THE DESIGN JOURNAL
https://doi.org/10.1080/14606925.2023.2275868

User-driven product development: Designed *by*, not designed *for*

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ABSTRACT

The current state of function and design of accessible assistive technology is lacking, evidenced by low usability and high abandonment rates by people with disabilities (PwD). A significant contributing factor to these negative outcomes is a lack of user-centered design or user-opinion in the product development. The Human Performance and Mobility Maker Lab (HPML) at the University of Illinois Urbana-Champaign is a new facility dedicated to developing assistive technology by PwDs. Rather than being excluded from the design and innovation process, PwDs are the primary drivers of innovation at the HPML. The HPML's the central tenet is 'Designed *by*, not designed *for*'. The purpose of this paper is to explore various assistive technologies developed in the HPML while providing an empathic framework for other research groups to follow in integrating PwDs into the development and design of assistive technology.

Abbreviations: PwD: people with disabilities; SwD: student with disabilities; SwoD: student without disabilities; HPML: Human Performance Maker Lab; PwoD: people without disabilities; 3D-printing: three-dimensional printing; PPE: personal protective equipment; PURE: Personalized Unique Rolling Experience

KEYWORDS
user-driven design, empathy, industrial design, assistive technology

Introduction

Currently, there are more than 1 billion people with disabilities (PwDs) in the world with minimal medical cures available to reduce the many mobility limitations associated with disability (World Health Organization 2021). Disability can be understood as being both static and fluid, affecting a broad range of individuals in degrees of permanence and affect (Altman 2011). Researchers project the number of PwDs to grow globally by more than 25% over the

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next 10 years, in part because life expectancy continues to increase for PwDs coupled with an exponentially increasing world population (Guzman-Castillo et al. 2017; World Health Organization 2019).

The physical consequences of disability can be debilitating (Reichard, Stolzle, and Fox 2011). Fortunately, advancements in assistive technology and human rights services can enable PwDs to more fully participate in society and live functionally independent (Wilson et al. 2009). For this reason, the World Health Organization has recently begun promoting the development of novel assistive technology devices for PwDs through its Global Research, Innovation, and Education in Assistive Technology Initiative to improve functional independence among PwDs.

Assistive technology is defined as systems or services aimed at improving the functional status of PwDs. A subset of assistive technology, assistive devices can be defined as the external products whose purpose is to improve the functional status and well-being of PwDs (Smith et al. 2018). Extensive evidence supports assistive technology as physiologically, psychologically, and economically beneficial to improving the quality of life of PwDs (Squires, Williams, and Morrison 2019; Stumbo, Martin, and Hedrick 2009), however currently more than 600 million PwDs lack a proper assistive device such as a wheelchair or prosthesis to improve their functional independence. Despite a rapid emergence of assistive technology, PwDs express experiencing many challenges to finding the optimal assistive device for their individual needs (Santos and Silveira 2021).

A lack of knowledge shown by assistive device manufacturers in the personal experiences of PwDs has led to operative solutions, but unsatisfactory design outcomes. According to Melles et al. this lack of user-centered design and opinion in the product design is the primary contributor to the communal dissatisfaction felt by PwDs towards assistive technology (Melles, Albayrak, and Goossens 2021). Howard et al. also reported that a lack of user involvement during the design and decision-making process has attributed to the rates of product abandonment seen among PwDs (Howard et al. 2022). Currently, 20–70% of assistive technology are abandoned by PwDs soon after product uptake, with some of the most abandoned products cited as mobility devices such as wheelchairs, walking devices (Howard et al. 2022; Toro, Eke, and Pearlman 2016). As mobility devices may be some of the most imperative assistive devices for engaging in the environment and participating in the community (Cook and Polgar 2008), novel, more balanced approaches that integrate a PwD's perspective in the development process may more likely ensure that a PwD can reach their full potential.

The lack of assistive technology usability and long-term adoption can be attributed to improper fit, high costs, social stigma, and environmental barriers, among others (Howard et al. 2022; Pape, Kim, and Weiner 2002).

Fortunately, design methodologies have emerged to correct these attributional errors. Empathic understanding, grounded in people-inspired innovation and the lived experiences of real people has emerged as an effective method for developing usable assistive technology (McDonagh and Reardanz 2020). This process, which demands the design team goes outside their comfort zone and work alongside the target population, ensures that a deeper level of understanding of the target population's needs can be developed during the manufacturing of assistive technology (McDonagh 2015; McDonagh and Thomas 2010; Mercer and McDonagh 2021). By working alongside PwDs in a fully accessible infrastructure, stigmas associated with disability may be removed. Additionally, with recent advances in prototyping tools (i.e. CAD, additive manufacturing, costs associated with custom-made assistive technology can be greatly reduced (Gherardini et al. 2019). In clinical populations, the integration of empathic, user-centered methodologies in the development of assistive technology has shown to improve both usability, long-term adoption, and overall health outcomes (Kannan et al. 2019). However, for assistive technologies designed for everyday use by PwDs, evidence suggests that technology has not been adequately calibrated in an end-user focused way (Howard et al. 2022).

Even as other research groups have engaged in co-participatory design processes over the past decade (De Couvreur and Goossens 2011; Drain, Shekar, and Grigg 2018), current methodologies do not appear to have translated to the general population of PwDs (Howard et al. 2022). Investigation into methodologies by Drain et al. and De Couvreur & Goosens reveal that infrastructure issues and project narrowness may have prevented the generalizability of their practices. Drain et al.'s central focus into agriculture in Cambodia limits its range and reach to the general population of PwDs that are not living in a developing country or involved in agricultural occupations. Additionally, the overall environmental infrastructures associated with developing assistive technology in a developing country may have inhibited full participation by PwDs (Drain, Shekar, and Grigg 2018). In De Courvreur & Goosens' universal design study, assistive technologies were centered around 'DIY methodologies' and recreational devices (i.e. guitar slider, badminton shuttle, and ice-cream ring). While these devices may have improved the quality of life of the users directly involved in the project, these devices may not be translatable to the broad needs of PwDs like devices needed for enhanced mobility and/or physical function (Kumar, Rahman, and Krovi 1997).

In order to optimize the assistive technology development process and usability for the general population of PwDs, researcher developed an empathically-driven, immersive infrastructure (i.e. environment, administrative, social) that is not only designed for PwDs, but led by them. Researchers hypothesize that this practice, which included a fully accessible environment and administration, would provoke social integration among people with and without disabilities so durable, effective, and applicable assistive technology could be developed for the broad population of PwDs.

Human performance mobility maker lab

At the Disability Resources and Education Services (DRES) program at the University of Illinois at Urbana-Champaign (UIUC), the nation's first program to provide comprehensive post-secondary education to students with disabilities (SwDs), faculty, students, and researchers are exploring ways to better develop assistive devices through user-centered design. Rather than being excluded from the design and innovation process, at the DRES Human Performance Mobility Maker Lab (HPML), SwDs themselves are the designers and innovators of assistive technology and assistive devices (i.e. 'designed *by*' rather than 'designed *for*'). The Industrial Design degree programme at UIUC also plays a role within the HPML by actively recruiting students with disabilities into their academic programs to ensure their voices are heard and they are equipped to play a strategic role in product development. Out of the HPML, which was established in 2017, several impactful research projects and initiatives have been developed to enhance the lives of PwDs. The purpose of this paper is to explore work conducted in the HPML regarding assistive technology development and identify key elements contributing to the HPML's efficacy. This paper will also serve as an empathic framework for guiding other research groups to integrate PwDs within the development and design of assistive technology.

Empathic design research strategies

The HPML's mission is to create and maintain a welcoming, inclusive and empathic environment where SwDs and students without disabilities (SwoDs) work together to develop novel assistive technologies that will create functional independence for PwDs. It is considered by the disability community, that the majority of assistive technology products are lacking in aesthetic appeal and optimal functionality (Maia and de Freitas 2014). The HPML seeks to counter this attitude.

The HPML is housed in the Rehabilitation Education Center (REC), which serves as UIUC's hub for SwDs, and an inclusive space where students, faculty, and staff from across the UIUC campus can collaborate in interdisciplinary innovation (Figure 1). The HPML is fully accessible and uses an open-floor concept with strategically placed shelves and machinery so PwDs can navigate and engage in the space safely and efficiently. Within this disability-first workspace, comprehensive investigations into the authentic needs of

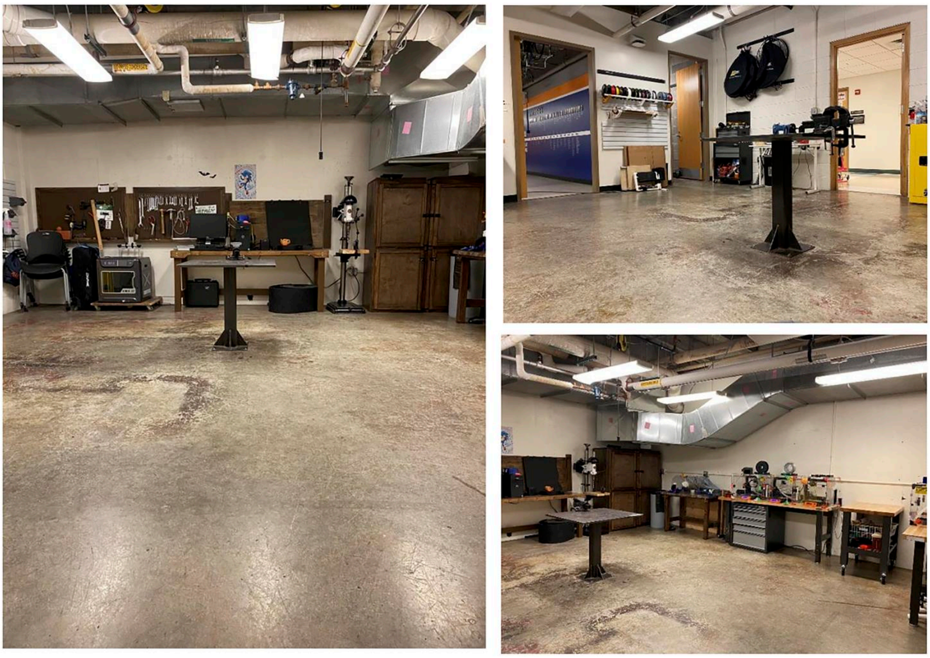

Figure 1. The Human Performance Maker Lab utilizes an open floorpan so wheelchair users can easily navigate around the space and work alongside their peers to develop assistive technology that enhances the lives of people with disabilities.

PwDs are conducted through interviews and focus group discussion and, more informally, through natural and organic conversation prompted by day-to-day interactions. In these discussions, all project team members contribute from their area of expertise to develop the most clinically appropriate (i.e. kinesiologists), mechanically efficient (i.e. engineers), and aesthetically sound (i.e. industrial designers) products, all grounded in PwDs' lived experiences (i.e. empathic design research). This integrative approach has led to a reproducible user-driven framework that lends to a continual creation of bespoke technology for PwDs.

Faculty and student collaborators from Engineering, Applied Arts, Health Sciences, and Business are notable innovators in the HPML, with project initiatives ranging from health and fitness technology to rehabilitation engineering. Figure 2 illustrates collaboration in the HPML between UIUC faculty and students from Industrial Design, Engineering and DRES (left image) and Paralympic wheelchair track athletes training on an HMPL-developed indoor roller in the adjacent to the United States Olympic and Paralympic Committee's (USOPC) National Training Site for Wheelchair Track (right image).

The outcomes of HPML initiatives have led to novel, ground-breaking technology in physical activity and health, pandemic-related supplies, accessibility, and ground-breaking human engineering. The participants involved

Figure 2. Human Performance Maker Lab (left) adjacent to the US Paralympic Training Site Facility (right).

in the development of the assistive technology are PwDs who are daily users of the HPML, ranging from 18–65 years of age. As previously mentioned, the lab is housed directly adjacent to the United States Olympic and Paralympic Committee's (USOPC) National Training Site for Wheelchair Track within the DRES Rehabilitation Education Center at UIUC. Finally, the HPML is directed by an individual living with chronic spinal cord injury. This is significant because it ensures that the HPML aligns with the manifesto: 'Designed *by*. Not designed *for*'.

Pilot projects

Bespoke racing wheelchair gloves

Three-dimensional printing (3D-printing) has played a major role in the production and manufacturing of previously arduous labour tasks (Petrick and Simpson 2013). A main initiative in 2018, the HPML implemented the design, development, and production of bespoke 3D-printed gloves, which is now the primary type of glove used by adapted sports wheelchair track athletes. Previously, bespoke wheelchair racing gloves were far less accessible and were developed by an individual using moldable, thermoplastic splinting materials, a process requiring esoteric knowledge of optimal build strategies and demanding precise craftspersonship (Willmott and Watts 2021). As such, access to optimized racing wheelchair gloves was determined by whether an individual had access to an expert builder, typically a veteran athlete with many hundreds of hours spent mastering the art of glove fabrication.

The HPML developed an easily replicable process that dramatically lowered the entry point of access to bespoke racing wheelchair gloves. Using a single measurement of hand width that is taken by the users themselves, each glove is custom-fit and personalized, produced in the HPML, and delivered to the user's home residence. The material cost of 3D-printed gloves is approximately 90% less expensive than the cost of moldable thermoplastic gloves, a cost savings that is passed along to the buyer. Equally important, 3D-printed gloves are up to 60% lighter than moldable thermoplastic gloves while being similarly durable. The savings in weight may aid in the prevention of shoulder pain and excessive connective tissue fatigue. Figure 3 illustrates athletes competing in wheelchair track at the 2021 U.S. Trials employing gloves developed in the HPML (top), ideation sketches used to develop a bespoke glove (middle), a pair of multi-material 3D-printed racing wheelchair gloves (bottom left), and an athlete training with a pair of these multi-material 3D-printed racing wheelchair gloves (bottom right).

Proper use of 3D-printed racing gloves requires special technique and coaching. Unfortunately, few coaches and resources are available to train adapted athletes in the proper technique. For this reason, the HPML has developed easily accessible webinars and on-demand videos that are publicly available to help train proper propulsion technique. These training videos are accompanied by printed instructional material and organized training plans to guide coaches and athletes during the learning process. If followed properly, it is projected that this educational material takes approximately 6-months to complete.

The impact of HPML's bespoke racing wheelchair gloves has led to several impactful partnerships, most notably with the United States Department of Veterans Affairs (VA). Working with the VA, the HPML is delivering bespoke 3D-printed racing wheelchair gloves with accompanied educational training modules to veterans and underserved populations with disabilities, facilitating greater ease of participation and access in adapted sports.

Indoor smart racing wheelchair trainer

The HPML has also addressed the absence of low-profile and affordable indoor training systems for racing wheelchairs. While readily available options for purchase exist for persons without disabilities (PwoDs), PwDs lack these options with respect to their adapted sports equipment. These indoor Smart Trainers made by companies such as Wahoo, Tacx, and Saris allow bicycles to be easily attached and provide variable resistance to riders, mirroring road conditions. In PwoDs, these applications have shown to increase adherence by removing barriers to accessing effective and fun workouts only offered at a fitness facility (Ramachandran, Bashyam, and Feldman 2019). For PwDs, who cite several barriers to accessing fitness outside of their home environment, access to an indoor adapted sports trainer has the potential to drastically improve this population's health. As several staff members of the HPML currently live with a disability and first-hand experience these barriers towards physical activity, they established an inter-disciplinary team to develop an affordable indoor training option for racing wheelchairs. This

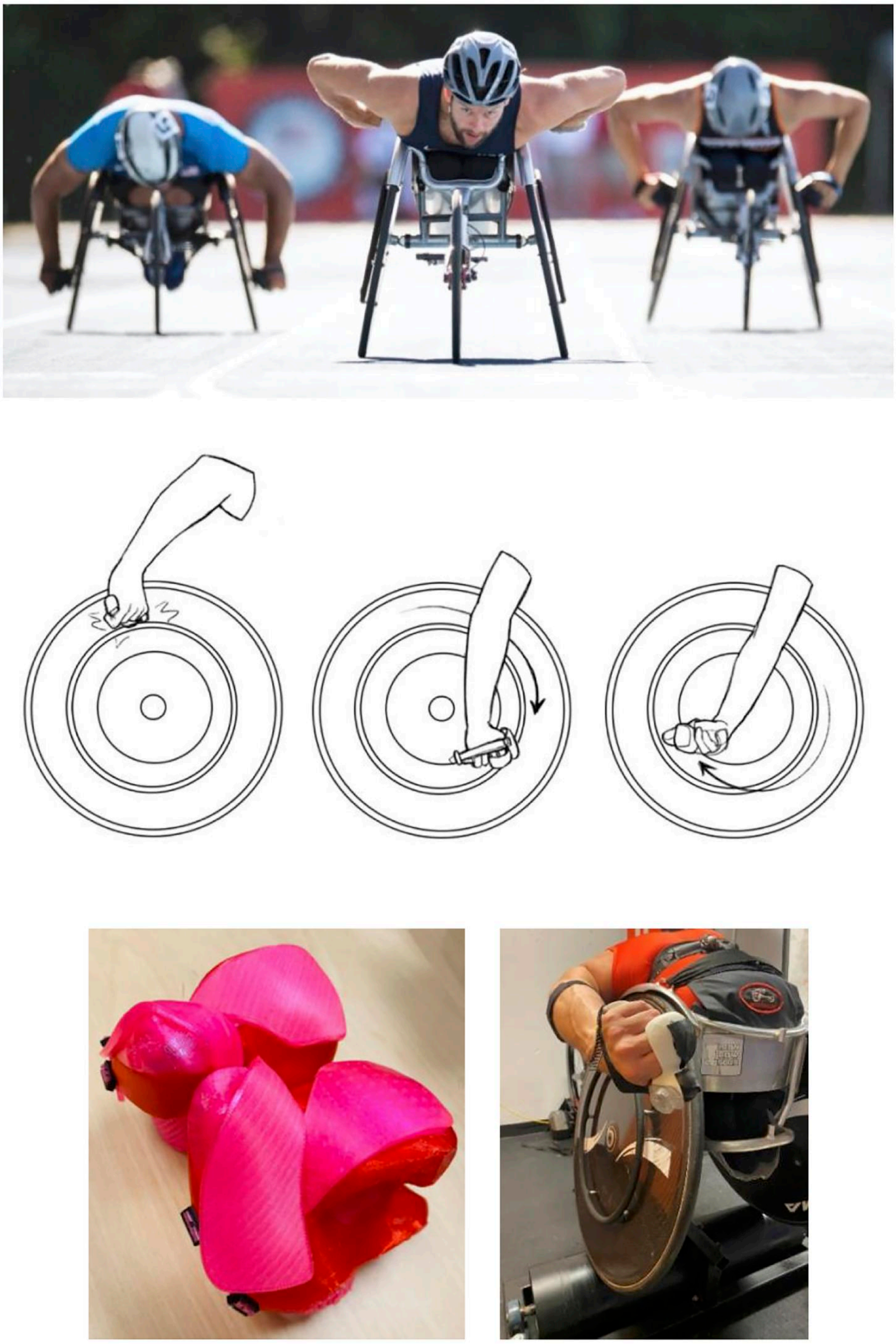

Figure 3. Athletes competing in wheelchair track (top), concept sketches used when developing 3D-printed racing wheelchair gloves (middle), a set of multi-material 3D-printed racing wheelchair gloves (bottom left), and an athlete training with a set od 3D-printed racing wheelchair gloves (bottom right).

collaborative effort between adapted sports coaches, engineers, and machinists retrofitted a load-generating flywheel coupled to a stationary free-spinning roller. The flywheel is controlled by a Bluetooth-connected tablet and allows the athletes to adjust the amount of resistance applied to the roller, replicating outdoor conditions such as hills and wind during indoor practices. Currently, ten of these assistive devices are utilized within the USOPC National Training Site for Wheelchair Track and have played a significant role in the development and improvement of elite wheelchair track athletes. Figure 4 illustrates the electromagnetic resistance flywheel adapted for use during indoor training by wheelchair track athletes (left) and an athlete using the smart roller during an indoor training session (right).

3D-printed personal protection equipment (PPE)

In early 2020, as COVID-19 was spreading across the United States, all work in the HPML shifted to assisting in the production of PPE. PwDs are a high-risk population, vulnerable to health complications caused by COVID-19 (Burns et al. 2020; Rodríguez-Cola et al. 2020), which was only exacerbated by the scarcity of PPE available to PwDs. As such, the HPML shifted all activities to the production of re-usable, 3D-printed masks that were designed to optimize respiration, prevent virus spread and reduce the risk of injuries to the face. These masks are flexible and composed of thermoplastic polyurethane and KN-95 grade filters (Azimi and Stephens 2013; Stephens and Siegel 2012). The HPML manufactured and delivered over 750 re-usable 3D-printed masks to PwDs across the United States from April to September of 2020. Figure 5 illustrates an off-the-shelf KN-95 mask (left) as compared to the

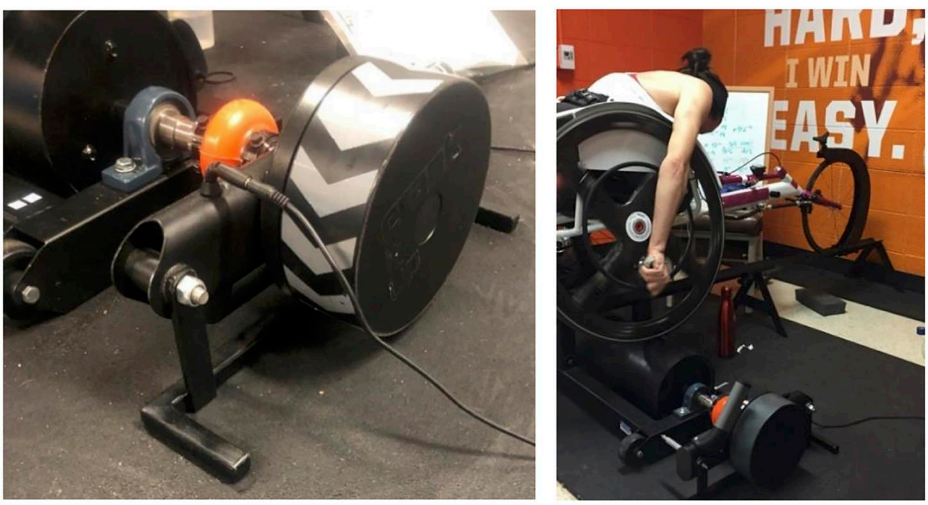

Figure 4. An electromagnetic resistance flywheel adapted and coupled to a free-spinning indoor roller (left) and an athlete using the smart roller while practicing (right).

Figure 5. A KN-95 mask (left) as compared to a reusable 3D-printed mask that was manufactured by the HPML and delivered to PwDs across the United States (right).

more comfortable, form-fitting 3D-printed mask that was manufactured and delivered by the HPML (right).

A wheelchair and mobility device accessible for travel

Although advancements have been made to improve the accessibility of travel and transportation (Leonard 2000), PwDs still face many barriers to an independent travel experience, especially during air travel. Currently, wheelchair users are forced to transfer from their personal wheelchairs onto a rigid straight-back aisle chair that is pushed by airport personnel to and from their seats. This current system strips all autonomy from the wheelchair user while also increasing his/her/their risk for pressure ulcer development during travel due to the lack of sufficient cushioning on existing aisle chair configurations (McClure, Nieves, and Kirshblum 2014).

To begin the process of enhancing autonomy during travel, the HPML is currently developing a lightweight, compact, and collapsible aisle chair that will allow wheelchair users to independently transport themselves to their seats. This chair will have the capability to be easily stowed under a seat and transported in a carry-on bag. Most importantly, the HPML aisle chair has the potential to give wheelchair users independence while getting on and off the airplane during a flight and better accessing bathrooms without needing the assistance of flight attendants. By integrating a seating design that uses soft fabric materials that should conform to one's body morphology, the

Figure 6. An individual transfers from airplane seat to aisle chair to move down the aisle and get off the airplane (left). The individual is not able to move independently and must rely on attendants (middle). A new design will allow individuals to easily carry and deploy a personal aisle chair for use, providing them independence while traveling on an airplane (right).

HMPL aisle chair may also reduce pressure at the buttocks and back and reduce overall risk for pressure ulcer development (McInnes et al. 2018).

Currently, this design is still in a proof-of concept phase and is projected to be available for commercial use by 2024. Figure 6 illustrates the current technology that is used to transport PwDs to and from airplane seats. In this image, one can observe how a PwD is forced to transfer and be strapped to a rigid seat by attendants who push the individual to the airplane seat. Figure 6 also illustrates our proof-of-concept design that is lightweight and easily stowable.

An autonomous wheelchair and mobility device system

Currently, HPML staff members are collaborating with mechanical engineers and designer researchers to develop a novel everyday mobility device for wheelchair users that does not require the use of one's upper extremities for human movement. The Personalized Unique Rolling Experience (PURE) is a seated, self-balancing ball-bot that can drive solely by trunk movements. PURE's unique design is discreet, minimalistic, lightweight, and safe, while offering users an organic, hands-free movement experience. PURE is being designed to be the sole mobility device used by daily wheelchair users as they navigate through their external environment and perform activities of daily living.

Currently, PURE is in its generation two (Gen 2) phase of development. Gen 2 PURE is a working prototype that has successfully demonstrated its ability to be used safely and effectively by PwDs *via* hands-free control. In a study of 12 novice riders, Gen 2 PURE was able to successfully complete indoor navigation tasks of increasing difficulty levels such as moving through narrow passageways and avoiding obstacles (Xiao 2022). In Gen 3 PURE, researchers intend to begin incorporating robotic motion controls to assist and regulate a user's input while controlling PURE. This innovative specification will enhance PURE's safety by providing its users with obstacle detection and avoidance (Xiao 2022).

HPML researchers believe that PURE's design and functionality will create life-enhancing opportunities while preserving long-term health and wellness. Its hands-free movement will reduce long-term overuse injuries to shoulders and wrists that result from manual wheelchair use. Equally important, its hands-free movement will open-up life experiences that are being compromised by the inability to grasp and carry objects during propulsion, activities like holding the hand of a loved one while on a walk. Finally, PURE's self-balancing technology may provide access to experiences and environments that are currently largely off limits for wheelchair users like accessing the soft terrain of beaches and uneven terrains of long nature hikes (Hoshino et al. 2016). Figure 7 illustrates both the design and functionality of PURE. Pictured from left to right, a 10% scale model of PURE and a sketch capturing the experience of a father engaging in hands-free movement.

Figure 7. 3D-printed scale model of PURE (left) and illustration of PURE's hands-free driving capability (right).

Perspectives through an empathic scope

By fostering a more empathic, user-driven environment within the HPML, UIUC staff, students, and researchers have sought to bridge many gaps in assistive technology and accessibility. In just 5 years, the HPML has developed novel assistive technology to enhance the lives of PwDs. These devices have related to physical activity and health, the coronavirus pandemic, accessible travel, and autonomous human-engineering systems.

Currently, PwDs represent one of the most inactive populations in the world (van der Ploeg et al. 2004). PwDs communally view exercise as unenjoyable and unproductive while available exercise applications and options for this population may not fully engage the individual or adequately enhance their health (Kehn and Kroll 2009; Totosy de Zepetnek et al. 2015). A variable-resistance Smart roller was developed in the HPML to counter these norms and outcomes. This assistive device has provided PwDs affiliated with UIUC with invigorating, adaptable, and performance-enhancing indoor workout options. The HPML has also manufactured and delivered novel adapted sports assistive technology and training methods to underserved populations with disabilities. While current evidence suggests that bespoke 3D-printed adapted sports equipment is usable among PwDs, future research will be able to examine the longitudinal usability of bespoke gloves in the veteran and underserved populations with disabilities. This feedback will be imperative to improve upon the user-centered designs and enhance future physical activity implementation initiatives of the HPML.

The use of bespoke assistive technology and remote training education also lends to the idea of novel assistive devices that effectively integrates technology and education together. For able-bodied individuals, fitness companies like Peloton have successfully integrated technology and exercise programming to develop online communities surrounding their indoor-cycling device (Berkowitz, Dzara, and Simpkin 2021). Unfortunately, PwDs do not have access to products that can replicate the Peloton experience. By integrating load-generating technology with bespoke 3D-printing and effective coaching techniques, the development of such a device for PwDs may soon be feasible.

Although the HPML staff initially used 3D-printing techniques to enhance adapted sports performance and increase access to customized sports equipment for PwDs, the coronavirus pandemic led to a transformation of the HPML into an additive manufacturing facility to efficiently develop PPE for PwDs. Utilizing existing frameworks developed by other university-affiliated 3D-printed groups during the lockdown (Advincula et al. 2020), the HPML effectively mass-produced PPE and provided PwDs with face coverings that reduced their risk for spreading the coronavirus. In doing so, the HPML demonstrated a flexibility to be responsive to users, prioritizing its work to be in congruence with their needs.

In response to frustrations shared by PwDs during air travel (Poria, Reichel, and Brandt 2010), the HPML has begun working on ameliorating flight experiences that may breach one's sense of autonomy. Whether it's navigating through airport security or through an airplane, PwDs may often be restricted to relying on inexperienced airport staff to help them navigate through an airport, likely leading to negative experiences. Like their able-bodied peers, PwDs should be provided the opportunity to independently transport themselves around an airport and airplane. The development of a lightweight, collapsible aisle chair may afford wheelchair users with this ability. As previously, the use of soft, conformable upholstery within the seating configuration may also reduce the major risks associated with pressure ulcer development during air travel in wheelchairs (McClure, Nieves, and Kirshblum 2014).

In the next few years, HPML's hallmark proof-of-concept idea, PURE, is projected to be available to consumers. The increased independence, access, and functionality of PURE has the potential to significantly enhance the quality of life of PwDs. Currently, wheelchairs are unable to perform simple tasks like texting or holding a loved one's hand during propulsion. PURE's custom design and revolutionary sensor system will provide PwDs with these abilities while also enabling them to access remote and confined spaces, long inaccessible to them.

The projects discussed illustrate how the HPML has positioned itself as an important model in disability-related assistive technology advancement and development. When considering the efficacy of the HPML – the why behind its success – we can identify key elements.

One such element is the HPML's location. The HPML is housed in a facility that serves as the University hub for SwDs. Because it is in the REC as part of the USOPC National Training Site for Wheelchair Track, SwDs pass through the HPML regularly, creating a design space in which disability is the norm rather than the exception. Advantaging this environment, SwoDs are integrated into the HPML through interdisciplinary activities such as formal independent study projects, ongoing research projects, and student organization initiatives. Departments from across campus – engineering, kinesiology, business, and more – merge into a single, shared space for innovation. According to McDonagh and Thomas, the use of a collaborative, empathic modelling and design process when developing a balanced and effective design team of users with and without disabilities can lead to the several innovative, yet usable assistive device prototypes (McDonagh and Thomas 2013). The HPML is the next-generation of this model and has elaborated upon its framework to take its many prototypes from proof-of-concept to real-life ideas and devices.

A second key element to the HPML's efficacy in assistive technology development is it's disability-first model. In contrast to many workspaces, the HPML's layout and organization is designed by wheelchair users to best suit their ease of use. As observed in Figures 1 and 2, the HPML exemplifies the primacy of an open floor plan so that barrier-free movement is ensured for wheelchair users. Stationary worktables are positioned against the walls away from the laboratory's main floor with mobile workstations on wheels that can be re-positioned as needed and easily moved out of the way when not in use. Lightweight, minimalistic office chairs are also utilized within the space that can be easily wheeled and stacked for storage. Third, wall space is extensively used to store sundry items, preserving open floor space. Finally, walls are partitioned and opened to allow easy traffic flow in-and-out of the HPML. These are features that allow ease of use by SwD and ensure that the flow of creativity and work is never inhibited because of architectural inaccessibility (Sukhai et al. 2014).

The ability to move tables and chairs on the fly to create an open space for PwDs provides a center point of gather for SwDs and SwoDs that is flexible and welcoming. Not only is the space used for direct design development where HPML staff and students work on assistive technology projects, it serves as a location for used to host group meetings, and a place where all can decompress and socialize. As previously mentioned, this inviting atmosphere encourages innovation through natural and organic conversation as SwDs and SwoDs seamlessly adapt to both working on assistive technologies and socializing.

The fourth element to the HMPL's success is its broad, campus-wide engagement. The community of collaborators who work together at the HPML possess a willingness to leave their silos of expertise and join a shared space that values diverse contributions. Equally, it is a community that perceives disability as a normal mode of living, free from stigma and paternalism. Rather than framing disability as a malignant characteristic to be overcome, disability is embraced and valued as integral and essential. This attitude permeates the HPML and is the fuel that drives each assistive technology project.

Limitations

Several limitations still exist within our case projects. Notably, 3D-printed gloves have only been reproducible for adapted sports participants with paraplegia. Minimal prototypes and designs exist for individuals with quadriplegia. Because many individuals with quadriplegia cannot open their hands for a measurement, our current measurement system is not applicable for this population. Future research may benefit from developing methodologies that can take moldable clay scans of a person with quadriplegia's hand size and morphological features and convert these scans into CAD renderings. While HPML staff members have attempted to develop these methodologies, they have been unsuccessful. In regards to the metrics that are able to be obtained from the indoor wheelchair racing roller system, our current devices can only provide users with speed outputs. In cycling-based sports the use of cadence and power have shown to be useful measures in improving performance and safety. Future research would benefit from developing algorithms within the flywheel that could capture useful metrics such as cadence and power. Third, our 3D-printed face masks were unable to provide support for people with quadriplegia that required sip-and-puff mechanism to operate their wheelchair and engage with their environment. Future research should find ways to create similar 3D-printed face coverings that can be operated by individuals that use sip-and-puff mechanisms to perform activities of daily living. Next, the overall weight of the aisle chair was heavy. In order to make sure that the device was sturdy enough to stably hold a PwD, heavy metal materials and high density 3D-printed materials were needed. The added weight added to one's travel supplies with this aisle chair may prevent PwDs from bringing this device with them to the airports. The additional weight could also put upper extremities at risk of injury during the transportation of the device. Future research may benefit from developing lighter and durable 3D-printing materials for the aisle chair. Similarly, current generations of PURE have proven to be heavy. In order to transport this device into a car, novel modifications to the device's infrastructure may be needed to reduce the weight. Future research may benefit from developing a ball-bot device that is able to be easily disassembled. With easy and intuitive disassembly, users may be more able to transport the device.

Conclusion

By systematically establishing a community of human-centered collaborators with expert knowledge from diverse disciplines (e.g. industrial design, engineering, kinesiology) to work within the heterogenous disability community as partners, the HPML has developed a best-practice framework for fostering an empathic culture that promotes far-reaching user-centered design and innovation. The result of such a framework is a collective of initiatives and outcomes in which assistive technologies are designed *by* people with disabilities rather than *for* people with disabilities, a shift in approach that is significant in that it provides agency for a group of our population that is often underserved.

We offer this reproducible framework as a guide, and we call for similar innovation laboratories to be established. What has been done in the HPML should not be perceived of unusual and serve as evidence that such a framework exists and can be employed as a basis for other labs—developed through empathic modelling—to be established. Living with a disability should no longer be perceived as a barrier to a high quality of life and/or independent living. The HPML is providing agency for a new generation of product developers that utilize diverse life experiences to design products that removes these currently existing barriers. It is our belief that having products designed by PwDs benefits the wider community, and ultimately will lead to more effective design outcomes for all of us.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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