"A Tool for Freedom": Co-Designing Mobility Aid Improvements Using Personal Fabrication and Physical Interface Modules with Primarily Young Adults

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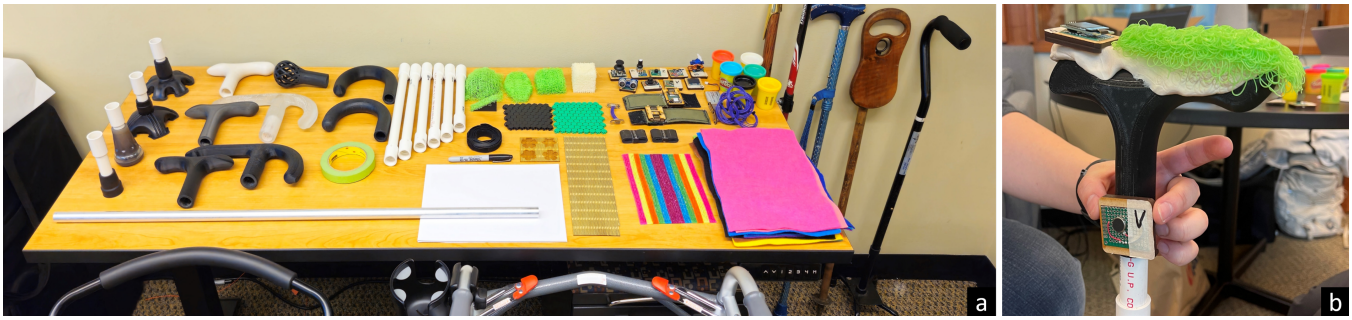

Figure 1: (a) Our co-design set-up with a modular cane, 3D printed TPU foam, laser cut decorative kerf patterns, physical interface modules, arts and crafts supplies, and an assortment of mobility aids to try. (b) A mobility aid configuration from a co-design session with an OLED display on top of the handle and a vibration motor at the base of the handle.

Abstract

Mobility aids (e.g., canes, crutches, and wheelchairs) are crucial for people with mobility disabilities; however, pervasive dissatisfaction with these aids keeps usage rates low. Through semi-structured interviews with 17 mobility aid users, mostly under the age of 30, we identified specific sources of dissatisfaction among younger users of mobility aids, uncovered community-based solutions for these dissatisfactions, and explored ways these younger users wanted to improve mobility aids. We found that users sought customizable, reconfigurable, multifunctional, and more aesthetically pleasing mobility aids. Participants' feedback guided our prototyping of tools/accessories, such as laser cut decorative sleeves, hot-swappable physical interface modules, and modular canes with custom 3D-printed handles. These prototypes were then the focus of additional co-design sessions where six returning participants offered suggestions for improvements and provided feedback on their usefulness and usability. Our findings highlight that many mobility aid users have the desire, ability, and need to customize and improve their aids in different ways compared to older adults. We propose various solutions and design guidelines to facilitate the modifications of mobility aids.

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CCS Concepts

• **Human-centered computing** → **Accessibility technologies**; **User studies**; *Interaction devices.*

Keywords

Assistive Technology, Mobility Aid, Digital Fabrication

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1 Introduction

Although mobility aids such as canes, walkers, and rollators are essential assistive technologies (AT) for individuals with mobility disabilities, their usage rate remains relatively low. Only 3% of Americans report using a mobility aid [30], despite 12% of the population having a mobility disability [8]. This low adoption rate has been attributed to the social stigma around mobility aids and the high abandonment rates (30-60%) correlated with not considering user opinions while selecting aids, poor performance or fit, and changes in user needs and priorities [20, 23, 24, 36, 50, 55, 64]. However, little work has been done to address these issues. While there are some recent innovations in the space of white canes and wheelchairs (e.g., [1, 31]), more basic mobility aids such as canes, walkers, and crutches have not received much attention. Work on basic mobility aids focuses only on improving performance [9, 48, 71], which is just one of many factors impacting satisfaction/abandonment [60]. Furthermore, most of the work on mobility aids focuses on the elderly, despite over 30% of people developing mobility disabilities under 50 years old [26].

We investigated some of these understudied issues, such as the consideration of user opinion during selection and changes in user needs/priorities, through a two-phase study with mobility aid users. We conducted semi-structured interviews with 17 people aged 18-72 and focused on recruiting mainly younger adults to highlight differences in how they use mobility aids compared to older adults who likely developed limited mobility later in life. In these interviews, we asked how participants used mobility aids in different scenarios (e.g., going to the store, adverse weather conditions) and investigated the types of concerns they had with using their aids. We also showed participants different off-the-shelf accessories, such as ice tip attachments and decorative cane covers, and asked how well the accessories addressed their needs. After understanding the problems users were experiencing, we then discussed strategies participants adopted in their daily lives to address the limitations of their mobility aids and brainstormed potential solutions to bridge the current gaps in existing mobility devices. We found that mobility aid users wanted four main criteria that they could not easily find with existing commercial solutions:

- **Aesthetic improvements** to be happier using their aid in public (e.g., express individuality, be more discreet)
- **Multifunctionality** to help support everyday activities other than mobility (e.g., carrying things, navigation)
- **Customizability** to create their preferred combination of mobility aid features (e.g., handle shape, material)
- **Reconfigurability** to modify their aid for different situations (e.g., going to the beach, hiking, shopping)

With these points in mind, we conducted an in-person co-design session with six returning participants and provided them with different low-fidelity prototypes we created based on their feedback to further explore their needs. These tools included a height-adjustable modular cane with interchangeable handles and tips, functional accessories such as 3D-printed foam-like material to customize handles, laser cut interchangeable decorative elements, smart modules (e.g., LED screen, vibration motor, buttons, etc.), and arts and crafts supplies. From the co-design session, we saw how participants prioritized different features by observing the variance in modifications participants made to create their ideal mobility aid. Through this process, participants shared how these low-fidelity prototypes could be further developed for real-world usage.

The main contributions of this work are 1) characterizing why and how mobility aid users, particularly young adults, want to customize their aids, 2) highlighting the strategies mobility aid users and their community created to address the limitations of mobility aids, and 3) demonstrating how common personal fabrication techniques (e.g., 3D-printing, laser cutting) can create do-it-yourself (DIY) functional and aesthetic modifications to mobility aids.

2 Related Work

Our background section highlights several different factors that may impact mobility aid users. First, we examine common shortcomings of mobility aids, such as aesthetics, fit, cost, and usability challenges. We then explore the importance of community on the customization and use of AT and the community movement towards using decorative AT to combat stigma and promote positive social interactions. Finally, we dive into the ways that researchers have attempted to improve performance and reduce dissatisfaction with both AT and mobility aids.

2.1 Understanding Mobility Aid Shortcomings

Researchers have identified several common shortcomings of mobility aids, such as unappealing aesthetics, poor fit, high cost, and challenges that arise from using these aids in different situations (e.g., grocery delivery, extreme environmental conditions) [1, 2, 50, 58]. However, most research on mobility aids has focused on complex mobility aids such as wheelchairs and prostheses [1, 6, 7, 41, 44, 70], leaving open questions about how these challenges apply to more simple mobility aids such as walkers and canes. Additionally, researchers in the mobility aid space have been critiqued for not having strong user involvement when attempting to create prototypes to address the various documented shortcomings [1, 62]. Although the importance of involving the disability community in the design, creation, and integration of AT has been well established within the HCI community [3, 29, 32, 46], mobility aid research involving tangible modifications to the mobility aid have predominantly conducted in non-HCI communities where participatory design practices have yet to become as common. The lack of input from disabled users may limit the range of ideas being explored and miss opportunities for design that are known to mobility aid users but not considered clinically relevant. Furthermore, existing work on understanding and addressing mobility aid shortcomings tends to focus on older adults [4, 18, 40, 55, 68], despite not all mobility aid usage being age-related. Younger people with disabilities tend to have different lifestyles and more positive attitudes towards disability [38], which can influence the use of mobility aids.

2.2 Community Aspects of Assistive Technology

The usage and customization of mobility aids are likely strongly influenced by community support. Although this has not been specifically studied in the use of mobility aids, researchers have highlighted the powerful role the community plays in the broader usage of AT. The community of AT users is known to leverage online

forums to provide support for one another [63, 65] and share practical solutions such as 3D printing files for custom-created AT [5, 59]. Community-based work also includes open-source wheelchairs[1] and policy efforts such as the Right to Repair movement (e.g., [19, 67]). There are also countless smaller supportive communities around the world where members help peers with their access needs. Examples include community members creating AT to share educational resources with peers who are blind or low vision (BLV) [69], creating custom low-cost head pointers to empower individuals to paint without needing hands [25], and making miniature wheelchairs for children [25]. These examples show how community plays a crucial role in the usage and adoption of AT as a whole; however, it is not yet clear how mobility aid users are specifically supported by each other and the community around them.

2.3 Aesthetic Modifications to Mobility Aids

Aesthetics play an important role in increasing the use of AT. AT users may feel hesitant to use their AT in public because of the negative associations with AT [33, 60, 61, 66]. Goffman defines this as stigma: the disruption of social interaction due to associating someone with an "attribute that is deeply discrediting" [15, p. 2]. For example, people may feel that using ATs may make them look old or draw negative attention to themselves/their disability [27, 60, 61]. Initially, the prevalent strategy to mitigate this stigma was to conceal AT by having AT blend in with the wearer's body, mimic a "missing" body part, or have a neutral design.

However, there has since been a growing movement to create AT with bolder, attention-grabbing aesthetic designs intended to instead *reverse* social stigma by promoting *positive* social interactions and encourage a feeling of pride in their users [12]. Some AT users are now decorating their AT with DIY art supplies such as fabric, paint, decorative tape, and stickers as a form of self-expression [13, 28, 51, 52]. To satisfy the demand for easy aesthetic options, companies have emerged offering decorative AT and AT accessories, such as decorative patches for insulin pumps from Peelz, hearing aids in the form of earrings from Hearrings, and aesthetic covers for prostheses from Unyq.

There are also a variety of aesthetic mobility aids available on the market, such as stylish canes from companies like Fashionable Canes, ELDERLUXE, and Neo Walk; patterned cane covers from Kickin' Cane Covers; stylish wheelchair covers from Izzy Wheels; and sleek rollators from byAcre.[2] However, these customization options come with a barrier; they are either limited in options or are significantly more expensive than non-decorative AT [53]. Although there are a lot of companies and organizations creating decorative AT and mobility aids, there is little work on understanding what types of aesthetics mobility aid communities want and how they want these aesthetics implemented.

2.4 Functional Modifications to Mobility Aids

Although the need for customization for aids has always existed because of the existing product gaps, disabled people embrace the value of creating DIY solutions to the problems they encounter [21, 24, 29, 52, 56, 57, 69]. Existing work has showcased how consumer fabrication approaches such as 3D printing, laser cutting, and knitting have been applied to customize or create different types of AT [5, 22, 24, 25, 37, 39]. However, in the realm of mobility device customization, less is understood about disability-led perspectives. Hurst et al. interviewed four power-wheelchair users about what modifications they would like to their wheelchairs and found there was a preliminary interest in DIY fabrication [25]. McDonald et al. explored how physical therapists (PTs) and PT students could be trained to customize ATs using 3D printing through classes around simulated patient case scenarios [39]. Buehler et al. studied the backgrounds and motivations of AT designers in an online 3D model-sharing repository and showcased a need for customized AT from end users and their loved ones [5]. Hofmann et al. conducted a case study into the design of prostheses and the need for modularity when creating custom, task-specific aids co-designed by end-users [22]. These papers explore different ways fabrication can be used to customize assistive technologies with the aid of experts, but everyday modifications and customizations by mobility device users who use common, inexpensive aids such as canes, hiking poles, and rollators have not, to our knowledge, been studied.

One category of modifications, smart technologies, has been explored in depth within the mobility device space. Examples include integrating sensors and motors for stabilization and fall prevention, creating power-assisted aids, and adding fall detection systems [1, 11, 14, 16, 42, 43, 47–49, 54]. However, most of these technologies are designed and evaluated without mobility device users. There is also substantial research on applying smart technologies for BLV white cane users to navigate/avoid obstacles and interact with smartphones through buttons/switches [31, 45]. However, it is unclear whether mobility device users want similar technologies. Overall, there is little work exploring if and how younger, more tech-savvy mobility aid users want technology integrated into aids.

3 Methods

To understand the types of mobility aid improvements users wanted, we conducted a two-phase co-design study. First, we interviewed people across the United States about their experiences using mobility aids. Then, we developed tools based on their feedback and invited participants to an in-person co-design session to investigate how these tools can be used to improve their mobility aids. The protocol was approved by our university's IRB. All participants consented to the study and were compensated $40 for our 60-90 minute virtual study and $100 for our in-person two-hour study.

3.1 Understanding Existing Mobility Aid Modifications

Before conducting interviews, we wanted to gain a better understanding of the mobility aid space. To accomplish this, we browsed existing mobility aids and their accessories on mobility aid forums (e.g., Walking Stick Forum, r/MobilityAids, r/Disability), popular online marketplaces (e.g., Amazon and eBay), and YouTube videos of content creators sharing advice and stories about having a chronic illness and using a mobility aid as a young adult (e.g., Aimee Ester, Chronically Jenni, Elinor Brown). For example, on Amazon, we looked at the top 100 products in relevant categories (e.g., "Canes,

[1] redpillinnovations.com/open-source-wheelchairs

[2] pumppeelz.com, wearhearrings.com, unyq.com, fashionablecanes.com, elderluxe.com, neo-walk.com, kickin-canes.com, izzywheels.com, byacre.com

Crutches & Accessories" and "Walkers, Rollators & Accessories"). From these resources, we compiled a list of almost 40 different categories of modifications and accessories that have been proposed or created within the community. These categories range from decorative solutions leveraging pyrography, hydrodipping, and crocheting to functional attachments such as flashlights, cup holders, and bags and different unique form factors such as upright rollators and beach rollators[3].

3.2 Study Phase 1: Virtual Semi-Structured Interview Design

We conducted 60-90 minute semi-structured interviews with 17 mobility aid users over Zoom to understand their needs, identify useful improvements, and brainstorm specific solutions. These interviews were divided into three parts. We asked participants about any accessibility needs ahead of time (e.g., captioning, breaks).

Part 1: Understanding Selection of Device. To learn why their mobility aids were chosen, we asked participants to describe their experience of receiving their first mobility aid and the transition process between aids if they had used multiple. Additionally, participants compared and contrasted their aids with any previous or present aids and identified reasons for switching mobility aids.

Part 2: Use of Devices in Specific Situations. We asked how participants typically used their mobility aids by prompting them to describe from recent memory how mobility aids were used in different situations and days, including 1) a routine day, 2) a day with adverse weather conditions such as strong wind, rain, and/or snow, and 3) a day when they felt uncomfortable or unsafe, such as when traveling using public transit or crossing the street.

Part 3: Brainstorming Solutions. We first summarized participants' experiences and asked follow-up questions to clarify any misunderstandings. Next, we walked through each of their expressed difficulties/desires and brainstormed solutions. For each issue, we first determined if a physical prototype would be useful. If the participant thought it would be, we worked with them to help determine what specific things they value and would want in the design by thinking through the following questions:

(1) What part(s) of the mobility aid needs to be modified to address their need? (e.g., tip, handle, wheels, seat)
(2) What are the key properties of the modification to prioritize? (e.g., appearance, ease of modification, weight, durability)
(3) Is there an existing modification that we discovered during our survey of the mobility aid space or discussed with a previous participant that is a close match with their needs? If so, we described/showed the modification and discussed what changes, if any, would be useful to meet their needs.
(4) What approaches using personal fabrication or embedded systems can be used to satisfy users' desired design criteria?

3.3 Study Phase 2: In-Person Prototyping

We followed up the virtual interviews with an in-person co-design study where we invited participants from Phase 1 to explore the design space of what an ideal mobility aid would look like using the physical prototypes we designed. When designing the prototypes, we drew upon Lim et al.'s framework of using "prototypes as filters" to create a collection of low-fidelity prototypes intended to support narrowing down the design space of mobility aid modifications [34]. Six of the original 17 participants chose to participate in this follow-up session. Each session lasted two hours and was conducted with one participant at a time, except for one session with two participants due to their travel/time constraints. Before beginning, we reminded participants about the initial interview and the potential solutions they had previously ideated on, setting the tone for future design solutions. Throughout the entire study, we continuously encouraged participants to verbalize if they had any suggestions for changing the prototypes. The co-design study sessions consisted of three parts each.

Part 1: Testing Commercially Available Mobility Aids. We first had participants test different types of mobility aids because did not test many aids before choosing their personal one. They used a walker, a rollator, seat canes, canes of different designs, and a prototype of a modular cane with interchangeable tips and handles (see Figure 2). We asked participants what they liked and disliked about each aid, specifically mobility aid features that originally came up in our virtual interview sessions (see Table 4) such as handle shape, material, and adjustability.

Part 2: Experimenting with Designed Prototypes. During this phase of the study, we had participants test the prototypes we created and provide feedback. To design the prototypes used in the study, we performed thematic analysis on the interviews (see Section 3.5) to extract four key criteria that users wanted in their mobility aids that were not available in commercially available options:

- **Aesthetic improvements** to be happier using their aid in public (e.g., express individuality, be more discreet)
- **Multifunctionality** to help support everyday activities other than mobility (e.g., carrying things, navigation)
- **Customizability** to create their preferred combination of mobility aid features (e.g., handle shape, material)
- **Reconfigurability** to modify their aid for different situations (e.g., going to the beach, hiking, shopping)

We then categorized the prototype ideas we brainstormed with participants into groups of similar concepts, chose the most commonly requested concepts, and created generalized prototypes that fit the majority of participants' priorities. We also wanted to allow participants to filter through the design space of their ideal mobility aid themselves. To support this, we made prototypes with adjustable/hot-swappable components so each parameter can be independently changed. We describe our prototypes in Section 5.1. For each prototype, we provided instructions on their usage and asked participants to think aloud about potential ways they would personally use them and probed them on their attitudes towards individual features on each prototype.

Part 3: Designing Their Ideal Mobility Aid. We asked participants to experiment with arts and craft supplies (e.g., Wikki Stix, Play Doh) and our prototypes to construct their ideal mobility aid. While experimenting, we asked participants to verbalize perceived tradeoffs when choosing between features. In particular, we wanted to understand how components interact together to influence desired design features (e.g., portability, usability). Afterward, we inquired

[3] elenkerwalker.com, wheeleez.com

about the usability and feasibility of creating modifications to understand ways to make the process easier.

3.4 Participants

Participants were recruited through various disability-related email lists, clubs, social media, and snowball sampling. Participants were required to have used at least one mobility aid other than a white cane. Seventeen mobility aid users participated in the first interview study. We mainly focused on younger participants, with 13 participants being under 30 years old and four participants being over 40 years old. Most of our participants were open and proud of their disabilities and were comfortable talking about their use of mobility aids. Fourteen participants were in community groups serving mobility device users. A variety of types of mobility aids were represented: 17 used canes, six used wheelchairs, five used forearm crutches, four used crutches, four used walkers, three used hiking sticks, two used rollators, one used a three-wheel scooter, and one used a service dog with a harness (see Table 1). For our in-person co-design workshop, we asked all local participants to join and had six accept. All participants who joined our in-person co-design workshop were under 30. A variety of mobility aids were represented in our co-design study: six used canes, three used hiking sticks, three used wheelchairs, two used forearm crutches, one used crutches, one used a walker, and one used a service dog with a harness. Participants had a wide variety of disabilities (see Table 2).

3.5 Analysis

We analyzed our data using reflexive thematic analysis [10]. The authors coded three transcripts together to develop an initial set of codes. The lead author unified the analysis for all interviews by reading and coding all transcripts, and other authors independently coded a subset of the interviews, such that each interview had at least two researchers reviewing each segment. Throughout the coding process, the researchers met weekly to discuss and reach an agreement on any codes that were ambiguous or needed to be added. This process was done for both the initial virtual interviews and the in-person co-design sessions. When coding our co-design sessions, we used codes from the prior virtual interview codebook if they applied (which occurred frequently) and introduced new codes specific to this session. The combined final set of codes included 235 different concepts. The group discussed codes and worked to develop themes until consensus was reached on our six main themes and 15 sub-themes. Top-level themes include "Wanting Improved Aesthetics" and "Deciding Between Mobility Aid Features."

3.6 Positionality

The last author is a mobility aid user with experience helping family members also adopt and use canes, rollators, and wheelchairs under various circumstances. These experiences, coupled with their discontent of solutions on the market, inspired this study.

4 Virtual Interview Findings

In this section, we highlight four key features our participants desired in mobility aids but found lacking in the market: **aesthetics, customizability, reconfigurability, and multifunctionality**. We also emphasize how only addressing the physical limitations of mobility aids is insufficient by showing various benefits our participants experienced within disability communities, such as knowledge sharing and promoting disability pride, which were crucial for our participants' successful adoption of mobility aids.

4.1 Improving Aesthetics

Participants came up with several innovative ways to decorate their mobility aids to counteract the social stigma of traditional aids. However, many DIY methods had a high barrier to entry, were difficult to personalize, and often lacked a polished finish. As a result, participants wanted more convenient and higher-quality aesthetic options to express their individuality better.

4.1.1 Desiring aesthetic mobility aids to combat social stigma. Matching our literature review (see Section 2.3), all our participants strongly considered aesthetics when choosing a mobility aid. As P3 described, *"I've always wanted a cane that I could at least enjoy looking at. Like, you know, if you're using something every day, you don't want it to be like… ugly."* Some participants even prioritized aesthetics above all other features, such as P2 mentioning that they would choose an ornate wood cane for its aesthetics even if they had to forgo functional features like handle shape, collapsibility, and weight. Participants highlighted that aesthetics were crucial because stylish mobility aids helped mitigate or even reverse the social stigma associated with usage. For many participants, the aesthetics of mobility aids also directly impacted their effectiveness and usage. For example, participants with fluctuating symptoms, such as fatigue, muscle pain, and balance issues, could choose to forgo their mobility aids, opting instead to endure more discomfort and fatigue. For these participants, having a stylish mobility aid was particularly important and could result in more consistent usage, as it reduced internal conflict between dealing with social stigma and experiencing less discomfort and fatigue.

It is also important to support discreet aesthetic styles. For example, when first choosing a mobility aid, P15 chose to use a hiking pole instead of a cane because they felt it was more innocuous and socially acceptable, especially since cane usage among younger demographics is less common.

4.1.2 Lacking effective commercial aesthetic options. Many of our participants considered commercial options for decorative mobility aids first but found that commercial options were fairly limited. As P11 described, *"Most mobility aids are not made with fashion in mind, like they just assume that most people who are using them just want something to get around... It's hard to find something that's pre-purchasable. It's something that I just have to, like, make [on] my own."* Participants found that commercial options had many drawbacks, such as being expensive, heavy, not height-adjustable, not collapsible, offering minimal customization options (e.g., limited handle shapes), and/or having outdated designs that seemed aimed at older demographics.

4.1.3 Exploring DIY aesthetic options. Most participants turned to DIY aesthetic modifications after recognizing the limitations of commercial options. Participants mostly chose to first start with mobility aids with preferred features that couldn't be easily changed or modified (e.g., collapsible, lightweight, handle/grip shape) and then later sought out DIY aesthetic modifications with a wide variety of

Table 1: Information about participants, including age, gender, and any mobility aids they use and used to use. Participants with an asterisk are people who also participated in the co-design session.

#	Age	Race	Gender	Past Aid(s)	Current Aid(s)
1	60-70	White	M	Cane	Wheelchair, three-wheel scooter
2	70-80	White	F	N/A	Cane
3	20-30	White	NB	Forearm crutches	Cane, walker
4	50-60	White	M	Cane	Rollator
5	<20	White	M	Cane	N/A
6*	20-30	White	M	Rollator	Service dog, wheelchair, forearm crutches, cane
7	<20	Asian	NB	Crutches	Cane
8	40-50	White	M	Crutches	Cane
9	<20	White	NB	Crutches, wheelchair	Cane, forearm crutches, wheelchair
10*	20-30	White	F	Walker, crutches	Cane, wheelchair
11*	20-30	White	NB	Hiking pole	Cane, forearm crutches, wheelchair
12	20-30	White	NB	Manual wheelchair	Cane, wheelchair with power assist
13	20-30	White	M	N/A	Cane
14*	20-30	White	NB	N/A	Cane, power chair
15*	20-30	White	F	N/A	AFO, cane, hiking pole
16	<20	White	NB	Forearm crutches	Cane
17*	20-30	White	NB	Cane	Hiking pole

Table 2: Aggregated participants' self-reported disabilities

Disability	#	Disability	#
Autism	1	Chronic pain	3
Auto-immune disorder	2	Deafness	1
Cerebral palsy	1	Dysautonomia	3
Chronic fatigue syndrome	1	Ehlers-Danlos Syndrome (EDS)	2
Fibromyalgia	3	Limited depth perception	1
Lyme disease	1	Muscle weakness	1
Paralyzed leg	1	Skeletal-related disabilities	3
Traumatic brain injury	1	Multiple disabilities	8

solutions. The most common modifications were adding stickers and wrapping decorative tape around their mobility aids. Some participants also tried more complicated modifications, such as making custom stickers to add using a sticker printer or Cricut[4] (P3, P16), painting their mobility aid (P9, P14), and embroidering/sewing custom designs to a decorative "punk battle jacket" to go over their wheelchair (P14). We also had one participant (P9) replace their wheelchair casters with Razor scooter wheels, which light up and come in fun colors. Almost all of our participants expressed that there were some decorations they wanted to make but ultimately chose not to because they were scared of messing up, were too overwhelmed with where to begin, and/or felt they did not have time to do a good job.

Our participants found that having decorative mobility aids helped mitigate social stigma in most cases. For example, after adding vinyl stickers to their cane, P16 noted that they were not *"ashamed of [their] cane anymore... [but] it would bring me more joy if it were more me coded."* However, there were also a few participants who experienced how certain DIY aesthetic modifications could sometimes have the opposite effect. For example, P15 decorated their hiking pole with colorful tape but ended up sometimes drawing negative attention from people who kept asking *"why [they] had a ski pole so covered in duct tape,"* as duct tape is commonly viewed as a repair tool.

[4]Cricuts are inexpensive digitally controlled cutting machines, see cricut.com

4.2 Wanting Customizability

Participants sought mobility aids that they could customize at home to their unique preferences. This desire was driven by the challenges they faced in finding aids with their preferred combination of features, the need to physically test aids to evaluate features, and the insufficient time and environment in stores to assess configurations.

4.2.1 Difficulties finding a suitable mobility aid. Time constraints, concerns with cost, and lack of market awareness were significant barriers to finding suitable mobility aids. P10 mentioned the reason they hadn't looked into different types of handles was because *"it's a big task that's gonna take a long time because I don't exactly know what I'm looking for."* Being unable to research available options comfortably meant participants did not know about potentially suitable mobility aids. For example, when we showed participants

seat canes, which are canes with a foldable seat that has been around for decades, we often received responses like P17's: *"Okay, I've never used one of these. I've actually never seen one of these."*

Participants emphasized how short trials in stores were insufficient for evaluating mobility aids. P11 highlighted how *"15 minutes in the store didn't give me an idea of what it would be like to be using it daily and the stress that I would put on my hands."* Most participants had their symptoms fluctuate between days or over a single day, and single short trial periods could not gauge how the mobility aid would help them across the full spectrum of their abilities. Several participants highlighted that certain features and issues only become noticeable after using their mobility aid in different environments, such as rough terrain or adverse weather conditions. For example, P3 realized their rollator did not have enough suspension for rough surfaces while hiking, and P2 noted that their hollow aluminum cane was too light for windy conditions when it *"taken out from under [them] by the wind."* Participants also discussed the need for longer trial periods to evaluate how easy a mobility aid is to stow and carry throughout the day. This was an important factor because many participants carried multiple mobility aids to accommodate different needs throughout the day and/or had fluctuating mobility needs that didn't require using a mobility aid at all times. For example, P13 brings both a cane and crutches when running errands so that they can use the cane for short tasks and the crutches for longer errands that require more support.

Some participants even noted how it took them several months to recognize the importance of some features, with many of them mentioning the effect of different temperatures on the feel of their mobility aid. Conversely, P13 highlighted the challenges of metal: *"Metal will get so cold, you really have to hold your hands in a specific position; otherwise you're gonna freeze yourself... and then other times it can get really hot."*

4.2.2 Exploring DIY functional modifications. Many participants expressed that maintaining and repairing mobility aids was quite difficult due to the lack of easily replaceable parts. Several participants also described parts for mobility aids as being more expensive than other accessories. For example, P11 described how *"wheelchairs [parts and accessories] have an incredible price markup. [Businesses] expect you to have insurance to pay for them, but insurance doesn't often cover them anyway, so they're really expensive."*

Participants did a variety of different DIY functional modifications to improve comfort, safety, and ease of use. For example, P9 *"wrapped hockey-stick grip tape"* around their handle to help their hand not slip. Another type of modification involved increasing the handle's width. P15, an occupational therapist and cane user themselves, explained that they commonly used bandages and pool noodles to get the handle to the proper width for patients. We also had participants with wheelchairs and scooters make DIY modifications to increase visibility when crossing the street by adding reflective tape to the device and/or having a flag pop up.

4.3 Wanting Reconfigurability

While people wanted better *customizability* to obtain a mobility aid that was ideal for general use, participants also wanted *reconfigurability* to fine-tune their aid for specific situations, such as going hiking or to a formal occasion. Participants described reconfigurations involving both aesthetic and functional changes.

4.3.1 Reconfigurable aesthetics. Participants desired an easy way to switch their mobility aid appearance depending on their outfits and the situations they were in. For example, P14 described a need for reconfigurability to help with code-switching, *"A lot of my stickers [on my cane] are really like punk, very queer, very disabled stickers. You're bringing your cane everywhere with you, and anyone can see those. I go places that I don't necessarily need everyone to realize all of my political opinions all at once."* P11 noted that currently, *"if you want a different style, you have to buy a whole new [mobility aid] and that's expensive."* As a potential solution for changing aesthetic designs, we brought up commercially available fabric cane sleeves from companies like Kickin' Cane Covers, but most participants did not like the repetitive patterns, lack of customizability, and how the designs were *"old-looking."*

Participants also expressed a desire to switch mobility aid appearances to signal a need for accommodations. P13, who uses a decorated cane, mentioned that *"a lot of people thought that it was like an aesthetic choice, and not something that I was using for like helping me exist without being in pain."* P11 talked about the importance of signaling their disability in certain situations, explaining, *"When you use a cane, there's a physical identification aspect where people realize, 'Oh, you're disabled.' And so sometimes, when you're on the bus, if you have a visible disability, people realize they need to, like, stand up and let you sit down."* Similarly, P14 uses a cane even on good days to *"signal to the world that [I] need accommodations."*

4.3.2 Reconfigurable functionality. Participants also wanted to be able to reconfigure their mobility aids to have different functional abilities for different situations. For example, almost all participants who used canes and hiking poles noted that they would prefer different tip designs for different scenarios. Participants mentioned key features of the tips, such as the amount of support offered, shock absorption, and how they handled various terrains such as wet pavement, ice/snow, rough terrain, carpet, and sleek indoor surfaces. However, many tips are hard to remove, making the process of switching between different tips cumbersome and often leading to participants needing to get a completely different mobility aid with the desired tip. While there are removable tip accessories like ice spikes, many participants found them difficult to toggle on and off. P9 explained, *"I don't wanna shred [the floor indoors] with spikes, but most ice spikes... aren't designed to be easily take-offable, especially considering that you're still like using the [hiking pole or cane] to move around."* This led P9 to pursue their own DIY modification for enhanced reconfigurability. They dismantled a few ice spikes to learn how they worked and attached a string to make the tip toggleable even while standing.

Participants also described wanting to reconfigure their mobility aids so that they could change how much support they offer. For example, many participants often carried multiple mobility aids with them for different tasks, such as P13 bringing both a cane and crutches when running errands and would use the cane for short tasks because of its ease of maneuverability and the crutches for longer errands requiring more support. Some of these participants wondered if it would be possible to have mobility aids that could "transform" into a different mobility aid. We brainstormed ideas,

including turning a cane into a hiking pole by extending it and then adding a different type of handle or turning a cane into forearm crutches by adjusting the height and then adding arm braces.

4.4 Wanting Multifuctionality

Participants highlighted that even though mobility aids help with mobility, their usage introduces new disabling factors because one or more hands are occupied with the mobility aid. Participants expressed the desire for multifunctional mobility aids that mitigate these disabling factors by assisting with tasks beyond mobility. Some participants talked about wanting features such as a flashlight (P8, P12) and a grabber/extension arm for reaching things (P6, P8, P10). However, here, we focused on two features that almost all of our participants wanted: storage space and phone interactivity.

4.4.1 Helping carry items. Most participants expressed wanting a mobility aid that could help carry things, with many having experimented with different ways of doing so already. For example, P9 got a cup holder for their crutches and wheelchair: *"I originally had it when I switched to forearm crutches because... with crutches, you don't have a hand to hold a drink... [The cup holder has] a clamp on one side, and then the cup holder is on an axle so it can be at whatever angle and still remain upright."* Participants with smaller mobility aids (e.g., hiking poles and canes) also described some other items they wanted to have readily accessible on their mobility aids, such as fidget toys and keys. These participants were careful not to add anything too heavy because they felt it would throw off the weight distribution of the mobility aid too much and/or make it too heavy to carry easily. On the other hand, most participants with larger mobility aids (e.g., walker, rollator, wheelchair) were less concerned with adding more weight and looked into bulkier storage options such as backpacks and fanny packs to carry various everyday items, spare mobility aids (e.g., a backup cane), and mobility aid repair tools (e.g., Allen wrenches to tighten loose bolts).

4.4.2 Helping with phone interactions. Most participants reported difficulties using their phones when moving around because at least one hand was occupied with using their mobility aid. Thus, many participants wished for a method to interact with their phones via their mobility aids. P13 uses a cane and they described some of these difficulties: *"It's really inconvenient... I have to walk to the side and stop completely to respond to a message. I often don't even listen to music while walking, just cause it's like, if I don't like the song, I just have to listen to it."* Several participants also described similar issues with needing to use navigation apps, and many of them tried brainstorming solutions, such as P11 thinking out loud, *"I suppose I could if I use headphones [to use audio navigation], but I prefer to look at the map and actually be able to see it... and if I add an attachment [to prop up] onto my crutches, it makes them heavier."* We also discussed potential solutions, such as using a smartwatch, but several participants explained that watches can also be difficult to look at when using a mobility aid for similar reasons, and/or they prefer not to wear a watch.

4.5 Community Involvement

Although not directly related to the physical design of mobility aids, one of the biggest factors of success in using a mobility aid for our participants was their involvement in a community with other mobility aid users. These communities allowed our participants to feel more empowered with using their mobility aids, helped them learn useful strategies for using them in everyday scenarios, and provided them with a strong support group of people they knew they could rely on for help.

4.5.1 Promoting disability pride. For some participants, strong community participation helped to counter social stigma and support disability pride. For instance, P12 mentioned that they didn't feel a lot of social stigma *"thanks to the ambient support from my community."* Similarly, P15 described, *"I initially joined a disability pride group being like, 'I'm going to support other disabled people. I'm not like them' and then was like, 'Oh... No, I am.' And so I learned a lot more about disability pride and like disability as a culture and not a diagnosis. And through that, I got more comfortable with the idea of using mobility aids more than what I absolutely needed to."*

Disability pride was common in our younger participants. These participants described how this pride grew from using their mobility aids at school, where there was a rich community of other students with disabilities who supported each other. For example, P14 is in their mid-20s and highlighted how this attitude is different from what they have seen in older demographics: *"I know a lot of the elderly population in wheelchairs use the term wheelchair-bound still, which is vastly disregarded by the younger set of wheelchair users... I would never say that about myself. Like, my wheelchair is a tool for freedom."* This attitude difference was also reflected in our participants. In contrast, P8, who is in his 40s and became disabled later in life, is not involved in any disability-related communities. He emotionally stated, *"to me personally, it's like... If I can [move] without [my cane], then I'll do it. And, it's like... No pun intended. It's like a crutch, right? I know it's a cane, not a crutch, but it's like, you know: Can you do a little extra effort? Do without it... It's like it's holding me back. Or maybe there's some shame involved in that... It's just like it's not really cool; it's not really fun. I don't like being put in that camp [of being disabled]."* P8 and P14's stories reinforce how varied disability identities can be. This may need to be reflected in design guidelines, such as how to approach aesthetics. P8 may prefer more discreet mobility aesthetics, while someone like P14 may prefer more vibrant, individualized designs.

Community also plays a significant support role in modifying mobility aid aesthetics to promote disability pride. Several participants mentioned attending or helping host decoration events for people in their community to come together and decorate their mobility aids. P3 mentioned, *"I work with a disability-related nonprofit, and I hosted [a] mobility and assistive technology decoration day, and I got a bunch of stickers for other people to [decorate their mobility aids]."* P7 mentioned, *"there's a club on campus that'll host a decoration for mobility aids event."*

4.5.2 Supporting each other with knowledge and resources. Participants also highlighted how knowledge sharing is another significant aspect of their disability communities. P9 described this in their community: *"People will be like, 'Hey, I've been having this problem, has anyone else experienced this problem, how do you solve it?' and like discussions and such evolve from there. And sometimes you are the one being like, 'Oh, I tried this thing, and this is what works for me!' And sometimes you're the one being like, 'Oh, wow, that's a cool*

suggestion, I'm gonna try that!"' These communities also relayed different tips and tricks that may be relevant to the local area, such as what type of paths are best. For example, P11 mentioned how even though reports *"say that the snow routes are clear and that the accessible routes have been shoveled, they've only been shoveled the width of someone who stands without any mobility aids"* and so participants rely on word-of-mouth to identify viable paths.

Sharing mobility aids within communities is another common practice. Many participants said that the mobility aid they used came from friends and family who had started using different mobility aids and thus had an extra lying around for them to use. P14 exclaimed, *"We trade mobility aids all the time! Like, yeah... [redacted] has my old cane, you have [redacted]'s old wheelchair. Like yeah... It's a thing. It's really common because the disability community is really big on mutual aid. Oh, I don't need this right now. You can have it!"* P12 highlighted the need for sharing mobility aids when they described how, when they first tried to find a mobility aid, they *"had so many problems having to try to make decisions without experience,"* which led them to create a loan closet and testing program where *"people can try different models of things, especially forearm crutches to see what they want because there's a lot of things on the market and it's just not accessible to everyone."*

People would also provide physical support for one another by handling the tasks that they are good at for the rest of the community. P11 described how they have an engineering student friend who helps with repairs because they *"run into physical barriers with making [their] own things."* Another example is how when P1's scooter breaks down, he calls friends who also have scooters to help out because they have vehicles that can fit it. P1 explained how he used to carry around a cane as a secondary mobility aid to help if his scooter broke down, but now he solely relies on his friends for backup support.

For many participants, community members also substituted the role of healthcare professionals by teaching each other how to choose and use mobility aids properly. For example, P11 described, *"I don't have like a doctor that's helping me or a PT. In some ways, I think that's interesting and nice because I can talk to my disabled community who have a lot of experience using canes and know why I would want certain things."* Many participants did not go to a healthcare professional about their needs for a variety of reasons, including not having insurance, not having a formal diagnosis, not trusting healthcare professionals, and/or having a hard time finding one that will support their needs. For example, P15 described how they could not find a suitable occupational therapist because *"There's this awkward like 18 to 25-year-old range, where no like adult [occupational] therapists want to really work with you, and no pediatric therapists want to work with you. And like, they just don't really understand college dynamics."*

5 Prototype Designs

From the first phase of our user study, we learned that participants wanted their mobility aids to have improved aesthetics, be customizable and reconfigurable, and be multifunctional. Additionally, we saw the important role of community in this mobility aid adoption and usage. However, there were still several gaps in our data, such as ambiguity on which features should be customizable (e.g., weight, sturdiness, ergonomics) and how to attach/detach different parts from the mobility aid to enable easy reconfigurability.

Figure 2: Parts of the modular cane, including four different types of cane tips and four handle shapes. The handles were fabricated with multiple types of materials and fabrication approaches (i.e., resin casting, thermoplastics 3D printing, and resin 3D printing)

In the second phase of our user study, we sought to address design gaps to develop a better understanding of what a participant's ideal mobility aid would look like. To do this, we developed low-fidelity prototypes to better interact with participants and fully explore the design space through tactile experimentation. As described in Section 3.3, this experimentation took place in person during a prototyping session where participants tested commercially available aids, experimented with our designed prototypes, and designed their ideal mobility aid using the available materials.

This phase of the study does not directly address community; however, our findings highlight how some of our designs could support community initiatives such as supporting sharing and swapping. The remainder of this section describes these prototypes and provides details on what we asked participants about for each prototype. The instructions for recreating some of our prototypes can be found on our GitHub repository.[5] The results from this phase of the study are presented in Section 6.

5.1 Modular Cane

Most participants wanted greater customizability (Section 4.2) and reconfigurability (Section 4.3) in their mobility aids, citing difficulties finding a suitable mobility aid that has the suitable combination of parameters (e.g., handle shape/texture, type of tip) and wanting a mobility aid that could be adapted to different frequented environments. (Section 4.2.1). To help facilitate this, we created a modular cane using four types of 3D-printed swappable handles, commercially available tips that attach through a friction fit to a PVC pipe (and later aluminum to support more weight), and extensions to adjust its height (Figure 2). For the handles, we created two 3D printable versions of popularly available handle styles (Fritz and Tourist handles), and we remixed two unique handle shapes from online repositories[6] to fit on the same sized base and be the same height when fitted onto a cane. We chose to focus on a cane because

[5] github.com/make4all/Mobility-Aid-Improvements
[6] thingiverse.com/thing:2951701, myminifactory.com/object/3d-print-150346

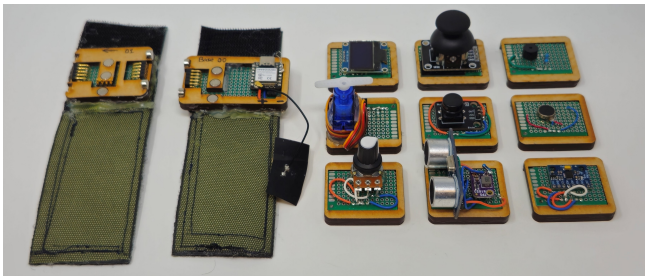

Figure 3: Hot-swappable smart modules design. On the left are the bases that hold the smart modules. The bases contain the battery and the Bluetooth module. On the right are the different modules, including a button, OLED display, joystick, and more. The modules are snapped onto the bases with magnets to facilitate easy swaps between modules. The bases are attached to a mobility aid through velcro straps.

all of our participants were familiar with using a cane, and from our virtual interview findings, we felt many modifications (e.g., handle/tip customization) translate well to other types of basic mobility aids like forearm crutches and walkers. During the study, we had participants identify their ideal handle and tip by trialing them while explaining why they chose one component over another.

5.2 Hot-Swappable Physical Interface Modules

Most participants wanted their mobility aid to help with other functions besides mobility. We focused on helping with phone interactions, such as GPS navigation or texting, because participants highly requested it and did not have satisfactory personal strategies for mitigating the issue of needing to stop moving first to use their phone when using their own mobility aids (Section 4.4). To support phone interactivity and also investigate other potential functional features users may want, we developed different physical interface modules, including an OLED display, joystick, servo motor, knob, button, vibration motor, IMU, ultrasonic distance sensor, and buzzer (Figure 3). These modules can be placed into a main housing unit with a microcontroller, Bluetooth module, and battery. Modules could also be used in secondary housing units connected to the main unit with a cable if participants wanted to place two modules far apart. The modules were made hot-swappable using magnets and spring-loaded connector pins to connect to the housing units to allow users to quickly experiment with different configurations. We also made a graphical user interface on a web app to allow participants to control the modules (e.g., change text on the OLED display) and see their output (e.g., distance reported from the ultrasonic distance sensor). During the study, we introduced participants to the system, described what each module did, and had users try each module out. We informed users that although the modules were currently connected to our computer, the modules could potentially be connected to a wide variety of devices such as cell phones, wheelchair control systems, and smart home systems. We encouraged participants to think aloud about potential use, how the modules were helpful or unhelpful, and suggest other types of modules they may want to explore.

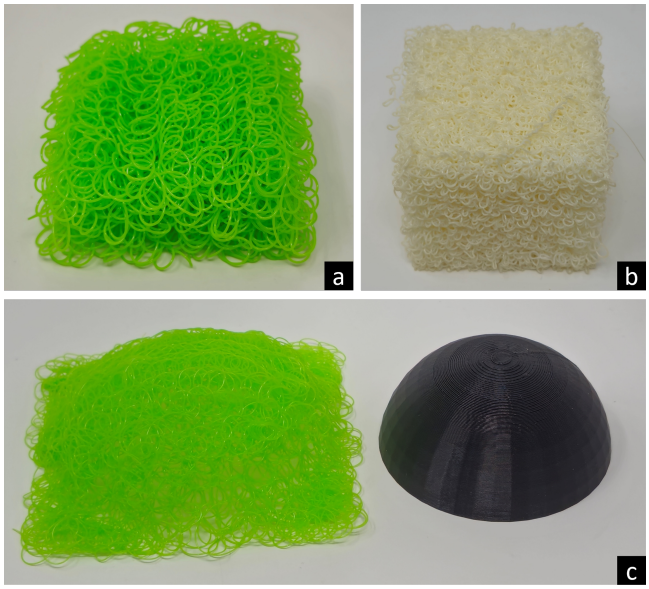

Figure 4: 3D printed foam created using the viscous thread printing technique [35] to modify the handle/grip of mobility aids. (a) Shows a medium stiffness foam, (b) shows a high stiffness foam, and (c) shows an example of the foam printed on top of a dome as a demonstration of how we could likely also print on top of mobility aid features (e.g., handle).

5.3 3D-Printed Foam to Augment Handles

Several participants wanted to customize or augment their mobility aid handles to be more comfortable and ergonomic, with some participants pursuing DIY modifications such as adding grip tape or using pool noodles to increase the width of the handle that helped but did not fully meet their needs (Section 4.2.2). To address participants' desire to create more dynamic and expressive modifications for ergonomics and comfort, we proposed using a novel 3D-printing technique called viscous thread printing (VTP) [35] to create a foam-like material to augment existing handles (Figure 4). During the study, we asked participants to try a handle augmented with foam and provide feedback on parameters such as comfort, perceived durability, texture, and ease of maintenance. After receiving feedback, we brainstormed with participants on different ways of addressing any limitations or if a different potential approach for adding soft padding to handles would be ideal.

5.4 Laser Cut Decorative Sleeves

Almost all participants expressed that aesthetics was a high priority; however, aesthetic mobility aids are often heavy, old-fashioned, and/or difficult to personalize (Section 4.1). Many participants explicitly mentioned they wanted a wooden cane because they are not as heavily associated with being a mobility aid. While brainstorming a solution with participants, we proposed using laser cut decorative sleeves to create a wooden aesthetic to existing mobility aids by creating a kerf pattern in a thin sheet of wood that would allow it to wrap around the body of a mobility aid and have additional designs rasterized on them to support additional personalization

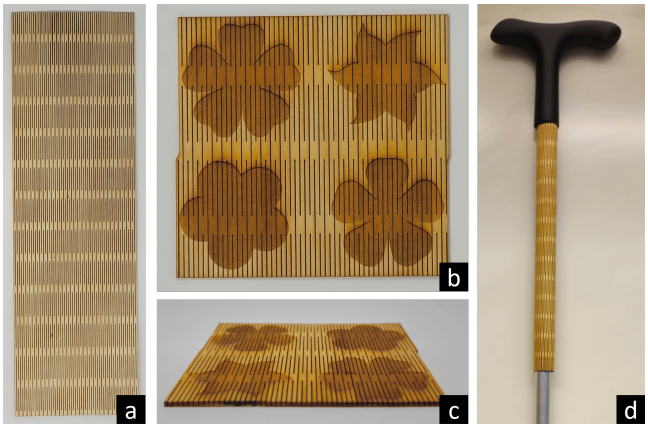

Figure 5: (a) A laser cut kerf pattern. (b) Flowers raster engraved on the kerf pattern to show how raster engraved designs look in contrast with the kerf lines. (c) A side view of the raster engraved design. (d) A laser cut kerf pattern wrapped around a cane to provide a unique aesthetic.

(Figure 5). During the study, we asked participants to provide feedback on aesthetics, perceived durability, and any other parameters participants felt were important for the prototype.

6 In-Person Session Findings

In this section, we describe how each of our prototypes contributes to refining our design guidelines for improving mobility aids and highlight the features that participants wanted that were most surprising to us and/or are not explicitly available in commercially available mobility aids. **We merged these findings with the first phase of our co-design study and compiled them into Table 4**, presenting a comprehensive list of considerations participants had for selecting a mobility aid and their modifications, such as portability, grip design, and weight. While many of our prototypes draw upon elements of multiple themes, we frame our findings on the main themes that each prototype was created to address.

6.1 Design Improvements for Customizability and Reconfigurability

We explore the dimensions of customizability and reconfigurability with our modular cane and 3D-printed elastic foam. We also had various art supplies available, such as Play-Doh and Wikki Stix. Through these tools, participants were able to customize and constantly reconfigure 1) the cane height, 2) the shape of the tip, and 3) the shape, stiffness, texture, tackiness, and weight of the handle.

6.1.1 Trying out options. Participants felt that the ability to try out multiple options had several benefits during the early phases of mobility device acquisition. For example, after seeing our modular cane, P15 exclaimed how it would be a *"great tool for [occupational and physical] therapists!"* As an occupational therapist themselves (and a cane user), P15 described how they have a closet for canes for patients to try out at her workplace to help them find a suitable mobility aid. However, one of the major limitations of the closet is that when you open the door, *"[the canes] all come flying out at you! [The modular cane] would be a huge spacing solution. That's an unmet need right there!"*

Participants were also excited about the modular cane's potential in community settings, where mobility aid sharing and swapping are common. P11 mentioned it could save time and resources *"if everyone has their own little pole, and we can all just trade tips and handles around until the configuration is correct. That's perfect!"*

Through using the modular cane, all participants, except one, discovered a mobility aid configuration they preferred over their current aid after trying various options and configurations of our modular cane, showcasing why a customizable, reconfigurable cane was so powerful. While trying out different configurations, participants noted that many of their initial expectations were incorrect when trying to determine if something would work based on appearance alone. For instance, P11 initially thought quad tips were unsuitable because they looked heavy and bulky, but later remarked, *"I really do like this tip. It is nice."* Most of our participants highlighted the usefulness of the reconfigurable design in isolating feature changes in contrast to how multiple features might change simultaneously when testing mobility aids in a store.

Participants also wanted to be able to explore more variations of the same type of handle, such as adjusting the handle width to better fit their hand, modifying the texture of the material, and altering the grip to better fit how they hold the cane. It was easiest to explore handle modifications using soft materials, such as 3D-printed TPU foam, to change a base shape of interest (Figure 4). Foams could also modify the stiffness and tackiness of the handle.

6.1.2 Responding to changing context. Having multiple handles and tips was well-received because several participants used different mobility aids for various situations. P14 explained, *"you can't buy like 10 different canes for each situation, so having interchangeable tips and handles would be really helpful"*. Participants suggested different mechanisms for swapping tips and handles to accommodate various capabilities and preferences. Ideas included screw-on handles with locking mechanisms, a "flick-lock" mechanism often used in hiking poles, and a heavier-duty locking mechanism using nuts and bolts for those who regularly carry tools like hex keys.

6.2 Design Improvements for Multifunctionality

Participants tried out our hot-swappable electronic modules and were satisfied with the selection of modules. Some examples of user-created configurations are in Figure 6. The OLED display, vibration motor, joystick, and button were the most popular modules. Some participants expressed a desire for smaller form factor modules, such as a trackpoint module instead of a full-sized joystick.

6.2.1 Software customizability and reconfigurability. Participants wanted to be able to customize the modules to do a variety of different applications (see Table 3). Due to the limited space on most mobility aids (e.g., canes, forearm crutches, hiking poles), participants preferred a single, conveniently located module near their grip to be customized to perform multiple functions. They suggested adding a separate toggle, potentially positioned less conveniently, to reconfigure the modules and switch between modalities.

Table 3: Applications brainstormed with participants for various physical interface modules

Module	Applications Brainstormed with Participants
OLED Display	Read text messages, list navigation information from an app, show miniature phone screen
Vibration motor	Get alerts from phone, provide haptic feedback for navigation directions
Servo motor	Point in physical directions for GPS navigation
Buzzer	Give loud, audible warning if someone gets close in a blind spot; alert users to notifications
Button	Press to use accessibility shortcuts on phone or activate its voice assistance
Joystick	Move a pointer to navigate on phone or a mirrored phone
Rotary encoder	Turn up volume for music on phone/music player, adjust function mode for other interfaces
IMU	Exercise tracking
Ultrasonic distance sensor	Detect obstacles or if someone gets too close

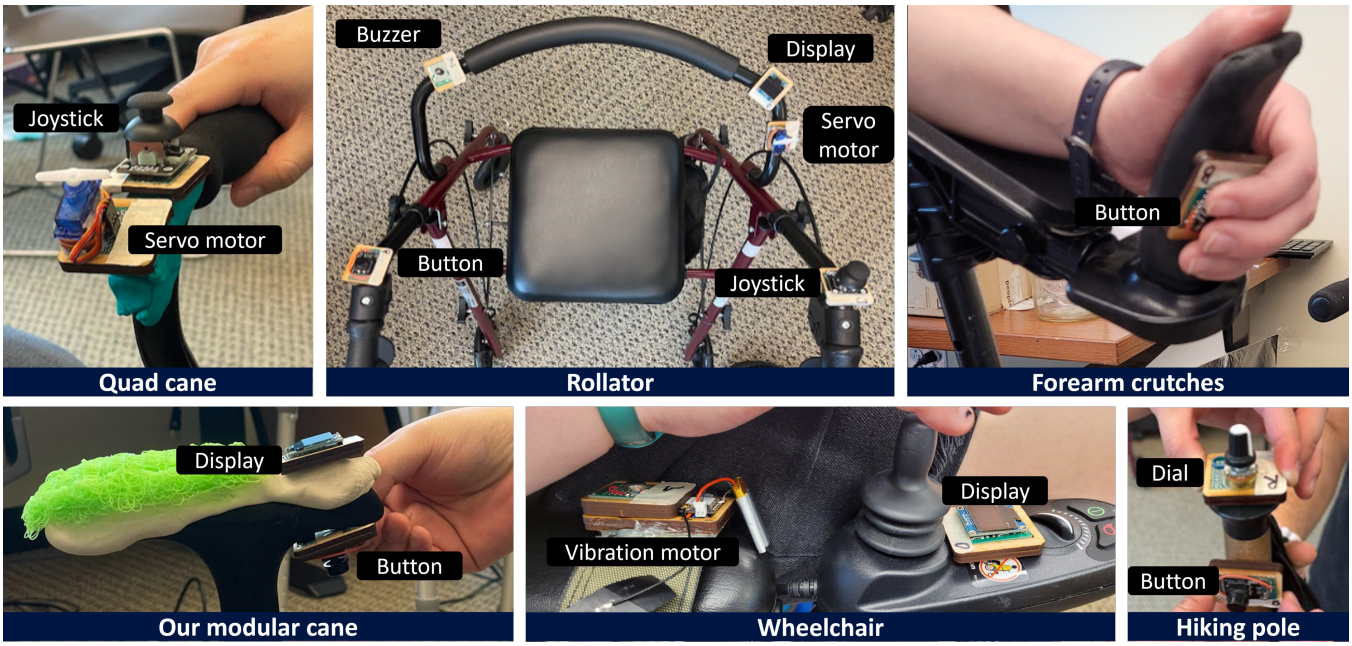

Figure 6: Participant-created examples of different configurations of the physical interfaces on a variety of mobility aids, including a quad cane, rollator, forearm crutch, single-point cane, wheelchair, and hiking pole.

6.2.2 Balancing integration and physical reconfigurability. Participants wanted to integrate the modules seamlessly into their mobility aids, such as having a custom cane handle with an indentation for the modules or having modules placed inside their mobility aid (e.g., the vibration motor inserted in the armrest of a wheelchair). However, participants still wanted to be able to reconfigure where modules went and move modules between mobility aids to prevent needing to buy and maintain multiple sets of modules. Participants also wanted reconfigurability support to ensure the easy repair or replacement of modules if anything broke. This meant that multifunctional mobility aids not designed for reconfigurability were not a preferred option.

6.3 Design Improvements for Aesthetics

Participants gave very positive feedback about the wooden decorative sleeve we created, with most participants thinking it *"was really cool"* and that they would use it, especially if there was a custom pattern engraved on it.

We asked participants to compare the decorative sleeve with other decorations they explored for their mobility aids. Most participants liked *"the look of the wood better [than fabric covers]"* (P10). They appreciated the durability and weather resistance that treated wood (e.g., the wood sheets we used with varnish applied) could offer compared to other decorative materials they have used, such as tape, stickers, and fabrics (P11, P14). Additionally, they enjoyed how the sleeve provided a wooden aesthetic without the drawback of added weight. P15 also suggested exploring using other materials, like plastics or carbon fiber, to create decorative sleeves (e.g., using 3D printing) since not everyone may want a wooden aesthetic.

Participants also liked how this decoration approach supported reconfigurability by allowing them to change out aesthetics easily. P10 said, *"I would either want a few of them that I can trade off or just get one that I would use all the time."*

6.4 Physical Features Participants Considered

Through experimenting with our prototypes, participants were able to articulate different preferences and considerations they have for choosing mobility aids. **We detail all the features participants considered in Table 4.** These features were gathered across all of the types of mobility aids participants used. In this section, we want to specifically call out two physical features that we think existing mobility aids do not consider sufficiently.

Proprioception refers to participants' awareness of their hand and body position relative to their mobility aid and surroundings. Participants noted that for canes, certain handles lacked a marker indicating the center pole's position by the hand, making proprioception challenging. This often resulted in accidental bumps or uncertainty about when the cane would contact the ground. We highlight this issue because we believe there is potential for handles to support better proprioception, such as by adding a tactile bump on the handle marking the center.

Grip location refers to the position or positions where you are intended to hold a mobility aid. Participants expressed a strong preference for grips that allowed for multiple hand positions to prevent discomfort from prolonged use in a single position, for example, having a rotatable grip to reduce strain on the wrist when using a walker or rollator. Another example is having an alternate gripping location on the cane pole, similar to a hiking pole, to assist with standing up. Several participants also mentioned how they like the grip position on hiking poles more than the grip position on most canes because it's more comforting on the wrist. When asked why they preferred a cane with this type of handle over a hiking pole, participants explained that canes offered a greater variety of tips for everyday use and better signaled to others that they had a disability and required accommodations. We felt this was important because it helps highlight how current mobility aids do not offer significant support for people who have fluctuating abilities and may occasionally want to use one grip when feeling stronger and a different grip when more fatigued.

7 Discussion

In this work, we conducted a two-phase study with participants. In our first session, we developed an understanding of mobility aid users' needs and collaboratively brainstormed solutions that built upon existing community-led strategies. We then invited all local participants back for an in-person session to modify mobility aids with low-fidelity prototype tools we gathered and created based on their feedback of wanting a mobility aid that was more aesthetically pleasing, customizable, reconfigurable, and multifunctional.

7.1 Development Led by the Disability Community

Although there is useful work on how medical professionals can make assistive technology more personalized to the end user [39], we echo Hamraie and Fritsch's Crip Technoscience Manifesto that calls for a **shift towards innovations that are instead led by or created with disabled people** [17]. Crip Technoscience challenges the mainstream view that disabled people are purely clients or users while non-disabled designers and engineers are the "solution experts" and argues that instead, we should recognize disabled people as experts with a wealth of experiential knowledge and designers who iterate on solutions to make their world more accessible on a daily basis. This stands in contrast to most existing mobility aid research (e.g., [1, 62]). Our study demonstrates participants' expertise as expressed in their practices: Almost all of our participants created one or more modifications to their mobility aids, from adapting accessories intended for other devices (e.g., bikes, strollers, scooters) to designing personalized modifications using fabrication equipment (e.g., Cricut, embroidery machine).

7.2 Improving Mobility Aids for Young Adults

Our study revealed many similarities between our participants' attitudes and behaviors and those found in existing literature on older adults, such as a common desire for diverse aesthetic options. However, our findings diverge from prior work on notable fronts:

7.2.1 Supporting fluctuating physical needs. A majority of the participants we interviewed had needs that greatly fluctuated, with participants often switching between using several types of mobility aids (e.g., cane, rollator, wheelchair) in a day. The need to support a range of needs caused participants to select mobility aids that are easier to carry with them, along with modifications that are easily swapped around.

7.2.2 Supporting a wide variety of physical activities. Our participants used mobility aids when going on hikes, tide-pooling, ice fishing, and more. This often caused their mobility aids to wear down quickly, affecting both aesthetics and functionality: decorations got damaged and tips/wheels of mobility aids needed to be replaced frequently. Thus, participants valued having parts and decorations that were more easily repaired/swappable. Furthermore, in our design exercise, participants expressed a need for form factors that could be adjusted, such as handles/grips, to reduce putting as much stress on their wrists/hands during long physical activities.

7.2.3 Supporting phone interaction. Being able to interact with their phone while using their mobility aid was something that almost all participants desired. However, this need was more prominent among younger participants who used smartphones and traveled longer distances using their mobility aid, particularly university students traveling around a large campus.

7.3 Reflection on Prototyping Using Personal Fabrication for Mobility Aids

The use of personal fabrication in this study allowed for efficient exploration of design features and modifications for mobility aids. For instance, slight variations in objects were easily created by altering materials for 3D printing or laser cutting and adding surface textures to CAD models. The rapid prototyping process also enabled real-time demonstrations during co-design sessions, such as fabricating a rasterized laser cut kerf pattern in under 10 minutes.

The ability to produce and test a large number of prototypes provided valuable insights. The second in-person follow-up study revealed significant discrepancies between participants' virtual interview expectations and their actual experiences with prototypes. Additionally, several parameters, such as proprioception, were only identified during physical testing. Testing each parameter independently reduced confusion and yielded richer, more accurate data.

Table 4: Features participants described as being important to their selection of mobility aids and their modifications.

Feature	Preferences participants mentioned
Aesthetics	Simple, sleek, modern, vibrant, eye-catching, "signaling" for disability accommodations
Cleanliness	Easy to clean, ideally just by wiping; does not trap grime and outside dirt or debris
Durability	High durability, but need to balance tradeoffs between durability and weight
Grip firmness	Soft, medium stiffness, firm
Grip location	Body/shaft, top of mobility aid, having multiple locations, adjustable
Grip tackiness	No tackiness, just enough to prevent grip from slipping
Handle shape	Reduce strain on hand, wrist, arm, and/or shoulder; help proprioception
Material	Aluminum, acrylic, carbon fiber, plastic, wood
Noise	No noise, but need to balance tradeoffs with portability (foldable mobility aids rattle more)
Portability/stowability	High portability, but need to balance tradeoffs with sturdiness, weight, noise, durability
Proprioception support	Ambivalent, need to have
Repairability	Ambivalent, nice to have, need to have
Temperature conductivity	Low conductivity (more resistant to extreme temperatures), high conductivity (cooling self down)
Texture	Smooth (for more pleasant sensation), rough (for better grip)
Tip shape / wheel shape	Balance between larger designs for stability versus smaller designs for more maneuverability
Vibration absorption	High absorption
Weather resistance	Resistance for rain, wind, snow, and extreme temperatures
Weight (distribution)	Bottom-heavy, balanced, top-heavy
Weight (overall)	Light, medium weight, heavy

We believe the list of parameters in Table 4 can apply to various types of physical AT, and we encourage its use as a starting point for other design space explorations.

7.4 Limitations

Our study focused primarily on younger users but was not designed to directly explore differences across age groups. In addition, our second co-design session only included younger participants. Future work could complement ours by exploring the design of mobility aids from other perspectives, or by conducting a comparative study across age groups. Another limitation was that we did not have participants explore using the prototyped modifications in real-world scenarios, which limited the amount of feedback we could gather about certain ideas, such as the benefit of aesthetics in reducing social stigma.

8 Conclusion

In this paper, we outlined different types of opportunities for meeting the needs of mobility aid users, primarily younger adults, and existing user-driven solutions. Through a co-design study, we developed different approaches for people to modify their mobility aids using easily swappable parts, physical interface modules, and personal fabrication techniques like laser cutting and 3D printing. Our findings and approach stand in contrast to standard expectations that healthcare providers and manufacturers will always provide solutions. We emphasize community-based and user-led solutions and highlight opportunities to facilitate these approaches.

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