"Occupational Therapy is Making": Clinical Rapid Prototyping and Digital Fabrication

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ABSTRACT

Consumer-fabrication technologies potentially improve the effectiveness and adoption of assistive technology (AT) by engaging AT users in AT creation. However, little is known about the role of clinicians in this revolution. We investigate clinical AT fabrication by working as expert fabricators for clinicians over a four-month period. We observed and co-designed AT with four occupational therapists at two clinics: a free clinic for uninsured clients, and a Veteran's Affairs Hospital. We find that existing fabrication processes, particularly with respect to rapid prototyping, do not align with clinical practice and its *do-no-harm* ethos. We recommend software solutions that would integrate into client care by: amplifying clinicians' expertise, revealing appropriate fabrication opportunities, and supporting adaptable fabrication.

KEYWORDS

3D printing; Adaptive Design; Digital Fabrication; Occupational Therapy; Rapid Prototyping

CHI 2019, May 4–9, 2019, Glasgow, Scotland UK

ACM ISBN 978-1-4503-5970-2/19/05…$15.00
https://doi.org/10.1145/3290605.3300544

ACM Reference Format:
Megan Hofmann, Kristin Williams, Toni Kaplan, Stephanie Valencia, Gabriella Hann, Scott E. Hudson, Jennifer Mankoff, and Patrick Carrington. 2019. "Occupational Therapy is Making": Clinical Rapid Prototyping and Digital Fabrication. In *CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019), May 4–9, 2019, Glasgow, Scotland UK*. ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3290605.3300544

1 INTRODUCTION

With digital fabrication, more people are creating assistive technology (AT) for themselves and others, which has led to research focused on Do-It-Yourself (DIY) and Do-For-Others (DFO) AT. The DIY/DFO-AT philosophy potentially inreases AT adoption by meeting highly individualized needs and directly engaging AT users in At deisgn [15, 31, 35].

However, DIY/ DFO-AT research often excludes clinicians. The consequences of this may include safety, quality, and even funding availability [30, 32, 42]. Additionally, DIY/DFO-AT is only accessible to a small set of people who can access the appropriate technologies; it excludes people who primarily access AT through clinicians. People may prefer a clinical model because they do not identify as disabled, because the AT treats a medical condition that requires clinical expertise, or they do not have the necessary technical expertise.

For people who primarily access AT through clinicians, custom-fabricated AT may only be accessible if clinicians can use digital fabrication. However, little is known about how this technology influences clinical practice, or the challenges clinicians might face in adopting them. We contribute insights about how digital fabrication might influence and be influenced by clinical practice. Further, we explore the role of clinical Computer Aided Design (CAD) tools.

The CAD tools used in clinical contexts must be usable by clinicians. In low-resource clinics, clinicians may be the only person capable of creating AT. Even when clinicians have access to fabrication and fabrication experts, it is critical that clinicians can directly interface with appropriate CAD tools that leverage their expertise and allow them to fully participate in co-design.

We present two case studies of AT-design with occupational therapists (OTs). Over four months, in two clinics, we provided fabrication expertise while the OTs managed their clients' treatment. The first clinic was free to uninsured clients and we worked with two OTs to develop a 3D printed thumb splint. The second site was a Veteran's Affairs (VA) clinic where we worked with two OTs to develop a knife grip and wheelchair transfer board.

We found that the OTs embed digital fabrication into their usual client-care process which is at odds with the rapid-prototyping characteristic of maker-communities [12, 50]. They base their designs on standard classes of AT (splints, grips, transfer-boards) and clinical expertise, rather than inventing new AT. If necessary they begrudgingly iterate on prototypes, but prefer to do so only if it results in a design that can be reused across many clients. They would rather adapt and customize a design within a client's appointment, using adaptive materials rather than digital iterations.

We also found a disparity between our sites based on their resources. The limited resources at the free clinic encouraged the OTs to adopt a maker ethos; they were excited to use common materials in unusual ways to support their clients. Conversely, the VA OTs had many fabrication resources and wanted to push the limits of what could be created with those tools, even when this drove the design process out of their area expertise.

Based on these findings, we propose the development of Clinical CAD tools with three design goals:

(1) **Amplified Design:** Clinicians see themselves, not as AT designers, but AT prescribers, prescribing variations on existing devices like doctors prescribe medication. CAD tools can amplify clinical effort by storing and distributing common designs.
(2) **Appropriate Design:** Tools should help select the appropriate prescription based on available resources. This helps clinicians calibrate their expectations to what is doable, and may broaden their perspectives.
(3) **Adaptive Design:** Tools should support adaptive modifications of a design rather than prototyping.

We start below by reviewing related work on fabrication in clinical and AT contexts as well as a larger socio-technical context. We then cover our two design case-studies. Lastly, we discuss our observations made at the two clinics and a set of design recommendations for building clinical CAD tools.

2 RELATED WORK

DIY/DFO-AT research examines and innovates within the personalized AT-design process, rather than inventing new classes of AT. Hurst and Tobias [35] observed people who created their own custom AT. They introduced the DIY-AT framework to increase AT adoption by empowering individuals and connecting them personally to their AT. Couvreur and Goossens [21] approached DFO-AT with design methods perspectives; they view DIY/DFO-AT practices as a bridge between a universal design philosophy and the design methods used in rehabilitation engineering. Unlike Hurst and Tobias, Couvreur and Goossens explicitly include clinicians as DFO-AT stakeholders with the primary goal of innovating the classes of AT clinicians distribute. Hurst and Tobias focused on personal adaptation as a means to reduce abandonment. Both revealed the potential for DIY/DFO-AT to transform AT production, but neither observed clinical practices and it remains unclear how tools can support clinicians.

The State of DIY/DFO-AT

Researchers studied DIY/DFO-AT online resources [12, 19] and communities [50], and AT creation by users [9, 26] and caregivers [33, 52, 53]. A revolution in *consumer-grade* fabrication produced novice oriented design tools for visual aids [11, 28, 56, 59], adaptive grips [14, 19], and e-textiles [26, 46]. Except [46], these tools do not target clinicians.

Tools that adapt existing solutions based on user-specific parameters can support novices. Examples include Facade [28], GripFab [13, 14], Reprise [19] and VizTouch [11]. This approach may be useful in clinical contexts, however that has only been explored in [14]. Where design solutions are unknown, low-fidelity prototyping may be of value (*e.g.,* [31, 34, 46, 59]). Prototyping is an oft-cited core value of 3D printing (*e.g.,* [6]). However, the value of prototyping in clinics is unstudied, and most prototyping innovations have not been employed to make AT (*e.g.,* [18, 20, 47, 48, 55]).

Who makes AT

Many researchers argue consumer-grade fabrication is a democratizing force that supports user agency [41, 60], but limited access to technical and educational resources [8, 10, 12, 36] prevents some AT-users from *doing-it-themselves* [34, 43]. The DIY/DFO-AT framework cannot assume that makers or volunteers (*e.g.,* [49], [45]) can support all AT-users [31].

Fabrication may increase AT access through user empowerment, but it has failed to engage clinical infrastructures. Clinicians are rarely involved in grass-roots efforts [30]. However, digital fabrication is not absent from clinics [25, 38]. Its primary clinical use is to create models of medical imaging data [54] or, more relevantly, to produce prosthetics and orthotics [16, 23, 24, 29, 57, 65].

Little research has studied how clinicians fabricate AT. It is generally believed that the benefits of digital fabrication technologies extend to the clinical setting [61], but visionary words must be accompanied by field evidence. In the few existing studies, clinicians believe in the potential of digital fabrication technology[13, 42] but existing tools fall short.

For example, McDonald *et al.* had physical therapy students create 3D printed AT in a classroom workshop. They found that clinicians adapted standard classes of AT and revealed a tension between potential benefits of digital fabrication and concerns about its adoption in clinical practice. However, they provide few insights into how this AT design process will involve real client-clinician interactions.

In contrast, Buehler *et al.* co-designed customized grips with occupational therapists in a special education setting [13]. They proposed easy to use tools that support AT customization and they developed, deployed at the school, and studied a tool for 3D printed grips [14]. The focus of this work was on the creation of AT in an educational setting. The occupational therapists who participated in the study focused on their role of facilitating education. It is unclear if these results would be reproduced in general clinical settings.

Unfortunately, because of the many challenges of researching client-clinician interactions [39], little work has built on these examples. Many open questions remain about how digital fabrication technology fits into clinical practice.

3 METHODS

We co-designed AT with OTs for their clients to understand the benefits and limitations of consumer-grade fabrication technologies in a clinical context. Our methods are informed by participant observation [37], co-design [21], and research through design [62, 63]. We most closely follow the methodology used by Buehler *et al.* who deployed3D printing in a special education context [13]. Like Buehler *et al.*, we note that 3D printing as a clinical practice is too rare to study, and tools specialized to clinical fabrication practices do not exist. Instead, we propose a *preferable future* [62] where clinicians and clients can co-design AT. From there we *intervene* [7] in the clinical context; as researcher and digital fabrication experts, we served the clinicians as a proxy for clinical-CAD tools. We evaluate this interaction [58], studying the relationship between CAD tools and clinicians.

Over four months of clinic visits we: (1) directly observed the clinics' day to day operations—including, at times, direct observation of the clinician working with the client—to get a sense of the clinical context; (2) conducted semi-structured interviews with each clinician to understand their decision-making process and the clinics' operating contexts; and (3) consulted with the clinician teams to digitally fabricate solutions with the potential of addressing their clients' needs.

Table 1 – OT Participant Demographics

Site	Pseudonym	Position	Client
Free Clinic	Julie	Instructor	Ron
	Sara	Student	
VA	Lorelai	Practitioner	Jon
	Anna	Resident	

We encouraged the OTs to perform as much of the design activities as they could and only use researchers to support fabrication. We supplied the fabrication resources (*e.g.*, 3D modeling software, 3D printers, printer filaments, carbon fiber) that each site could feasibly access and afford. These case studies were contemporaneous and actions in one case study may have impacted our design activities in the other.

These methods were approved by a full board IRB.

Participants

We recruited OTs through word of mouth and had no pre-existing relationships prior to the study. Although we did not require it, all of the OTs had prior 3D printing experience. None had used it with a client. First, we met Julie at a free clinic for uninsured clients. She instructs occupational therapy at the nearby university and mentors Sara, a student who volunteers at the clinic. Next, we met Lorelai. She is the head OT in a VA clinic and supervises the OT residents there. Anna is the resident who works most closely with Jon.

The clinicians selected which client to work with, ensuring that we did not fabricate clinically-inappropriate solutions. The clients were bystanders to the study; only the OTs are participants. We did not analyze and will not reflect on client quotes as this may violate the OTs' HIPAA responsibilities.

Site 1: The Free Clinic

Julie wryly summarized the free clinic's limited resources:

> *"It's silly . . . we don't have. . . a splinting tray, so I've just been using a coffee pot"*

Julie and Sara avoid prescribing expensive procedures or AT, preferring free pain reduction exercises. Julie recalled:

> *"He couldn't afford a surgery so we gave him [exercises] to adapt."*

When Julie prescribes AT, it is usually an over-the-counter hand/wrist splint. Julie donates her personal supply of these splints to clients who cannot afford them at her own expense.

> *"It was $20 so whatever. . . I like making his life so much better."* (Julie)

We were concerned that this low-resource clinic could not afford 3D printers, but, Julie classifies printers as a medical tool for the clinic to use and pay for. In contrast, AT benefits only one client; it is the client's financial responsibility.

We observed and participated in six clinic days to design Ron's splint. Julie and Sara did the majority of the design work (*i.e.* sketching, thermoforming); researchers translated the sketches into 3D models and printed them.

Site 2: The VA Clinic

The VA has many fabrication resources such as a VA rapid prototyping laboratory in another state. Lorelai joined the study to learn more about fabrication so she can create AT locally before sending out requests. She was unaware of the facility's capabilities and relied on local experts to guide her through AT design that used these resources.

> *"If you can make it, we can probably make it too. I just send it off. . . and they will build it. . . The only problem is time. . . it may take them months to turn it around."* (Lorelai)

The main limitation of these resources is their slow turnaround time. Lorelai described sending a wheelchair component to a VA facility and waiting four months to receive a solution. The slow turnaround time and lack of interfacing with the client meant that the device was no longer relevant when it arrived and the resources were wasted.

> *"By the time I got it back. . . the client needed something else. . . And it didn't even fit him, so what was the point?"* (Lorelai)

We visited the clinic four times but never met Jon due to VA policies. Our second visit took place during one of Jon's appointments and we met with the OTs in a separate room. Lorelai asked Jon questions and shared artifacts with us, running between each room. She viewed us as a stand in for the engineers at the rapid prototyping facility, so we conducted more of the design and fabrication activities than we did at the free clinic. Lorelai provided design specifications and sketches but we determined the fabrication methods, produced 3D models, and fabricated each design.

4 DATA AND ANALYSIS

We collected twelve hours of interview/design session audio data which we transcribed and segmented into sentences. Notes and memos were related to audio data with a smart pen. We took photographs and created design artifacts.

Using thematic analysis [44], two coders developed 268 bottom-up codes then a third coder synthesized 27 axial codes. We collectively reviewed the artifacts, researcher notes/memos, and axial codes to develop themes. Several of our themes are dependent on a particular site's resources and clients. For instance, the lack of resources forced OTs at the free clinic to adopt a maker-ethos while the abundance of resources at the VA clinic encouraged them to push the limits of consumer-grade digital fabrication. As a result, we describe themes in the context of the most relevant case.

5 RESULTS

In this section, we present the themes through study narratives that derived from the design and fabrication of our three key artifacts: Ron's thumb splint, Jon's knife-grip, and Jon's transfer board. We summarize the themes as follows:

The Importance of Clinical Expertise: Clinical expertise played a role in the design of each artifact. In each case, what the OTs and researchers designed was determined by the clinicians' perspectives on traditional-AT and ergonomics. This theme was made clearest by Julie and Sara's evaluations of Ron's thumb pain over time, and their impact on the design.

Cross-Client Reuse: Julie and Sara focused on creating a splint pattern that would be reusable with other clients. This same reusability was not necessary at the VA, which had the resources to create highly customized and unique designs. For the free clinic, reusability excused the costs to a particular client, Ron, in a research context.

Maker-OT Identity: Julie highlighted the relationship between maker-culture and occupational therapy when she reflected on her practice and how it has change over the years. Because of the limited resources at the free clinic, both Julie and Sara were creative in how they made AT, in a way that they associated with a maker identity. In contrast, the VA clinic had abundant resources, so Lorelai viewed the work as engineering and rarely called out a maker ethos.

Prototyping as Failure: The OTs strongly rejected rapid prototyping (*i.e.* iteration on low fidelity versions) because of the cost to clients. Lorelai had already iterated on the knife-grip before joining this study, and saw the lasting effects of those failures on her client, destroying his preferred knives and requiring multiple clinic visits over months.

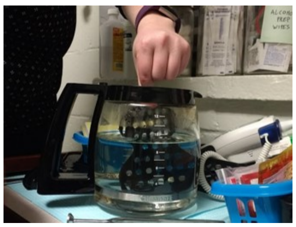
Focusing on Adaptation: Adaptable materials were effective at both clinics. We developed the splint by adaptively thermoforming the 3D printed pattern, and we coated the knife grip with a silicon coating that adjusts the fit. Adaptation brings the design process into client-clinician interactions, rather than a separate costly prototyping process.

Socio-Cultural Design Influences: Socio-cultural requirements impacted both sites. Aesthetic properties affected adoption of the splint and the transfer board had to be airport-security friendly. At the VA, the transfer board represents a primarily socio-cultural challenge which cannot be fully resolved using clinical expertise.

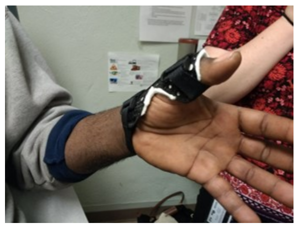
The Limits of Consumer-Grade Digital Fabrication: The VA used its vast resources to push the limits of consumer-grade fabrication. The OTs at the free clinic had few resources, so they scoped the work well within the domain of consumer 3D printing. The VA case revealed key limitations of what consumer-grade digital fabrication methods can produce and how those align with AT requirements.

(a) Ron's original over-the-counter splint

(b) Thin, brittle designs snapped when molded



(c) OTs molded splints in a coffee pot



(d) Ron's final splint which he took home

Figure 1 – These images show the progression from Ron's over-the-counter splint to the final design.

Case 1: A Customized Thumb Splint

At the free clinic, we worked with Ron, an African American man with chronic thumb pain. Julie asked us to 3D print a thermoformable splint that fit Ron's hand precisely and blended in with his black work uniform and dark skin.

The Importance of Clinical Expertise.

Julie and Sara brought in a clinical perspective that identified the causes of Ron's hand pain and applied standard solutions. Julie set the goals of the design process to balance between anatomical needs and Ron's social needs. We observed his second appointment where Julie and Sara tested his thumb's range of motion. One author noted:

> *Sara systematically wiggled his thumb, leaning from left to right and bending the joints in isolation. She constantly asked him to rate his pain. He always reported a ten.*

Ron's large hands, swollen by his condition, had stretched and ripped the one-size-fits-all splint (Figure 1a). Sara explained that he had aggravated the condition:

> *"He keeps moving his thumb. The splint is so loose! He doesn't give it time to heal."*

Julie was concerned that Ron's swelling had not improved because he would not regularly wear the splint. She hoped that an aesthetically pleasing splint would increase his prescription adherence. When Sara completed the first splint (Figure 1d), she noted that the splint was much less noticeable than the traditional alternative, remarking:

> *"I was excited because you had a black splint and I had black Velcro. It is usually white with black Velcro."*

Julie and Sara used their clinical expertise to identify the source of Ron's pain. Julie patterned the splint to target the outer thumb joint restricting movement enough to reduce damage while giving him a range of motion that supported his work activities, making it easier for him to adopt this splint. The OTs followed up with Ron after he reported wearing the splint every day for two weeks. The swelling had visibly reduced and he reported his pain at a five, compared to the prior ten.

Overall, Julie and Sara applied their clinical expertise to identify the root cause of Ron's pain and the barriers that kept him from using an over the counter solution. Balancing between Ron's medical needs (an immobilized thumb), daily living needs (moderate mobility), and socio-cultural needs (an aesthetically minimal splint) improved his condition.

Cross-Client Reusability.

We developed the final splint over two appointments, which we viewed as an unusually quick turnaround. Julie viewed it as a failure to require Ron to attend multiple appointments without receiving treatment, stating that it was the novelty of the research that kept Ron coming back.

> *"He's only coming back because he thinks you're [the researcher] cool. He wouldn't come back for just [me and Sara]"* (Julie)

However, Julie hopes to save time with future clients by reusing the 3D model. In the first design session, we asked Julie to describe what she expected of 3D printed splinting. She presented samples of 3D printed splinting patterns that she had borrowed from a colleague and instructional materials which demonstrated traditional splint patterning on fabric and Thermoplast[1]. She annotated a splint pattern with Ron's reference measurements and asked us to create a parameterized model of the splint that she could reuse like her colleague's experimental 3D printed patterns.

OTs shape splints by heating and forming Thermoplast patterns in hot water and cannot iterate on the design without creating a new pattern. The more times Thermoplast is heated and cooled the more deformed it becomes, making it difficult to use. In contrast, Sara found 3D printed PLA easier to repeatedly reshape. She complained about the difficulty of using Thermoplast and encouraged Julie to bring PLA printing into her splinting courses. She especially liked the fact that the pattern was reusable after thermoforming.

[1] Thermoplast is a thermoformable plastic for creating splints. It is malleable when heated in hot water, similar to PLA 3D printed filament

> *"I love this pattern…it lays flat in the water instead of bubbling up (deforming)…So much easier than [Thermoplast]"* (Sara)

Over the next two appointments, Sara molded the different patterns to fit Ron's hand (Figure 1c). Each pattern had a slightly different shape, but all had the same underlying problems that led to failure. The patterns were too long, digging into Ron's wrist, and were thin and brittle (Figure 1b). Sara cut-off the bottom edge with splinting scissors, which gave us the correct length for the next pattern but the edge was ragged and brittle. We made small adjustments to the 3D printed pattern and were able to fit him with an effective splint during the next session.

While prototyping the splint across appointments was not ideal, she felt that the outcome was valuable beyond Ron's care. She now knows the relevant measurements on the hand and will no longer need to consider factors such as the thickness of the pattern, or how long the splint should be relative to the wrist. All of the information we learned in this process is generalizable. She expects to reuse the splint pattern with other clients without the prototyping process from the study.

> *"Once we have the right pattern and know how to measure it, we wouldn't have to test it over so many sessions."* (Julie)

Reuse occurred at two levels: (1) the OTs reused standard splint patterns and (2) the thermoformed PLA supported in-situ rapid reuse of the pattern. Julie viewed iteration on the 3D modeled pattern over two sessions as a failure, but hoped that it would be worth it in the long term because she could reuse that model. Sara, who interacted more directly with the materials, was excited about the ability to make quick in-situ adjustments to a standard pattern rather than having to re-create unique, but highly similar, patterns for each client. PLA and 3D printing lend themselves to quick reproductions of parameterized splints, while Thermoplast is exclusively manual.

The Maker-OT Identity.

Throughout the process, Julie and Sara prided themselves on their ability to make creative use of common materials. For example, they used a coffee pot as a splinting tray because the free clinic has no other sources of hot water. This excited both of them because they believed creating AT with their limited resources expanded the capabilities of the free clinic. When finishing the splint, Sara applied adhesive padding, and Julie sewed on Velcro straps. While Julie sewed the straps, Sara commented that she wished she knew how to sew and that it would make her work easier; Julie responded,

> *"OT is making…you should learn"*

Despite this espoused maker-ethos, Julie and Sara were uncomfortable with 3D modeling in the clinical context. They understood and could use the tools but it did not align with medical software requirements. Julie pointed out the features of medical records software to highlight differences between it and the CAD tools. She was concerned that there was no support for medical record keeping, for maintaining client privacy, or for ensuring clinician accountability. To her, the software was not appropriate in a clinical setting:

> *"So if you give me the files, what do I do with them? I can't just print them, what if he needs them?"* (Julie)

Julie's maker-identity is superseded by her clinical goals: to protect and heal her clients within the regulations of health care. In this quote she is concerned that while the CAD tools produced an effective splint design, she did not see means to follow HIPAA regulations [4]. Legally, a client's treatments must be documented and the client must be able to access that documentation if they choose to switch providers or get a second opinion, but Julie saw no way to ensure this with traditional CAD.

It seems that Julie and Sara are comfortable with the craftiness of being a maker, but when that maker ethos enters a digital space it is subject to regulation. The maker identity invites digital fabrication into clinical practice but it does not override the cautious do-no-harm philosophy of clinicians.

To summarize, the design of a thumb-splint at the free clinic revealed a tension between clinical and maker design methods. This contributed to Julie's concerns about the high cost of design iterations even though the result could support other clients. Julie and Sara's *clinical expertise* helped to identify the biological and ergonomic requirements of the splint in a way we would not expect of non-experts. The tools and adaptive behaviors characteristic of a *maker-identity* were necessary for the production of an effective and reusable splinting pattern. This splint *model reusability* made the prototyping behaviors acceptable. In the next section, that reusability is not present and the *consequences of a rapid prototyping* are more apparent, as are the benefits of *adaptive materials and design.*

Case 2a: A Modular Chef's Knife Grip

Jon, a veteran with a spinal cord injury, was the focus of our study at the VA clinic. Jon loves cooking but he needs customized AT. Prior to this study, Lorelai made two customized knife grips out of Orthoplast[2] (Figure 2a). Jon had limited success with these because they did not ergonomically align with the knife.

[2] Orthoplast is a thermoformable plastic similar to Thermoplast. It is nearly impossible to remove it from affixed surfaces. This makes a food safe grip, but prevents subtractive modification.

(a) The Orthoplast grip

(b) Non-ergonomic design

(c) Modular flexible insert

(d) Final knife set

Figure 2 – The progression of Jon's knife grip from a permanent Orthoplast grip to flexible modular grips.

Prototyping as Failure.

Lorelai had iterated on Jon's knife grip prior to the study, but these prototypes failed, costing Jon his time and favorite knife set. From Lorelai's perspective, iteration fails because clients have no use for failed prototypes. Lorelai prototyped two knife grips over a series of months prior to this study. With her first iteration of the knife grip (Figure 2a) had a basic grip pattern with a guard loop to keep the knife in Jon's hand. This grip fit Jon best, however too much Orthoplast was up against the base of the blade which blocked him from pressing the blade down completely. Lorelai created a second prototype on one of Jon's other knifes. This version did not block the blade but the grip did not fit Jon nearly as well.

Essentially, because the Orthoplast permanently modified the knives, he had lost his favorite knife and had only received ineffective grips. When we began working with Lorelai, Jon had abandoned the knives entirely. Lorelai hoped that by applying our research to the problem she could make up for Jon's lost knives and time.

Focusing on Adaptation.

In response the permanence of the Orthoplast grips, Lorelai emphasized adaptability. During an initial design session with Lorelai, she laid out three key goals for the 3D printed knife grip. First, it would be food safe and hand washable just like the Orthoplast material. Second, it would closely match the geometry of the original grip and guard but accommodate Jon's ergonomic concerns. To support that close organic fit, we need a material (*e.g.,* clay [14] or Orthoplast) that adapts to Jon's grip. Third, it would modularly adapt to more than one knife in a set rather than permanently modifying his knives.

Lorelai encouraged us to do what we was felt necessary, reiterating that she had access to many resources and experts through the VA. As long as she had digital versions of the final grip, she was certain that the VA could reproduce the work for Jon or other clients independently. However, she clarified that any iteration should be tested before she presented it to Jon. Her goal was to minimize his time spent on this project. One author noted in a memo:

> *Lorelai is confident in what the VA can make for her but not in what she can design herself. Just like Julie, she seems to be in a rush to get something to the client but without access to the client himself, it is a challenge to make everything fit.*

Emulating previous research on 3D printing grips [14, 31] we printed the outside of the grip with black PLA plastic (Figure 2b). Inside the outer shell we added an "uncertainty buffer" [40] of red flexible material which allows Jon to replace the knife without re-printing. Finally, we coated the components in silicone to make grip soft and food safe. Lorelai can use this silicon coating to add or cut-away padding layers to better adapt the grip to Jon's hand.

We delivered the grip (Figure 2c, 2d). Lorelai examined it without Jon present to determine that the grip would be effective and safe, then she kept it and delivered it to Jon for testing to ensure that it would meet his needs. Afterwards, she emailed us:

> *"He loves them! He took them to trial."*

Each component of the design emphasized adaptability: the outer shell fits onto new knives, the "uncertainty buffer" adapts to different handle shapes, and the silicone supports adaptation of the fit of the grip. This adaptability distinguished the design from Lorelai's prior prototypes.

To summarize, the knife grip design demonstrates the tension between rapid prototyping, a practice ubiquitous in maker culture, and adaptive design. In prototyping, the goal of any individual prototype is not entirely to produce a final product but to produce a version that reveals flaws or opportunities for improvement. The *negative consequence of rapid prototyping* in clinical practice is that a prototype that is not safe or effective could hurt a client, or at a minimum could discourage them from adopting the AT. *Adaptive design*, rather than prototyping, better reflects the iterative structures we observed. Lorelai focuses on adaptive design explicitly in her goal to make a modular grip, but we also saw adaptive design in the splint thermoforming techniques at the free clinic. We did not observe this adaptive behavior in the next case study, we believe this is because malleable (adaptive) materials are not strong enough to hold a person's weight and were not applicable to the transfer board.

(a) Metal transfer board being inserted into a wheelchair

(b) Carbon fiber board with mechanism unfolded

(c) Carbon fiber board with mechanism folded-up

Figure 3 – The progression from the original transfer board to the carbon fiber design

Case 2b: TSA Friendly Transfer Board

Jon has a wheelchair transfer board (Figure 3a) that raises and lowers as he slides across it. This unusual design was made in the 1970s by a company that no longer exists, so he cannot replace it. When Jon travels, airport security (TSA) intrusively questions Jon about the device. Lorelai asked us to build a similar replacement board that was TSA friendly.

Socio-cultural Design Influences.

Anna shared Jon's description of TSA's concerns:

"TSA says, 'It looks like a pipe bomb!'"

While discussing the challenge, the researchers agreed that the "pipe-bombishness" may have been dramatized when Jon passed on the story to the OTs and they to us. We questioned what made the device seem threatening. A TSA representative on a hot-line for travelers with disabilities discussed the potential security concerns. She quickly dismissed the notion that agents had identified the device as a pipe bomb because they would have tested it for explosive residues. She concluded that that the board was heavy—made of hardwood and a steel pipe—and could be used like a baton or bat. The problem is probably a combination of the peculiarity of Jon's device and the weight.

Our challenge was social not biological or ergonomic. It was crucial that TSA's perspective was accessible. Clinicians bring a valuable clinical perspective to the design of AT, but that does not mean that the design of AT can exclude other stakeholders' perspectives. The TSA agent's input reduced our *wicked problem*—normalize and make an unusual and vaguely threatening device socially acceptable—to an engineering problem—reduce the weight so it cannot be used as an effective blunt weapon.

The Limits of Consumer-Grade Digital Fabrication.

We reduced the board's weight by re-creating the original device using lighter wood and carbon fiber. Since standard 3D printed plastics could not hold Jon's weight, we printed connectors between carbon fiber pipes on a MarkForged [2] printer with nylon and carbon filaments. Because carbon fiber pipes are difficult to modify (*i.e.* cut or join), we created the majority of the mechanism by assembling pieces that had been cut to standard sizes by the seller. We bound the connectors to the pipes with carbon fiber threads and resin.

By re-creating the original steel mechanism using carbon fiber, we made it significantly lighter. However, this limited us to prefabricated materials, which we purchased online [3]. Although the available pipe diameters could fit a standard wheelchair, Jon had an unusual wheelchair configuration that no available pipes fit. Unlike the thermoformable splint or flexible knife-grip, the rigid carbon-fiber composites cannot be adapted on the fly. Further, limited to the sizes commercially available, we could not make the pipe fit the wheel chair footrest.

In the end, Lorelai and Jon loved the final board design because it was lightweight and novel. Although we could not fit the device to his current chair, Jon asked to keep the new transfer board. He hopes to find a set up that will fit the device in the future.

Digital fabrication and customization have a role to play in advancing AT, but due to limits on consumer technologies, whole classes of AT that require strength (*i.e.* holding Jon's weight) are currently out of reach. The values of digital fabrication in AT (*e.g.,* customizability, adaptability, ownership) still apply to this type of AT. Ongoing research to expand the materials and fabrication tools available to consumers will open new pathways in this space.

To summarize, the transfer board presented more of a challenge than the splint or knife grip and revealed the *limitations of consumer-fabrication* in a clinical context. First, unlike the splint and knife grips which principally serve ergonomic functions, the transfer board presented problems that were primarily social. Like the splint, the transfer board addressed cultural expectations about AT, but the transfer board was redesigned primarily to address social function (not resembling a weapon) while social function (match Ron's skin) was a secondary consideration for Ron's splint. Julie and Sara appreciated that color choice, but prioritized medical treatment for Ron's condition. Further, once we re-framed the transfer board as a weight-reduction problem it required more advanced fabrication technologies than the splint or the grip. This pushed what we, fabrication researchers with consumer grade technologies, were capable of producing, rather than what the clinicians could design.

6 DISCUSSION

One model of clinical fabrication is to place fabrication professionals in clinicians, as the VA has done in more than twenty hospitals [25]. However, even with access to state-of-the-art fabrication facilities and dedicated experts, it is clear from our VA case study that current design methods and tools do not support clinicians. Further, many clinics, like the free clinic, cannot afford expert fabricators. CAD tools that would support fabrication in these limited resource environments would have a broad impact on low-income populations who are unlikely to fabricate for themselves.

We argue that a rapid prototyping process does not translate into the clinical context. Maker culture has a fail quickly and take risks attitude that conflicts with a do-no-harm clinical mentality [30]. Instead, iteration in clinical practice occurs at a macro-level, through carefully regulated research and development of new technologies, and at a micro-level of adapting a user's device inside client-clinician appointments. We found few opportunities to present client's with low-fidelity prototypes, even if it produced a better design.

Amplified Expertise: A Prescriptive Model of AT

The OTs in our study did not view AT creation as design or engineering, but as prescribing AT. After all, we did not invent a new splint, knife grip, or transfer board; we merely customized existing designs. This builds on the themes regarding *clinical expertise* and other *socio-cultural perspectives* as well as the OTs' desire *reuse their designs across clients*.

There were two reasons for the prescriptive approach. First, the OTs began the process using a wealth of knowledge on existing AT, rather than considering what they could invent; their goal was to match clients to the best existing and effective technology. Second, a prescriptive approach takes less time, requires fewer resources, and poses fewer risks than inventing a new technology. It is better to provide a safe, working solution quickly, than a novel solution too late and after harm has been done. It also amplifies the utility of each design by ensuring its reuse across many clients.

Work to build a AT prescription repository could benefit from pre-existing efforts in DIY-AT communities as well as traditional health fields. Buehler *et al.* [12] and Chen *et al.* [19] analyzed DIY-AT artifacts available on online, and e-NABLE has multiple efforts to distribute their prosthetic-like designs [49]. However, these efforts almost exclusively capture the expertise of engineers [12]. Clinicians have rarely vetted these designs [64], which may reduce clinicians' trust [30]. The NIH 3D Print exchange [1] has collected designs made by medical professionals, but few of these models are AT. To have the most impact, efforts to collect and distribute 3D printed AT must amplify many stakeholders' expertise (*i.e.* activists, clinicians, engineers, and people with disabilities).

Appropriate Design: Resources Across Clinics

Fabricating AT in occupational therapy highlighted a relationship between design processes and available resources. While these considerations occurred at both sites, the disparities between the free clinic and the VA revealed the limitations for low-resource clinics. The presence of a *maker-OT identity* at the free clinic revealed a willingness to bridge clinical and maker practices to make better use of limited resources. In contrast, the VA OTs desire to *push the limits of consumer-grade digital fabrication* revealed challenges for clinicians to determine what can be done with consumer-grade fabrication and how to make best use of resources.

Because of the low-income status of the clients at the free clinic, Julie based her design decisions on materials she knew were available and inexpensive to the clinic (*i.e.* PLA replacing Thermoplast, a coffee pot replacing a splinting tray). It was easy for the OTs to reason about these materials which may have contributed to the success of Ron's splint.

In comparison, Lorelai was relatively unconcerned about material cost or the fabrication process. Her challenge was knowing how to effectively use her fabrication resources. Lorelai and Anna had a general sense that the VA could fabricate complex designs, but had no knowledge of what the fabrication process involved. This made it more difficult for Lorelai and Anna to reason about their designs.

Adaptable Design: Iteration in Clinical Practice

The common belief in HCI is that iteration is the core of design, necessary to "getting the design right" [17]. Even considering time and material costs, iteration still produces the best solutions [22]. As a result, CAD tools are nearly synonymous with rapid prototyping [6].

Despite this, our OTs rejected prototyping; they had one shot. This represents the themes of the OTs rejecting *rapid prototyping as a failure* and embracing *adaptive designs and materials*. On the surface, our findings contradict Moraiti *et al's* description of rapid prototyping process and "tinkering" in e-textile design by OTs. Tinkering (*e.g.,* cutting materials to fit the client) is an adaptive process, but iteration of programs and circuits is more aligned with rapid prototyping. It may be that the type of AT being created, the perception of potential risks, and/or the fabrication processes affect clinicians' willingness to prototype.

When clinicians present clients with AT, it does not need to be perfect, but it must be verifiably safe and useful. It is possible that prototype iterations would work in certain cases—especially when there is no urgent need for the AT—but clinicians must trust the quality and safety of any prototype they deliver. Such high-quality prototypes seem antithetical to a rapid prototyping process; rapid prototyping, by definition, does not produce results on the first try.

7 DESIGN RECOMMENDATIONS

A design and fabrication exists in clinical practice, but for it to become more wide spread will require a new set of clinical CAD tools that support macro and micro iterations on AT design. We recommend that a clinical CAD tool (1) *amplify clinical expertise* through a *prescriptive library of AT* that (2) is filterable by *appropriate design* characteristics based on *available resources* and (3) uses *adaptable tools and materials*.

Amplifying Expertise with a Prescriptive Library

Clinical CAD tools should include AT libraries that help clinicians to leverage their expertise and build on medical research. Ideally, clinicians could search the library based on diagnoses. These libraries should update based on new research and contributions from multiple communities and stakeholders (*i.e.* DIY/DFO-AT organizations,medical professionals). Clinicians could adjust models to fit clients.

Appropriate Design: Make Resources Salient

Clinicians must know what is feasible, enabling them to use their resources without overreaching. The clinical CAD tool must make resources salient, including available materials and costs. Resource awareness must scale to resource-diverse environments and present context appropriate solutions.

Adaptable Tools and Materials

Clinical CAD tools should emphasize adaptation: starting with a prescribed model, the clinician can tweak the design using adaptable materials or quick fabrication approaches. Ideally, adaptation is physical not digital. Researchers are already exploring shape and property changing materials [5, 27, 51], and this is a promising first step towards adaptable design. Researchers must continue to explore adaptable materials that can handle larger forces, such as human weight, and more researchers should apply these techniques to AT.

8 ETHICS AND LIMITATIONS

The generality of our approach is limited by scale; four OTs at extremes of the US health care system are not representative of all OTs and clinicians. However, this is not unusual among similar case studies [13, 31]. Our goal is to contribute a rich examination of this space and propose a preferable future where clinicians are a supported stakeholder in the DFO-AT ecosystem. We present one possible interaction between clinicians and digital fabrication; others certainly exist and are worth exploring, and ours requires further study.

While the OTs were primarily responsible for the design of the study artifacts, researchers did the 3D modeling and printing independently. Therefore, our findings focus on the ideation, construction, and testing of AT. It is unclear what barriers clinicians may have to the act of 3D modeling itself.

Introducing digital fabrication into clinical practice may place an undue burden on clinicians. For instance, insurance companies may reduce compensation because of competition with amateur designs [30]. Further, it is unclear how to evaluate the resulting AT, posing concerns about tracking long-term adoption and safety. We must address these concerns to integrate digital fabrication technologies and a DFO-AT framework into clinical practice.

9 CONCLUSIONS AND FUTURE WORK

Bringing consumer-fabrication and a DIY/DFO-AT approach to occupational therapy demonstrates similar benefits to past research and increases access for people with disabilities. However, we found the OTs negatively regard rapid prototyping. Instead, clinicians emphasize minimizing iterations at the cost of innovation. Their primary goal is to quickly deliver something that helps the client, and we must build clinical CAD tools around this constraint. Instead, clinical CAD must leverage the iterative cycles done by the broader medical research community, and support adaptive design.

In this study of two occupational therapy clinics, a free clinic for uninsured clients and a VA clinic, we applied digital fabrication techniques to opposite ends of the US health care spectrum. Each OT saw a barrier to applying such technology because it did not align with clinical practice.They saw their work as being primarily with the client, so when an iteration on a design failed, they felt they had failed.

Unsurprisingly, resources significantly impacted outcomes. Differences in resources between both clinics caused divergent themes. OTs at the free clinic limited the scope of their AT fabrication to reducing pain because of resource limitations. They developed a maker-identity around their creative uses of resources. In contrast, the VA's vast resources enabled them to push the limits of consumer-grade fabrication. At the VA we pushed too far, resulting in an ineffective design.

Overall, these studies corroborate past DIY/DFO-AT research findings and present a positive view of the techniques. However, it clarifies that the application of digital fabrication in clinical contexts may require an entirely different set of tools than those created for disabled people or their non-professional caregivers. In future work, we would like to include more clinicians, different clinics, and a wider range of clients. In addition, we would like to build generalized CAD tools that support adaptation rather than iteration.

ACKNOWLEDGMENTS

We thank our participant clinicians and their clients and our reviewers. This research was funded in part by the Center for Machine Learning and Health Fellowship and and a NSF GRFP Fellowship and NSF Grants 1836813, and IIS-1718651.

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