb for tasks such as weight lifting where an imbalanced length could result in injury; "*So like for weight lifting I use a prosthesis that's equal to my actual arm*" (Brett, Interview 1). For Ellen, the length of her prosthetic must match her other limb while hand-cycling to avoid an awkward shoulder position, *"You don't want me to be completely catawampus…it's a lot harder on your back"* (Ellen, Interview 3).

Although mirroring is important, it was not always used. For example, Brett chooses to use a shorter myoelectric prosthetic while working as a nurse, playing the guitar, and for general use during the day because they afford better fine motor control in one-handed tasks.

In addition, many existing off-the-shelf prosthetics are designed to mirror standard arm shapes, but this may not account for multiple limb differences. For example, Ellen's hand-cycle prosthetic fit badly because it made assumptions about her arm angle that did not match her existing arm, which was lacking deltoid muscles. Adapting for these specific variables produced more successful prosthetic devices, whereas traditional prosthetics are limited by the parameters recognized for general use. "*The problem is I don't fit anybody's cute little box*" (Ellen, Interview 1). Unfortunately, the exact physiology of a residual limb is highly dependent on the participant, making custom designs a necessity, which adds expense. However, customizability is a place where DIY technologies shine.

Significant Parameters of Prosthetic Devices

Although each participant had different task specific requests, customization parameters common to all tasks and participants arose. The three most significant parameters were: length, angle, and rotation. Each of these parameters had a significant effect on how users position their body and perform the task. Accurate adjustments to these parameters improved the comfort and success of tasks.

In many cases, the necessary parameter value could not be predefined given task requirements. Instead, participants tested a variety of parameters to find the "*natural fit*" (Brett, Interview 3). This iterative testing allowed participants to discover the relationship between parameters and the prosthetic's comfort and functionality.

Length from the end of the residual limb impacted every participant in the tasks we tested. In many cases, devices needed to be longer to support the participant in reach distance, "*[the cello-bow] is a bit high, well when I jump high [towards the cello bridge]*" (Kevin, Interview 1), or to increase the participants leverage on heavy objects, "*there is an additional 10 inches to pick something up*" (Brett, Interview 2). Brett also needed to adjust the length of the knife in trials of the knife holder prototype.

Length was not only participant but also task specific. For example, tasks that required fine-motor skills consistently required a shortened prosthetic because it allowed participants to mentally map the position of a tool relative to their hand. For tasks that required heavier tools, length was also shortened to decrease the distance of the fulcrum and increase the participant's control of the device, "*I'm able to exert more pressure when it's shorter.*" (Brett, Interview 3). For other tasks, comfort dictates a longer prosthetic, as when adjusting Ellen's hand-cycle, and Brett's weight lifting to match the length of the other limb. In the weightlifting example, length effected the two-handed task of balancing the length of his full arm in the length his amputation.

Two angles were significant for participants: the *hinging angle* from the end of the residual limb and the angle of *rotation* around the axis of the forearm. Hinging angle

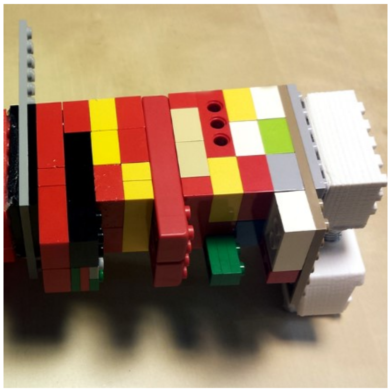

Figure 5.a. Legos are used to iteratively adjust the length between the socket and cello bow holder

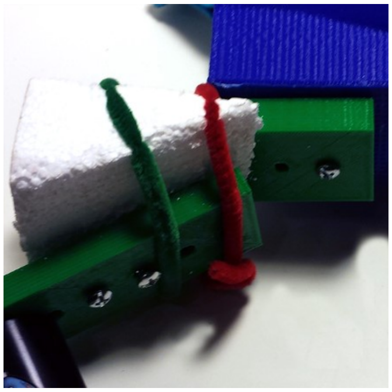

Figure 5.b. Pipe cleaners are used to fasten carved Styrofoam angle blocks for iterative testing.

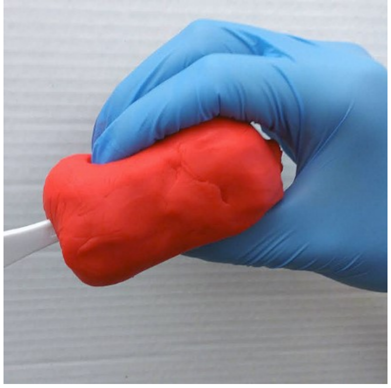

Figure 5.c. Clay is used to mold grip of a myoelectric hand. Clay is 3D scanned and reproducible.

significantly affected Ellen's hand-cycle adaptation. Her limited range of motion in the residual limb impacted her ability to spread her elbows outward. As a result, standard hand-cycle adaptions were not useful because they forced her to assume a painful cycling posture. To combat this, our final design used an angled block to bridge the connection between her arm and the hand-cycle. This angle allows Ellen to keep her elbows pointed inward while gripping to the hand-cycle securely. Similarly, Brett mentioned a need for "*something that I would be able to supinate and pronate…without needing to switch a button*" (Brett, Interview 1) when discussing a prosthetic he envisioned using for his job.

Rotation about the axis of the forearm also impacts the usability of a variety of tools, in a dynamic fashion. Brett's myoelectric arm could be rotated at the wrist using his unimpaired hand, which he frequently found useful. For example, he needed a different angle to spread peanut butter on bread than to cut it. This was also a significant parameter for Ellen, and tasks such as hair brushing or eating are difficult for her "*I'm cursing out because I can't rotate my hand*" (Ellen, Interview 2). This lack of rotation led to a sense of "*a very constricting range of motion*" (Ellen, Interview 1). In contrast, all participants could change angle and distance somewhat (by bending at the elbow).

Because these parameters depended on both task and participant, we found it necessary to test iteratively. Getting the right length required dynamic adjustment and an ability to compare small adjustments side by side. Similarly, a prosthetic's angular design needed to be correct for the task and person. Rapid dynamic adjustments during prototyping were ideal to assess correct parameters.

Playful & Practical Prototyping Materials

The importance expressing *significant parameters* like length, rotation and angle directly led us to introduce cheap and *quick prototyping mechanisms* into the design sessions that could be used for iterative rapid testing in context. These also provided an easy way to translate the results into 3D modeling parameters. We used prototyping materials including hot glue, Legos, foam (for carving), pipe cleaners, zip ties, and clay to encourage participants to directly modify their prototypes and increase their involvement in the design process. These prototyping materials were selected for their playfulness as well as their practicality.

This was especially effective for Kevin, who did not always communicate his needs verbally to researchers. Legos represented a design context he understood, and allowed iterative experimentation with length as shown in Figure 5.a. Lego experimentation led him to provide direction about the comfort of his prosthetic and to make concrete suggestions to researchers regarding the addition or removal of Lego layers. During breaks in the design session, Kevin remained engaged with his prosthetic prototype by constructing a "*ketchup factory*" (Kevin, Interview 1) using spare Legos and the 3D printed Lego base on his prosthetic.

The introduction of prototyping materials also impacted how Ellen and Brett engaged with the design process. Both offered creative designs and ideas in response. While adjusting her Styrofoam prototype (see Figure 5.b), Ellen commented that, "*life changing technology can come in many forms; it can come in the form of Styrofoam and pipe cleaners,*" (Ellen, Interview 4). When asked to use modeling clay to mold a grip (see Figure 5.c), Brett joked about the utility of custom 3D printed prosthetics by comparing them to tools for spies, "*Just like James Bond. There's one of the bad guys who had a torch a lighter in his arm [sic]*" (Brett, Interview 1). In addition to being useful prototyping tools, these materials encouraged an open dialogue between participants and researchers.

For each participant, using materials that allowed them to build onto their prototypes allowed them to adapt the prosthetic to their specific needs and increase their comfort of use. This allowed the users and designers to adjust parameters in one design session rather than requiring multiple, which increased the speed of the design process in addition to providing measurements that were easy to incorporate into parameterized 3D models.

Figure 6.a. Kevin adapted an old prosthetic to hold the cello bow. The grip was loose and ineffective.

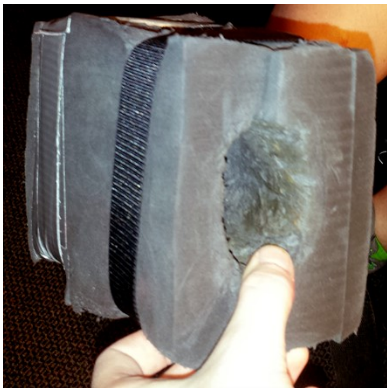

Figure 6.b. Foam kayak handle developed by Ellen and her assisted-kayak instructor.

Figure 6.c. Brett demonstrating how he uses a paper clip and myoelectric arm to perform tasks as a nurse.

A Support System for DIY-AT

All participants used DIY-AT to perform a variety of tasks and had a support network to help them in the design and develop of these DIY solutions. These support networks include, but are not limited to, friends, family, teachers, co-workers, and clinicians with varying levels of experience.

For example, Kevin's mother and music teacher had adapted his old prosthetic to play the cello; this can be seen in Figure 6.a. Although they had no formal experience with rehabilitation engineering, they were able to adapt the older device using household tools. Ellen had a similar experience; she grew up in a "*mechanically inclined family*" (Ellen, Interview 4) where her father had a master's degree in biomedical engineering, and her grandfather owned a workshop, which influenced her approach to addressing her needs *"I've been doing my own adaptations since my dad started doing them when I was a little kid," (*Ellen, Interview 2). This contributed to her decision to research robotics and prosthetics. In addition, Ellen's network of support extended to friends and coworkers in the rehabilitation technology field. Ellen owned a variety of custom assistive devices that she and friends had designed including: a foam kayak handle (see Figure 6.b) designed by an assisted-kayak instructor, weight machine grips provided by disabled fitness trainer, and custom leg braces provided by researchers in her university's prosthetic and orthotics department.

As a child, Ellen's father would build her adaptations and, in some cases, was asked to make more devices for peers with disabilities, "*My dad made at least half a dozen of those blocks [used to support children who cannot use standard scissors] over the years for when there would be another kid in the program who needs [the adaptation]*" (Ellen, Interview 2). This demonstrates the benefit of support systems for sharing DIY-AT.

Brett did not receive help from family or friends; rather, his custom devices were created by collaborating with his prosthetist and prosthetic supplier. This involved less collaboration between Brett and his prosthetist than there was between the other participants and their designers. Instead, Brett completed the design process on his own and gave manufacturing instructions to his prosthetist, "*I came to the supplier and they just did what I asked them to do to make it short*" (Brett, Interview 1). Although Brett made extensive use of prosthetics for his job the financial cost of collaborating with clinicians limited the set of tasks had solutions for, "*I know if I wanted to have a hammer adaptor, I know that's very costly*" (Brett, Interview 1). He was limited to devices available through his prosthetist that were also covered by insurance or were with in his budget for out of pocket expenditures. Because of these limitations, he also adapted his prosthetics with low-tech components. For example, one of his prosthetics had a binder clip attached to the side that he used to hold objects; this can be seen in Figure 6.c.

To summarize, co-designing assistive devices with family and friends was a common activity, and it resulted in devices that were unique and customized to meet participants' needs.

RECOMMENDATIONS: PROTOTYPING PROSTHETICS

Our findings provide a rich picture of the role of DIY prototyping in meeting peoples' prosthetic related needs. The types of tasks that participants wished to accomplish varied widely, from operating a hand-cycle to soldering, and thus we produced radically different end-effectors for these tasks. However our research uncovered common needs and opportunities across participants. In particular, we introduce the concept of an *extension* for increasing prosthetic comfort and modularity; argue for advances in *prototyping parameters;* and suggest options for further *community engagement.*

Extensions for Parameterization and Modularity

Although the value of modularity has been demonstrated in the DIY community [7,32], this work has focused primarily on *sockets* and *end-effectors.* We argue that the *extension* connecting the two should receive more attention. This extension has two important roles to play. First, it can increase modularity by allowing the same socket to be used

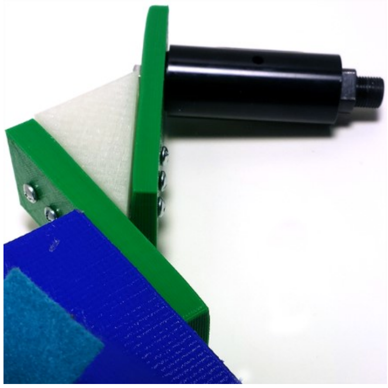

Figure 7.a. A *static* angled and lengthened extension from Ellen's socket to the hand-cycle handle.

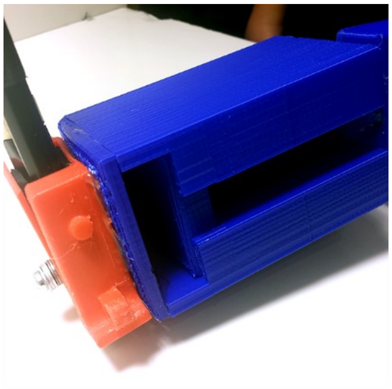

Figure 7.b. A *modular* length extension between Kevin's socket and cello bow holder.

Figure 7.c. A *dynamic* extension of Brett's myoelectric prosthetic that can rotate with his wrist.

with a variety of different end-effectors. Second, it can capture key design parameters such as angle and length independently of the socket and end-effector. This in turn can increase iteration speed. Figure 7 shows examples of different extensions prototyped in the course of our study (7.a and 7.b) and included with an existing prosthetic (7.c).

Static extensions capture a key design parameter (such as angle or length) but are fixed to a single socket and end-effector. *Modular extensions* consist of two separable components, one of which attaches to the prosthetic and the other of which attaches to one or more *end-effectors*. This allows a user to use the same socket for a variety of tasks, and also captures design parameters. An example is Kevin's in Figure 7.b. A *dynamic extension* allows for one or more parameters of the extension to be adjusted by the user without removing any part of the prosthetic. An example is the wrist articulation included in Brett's myoelectric and body-powered prosthetics, which allow for rapid adjustments to highly dexterous tasks such as cutting food (Figure 7.c).

Additional work on extensions could address several issues. Designs that bridge from 3D printed end-effectors to common commercial designs for modularity are needed. Designs that support dynamic modification of parameters would be of great value. Finally, tools that can adjust modular extensions to capture measurements about angle, rotation and length would be of value. This would function best if embedded in a process for prototyping that generated design parameters.

Relatable, Rapid Prototyping Materials

A prerequisite for the tool that supports mixing modules is an ability to prototype effectively so as to gather the requirements needed to generate a reasonable prosthetic. Our results point to the value of prototyping materials in increasing engagement and playfulness as well as eliciting design requirements. For example, Kevin was more comfortable adjusting the length of his prosthetic by adding on layers of Lego, rather than discussing length with researchers. These components encourage users to participate in the design process and give novice users access to physical design features, rather than accessing changes through computer interfaces and 3D models. Thus, the ideal prototyping materials should be relatable, and easy to construct and destroy as the users need.

In addition, due to the lengthy time required to change and reprint 3D models, using a range of materials can increase the speed and effectiveness of iterative design. This allows rapid physical changes to be made to a working prototype, allowing a user to quickly adjust devices to their needs. For example, none of the participants in this study could clearly express the exact parameters that a design required to meet their needs, however, all participants were able to determine a "natural fit" when comparing small adjustments of a working prototype. Again, ease of construction is critical here.

These rapid iterative testing phases allowed users to adjust the device to a correct fit and resulted in an existing prototype that designers could measure or 3D scan. These low-tech models presented designers of with a blueprint of the exact parameters users require and final models can be easily produced given this data.

Participant and Community Engagement

Our study revealed that having a support network of novice and professional designers increased the range of AT that participants could access. This relationship with designers resembles the social ecology of elder support described by Forlizzi *et al* [13]. The advent of sophisticated consumer manufacturing devices, such as 3D printers, makes it feasible to develop tools that lower the floor for assistive device production and further broadens the range of people who can contribute to this process.

We also observed that the existing tools and designs available from communities such as E-nable, Open Prosthetics, and Thingiverse improved the quality and efficiency of the design process. This reiterates the conclusions of Buehler *et al.* considering DIY-AT and open source 3D modeling [5]. The open sharing of DIY designs is significantly more cost effective than the practice of using professional prosthetic devices that are prohibitively expensive and facilitates the adaption of AT to meet user needs on a case by case basis. Aside from the sharing of physical models, designers in these online DIY communities may often discover significant parameters related to specific tasks and education types. As a body of common knowledge on DIY prosthetics grows these communities will need techniques to help discover and manage the abundant information.

The value of this type of engagement is visible in Kevin's final prosthetic, which a terminal device and gauntlet designed by E-Nable volunteers and fit using a thermoforming process E-Nable developed.

Building a relationship between users with amputations, support networks, and online communities will increase the number of assistive devices available to users. Specific challenges include how and when to provide clinical oversight, how best to extend the expertise of volunteers with the help of the broader community, and how to provide follow up support for devices that are produced.

LIMITATIONS AND FUTURE WORK

We studied a small but diverse group of users with congenital amputations and future work should explore the efficacy of our recommendations in a broader context. In addition, our study focused on 'pain points' as defined by participants (where they were not satisfied with their existing solutions). Thus we did not fully cover the standard set of activities of daily living. We tested prosthetics in the lab or home setting but our focus was early stage, iterative design, not long-term use. Thus we do not have any field data on their use. Our cases included a range of grip types, but gripping was not a focus of our work. Our participants did not specifically want prosthetic hands which could grip, they wanted task specific solutions.

In the future, we hope to produce a formal method and toolset appropriate for prototyping prosthetic devices. We also plan to study the use of these prosthetic devices outside of laboratory settings.

CONCLUSION

In this study, we worked with three participants with congenital, upper-limb amputations to examine how participants prototype assistive devices. From these findings we derived a recommendations for advances that would enhance the production and relevance of task specific prosthetic devices.

We argue that a modular prosthetic assistance system would benefit from the addition of *extensions* as a key component that can capture *parameters* affecting comfort such as length, angle and rotation. We argue that dynamism is needed in such extensions. We highlight the importance of relatable prototyping materials that encourage user engagement in design by presenting household tools as a means to iteratively adapt a physical prototype. Finally, we argue that a diverse ecology of people can help to support prosthetic design, including the open source DIY community.

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