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Creating 3D Printed Assistive Technology Through Design Shortcuts: Leveraging Digital Fabrication Services to Incorporate 3D Printing into the Physical Therapy Classroom

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ABSTRACT

Digital fabrication methods have been shown to be an effective method for producing customized assistive technology (AT). However, the skills required to utilize these tools currently require a high level of technical skill. Previous research showed that integration of these skills within physical therapy training is appropriate but that the level of technical difficulty required can be an issue. We worked to address these issues by introducing a group of PT students to maker concepts and having them develop custom AT for real end users with the help of makers. We present three considerations when integrating making into PT curriculum: 1) including all stakeholders, 2) developing interdisciplinary competencies for PTs and makers, and 3) leveraging academic training programs to connect makers and PT students. In this paper, we contribute to knowledge on how to facilitate the 3D printing of customized ATs for PT students by connecting them with a community organization that provides digital fabrication services and technical expertise. By connecting multiple stakeholders (i.e., PT students, digital fabricators, and AT users), we offer an approach to overcome time and capacity constraints of PT students to utilize advanced fabrication technologies to create customized ATs through connecting them to professional makers.

CCS CONCEPTS

• **B7; Human-centered computing** → Accessibility.

KEYWORDS

3D Printing, Assistive Technology, Physical Therapy, Makerspaces, Education, Digital Fabrication

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1 INTRODUCTION

Previous research has shown that consumer-grade fabrication methods, such as 3D printing and laser cutting, can improve Assistive Technology (AT) development and production [1-3]. In a recent article, Mankoff et al. provided an overview of the possibilities and challenges of using consumer-grade fabrication methods to develop customized AT solutions [1]. They found that these fabrication methods have great potential for creating small-batch customized devices that may better meet the needs of a user and for involving users more closely in the design and creation of their own technology. Despite this, the research also identified that current fabrication tools and processes are not inclusive of people without prior technical expertise or knowledge and that without stakeholder involvement at all levels of fabrication design and implementation, important challenges in integrating these techniques into therapy and medicine remain [1]. In the last few decades, several online communities of makers interested in creating customized ATs have formed [2, 4]. While successful outcomes from these communities are documented, previous research has also shown a tension between the priorities of hobbyists and makers and those of clinicians and therapists [5]. The tension, manifesting in concerns about the safety and practicality of ATs customized or created by makers, may be due to the difference between the clinical ethos of "do not harm" and the making ethos of "help where you can" [5].

Previous research has explored how to better connect digital fabrication and physical therapy skill sets. McDonald et al. conducted a study on how to introduce Physical Therapy (PT) students to 3D printing [3, 6]. The study was motivated by the potential of enhancing clinician's ability to use digital fabrication skills to develop customized, usable, and safe devices by providing them with the needed maker skills and experience. While the research showed that 3D printing can be a viable and useful addition to PT students' current curriculum, it also identified several issues with integrating it. Specifically, it identified the significant amount of time required for clinicians to learn Computer-Aided Design (CAD) skills necessary to model a 3D printable object or specific and detailed features of an AT device. Furthermore, the study identified the lack of consistent access to fabrication tools and the challenge of getting end users to return for multiple visits required to tweak and evaluate the designs, as barriers for PTs using digital fabrication for AT design and creation [3]. Overall, this previous research shows that while digital fabrication tools have great potential for supporting PTs to create and customize ATs for their clients, it is unclear how to make them accessible without requiring PTs to become experts in 3D printing or CAD.

To investigate how to make digital fabrication processes accessible to PT students without the need for them to become experts at using them, we conducted a study that connected PT students to staff at a community makerspace that provides 3D printing and scanning services to local organizations and individuals. By leveraging the services and skills of expert makers, rather than learning complex and time-consuming 3D modeling and printing skills, PT students could focus on understanding and translating their clients' needs to a physical design to be communicated for realization. Furthermore, by including real end users in the design and fabrication process, we investigated how to form small stakeholder groups consisting of a group of clinicians, an end user, and a community maker, who would communicate and work together to create a customized AT. This approach allowed us to investigate the communication possibilities and challenges involved in this process to design future communication protocols that may alleviate the need for PTs to learn digital fabrication skills and instead use external fabrication services and resources to create customized ATs.

In this study, we seek to understand (1) if consumer-grade fabrication with 3D printers can be used to produce customized and usable ATs for real end users in the context of a graduate PT classroom, (2) if resulting AT designs could be accurately communicated by PT students to a youth-staffed community makerspace for fabrication, and (3) what information would be needed by makers and PTs to successfully communicate with each other about this process.

We investigated these questions by integrating six 3D printing class sessions into the curriculum of 58 PT graduate students over two semesters. The students were first given an introduction to 3D printing, then they designed AT devices for 5 simulated end users leveraging the resources of a community makerspace, and then repeated the process for creating AT devices for 12 real end users.

In this paper, we contribute to knowledge on how to facilitate the 3D printing of customized ATs for PT students by connecting them with a community organization that provides digital fabrication services and technical expertise. By connecting multiple stakeholders (i.e., PT students, digital fabricators, and AT users), we offer an approach to overcome time and capacity constraints of PT students to utilize advanced fabrication technologies to create customized ATs through connecting them to professional makers. We describe our observations, including feedback and reactions from PT students who worked with real end users in a classroom setting to design and realize customized AT products. Our findings provide insights on how the AT design process can be improved for PT students, how the communication between PT students and professional makers can be strengthened, including when to use clay modeling and when measurements and sketching might be a better option, and how future PT training programs can better integrate interdisciplinary skills and competencies related to digital fabrication, including those related to 3D scanning and printing practice.

We will contextualize our study using previous research into AT abandonment, the use of consumer-grade fabrication tools by people with disabilities, the practices of online DIY communities, specifically focused on designing ATs, and previous efforts to use 3D printing in the context of PT education. We then describe how we designed and implemented class sessions on 3D printing and fabrication into a graduate PT course and describe our data collection and analysis procedures. Next, we report findings from our study and describe each end user's resulting customized AT device. We conclude with a discussion of PT students' experiences with respect to the different aspects of the project and suggest directions for future work.

2 RELATED WORK

Our work builds on the existing body of research that has explored the possibilities and challenges of using digital fabrication processes, such as 3D printing, for AT development and customization. In this section, we provide an overview of this previous research, including work on AT abandonment that motivates efforts to customize ATs to better meet the needs of end users, studies of Do-it-yourself (DIY) and bespoke approaches to AT design, and the role of AT development in physical therapy education.

2.1 AT Abandonment and Fit Issues

According to the Center for Disease Control and Prevention, 61 million adults in the United States live with a disability, equating to 26% or 1 in 4 adults [7]. Worldwide, an estimated one billion individuals need ATs. This number is expected to increase to 2 billion by 2030 [8]. Without appropriate AT, individuals are often unable to fully participate in society and live active, independent lives. Therefore, it is increasingly important for AT procurement to become accessible by a large number of people.

AT-focused projects tend to have very high social impact but a low economic impact [9] and related profit margins. Because of these relatively small profit margins, it is uncommon for companies to fund research and development that advances the field of AT to meet the growing need. This leads to many issues.

One issue is the high abandonment rate of ATs. Of all ATs that are prescribed, 20 to 30 percent are abandoned by end users [10]. Poorly designed or fitted devices that do not meet the needs of the end users is a key factor related to abandonment [11, 12]. Though improved service techniques have been shown to reduce abandonment, there is a growing concern that the quality and reliability of ATs are decreasing over time [13-16]. Reduced quality may be due in part to the reduced reimbursements for ATs and related services [14, 15, 17], which leads to a second major issue in AT – a lack of financial incentive for companies to provide post-launch support.

These issues have motivated efforts to develop ways for end users to be more involved in the design and customization of ATs to reduce poor fit and increase user technology buy-in. Our study contributes to this space, by investigating how to connect PTs, makers, and end users to allow for the creation of assistive devices that are customized based on user needs and are, therefore, less likely to be abandoned.

2.2 Consumer Grade Fabrication Tools for People with Disabilities

Over the past decades much research has investigated the possibilities of using consumer grade fabrication tools and prototyping materials for creating customized and Do-It-Yourself Assistive Technologies (DIY-ATs) [4, 18-20]. Much of this effort has focused on understanding how creating their own technologies can lead to empowerment for people with disabilities [18, 19, 21]. Previous studies have shown that AT users find it empowering to create their own AT, which could lead to fewer cases of abandonment. Hurst and Tobias showed that individuals with disabilities were motivated by increased control over design elements, passion, and cost to create and use their own DIY-ATs [18]. Meissner et al. found that participants with disabilities in DIY-AT workshops reported several empowerment-related outcomes, including viewing maker skills as extensions of their own accessibility hacking abilities and as tools to gain recognition in their community. Other efforts have shown that creating DIY-ATs can lead to community building both offline (e.g., [22]) and online (see next subsection).

A number of barriers have been identified in relation to DIY-ATs. For example, many of the tools that are used in makerspaces, along with makerspaces themselves, are not accessible. This greatly limits the ability for individuals with disabilities to work in these spaces independently. Recommendations have been made for special education makerspaces [23, 24] but this has yet to become the norm for these settings. The design of CAD tools, informed by HCI research, could greatly increase the inclusiveness of consumer-grade fabricating [25] but has yet to produce meaningful changes. Furthermore, Hook et al. found considerable skill and time are required in creating DIY-ATs, putting additional pressures on parents or teachers [26].

Recognizing the need for diverse expertise in this space, research efforts have brought together multiple stakeholders (e.g., end-users, digital fabricators/makers, therapists) in this space [5, 27]. For example, Aflatoony and Lee conducted a study that brought together an end-user with physical disabilities with four occupational therapists, and four industrial designers in a series of workshops to co-design ATs [27, 28]. They found that working together resulted in knowledge exchanges and mutual learning that resulted in applying combined expertise to co-designing novel and advanced AT solutions. They further identified the lack of tools, methods and materials to co-design ATs.

Our work builds on these efforts to leverage the potential of consumer grade fabrication tools to create ATs with input from end-users. While it is important to continue making digital fabrication tools accessible, creating processes that bring together stakeholders with complementing skills and lived experiences can enrich the space of AT development and reduce the burden of learning new skills. While some individuals will enjoy the process of design, there should not be a requirement to also be an engineer to create or customize appropriate AT devices for users in a PT setting.

2.3 DIY Online Communities for AT

In addition to hands-on localized efforts to create DIY-AT (described above), many studies have looked at how to create or leverage online communities to connect makers interested in developing ATs, end users, and other stakeholders together. For example, Buehler et al. studied technologies related to AT posted on the online community of Thingiverse [2]. While they found that the platform housed a rich collection of AT designs for free usage and customization, they also found that a majority of the AT designers using it did not have disabilities nor any training in AT.

While Thingiverse is a general-purpose fabrication design repository that houses AT designs in addition to many other designs, other communities have formed that focus specifically on DIY-ATs. For example, the e-NABLE community was created specifically to support makers that focused on prosthetic devices [4]. Their open-sourced designs are shared online and can be printed by volunteers for those who need them. Despite its promise and potential to offer customized ATs to a wide range of users across the world, previous research has identified several challenges in this community. For example, Parry-Hill et al. showed that while there are a number of e-NABLE chapters around the world, there are only a few members who can design devices as opposed to those who can fabricate and deliver them. Furthermore, there is an issue when someone receives a device of not being able to get back in contact with the volunteer if something goes wrong [4]. At a workshop that brought together various stakeholders of this community, including makers and clinicians, serious tensions were identified between the "do no harm" culture of clinicians and the "help where you can" culture of makers [5]. Furthermore, the workshop surfaces concerns about the ability of consumer grade materials and design tools to produce artifacts and customizations specific enough for clinical practice.

Previous research into online DIY-AT communities provides motivation to develop better communication protocols and mechanisms that bring together the expertise of digital fabricators, professional PTs, and the lived experiences of end users in the design and customization of ATs. These approaches may ensure device safety and medical appropriateness by including feedback from PTs while strengthening device acceptance by incorporating feedback from end users.

2.4 Digital Fabrication for AT Development in Clinical Education

Until recently, there were few projects that studied how to bring in digital fabrication, including 3D printing, into the physical and occupational therapy classrooms. A recent systematic review of using 3D printing in biological education, found only one paper focused on PT [29]. In this pioneering project, McDonald et al. developed a course to introduce PT students to 3D printing [3]. They identified several opportunities for connecting PTs and makers in the future, including that (1) PTs already perform making tasks and presenting them with new DIY tools could expand this existing practice, (2) PTs bring important and complementary medical expertise to the table when engaging with DIY practice and could ensure that DIY-AT products are created to be safe and appropriate for extended use, and (3) PTs had access to actual end users who could inform the DIY maker process. They also identified multiple barriers in introducing PTs to digital fabrication. These included PTs having limited time to learn new digital fabrication skills, the availability of easily purchased devices that most PTs can default to rather than creating new artifacts because of their limited time, and the lack of tools to ensure standardized reliability of DIY-AT products, leading to concerns about their liability.

More recently, several efforts have explored interdisciplinary approaches for integrating digital fabrication in PT education. For example, Wagner et al. described a project which connected PT and OT students and faculty with librarians operating 3D printers on a college campus [30]. The librarians were able to connect OT and PT students to a group of biomedical engineering students to help with 3D modeling tasks. School faculty collaborated with the librarians to develop assistive technology assignments for students that were then printed at the library. Over three years, 78 students collaborated with librarians and faculty to 3D print ATs. The stakeholders used in-person and virtual meetings as well as email and shared spreadsheets to keep track of projects [30]. This case study shows that leveraging on services (e.g., librarians trained in 3D printing) can be an effective way to introduce 3D printing in OT and PT education through the creation of ATs. In another recent project, Davis and Gurney assessed the impact of using 3D printing in project-based OT learning and found that compared with a control group, students who used 3D printing in their projects had increased technology self-efficacy [31]. While students were asked to consider a "real-world" user of their designs, they did not interact or work iteratively on their work and following a month-long module in 3D printing were asked to design and print devices for their projects. While both of these projects provide evidence that 3D printing can be successfully introduced in the PT and OT classroom, they did not provide details on challenges faced in implementing the programs and communication strategies that proved successful or otherwise with respect to specific student projects.

Other work by Chen et al. elicited positive attitudes in OT clinicians towards integrating 3D printing into their practice, especially with respect to the potential for reducing cost of customized items and the potential for the customizability of digital fabrication to fill in a gap in creating ATs [32]. The clinicians stressed that the time to learn how to use 3D printing effectively can be a barrier to adoption. While most previous efforts have focused on general applications of 3D printing for PT and OT, Paterson et al. developed and evaluated a computer-aided software design specifically for creating wrist splints [33]. The software and associated workflow allow practitioners to customize a base model to match a client's 3D scanned wrist model and create a customized model of an aesthetically pleasing splint. In interviews with 10 clinicians, they found that users were able to navigate and use the software to create models but also were concerned about capturing patient scan data (needed as input into the software tool) and the material and cost suitability of the designs (since the models need to be created on higher end fabrication devices) [33].

Finally, several studies have focused on the existing practices of OTs and PTs when adapting ATs. For example, in an interview study with 17 OTs, Aflatoony and Shenai investigated how clinicians customize and adapt ATs using low-tech materials to better fit the needs of their clients [34]. They found that while most OTs tried to use off-the-shelf ATs, adaptations were often necessary to fit a client's needs. Most OTs described using low-cost craft materials (e.g., foam, duct tape, etc.) and techniques (e.g., gluing or cutting to enlarge or reduce size, or to attach items together) to make adaptations. They described a process where they would assess a client's need, make an adaptation for them, and then iterate on it with the client to troubleshoot and refine it over time. Additionally, OTs mentioned having concerns around liability and safety of modified devices that makes them try to do minimal mechanical adaptations and, for some, to avoid adapting ATs with electronic components all together. In another study, where authors worked with four OTs as digital fabricators over a period of four-months, Hofmann et al. found a misalignment between the priorities of ATs and digital fabricators/makers: specifically, OTs prioritized client safety over taking risks in fabrication and aimed to come up with effective adaptations for their clients in one shot (rather than using iterations) [35]. Furthermore, they identified a need to make it clear what resources are available and what is feasible to the clients, so they are not overreaching when using digital fabrication methods. These findings show that adapting and customizing ATs is an important part of OTs practice and could be supported by utilizing emerging technological tools and processes. Furthermore, clinicians have concerns and priorities that may differ from makers and digital fabricators.

Our work builds on this previous research by both recognizing the potential of 3D printing to enhance the learning of OT and PT students and by studying an approach to limit the need for time and technical expertise on PT students when using digital fabrication for AT development through connecting them to professional services provided by staff at a community makerspace.

3 METHODS

3.1 Educational Series Design

We designed and implemented a digital fabrication educational series for a single cohort of PT students that consisted of six face-to-face learning sessions. This course series was modeled after an earlier course designed by McDonald et al. [3] but there were three major differences. First, in contrast to the earlier course, CAD was not attempted to be taught in this course, but simply introduced to allow the PTs the ability to communicate with makers effectively. Second, after the design with simulated end users, PT students in our course designed with real end users. Finally, instead of the research team 3D printing the design, they were fabricated by a local community makerspace.

The first session was a 1.5-hour introduction to AT with the subsequent five sessions involving AT development (modeling, revising, reviewing) with the later five sessions each spanning 3 hours in length. All six sessions were conducted with the same cohort of PT students over a total of 2 semesters within the PT educational curriculum. During the initial sessions (2, 3, and 4), students designed AT for simulated end users and during the later sessions (5 and 6) they worked with real end users on AT devices. We will describe the format and content of each phase next.

Table 1: Simulated AT Design Cases (adapted from McDonald, et al. 2016)

Case Number	Age	Gender	Diagnosis	Specifications
1	62	Male	Left Hemorrhagic stroke	Requires use of hemiwalker; limited ability to grasp with right hand
2	45	Female	Traumatic Brain Injury (TBI)	Requires use of a quad cane; limited by right wrist flexor synergy
3	32	Male	Humeroradial fracture	Requires use of auxiliary crutches for recent ankle sprain; limited by right elbow flexion range
4	60	Female	Right adhesive capsulitis	Requires use of straight cane for balance; limited by shoulder flexion range
5	8	Male	Cerebral Palsy	Balance issues; limited by fixed trunk flexion to 20 degrees; fixed trunk right side bend/rotation to 10 degrees

The fabrication for the educational learning series took place at a local community makerspace staffed by youth employees with expertise in 3D modeling and CAD, 3D scanning, 3D printing, and other digital fabrication methods (e.g., laser cutting). The makerspace houses a 3D print shop with multiple consumer-grade mid-range printers (e.g., LulzBots, Prusas, and Ultimakers) that use common plastic filaments including PLA and NinjaFlex flexible filament.

3.1.1 Phase 1: Building Foundational Skills with Simulated End Users. The six session, in-person educational series introduced PT students to 3D printing and designing custom assistive technologies across two semesters of the PT curriculum, with the first four sessions being incorporated into a foundational PT course and the last two sessions embedded into a clinical focused PT course.

The first four sessions were embedded into a PT course designed to bridge foundational sciences with introductory clinical skills. For instance, in this course PT learners are exposed to principles of biomechanics and the application of these concepts to assistive devices. Session One began with a definition of additive manufacturing and a description of current applications of 3D printing with specific examples of PT products (such as handgrips). The students were then given an overview of the common types of 3D printers (including SLA, SLS, and FDM) and their pros and cons. The students then went through a detailed description of the process of designing for 3D printing and a detailed description of additive 3D printers and how they work. Students were finally asked to complete a thought exercise in which they came up with an assistive device that could be augmented by 3D printing. The intended outcome of this session was an understanding of the process and the limitations of 3D printing and to brainstorm some practical uses. In the second session, the PT students were separated into 5 teams and designed assistive devices for imaginary end user cases (Table 1). In these cases, the PT students were presented with scenarios in which an end user needed an assistive technology device that was no larger than 5 by 5 by 5 inches. This limitation was to ensure that it could be printed on consumer-grade 3D printers that were available at the makerspace.

The imaginary design cases were presented as shown in Table 1 below and adapted from McDonald et al. They were created by the PT instructor and focused on designing augmentations to pre-existing devices. The scenarios reflected the students' learning objectives in the course and, therefore, centered on walking aids such as canes, crutches, and walkers. The cases reflect common pathologies and frequently used assistive devices. They provided an opportunity for practical application of the student's existing knowledge and skills in the new domain of 3D printing. By utilizing familiar content, we reduced cognitive overload.

The second session used the specifications provided in the table to fill out order forms (Table 2) that would be sent to the local makerspace where staff printed prototypes based on their specifications. Question five and question nine were added to this form based on feedback after phase 1. In the third session, PT students presented the first version of their designs to the class and had an opportunity to make final revisions by resubmitting revised order forms. In the fourth session, the 3D printed models were delivered and evaluated by the PT students.

3.1.2 Phase 2: Designing with End Users. For sessions five and six, PT learners were asked to apply knowledge from the first phase of the course to design AT devices for 12 volunteer end users (Table 3). Sessions 5 and 6 were incorporated into a course designed to teach advanced concepts of clinical care across patient populations, specifically, with medically-complex patient populations. In session five, the PT students were broken into 12 teams and assigned to do design and modeling sessions for a particular end user.

For these sessions, we kept the constraint of the maximum 5 by 5 by 5-inch dimension. Based on our observations from the first sessions, we reevaluated and refined the order form. The main changes were to add two questions: one regarding the physical properties and how the object should feel and one clarifying if this object was to be attached to another object. This final version of the order form (Table 2) was used to provide specifications to the community makerspace.

During this phase, students' groups had the option of using clay models to specify AT designs. If the group used clay models, they were left to dry and then brought back to the print shop for scanning using a NextEngine 3D Laser Scanner. Once the 3D model was captured and refined by the staff, it was 3D printed. Some groups had their designs printed based off of sketches and given dimensions through the order form. Before the final review session, all 12 teams were allowed an opportunity to make modifications to

Table 2: Questions from the Final Order Form Used in the Course

Question Number	Question Text
1	Client description: age, diagnosis, expected use of device, expected impact of device use
2	Object Drawing: Please provide a drawing of your final object design (with dimensions in mm).
3	Surface Details: Are there any decorative aspects (surface details) that are not important to your finished print?
4	Material (circle one): STIFF FLEXIBLE a. Please provide a detailed description for why your object should be stiff or flexible? b. Will this 3D printed object come in contact with your client’s skin? (Circle one): Yes/No c. If yes, please describe where the client will touch it, and how much weight you think they will put on it.
5 (not included in phase 1)	Will the 3D printed object attach to an existing object (circle one) Yes/No a. If yes, please describe that object and provide a drawing showing how the 3D printed part will touch the other part
6	Density (circle one): HOLLOW PARTIALLY FILLED SOLID b. How much weight will your object hold (e.g., in pounds)? How much stress will it be under?
7	Size: Should your printed object be the same size as your clay model? (Circle one): YES/NO c. If no, should your model be scaled up or down? (Maximum dimensions of 139mm x 139mm x 139mm)
8	Color: What color is your object? (Circle one): Black/White
9 (not included in phase 1)	Physical Properties: How should your printed object feel? Describe another object that has similar physical properties (strength/flexibility/texture)
10	Additional notes

Table 3: End Users Information and Description of Diagnosis and AT Design and Use Description

Case Number	Age	Need for AT	Expected Use	Expected Impact
6	56	Grip issues when writing with pencil	Increase size of pen/pencil	Decrease effort exerted while writing
7	74	Flexor Synergy	Increase left wrist extension	Increase wrist extension and decrease flexor synergy
8	68	No Diagnosis	To stabilize wrist	Help her type, eat, shower, use stairs
9	61	Cerebrovascular accident (CVA)	Finger extension	Improve left finger and wrist extension
10	66	Right stroke and left hemiparesis	To allow left hand to open and supinate restoring some function	Would allow user to restore some functional use with grip strength
11	78	Right CVA	Holding eating utensil	Achievement of goal of using left hand more
12	68	Decreased grip strength	To open caps and lids	Able to open jars and can independently
13	72	Severe bilateral collapsed arch	Daily in-shoe	Reduce pain by straightening ankle and supinate in his foot; relieve pressure on bone spur callous
14	70	Extension of right metocarpophalangeal joints and proximal interphalangeal joints	Assist with opening of right hand	Improve door opening and cooking
15	66	Lower grip strength and control due to stroke	Wear on wrist to improve grip on left side	Improved grip and steadiness
16	63	Stroke; flexor synergy	Extend fingers	More functional use of arms
17	61	Stroke	Help cut vegetables when cooking	Helps with activities of daily living

their models through the order forms again. When necessary, prints were brought back to the makerspace and modified or reprinted. Almost all of the communication was through the order forms or face-to-face with a minimal amount of communication happening over email.

The final session of the second phase consisted of the final review and AT delivery session with therapists and end users. During this session, 3Doodler Pens were provided to student teams for any final customizations. These pens allow users to draw a raised graphic using PLA filament on an object's surface. This allowed the students to quickly add small additional changes to their devices without any modeling or measuring. They could directly "draw" new additions onto their devices. Only a small number of groups (between 1 and 3) utilized this tool. They were also provided with extra components such as Velcro which is common practice to include with AT devices in the PT profession.

3.2 Participants

58 Physical Therapy (PT) students participated in the educational series. Sessions 1-4 were conducted during the Spring semester of their first year of the PT curriculum and sessions 5-6 were completed during the following Fall semester, correlating to the second year of the PT program.

Twelve end users also participated in sessions 5 and 6 of the series (Table 2). Finally, 12 youth (6 female, age range 14-18) staff members at the community maker space participated in the study. The youth had received training in 3D printing, 3D modeling, 3D scanning, and other aspects of digital fabrication (e.g., laser cutting) prior to this project and worked collaboratively on a part-time basis in the community maker space primarily on 3D printing tasks for between 3-12 months prior to this project. In this paper, we focus on data collected from the PT students and will discuss data from makers in the future.

3.3 Data Collection and Analysis

Our data consisted of PT student surveys to gain feedback about their feelings on 3D printing being integrated into their profession from both phases of the course, AT model order forms, AT design documentation, and observations of the courses by researchers. We have described the order forms and AT design documentation previously and, in this subsection, will describe the surveys collected from the students.

During the first phase, at the end of each session, the PT students filled out a survey. Each survey served to evaluate how each student felt about the different aspects of sessions. It helped to ascertain their reservations and expectations about the 3D printing process. It also contained their evaluations of the final products.

During the second phase of the course, because the PT students had already completed a similar process with simulated end users, only two sets of surveys were collected for this study. One was used to collect data about the student's experience in comparison to simulated end users as well as how they feel about 3D printing in their field overall. The other survey was used to garner feedback from the PT students and end users about the final products. Observations were utilized throughout both phases to capture verbal questions that the students raised throughout the course that were not reflected in the survey responses.

The data was analyzed using qualitative content analysis with an inductive approach, as well as thematic analysis [36]. All collected data was stored in a spreadsheet and coded according to repeated themes brought up by PT students. The themes were abstracted and labeled with a code. Fourteen different codes were used and identified. These 14 categories were used to identify six themes that addressed most of the topics brought up by the PT students.

4 FINDINGS

Our findings consisted of device design outcomes and PT students' feedback on their experience with the learning material presented in the sessions. We will first present end products that were designed by the PT students throughout the course followed by qualitative findings from student surveys and observations. It should be noted that in direct participant quotes throughout the paper, PT students refer to the end users as "patients" which is consistent with their educational context. However, we will use the term "end user" in our writing as it better reflects a social model of disability.

4.1 Device Outcomes

At the conclusion of each course, all 5 student teams from sessions 2-4 for simulated patients (case numbers 1 through 5) and all 14 student teams from sessions 5-6 for end users (case numbers 6 through 17) had successfully created customized AT designs (Table 4). Small changes were required in almost every case mostly relating to the attachment mechanisms or smoothness of the devices, as seen in Table 4.

Overall, the designs were successfully printed in large part due to the sketching skill of the PT students as seen in Figure 1. The PT students were able to provide incredibly detailed technical sketches with precise measurements to assist the makers in developing their designs. This skill from the PT profession allows makers to easily understand specifications needed in the end product. Figure 1 shows the sketch for case 2 that was the first step in the development of the printed device shown in Figure 2.

However, even with their sketching talents, PT students learned the value of iteration when some of the devices were unusable after their first order form. For example, the first print of their sketch in Figure 1 was entirely unusable, as seen in the left-hand image of Figure 2.

This failure was caused by attempting to use cheetah filament for printing. They originally thought this would be an ideal material because of its flexibility, but it led to the failed print. They had to re-evaluate their techniques to better align with the skills of the makers and the use case of their design and ended up with a successful product at the end of phase 1 as seen in the right-side image of Figure 2 by changing the filament type.

Despite all end devices being determined as successful, some devices, for example as seen in the top right image of Figure 3, were printed in such a way that they could not fully be used by the end user due to lack of fit. However, the devices in the top left and bottom images of Figure 3 were all more appropriate and fitted properly.

Table 4: Final product description and PT student comments on the 3D prints for imaginary (phase 1) and real (phase 2) users

Case Number	Product Created	PT Student Comments	End user comments
1	Custom fitting hand grip for a hemi-walker	Worried gravity effected their clay model and that the device wouldn't fit on the hand of a hemiwalker	N/A – simulated case
2	A bowl for someone to use a cane with their elbow	Worried it is not strong enough to be weight bearing	N/A – simulated case
3	Custom elbow splint that can attach to crutches	The overall size would need to be bigger to fit an adult patient	N/A – simulated case
4	Shoe wrap to improve balance	Side loops for the Velcro aren't big enough	N/A – simulated case
5	Forearm rest on a walker	It is only 70% of the size of their model so the dimensions are off and the clay model captured many imperfections	N/A – simulated case
6	Custom grip for pencil	Would round edges more if given time; would want a "squishier" material	He is hopeful that this will relieve the tiredness and aching in his hand allowing him to write better
7	Curved splint with holes for straps	Round the edges and cut more room for the thumb	N/A – did not share feedback
8	Wrist splint	Smooth rough edges; design change to hollow if given time	This will give her more confidence in holding the railing while going up stairs; needs smoothed for comfort
9	Finger straps to help increase flexibility	The fingers were not wide enough; wrong color	The stretch felt so good; needed to be smoothed for comfort
10	Wrist splint with holes for straps	Slightly too small	Too small and does not believe it can sustain enough pressure to pull him out of pronation; generally, very curious about 3D printing, however, and willing to try again
11	Larger handle that attaches to fork for eating	The angles did not match the design so it wasn't properly ergonomic	If the design is not correct in 8 weeks, he would be uninterested
12	Y-shaped handle that attaches to a jar that requires lateral force instead of twisting to open	The material needs to be more flexible and a hole needs to be drilled to attach a handle	She is hopeful that it will allow her to open all jars and bottles easily because that is tough for her
13	A shoe insert for heel	The material was too rough and there were concerns about breakdowns with continuous use	Looking forward to the potential pain relief; needs smoothed for comfort
14	Prints that fit over joints on the hand to allow for training to open hand wider	Smoothness was great just needed bigger holes for attachments	Really excited; exactly what she wanted
15	Cylinder weights that allow patient to strength build throughout their day	Better print than they were expecting	Comfortable and stable enough to wear and not interfere with his activities; ideas are worth printing as a prototype to see if the idea is feasible
16	Splint to assist in extending fingers	Need a hole for attachments	N/A – did not share feedback
17	Customized extended grip holder that can fit silverware	Need to adjust hole size for attachments	Exactly what was expected and she is hopeful that it will help her effectively cut fruits and vegetables safely

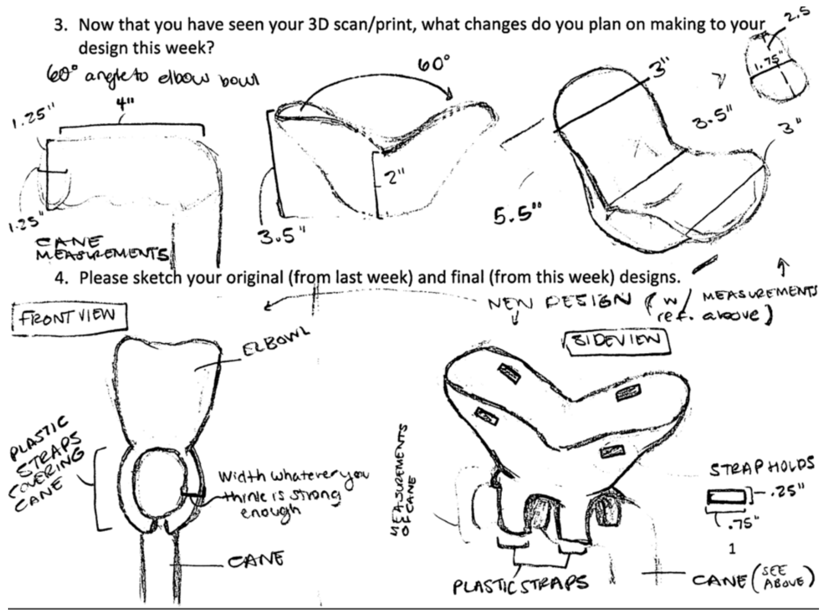


Figure 1: Example of sketching skills from Group 2 in phase 1 depicting a bowl designed to be comfortable for an elbow and attachable to a cane.

Figure 2: (Left) This image shows a failed cheetah print of an elbow bowl for case 2 in phase 1 and (Right) This image shows the successfully printed version of the image on the left.

4.2 PT Student Reactions to Working with Real End Users

After completing designs for simulated and real end users, the students filled out a survey asking for their opinions on the process. When asked to compare the experience to designing for simulated patients, most PT students said that designing with a real end user was helpful to their design process and led to more impactful AT device creation. For example, Student 24 stressed the importance of the relationship with the end user stating, "*I am more motivated to make an object that will really make a difference for my patient because I am forming a relationship with him.*" Furthermore, working with real end users made the process more meaningful in comparison to simulated users for the PT students and made them more motivated to produce successful results. Student 20 stated, however, that this added some stress by saying, "*There's more pressure! [You] don't want to disappoint. An emotional aspect has been added*". While many felt this emotional pressure, real end users helped the learning process. Student 33 stated, "*It is definitely more challenging working with a real patient but it allows us to get real feedback on things that will benefit the patient*", showing how feedback from end users was found to be very important. Many PT students also found

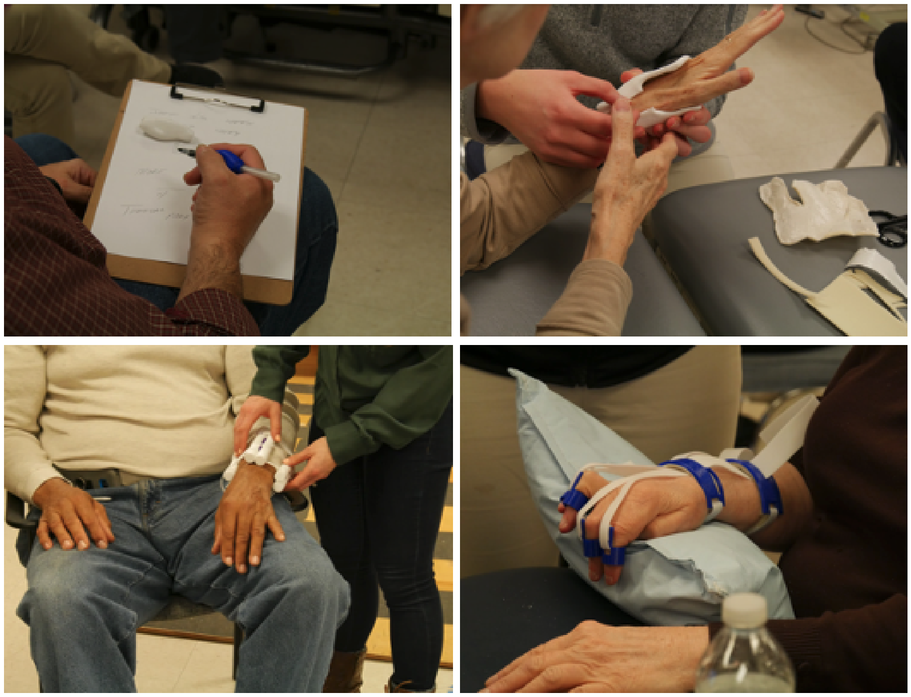


Figure 3: (Top Left) The pen grip designed for and being used by end user 1. (Top right) the hand splint designed and being used for end user 5. (Bottom Left) The strength building arm device designed for and being used by end user 10. (Bottom right) The device to train users to open their hand wider being used by end user 9.

that designing for real end users helped them to form a more realistic understanding about what designs could actually be created utilizing the methods that they were learning. Student 49 stated, "*Some things that seem functional or well designed in simulation don't work out or show flaws when applied to a real patient. Working with a patient shows how to create a more realistic design*".

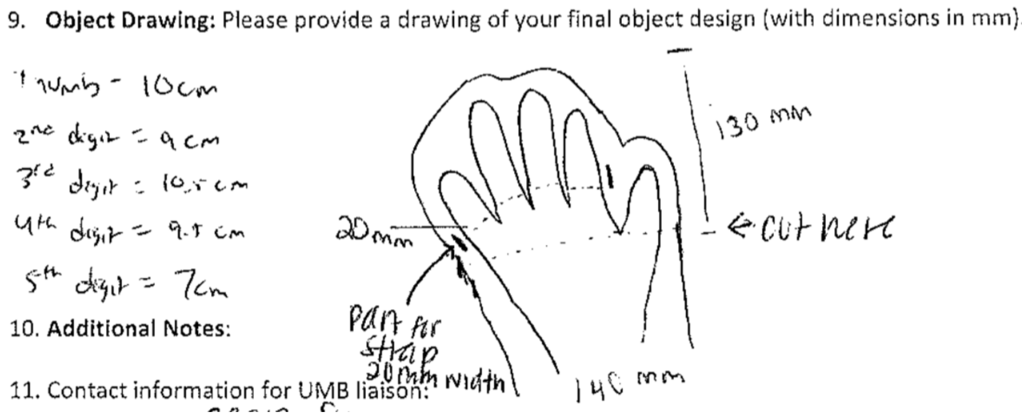
4.3 Challenges Experienced by PT Students Communicating with Makers

PT students identified a series of challenges in using both paper forms (Figure 4) and clay models (Figure 5) to communicate with makers. Many of these comments point to a need for face-to-face meeting and discussion with makers. While CAD was introduced to the PT students in initial sessions of the project, PT students found it incredibly difficult to learn how to effectively communicate about CAD designs in a short time. Therefore, all PT students relied entirely on drawings and clay models for the development of AT with end users.

With respect to the paper forms, most of the feedback pointed to not knowing the best way to communicate what needed to be done to the makers because of lack of personal connection and shared language. Student 2 stated after phase 1, "*It really seems like some groups benefited from having their design tweaked by a CAD program. So without a good working relationship with a computer engineer or a personal knowledge of CAD program this seems like a difficult and clumsy venture*". As seen in Figure 4, the forms contained places for drawings, measurements, materials, etc. but the PT students felt that the drawings and precise measurements were the most important. Student 2 stated, "*I don't think the designers were able to use our drawings, measurements, and written descriptions. I would like to have seen what could be produced by our written plans. If I had to guess, more views of the designed device may have been useful*". PT students also felt that face time with the makers would have greatly benefited them, student 19 stating, "*I think you just need to be as specific as possible. Maybe it would help to talk directly to the individual printing*".

A specific example of a communication breakdown can be seen in Group 4. This group's printed project had finger holes that were too small. A possible reason for this was because in their order form they simply gave a list of diameters in centimeters. Not only were dimensions asked for in millimeters, but they also never specified if this was to be in the inner or outer diameter of the finger holes. Their sketch is shown with these specifications in Figure 4 below. With this lack of understanding, the makers made assumptions that were incorrect.

We found that using clay for 3D modeling was a great way to engage the end users and provided an easy way to get exact measurements in the moment. However, there were major issues with digitizing the clay model and turning it into a 3D printed object. A major issue was the shrinking and deforming of clay models while drying. For example, Student 6 explained, "*I found that the clay was not super helpful in the transition to the 3D printer. The clay tends to lose its shape during the drying process*". There were also complaints about the surface issues created by scanning clay. When using


9. **Object Drawing:** Please provide a drawing of your final object design (with dimensions in mm).

Thumb - 10cm
2nd digit = 9 cm
3rd digit = 10.5 cm
4th digit = 9.5 cm
5th digit = 7cm

130 mm
20mm
← cut here
part for strap 20mm width
140 mm

10. **Additional Notes:**

11. Contact information for UMB liaison:

Figure 4: The sketch depicting a drawing of a hand with measurements for each finger hole that was provided by Group 4 to guide the makers in printing

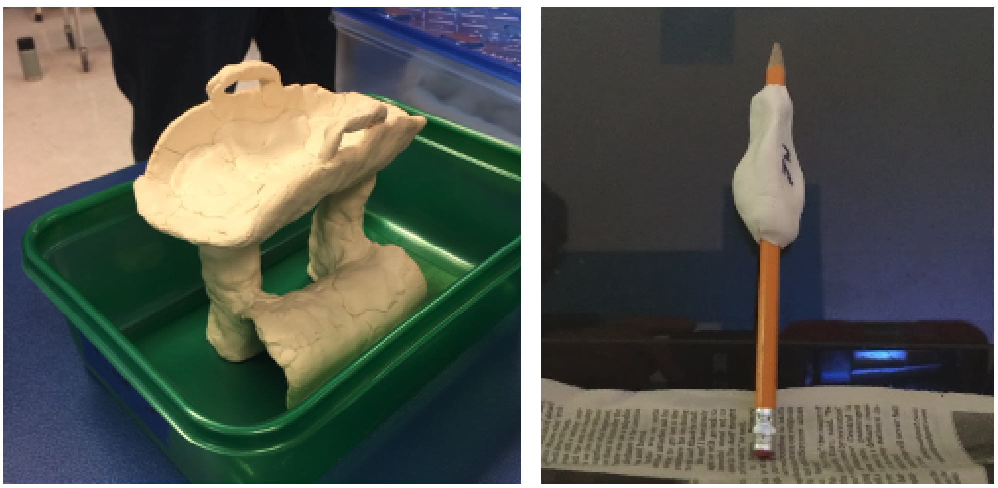


Figure 5: (Left) Clay model of an attachable device for a walker that has deformed slightly because of the method used for modeling an object that is heavy. (Right) A clay model of a pencil grip that has held its shape well because of the small dimensions and uncomplicated nature of the item.

clay, modeling smaller devices, such as the pen grip seen in the right image of Figure 5, were very successful because they did not suffer some of these deforming issues. Whereas bigger objects, such as the walker addition see in the left image of Figure 5, suffered from some of the issues with shrinking while drying. These issues led to measurements and sketches being the most reliable way to communicate their device needs.

Overall, we saw that while the paper forms and clay models each offered different possibilities for engaging PT students, end users, and makers but they had limitations that ultimately led to a lack of a robust shared language and communication approach. Because of the lack of face-to-face time and shared language, communication between the PTs and the makers required a large number of specifics communicated through the forms and clay objects. Some of the most successful products utilized multiple communication methods to develop exact specifications for the makers. The clay model seen in Figure 5 on the left-hand side can be seen in Figure 6 being used to generate exact measurements for a sketch on the paper form.

This combination of sketching, measuring, and clay modeling allowed the students to create a very smooth and successful final product as shown in the right-hand images of Figure 6. While the clay model deformation led to a product that was unusable, the sketching and modeling together helped to form a usable final product.

Overall, the PT students felt there was a disconnect between what they thought they were communicating to the 3D printer operators and what they interpreted. PT student suggestions to address this were to have more face-to-face time with makers, more frequent communication, and a better way to communicate. Another suggestion was that more knowledge of CAD might be helpful for

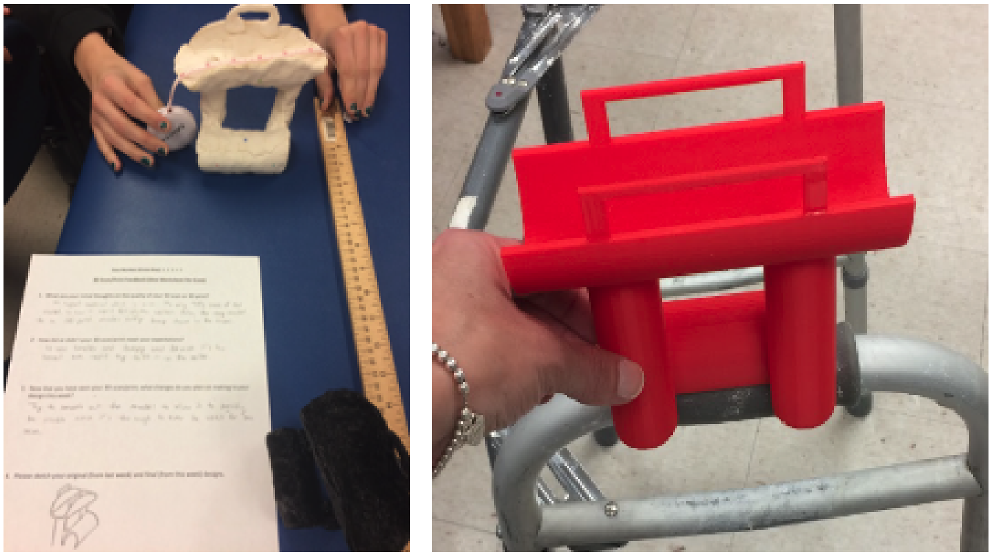


Figure 6: (Left) The failed clay model from figure 5 is being measured and used to create a detailed sketch also shown in the image. (Right) The final 3D printed item that is smooth and attached to a walker device.

communication. This lack of competency with technology also led to mismatches between what the PTs were imagining and what was possible to achieve with 3D printers.

4.4 Observations on Design Process

Several PT students identified the mismatch between the engineering design process and the PT clinical process because in practice, to get feedback for each design iteration, they would be required to have repeated end user visits. PT students observed that they felt it would be difficult to bill for multiple iterations of the same product or repeat visits for iterating on their design. Student 16 summarized the issues stating, "*The design process is very similar to the traditional engineering design process...time constraints and the number of available patient visits (insurance-wise) could be a challenging aspect of actually using 3D printing for devices for real patients*". The iterative nature of the making process is at odds with the time-pressured and insurance-run nature of healthcare. It led to some frustrations amongst the groups when they were not able to actually achieve their full vision. Some PT students offered suggestions about what might help ease this tension including ensuring that end users were more communicative in the short time they spent together. Student 7 stated, "*I think having a patient that explicitly states what they want help in will help in the creative process*". The lack of end user availability means that the communication between the PTs and the end users' needs to be informed and accurate the first time so that they are able to fully execute their design with the makers.

After being introduced to the concepts of 3D modeling in phase 1 of the course, many PT students had a moment of realization that the CAD modeling might be too difficult to learn on top of their other curriculum but that there are experts out there whose services can be leveraged. Student 18 stressed the importance of these experts stating, *"I've felt like 3D technology was incredibly useful for PT throughout all workshops. Seeing our failed attempts made me realize how detail-oriented 3D printing is and how difficult it can be. I've also learned that even though there's a lot of obstacles it most definitely is possible to perfect."* Perfecting technology literacy to facilitate communication with makers as well as ensuring that PT students are aware of the possibilities with 3D printing could be an important next step in furthering the potential of 3D printing in AT. Student 5 expressed that the knowledge of what is possible is an essential next step for the relationships between AT and making to flourish stating, *"Yes, it is a cool tool that we can hopefully use to help patients in the future. I would like to see examples of more products and become more familiar with items that are possible to see what works. The failed prints allowed us to see what doesn't work or what should be reconsidered."*.

After the course, we found an interesting difference between PT students in their knowledge of the prospects of 3D printing and how many materials were available. For example, Student 17 stated that, "*There are many materials available, which allows us to tailor our device to the likes of our patient*". However, Student 30 stated "*3D printing has limitations and I wish there were more options to incorporate other materials*". This mismatch in understanding of the availability of materials is an indication that there might be some additional information about materials that would be helpful to impart to the PT students so that they all have a full understanding of what can currently be done with this process.

4.5 Final Products and Appropriate Use Cases

PT Students provided detailed feedback on the process of using digital fabrication to develop and create AT devices. Many of them saw the potential but just didn't feel that the digital technology was where they needed it to be to make exactly what they wanted due to the difficulty of the software and the time needed to iterate and create projects. Some acknowledged the limitations of the technology but instead offered some solutions for them. Nine PT students had specific suggestions for appropriate contexts and how 3D printing could be used in the meantime. For example, Student 3 was very specific in stating, "*I think that 3D technology is most applicable for patients that require customization for the grip and fine motor control but not for general adaptive technology. For example, I think our elbow cup was not a good device to 3D print whereas the customized walker grip on case number 1 was ideal and patient centered*".

Multiple PT students brought up how the printing might have made more sense as an addition to already created devices. For example, Student 2 stated, "*Perhaps attaching the device to the cane would be more effective using some sort of commercially available hardware".* This could mean having AT on hand to build off of and specify from or printing something similar and then adding these customized components as Student 3 stated would be helpful, "*I think our device could benefit from a non-3D printed component to affix it to the quad cane. I would have liked to modify the AT in addition to just affixing the device – we really wanted to screw into the cane itself".* All of them said it was beneficial to have the old device with them for reference, usually along the lines of how Student 18 stated, "*I think [makerspace staff] having access to the assistive devices we used to make our design [would be] incredibly helpful".* Considering this feedback, it might be helpful to encourage an understanding of off-the-shelf devices for the makers so that they can just add additions to standards instead of having to create a device entirely by themselves.

Despite the challenges, 37 of the PT students expressed that they were excited to see where the use of digital fabrication in AT was going but not as excited about their current outcomes, with Student 49 expressing, "*[3D printing] will be more and more useful as printers and materials improve".* They seemed to believe that only significant improvements in technology could get them where they wanted to be in terms of designing items with 3D printing but saw the potential. For example, Student 56 stated, "*Your imagination is your limit".* Overall, following the course the PT students were able to identify what the shortcomings for this type of device development were and offered suggestions of how to make more appropriate projects.

4.6 Expected Material and Time Costs

The PT students were asked to share what they would be willing to pay for 3D printing services and the amount of time that they were willing to wait for the fabrication process to be completed. This question was not asking about the amount of time the PTs themselves would spend, but the amount of time they were comfortable waiting for a device to be printed. Twelve PT students said they would be willing to pay any cost for a device that was perfectly suited to the needs of their end user. Otherwise, they said that they would be willing to pay 40.81 dollars on average with the median response being 25 dollars. Student 56 who said there was no limit, stated, "*It could change our patients' lives. She said within minutes that the mid/stretch felt 'so good'. That is invaluable*". Of the PT students included, on average they said they would be willing to spend 345.34 hours with a median of 168 hours to develop these products. PT students generally do not have much formal education about the cost of customization and it is something they learn from real-world clinical practice. Therefore, the PT students did not have much practical knowledge on which to base these estimates.

End users also gave feedback on the amount they would pay and the time they were comfortable spending. Four end users stated that they would spend any amount of time necessary to have a custom device. However, most end users had a cost limit that was based off of previously paid for AT.

4.7 Liability Concerns

During observations, several PT students expressed concerns about liability issues stemming from the types of materials available to 3D print with. However, no students brought up liability in their written responses, possibly due to the format of our surveys. The questions brought up in the classroom were in regards to concerns about who is liable if these products were to break or injure an end user. In one survey, Student 46 also expressed fears about device failures due to materials and ill-fitting devices stating that in regards to 3D printing in PT, "*[Their] opinion has grown, but I feel specifics are very important to ensure a reliable print with limited failures. Failures could become costly for patients*". There was an apparent fear that the materials available were not exactly appropriate in the medical context. Though not much data was collected in regards to overall student opinions about liability, the concerns brought up by the students are valid and need to be addressed in order to fully integrate 3D printing into PT practice.

5 DISCUSSION

Conducting the course provided insights into the possibilities and challenges that exist when PT students, makers, and end users work together to use digital fabrication tools to create customized AT. We found that working with end users and outsourcing the fabrication was overall successful at providing PT students with an opportunity to utilize digital fabrication tools and techniques in their learning. Compared to previous work, where PT students learned how to use 3D modeling and printing tools [3], outsourcing the digital design and fabrication to a community makerspace addressed many of the issues PT students faced. By creating this connection between makers and PTs, our approach eliminated the need for either group to become experts in each other's fields. Instead, they developed a shared language to communicate their needs to each other. While our study showed that developing and effectively using this shared language is non-trivial, it is a promising direction and can equip all stakeholders with relevant interdisciplinary competencies. Outsourcing the 3D modeling adds an overhead of communication, however, and training clinicians in fabrication skills has value that needs to be balanced with other factors when outsourcing fabrication. Based on these findings, a promising future direction to focus on is developing training programs that provide both PT students and makers with a shared interdisciplinary knowledge and language that can be leveraged for using effective and efficient communication protocols. In the following subsections, we will discuss lessons learned from the educational series in more detail.

5.1 Involving All Stakeholders

A key aspect of our approach was including real end users in the second phase of the project. We found including end users effective at motivating PT students in creating functional and safe AT devices. After iterations, all AT devices designed in the sessions incorporating end users were evaluated as successful. Furthermore, PT students described working with actual clients as valuable, meaningful, and "real". While previous research has shown that clinicians have concerns about device safety and liability if injury occurs and if the materials used in digital fabrication is inappropriate for therapeutic or medical use [3, 5], we saw that these considerations were heightened for our participants in the later sessions of the educational series when they were working with real users.

To address concerns about safety and liability, AT project selection needs to be carefully considered. If a design case has the potential, if broken or used over time, to cause injury, the appropriateness of using 3D printing to create it needs to be approached with caution. In this study, the project that was the most successful was also happened to have the lowest liability (e.g., the pen grip). Working with real users can emphasize the importance of AT device safety, not only in the context of the PT classroom but in any context, such as online communities or community makerspaces, where digital fabrication methods may be used to create ATs. In the future, more input from PT experts on the type of ATs that are appropriate for digital fabrication could help inform future iterations of similar courses and programs, and also inform community DIY-AT efforts.

5.2 Developing Interdisciplinary Competencies

One of the key findings from our study was the need to develop an interdisciplinary shared language between makers and PTs. While in the final sessions of the course, all AT devices were evaluated as successfully designed, throughout the process, PT students expressed challenges in communicating the characteristics of the devices they designed to makers. Compared to previous research which required PT students to use CAD software and engage with 3D printing directly [3], our study facilitated the process of digital fabrication for PT students and allowed them to focus more on AT specifications through methods they are already familiar with (e.g., sketching and drawing on paper). PT students were very skilled and able to provide very detailed sketches to the makers. PT leaders are very hands-on and much of their training focuses on the development of psychomotor skills in manipulating objects with their hands. They were able to utilize these skills to make use of the clay for modeling as well. However, effectively communicating the design with clay in precise enough language to produce a perfect product remained challenging. This paper identifies smaller objects that are molded directly to a patient as more appropriate for clay modeling while large objects, especially with unequal weight distributions, were less successful and might be better suited for sketching and measurements.

These challenges can be addressed in the future in several ways: first, more detailed information about the fabrication and design process can be provided to PT students as part of the training. For example, a set of sample 3D printed ATs, including failed ones, can be used to demonstrate the possibilities and challenges of using these techniques for AT development. Conversely, an overview of common PT terminology used to describe and evaluate ATs can be provided to makers to help develop a common language. Makers would need to have an understanding of what off-the-shelf AT looks like and the basics of the PT practice in order to more quickly understand what they are being asked to create.

Second, a combination of digital and paper forms combined with a mechanism for continuous asynchronous communication (e.g., a Slack channel [37]) between makers and PT students can be established to provide detailed and frequent feedback on designs and fabrication iterations. These forms can provide a template with explicit fields for the most important measurements and descriptions. Another possible facilitator to communication could be creating a shared VR workspace that would allow the makers and the PTs to send CAD files to each other and interact with them in a more tangible way before printing.

Third, in line with what McDonald et al. also recommended previously, creating a base set of 3D printed AT designs to start from and build off, in combination with detailed documentation about each design's purpose, consideration, and possible variations would be incredibly beneficial [3]. In addition to capturing existing knowledge, this document can be informed by expert clinician and maker perspectives.

5.3 Leveraging Academic Training Programs to Connect Makers and Clinical Students

An important aspect of our project was to connect university PT training programs to community organizations. Our project provides an example of how community resources, such as makerspaces or other youth technical learning programs, can connect with university programs to form mutually-beneficial relationships. Our research team comprises experts in physical therapy, digital fabrication, and community engagement and the interdisciplinary nature of our collaboration as well as the range of resources and relationships available to use facilitated the design and implementation of the project. Several co-authors had a long-term working relationship with the community makerspace, and another research team member was a core faculty member, with lead teaching responsibility for the PT training program. Researchers and practitioners considering setting up similar future programs should consider the need for long-term relationships between all organizations involved and identify clear roles, timelines, and expected outcomes for everyone involved. In our case, working out these details were essential to project success.

While community engagement was central to our project, an alternative configuration can leverage the increasing number of universities that are creating makerspaces on their campuses [38]. These spaces provide ample opportunities for interdisciplinary collaboration across different academic programs, such as PT and engineering, and can be sites of AT innovation and development. Introducing engineers to the AT design process can offer meaningful and motivating experiences for different students in these programs and lead to more sophisticated designs that draw on skills from multiple engineering disciplines, for example to also add sensors to AT devices. Such collaborative programs can benefit by ongoing input from existing medical professionals in interdisciplinary roles such as Assistive Technology Professionals (ATPs) or experts who generally have both engineering and medical skills. Further collaborations can include connections with hospitals and therapy centers.

6 LIMITATIONS AND FUTURE WORK

This course was run with one group of PT students over one academic year and needs to be verified with more students in the future. The specific characteristics of the community makerspace that was staffed by trained youth may have impacted some of the project outcomes and in future work we plan to study how these factors may be different if collaborations are with other types of community organizations or digital fabrication services. The community makerspace we worked with was staffed by youth makers who while trained and knowledgeable in fabrication were not as experienced as professional industrial designers, engineers, or other professional fabricators.

Future work can explore how working with other organizations, for example makerspaces at universities or colleges or online professional services, such as Shapeways, would impact the process and outcomes. Given the PT student feedback on wanting to work with more materials and fabrication techniques, in the future, it would be helpful to collaborate with multiple makerspaces or fabrication facilities that may provide a wider range of options for the students to work with. For example, the use of thermoplastics or two-part modeling materials could alleviate some issues with clay shrinking.

Furthermore, this study took place before the COVID-19 pandemic and most design communication between makers and PT students was done through order forms or face-to-face. In future iterations of the course, the learned familiarity with online conferencing tools (such as Zoom) can potentially help to facilitate these interactions. For example, video conferencing tools can be leveraged to communicate about designs. This will be especially helpful in the future if individuals choose to design projects at a larger scale or that contain external components or perform mechanical functions.

A challenge of 3D printing in the PT classroom is that it is difficult to get end-users back for multiple iterative cycles, especially in this study as the end users were volunteers, many of whom had limited access to transportation and technology. Increasing the frequency of in-person visits would have created an undue burden on the volunteers and digital communication as an alternative would have been a challenge. In the future, we would like to explore facilitating more collaboration between makers, PT students, and end-users. We also plan to gather more feedback from all three stakeholders in order to get a fuller picture of the whole design process.

Finally, in this study, we worked with PT students rather than expert clinicians and while student perspectives provide valuable insights into what may be relevant in PT practice, inquiring into the perspectives of expert clinicians in the future can further enrich this research area.

7 CONCLUSIONS

This study has continued investigating the effectiveness of customized assistive technology developed through a collaboration between PT students and makers. It has demonstrated the potential for this collaboration as one way to address many issues encountered when attempting to teach PTs to design and fabricate these devices independently [3]. This study further worked to identify specific barriers to 3D-printing adoption in PT and some acceptable use cases. Specifically, we highlight the need to involve all stakeholders in the process of custom AT development and the need to develop interdisciplinary competencies to further facilitate this relationship. We also discussed an important finding in regards to the best communication methods for this design process. We highlight some cases in which clay modeling is the most efficient and in which paper forms and measurements are the most efficient method of communication. In all cases, however, we point to the importance of face-to-face communication is for makers and PTs and how these connections might be facilitated by universities. In the future, we hope to continue teaching 3D printing classes to PT students, as well as expand to a variety of medical professionals. We also hope to develop the tools and competencies needed to make 3D printing a seamless part of medical practice.

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