"But, I Don't Want/Need a Power Wheelchair": Toward Accessible Power Assistance for Manual Wheelchairs

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ABSTRACT
Power assist devices help manual wheelchair users to propel their wheelchair thus increasing their independence and reducing the risk of upper limb injuries due to excessive use. These benefits can be invaluable for people that already have upper limb joint pain and reduced muscular strength. However, it is not clear if the way that assistance is provided by such devices is what manual wheelchair users need and expect. 12 manual wheelchair users were interviewed to understand: the situations in which they find it difficult to propel their wheelchairs; situations they considered paramount to have power assistance; their experience or knowledge of power assist devices; and likes and dislikes of commercially available power assist devices. Finally, they were asked to comment on their ideal form factor of a power assist device. Users have suggested improvements of the devices' accessibility and visualized new ways in which they could interact with the technology. These interactions involve "chairable" devices independent from, but not excluding, wearable devices and mobile applications. We have identified the need of monitoring emotions and the need for designing an open source do-it-yourself wheelchair propelling assistance device which we believe is required equally in developed and in developing countries.

CCS Concepts
• H.5.2 (Information Interfaces and Presentation) User interfaces: User-centered design, Prototyping
• J.3 (Life and Medical Sciences) Health
• K.4.2 (Computers and Society) Social Issues: Assistive technologies for persons with disabilities

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Manual Wheelchair; Power Assist Device; Participatory Design, Interviews, Assistive Technology, Human-Centered, Accessibility, Interaction Design

1. INTRODUCTION
The World Health Organization estimates that there are 70 million people that need a wheelchair worldwide and only 5% to 15% have access to one [57]. There are around 1.2 million wheelchair users in the United Kingdom [56]. A wheelchair user is a person that uses a wheelchair for personal mobility due to difficulty in walking or moving around as a result of different neuromusculoskeletal impairments [58]. Manual wheelchair users often injure their upper limbs due to continuous and excessive use. The incidence of shoulder pain is reported to range from 42% [13] to 66% [17], with the most commonly reported injury occurring to the rotator cuff muscles [1]. Bilateral carpal tunnel syndrome is also a common side effect of handrim manual wheelchair propulsion [6]. Those injuries can be prevented by reducing the frequency of wheelchair use, reducing the weight of both the wheelchair and the wheelchair user and adding a power assist system [31]. Injuries are thought to arise in part to the cyclical nature of the wheelchair push cycle [39, 47]. They are exasperated by the low gross mechanical efficiency of wheelchair pushing - only 10% of effort goes directly into making a person and the wheelchair move forwards [14] and this is when pushing along flat, smooth surfaces such as a hospital floor. On more challenging surfaces, such as ramps, side slopes and rough or loose surfaces (e.g. gravel) the push forces required are much higher [24], which increases the risk of injury.

There is broad agreement in the literature that using an electric motor to augment a manual wheelchair user's power, has multiple benefits. It reduces metabolic demand [2, 12, 22, 43], increases mechanical efficiency of manual wheelchair propulsion [5, 44], helps decrease repetitive strain injuries [11, 30-33, 36] and enables users to propel their wheelchairs for longer, farther [35]. In addition, people travel through places they never travelled with a conventional manual wheelchair [3, 34]. A power assist device attaches to a manual wheelchair to help the user propel the wheelchair. Power assist devices are typically installed in front, behind or replace the wheels hub. It is not a device that converts the manual wheelchair into a joystick controlled electric or power wheelchair.

We present the findings from the exploratory stage of a new project. The aim is to set the requirements of future manual wheelchair propelling assistive technology. In later work these shall be designed. The contributions of this paper include: (1) a review of previous work on power assist devices for self-propelled manual wheelchairs, (2) an examination of the current market of power-assist devices from a user and human computer interaction (HCI) perspective; (3) similarities between form factors of ideal power assist devices and (4) the identification of opportunities to improve the usability, interaction and user experience with power assist devices for manual wheelchair users.

2. RELATED WORK

Only three studies have explored the perceptions of pushrim activated power assistance by manual wheelchair users [18, 20, 26]. They each assess a different power-assist device: e-motion by Alber [54], Servomatic by Meyra GmbH [41] and one undisclosed device [26]. They found that 5 out of 12 users had a positive experience with power assist. In other study [18], users indicated that although the addition of power assist enabled them to have access to new activities, greater social life and less fatigue, the devices were still cumbersome, prohibitive in public transport and had battery problems. Guillon, Van-Hecke [20] found lower user satisfaction for e-motion in contrast with using a manual wheelchair and Servomatic. User satisfaction was also low for power assist devices during indoor use and while performing car transfers.

Only one study assessed three power-assist devices in terms of their performance against the standards of the American National Standards Institute and the Rehabilitation Engineering and Assistive Technology Society of North America available in the year 2008 [29]. These standards assess the safety, durability and efficacy of wheelchairs by testing: static and dynamic stability, braking effectiveness, maximum speed, maximum acceleration, maximum retardation, energy consumption, statics strength, impact strength and fatigue strength. The study was completed as power-assist wheels are an addition to the wheelchair frame and as such they must not adversely affect the safety, durability and effectiveness of the manual wheelchair. Through fatigue tests they found that the e-motion had the least estimated life years (1.3-2.3) in comparison with the Xtender (3-5). The e-motion was found to have "extraordinary" rates of failure, most of them related to the design of the device (weight, size, location within the wheelchair) [29]. Despite these failures the e-motion wheels are still a popular choice for manual wheelchair users in the UK.

Although a geared fully mechanical wheelchair wheel exists, it only has two gears which require undesirable sustained user's effort and greater time when ascending ramps [25]. The concept of a fully mechanical assistance device is desirable but it requires improvements in order to be able to compare against powered assist devices.

In conclusion, there has been limited work conducted in the area of power assist devices for self-propelled manual wheelchairs. In terms of interaction and overall user experience the handful of studies which have been conducted have all found failings in the current product range.

3. POWER ASSIST DEVICES OFFERED

We focused on the power assist devices that are available in the UK market. There are six popular power assist devices commercially available in the UK, all with price tags over £4k ($4.9k). Images of these devices can be seen in the supplementary information. These vary in the method they attach to a manual wheelchair. There are three attachment methods: (1) anchor to the frame of the wheelchair behind and below the seat, (2) replaces rear wheels and (3) anchors to the wheelchair frame below and in front of the seat converting the wheelchair into a tricycle. The SmartDrive [38] is the only one that attaches to the frame using method (1). The Twion [54], e-motion [54], WheelDrive [52] and Xtender [53] attach to the wheelchair using method (2). Batec handbike [7] is an example of attachment method (3). The devices also differ regarding their weight, their color, their modes of operation and accessibility features (Table 1). The SmartDrive and Pushtracker were recently released (December 2016), which promise to enable a better user experience through an updated wristband and a mobile application.

The expected user ability also varies among devices. All devices require good upper body stability and coordination of arm strength (apart from e-motion wheels). Any user with little residual or reduced upper limb strength can use all devices excluding the Twion wheels. Users with unequal arm strength can use all devices with exception of the Twion wheels and the WheelDrive. Regarding appearance, greys and blacks predominate. SmartDrive is black including its wristband. Twion wheels is offered in light grey with dark grey details. The Batec hybrid handbikes have hardware in black as standard with colorful frame options: red, orange, blue, green, light grey or pink.

Although power assist devices have been available in the market for some time, it is unknown how the users perceive these devices and if the current interaction with the user is what users expect and need.

4. PROCEDURE

Twelve manual wheelchair users, with different ranges of experience in using power assist devices, were interviewed individually for an average of 1.5 hours each using an in-depth, semi-structured method [8]. Users were recruited through a website, posters and the UK National Health Service wheelchair services. Eight were interviewed in person and four by telephone. A synthesis of the interview questions is:

a) When propelling your wheelchair, what issues do you have and what is your greatest need?
b) What type of journeys do you find difficult and why?
c) Which power assist devices do you know and which have you used before or use currently?
d) What do you think of power assist devices?
e) Under what conditions do you need power assistance?
f) How would you like power assist devices to work and what do you think they should look like?
g) Would you like the power assist device to give you information and if so, in which form and what?
h) Can you please describe your dream power assist device?

Questions were adapted depending on the experience of participants with power-assist devices. Interviews were transcribed and analyzed by the first author. An inductive approach was used, where the data was used to form codes and themes. Data was analyzed using thematic analysis akin to the approach by Braun and Clarke [8]. Themes and concepts were developed in order to interpret data; and to identify key concepts and relationships between them. Transcripts were analyzed iteratively until no new concepts emerged (saturation) [55]. A discussion and review of the themes was done with the second author. Thematic analysis was used as it enabled the creation of rich descriptions of the needs, expectations and form factors and to identify implicit and explicit ideas within the data, such as social and functional accessibility.

Table 1. Characteristics of power assist devices available in the market.

Device	Weight (Kg)	Accessibility features
SmartDrive MX2+ with PushTracker	6.1	Wrist band: senses movement, digital display of number of pushes and controls the device through inertial gestures. Mobile application to track push count, distance and time during assistance and no assistance modes. LEDs for battery status. Double tap on handrim and single tap activate specific responses from the motor. Double tap: start up or ramp up speed if already moving or slow down if already moving. Single tap: coast at current speed. Rollback prevention. Modifiable tap sensitivity, top speed and acceleration.
Twion wheels	6.3 each wheel	Handrim activated. Mobile application: track distance, battery status, speed, altitude, use GPS of mobile for visualizing journeys and remote control of unoccupied wheelchair. LEDs for battery status. Reverse assistance.
e-motion wheels	10 each wheel	Handrim activated. Wireless hand held control with a digital screen and buttons for adjusting device settings. LEDs for battery status. Rollback delay. Left/right power adjustment to different arm strengths.
WheelDrive	11.5 each wheel	Double hand rims. Outer rim assists while the inner rim provides continues drive. LEDs for battery status. Three levels of power assistance: low, medium and high. Reverse assistance. Battery can be detached for travel.
Xtender	17	Handrim activated. LEDs for battery status. Rollback prevention, downhill speed control and one arm drive possible.
Batec hybrid handbikes	29	Digital display panel and button controls. LEDs for battery status. Manual, hybrid or fully powered propelling assistance.

Table 2 Participant's characteristics.

User	Age (years)	Time using a manual wheelchair (years)	Power assist device use experience	Disability
U1	24	8.5	e-motion user for 2.5 years	Spinal cord injury (SCI), tetraplegia
U2	29	3.75	Batec hybrid handbike for 2.5 years, e-motion for 0.5 years	SCI, level C6
U3	37	1.16	Tested e-motion wheels and SmartDrive MX2 in a mobility shop	Spina bifida meningocele and hydrocephalus with SCI level C4/C5 and syringomyelia with SCI between T1 and T10.
U4	43	23	Tested SmartDrive M1 and emotion for a few hours	SCI, level L1
U5	69	0.75	Tested similar to Batec handbike for a few hours in a hospital	Spinal stroke, T11
U6	48	32	None	Spina bifida with carpal tunnel syndrome on both wrists for last 3 years
U7	44	11	e-motion for 11 years and M1 SmartDrive for a few hours	SCI, level C5/C6 complete
U8	21	16	e-motion for 3 years	Cerebral palsy
U9	59	2.5	e-motion for 3.5 years	Multiple sclerosis
U10	55	53	None	Post poliomyelitis syndrome
U11	36	32	None	Spina bifida, paralysis from waist down
U12	53	1.16	Tested e-motion wheels for a few hours in a hospital	SCI, level C3/C4 motor incomplete

5. FINDINGS

Although participants were of different ages, had different levels of experience using power assist devices and had different disabilities, there was a strong agreement in their responses regarding daily struggles using a wheelchair. We present these barriers as physical and non-physical. The individual form factors of an ideal power assist device showed similarities and offered an insight into individual preferences that could become ubiquitous forms of interaction with power assist devices. Differences in opinions were more evident regarding the way in which they wanted to interact or not interact with the assistance device.

5.1 Physical barriers

Physical barriers were identified in relation to the built environment, wheelchair propelling skills, non wheelchair users, weather, and the length of a journey in distance. Users had different strengths in their arms, thus the difficult situations they faced were at different levels and in different priorities. Challenging situations related to the UK built environment are: up and down level changes (curbs), negotiating rough surfaces (with gravel, cracks, gaps, broken pavement, cobble stones, thick carpets, park grass that hasn't been cut), potholes, door thresholds, side slopes, ascending steep inclines like ramps including those used in buses and trains (due to the need of power) and descending inclines. For example, U6 said *"on thick carpets you feel that you are sinking down and you have to do a special effort to move the chair"*.

Wheelchair skills that users found difficult are stopping suddenly and reversing. Regarding the length of their journey, wheeling long distances is difficult for every manual wheelchair user, regardless of the smoothness of the surfaces and the strength of their arms. Other people become a barrier when travelling through a crowd and having people crashing into their wheelchair accidentally. For instance, U4 pointed out *"it is not about the device, it is about how the world works and how unpredictable situations can be"*.

Weather poses challenges in autumn when surfaces become slippery with wet tree leaves or when surfaces are difficult due to dry tree leaves accumulation. Winter snow and frost were least mentioned. U3 said *"if it is wet it is horrible, I try not to go out if it is raining as it is difficult to get traction"*.

5.2 Non-physical barriers

Non physical barriers were identified as lack of awareness, incorrect understanding, lack of interest and the experience of emotion and it consequences.

The majority of users showed a lack of awareness of current technology available in the market and this added to the sometimes incorrect understanding of what the devices did. Similarly, lack of interest in understanding power assist devices was observed, signaling: a lack of interest in preventing repetitive strain injury as getting older, a lack of awareness of repetitive strain injury and a lack of awareness that handrim wheelchair propulsion is inefficient. Users that are interested in power assist devices appear to rely strongly on the experience and knowledge of other manual wheelchair users regarding wheelchair technology. For instance, U8 confessed to having thought that the assistance device would allow him to get fitter and then progressively he would have been able to return to use a manual wheelchair without assistance.

The experience of emotion is an additional barrier that manifests itself as physical pain. Stress and anxiety commonly cause shoulder pain which affects the user's ability to propel their wheelchair.U6 said *"at the moment my shoulders are quite sore but that is because of stress with the current season (Christmas), starting a new job, and setting up at a new desk"*.

All users agree that the cost of the technology is too high.

5.3 In which situations do users need power assist?

Most of the situations identified were to compensate for the barriers of the built environment. Adding power assistance is needed not only to wheel for longer distances and for a longer time; but also to be able to hold the weight of the user and the wheelchair down a slope for safety. Particular situations are: ascending (add power) and descending (rollback prevention) inclines, travel across side slopes, to complete an emergency stop (especially when the user has reduced arm strength and coordination), and rough terrain as mentioned in the previous section. Power assistance is also needed at the end of the day when tiredness is experienced. U4 said: *"I struggle with having to propel my wheelchair for long distances. After 2 hours you can notice aches and pains"*.

5.4 Social accessibility

Assistive technology that has a socially accessible design is a tool that conveys both ability and social identity. Social discourse is facilitated when the user's identity is not only functionally but also socially supported; acting as complementary dimensions [48]. This concept is supported by the users since they like power assist devices that conceal their function by integrating themselves within the wheel hub; as in not modifying significantly the general accepted appearance of a manual wheelchair. Assist devices which are easy to install and charge are also seen as likable. Upon the discovery of mobile applications able to synchronize with power assist devices, users expressed interest and inquisitiveness but caution. U2 and U12 expressed the importance of stability of the wheelchair with the power assist installed and gave greater importance to it over appearance. U1 said: *"I would have made them look nicer, closer to (what) a manual wheelchair looks like"*.

Other than the hybrid handbike, the color range of power assist devices are not an issue for users although one considered it either medical (grey) or "futuristic but old" like a "90's PC" (U2). U3 said *"the appearance of the e-motion is not best looking, it looks medical. I think they should be black. Being grey and white they look like a hospital. I think they should be able to come in any color"*.

5.5 Functional Accessibility

The main objective of assistive technology is to maintain or improve functioning thereby facilitating well-being through independence, dignity and participation in society [57]. In this paper functional accessibility refers to the capacity of assistive technology to maintain or improve functioning of its user.

Physical spaces are being modified or created in order to be accessible to wheelchairs, therefore users rightly point out that it is expected that chairable devices would not increase the width of their wheelchair to the extent that they can no longer travel through door thresholds or increase the weight of their wheelchair to the extent that they cannot propel the wheelchair with the device turned off. Power assist devices that have sensors installed on the handrims make these the weak and delicate feature of the wheelchair creating problems when someone handles the wheels from the handrim when boarding cars and airplanes. In general users are comfortable with the current battery duration and charging time required. Reported problems of batteries not lasting enough during the day are due users forgetting to charge the devices rather than a problem with the batteries themselves. However, some sealed batteries that cannot be separated from the hub of the wheels during air travel are not seen as practical. U4 said *"the downside of e-motion is that when you are flying the fact that the batteries are in built (you cannot separate the battery from the wheels), some airlines have problems with the battery being inside the wheels"*.

Power assist devices designs that are installed at the hub require the owner not to lift the wheels from the handrim in order to avoid damaging the sensors. Users fear that even family members fail to remember not to handle the wheels through the handrim, let alone strangers that want to be helpful but end damaging the sensors. This highlights a major design problem, where the user was not taken into account. Regardless of how careful the users themselves are with handling their wheelchairs and power assist devices, the power-assist devices are often broken by other people moving and lifting their wheelchair e.g. in taxis, airports and restaurants. As U2 said *"no one wants to have to grip the wheels by the tire where it is dirty and rough"*.

The hybrid handbike user expressed disappointment due to the lack of assistance when moving the wheelchair in reverse and that sometimes the motor provides too much power (even at the lowest power setting) creating a loss of control. Although vibration is expected when traveling at higher speeds, the hybrid handbike user finds such vibration disorienting causing occasional crashes. U2 said: "*I think I can manoeuver the obstacle but then I can't. The power is instant and is always there, even on the lowest setting, you can control the speed but it is not as fine as using your own hands."*

Regarding the PushTracker's option to track the number of pushes, U8 highlighted that the technology may affect self-esteem of manual wheelchair users if they start comparing their daily number of pushes while forgetting that everyone has different abilities. Comparing pushes among wheelchair users with different abilities is not only clinically invalid, but has potential for creating negative emotional responses when there is a significant difference in the number of pushes between wheelchair users.

In general users are comfortable with receiving assistance to hold the wheelchair while going downhill (such as with the SmartDrive).

5.6 Ideal form factors

We gathered the personal ideal form factors of each user and found similarities and differences. Similarities focused on the form of the hardware used. Functional requirements, including interaction methods, where differences arose, have been adapted into a range of modular options for the ultimate power-assist device. In offering a range of functional options we aim to make the power assist device accessible to users with different abilities. What we are not attempting is to suggest an ideal form factor that fits every wheelchair and suits every user.

5.6.1 Hardware

The ideal power assist device would attach to the user's most comfortable and favorite manual wheelchair regardless of the weight, size and type of rear wheels of the wheelchair. The power assist should be concealed by attaching it below the chair where it "clicks" into the axle powering the rear wheels through a mechanical transmission (Figure 1) just as electric bike motors. The feasibility of this design needs to be tested. Ideally, the battery also clicks below the seat where a concealed connection feeds the motor, a system similar to the battery of the WheelDrive. The battery can be a set of two installed below the seat on each side, but not on the back wheels, and these can be separated from the device for air travel. In this way, backup batteries can fit into a backpack, just like books. User U4 believes the ideal attachment weight would be 0.5 Kg without batteries and 2 Kg with batteries, which may only be achieved if the battery is separated into various components of maximum 2Kg each. Reducing the weight of the device will ensure that wheelchair users who drive a car will be able to lift their wheelchair into their car without having to detach the ideal power assist device and without additional struggle since the added weight of the power assist device would not be significant.

"At home, I could reverse the chair and click and it starts charging, then in the morning I just move forward unclick and go" - U3

5.6.2 Functions

All users expressed their desire to be able to control the amount of power the device provides, and this control should be through a concealed and easy to use interface "while on the go". Most users suggested having as a minimum three different power settings; one user suggested having an unlimited choice of power through a sliding or rotating control (comparable to a volume control). User (U1) suggested a control system that could predict the risk of tipping in order to be able to use the wheelchair without anti-tippers. Two other users also expressed a dislike for the appearance of the anti-tippers and their choice of not using them regardless of the risk of tipping over. User U2 suggested adding a downhill break feeding and charging the battery, to make it last longer. One user (U2) suggested an automatic change of power to the minimum level of assistance as soon as the battery reaches a certain low level, in order to enable the user to reach a charging point. This should be accompanied by a timely notification to the user. The way notifications are desired is covered in the next section. Users indicated that it is better to have an optional reverse downhill and forward downhill slow down settings (activated by the user rather than an automated feature), especially when using public transport ramps.

Users also agree that the use of a power assist devices should be intuitive rather than requiring the users to learn to use a wheelchair like they have never used one before. U1 said *"I would like them to work closer to what a manual wheelchair is like" and U4 said "a power assist device needs to feel part of the wheelchair rather than being something unpredictable"*.

U6 was interested in the device being able to remember the easy and the difficult journeys, a feature which is possible with current technology [21].

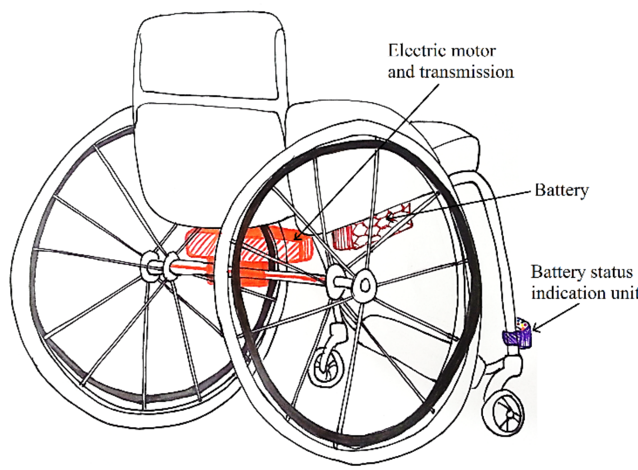

Figure 1 Sketch of power assist electric motor and transmission feeding the rear wheels through the axel. One battery on each side to distribute weight, only right battery visible on sketch. Also an alternative battery status indication unit, when the user cannot turn around to read LEDs on the back wheels hub or behind the chair, the unit is attachable to any part of the wheelchair frame.

5.6.3 Interactions

Eleven users were comfortable with the idea of interacting with the device through a mobile application. However, they stressed the importance of having the flexibility of not having to access a mobile device to setup and use the device, but having the opportunity to do so. Thus the use of smartphones was perceived as inaccessible for some manual wheelchair users. U5 said "*I am not sure I want anything that operates with my mobile phone, unless I have a third hand" in contrast with U8 that said "like my phone recognizes my voice, I would like to be able to speak to my mobile phone or directly to my power assist in order to change settings on the go"*.

One user suggested using a portable Raspberry Pi computer [45] with a small interface that could be attached to any part of the wheelchair frame to control the device without the need of a smartphone (U4). This additional interface could look like and be installed just as the battery status indication unit in Figure 1. U6 suggested tactile buttons below the seat, accessible in between the knees for quick and easy power and speed settings control and on/off choice. Thus, users appear to prefer both a primary and secondary ways of controlling and setting up their ideal power assist devices, where one of those ways does not require them to have and use a smartphone with an application.

"I would like some sort of touch identification, or recognize the person sitting on the wheelchair. Identifying me and then automatically activating my preferred settings" - U8

Most users are interested in being able to track wheelchair pushes and have a mild interest in being able to set a fitness program (desired pushes per day). U3 said "*I would also like the device to help me remain fit, be able to tell the device how many pushes I want to do, to not get lazy. Being able to set up a program".* U4 suggested being able to monitor the correlation between the number of pushes and shoulder pain, in order to receive a notification before becoming too tired and getting pain. This could be possible with a learning algorithm. U4 said *"maybe I can have an app on my mobile and after I have used the device at the end of the day I can indicate to the app how much pain I had that day".* Similarly, we identified an interest in knowing the amount of effort they put in versus the work done by the power assist device.

Regarding data, users would like to be able to fully customize notifications, warnings and reports in order to suit their interests, including having the option to turn off all notifications. Data they indicated an interest in are: time and distance travelled, number of pushes, power provided by the device, battery status in percentage or LEDs or a coating or thin film installed on one handrim that changes color according to battery level (Figure 1), distance and time that can be travelled with the current battery, heart rate, calories consumption and global positioning system tracking not relying on a smartphone. U8 indicated that the power assist device could include GPS and keep track of the location of the user in order to provide suitable weather forecast and transport information, not only during the morning when starting the day but also throughout the day. U10 and U12 were interested in being able to record a journey and then indicate to a mobile app synchronized with the power assist the destination (user input), they then expected confirmation or rejection of the proposed journey depending on the battery status (sufficient or not to complete a single or return journey; and recommended charging time required if rejected).

Optional detailed reports on effort, journeys and comparisons would also be interesting. Most users indicated that they would like to have more information regarding the battery status, such as a percentage in addition to the LEDs. One user (U7) would like the device to be able to identify the propulsion pattern [50] and notify if the incorrect one is being used. Current technology can identify propulsion patterns [23].

The handrim tapping gesture sensed by the wristband (Table 1) available with the PushTracker of the SmartDrive MX2 is a HCI feature that was thought provoking. Suggested improvements to the PushTracker were the addition of gestures (up and down movement with palm facing down and frozen wrist) and voice notifications from the device to the user.

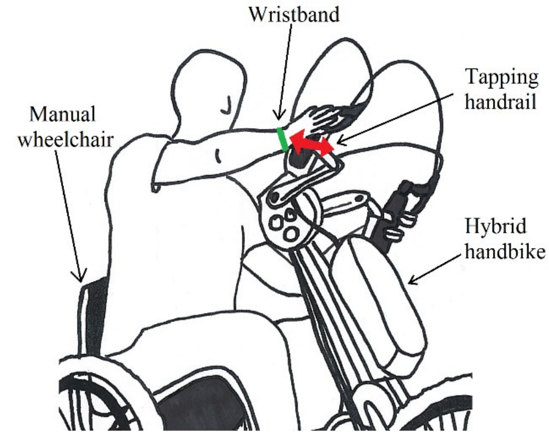

Figure 2 Sketch of tapping gesture on the handrail of a hybrid handbike being detected through a wrist worn device.

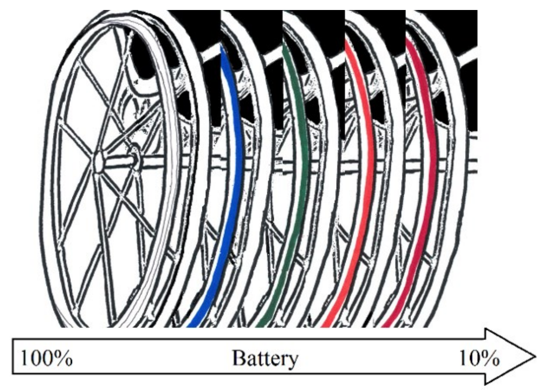

Figure 3 Sketch of battery indication option when user cannot turn around to read LEDs on the back wheels hub or behind the chair, thin LED film covering the handrim changes color according to battery status. Suggested by U8.

U10 and U12 suggested being able to interact with a handbike through a wrist band, just as the SmartDrive does with the PushTracker. U10 suggested the gesture of tapping on the handrail of the handbike to increase/decrease the power when negotiating inclines – wearing a wristband for detection (Figure 2). The suggestion of providing a smartphone docking area between the handles of the handbike was appealing to most users, given the ease of access to on-screen interaction possibilities such as: battery status, changing power assistance, switching between manual and hybrid modes and also keeping track of their other applications such as social media.

U8 also pointed out that there is generally the assumption that manual wheelchair users cannot move their legs, but with certain disabilities this is possible and in his case he considers possible and desirable to have the option to propel the wheelchair or control the power assist device through his legs and feet.

5.7 Summary of findings

Table 3. Summary of findings.

Physical barriers	built environment, wheelchair propelling skills, non wheelchair users, weather, and the length of a journey in distance
Non physical barriers	lack of awareness, incorrect understanding, lack of interest and the experience of emotion and it consequences
Needs	compensate for the barriers of the built environment, power assist devices that preserve socially and functionally accessible
Expected Hardware	concealed below the wheelchair, lightweight, attach to the user's chosen manual wheelchair regardless of its weight, size and type of wheels, optional backup batteries
Expected Functions	control power like volume, tipping risk prediction, downhill break feeding battery, automatic low power set at low battery with notification to user, user selectable downhill and forward downhill resistance, intuitive, location and journey tracking with intelligent journey memory
Expected Interactions	mobile and no-mobile app control options, portable Pi computer attached to wheelchair frame, tactile buttons below the seat for speed, power and on/off control, track wheelchair pushes, distance travelled, set fitness program, pain tracking, statistics of user work versus power assist, customizable notifications, warnings and reports, battery status in percentage apart from LEDs or visually interactive on one handrim, smart weather forecast and transport information based on location, journey feasibility prediction based on battery status, propulsion patterns identification with notification to user, handrim tapping gestures

6. DISCUSSION

We interviewed manual wheelchair users with various levels of experience using power assist devices. To our knowledge, this is the first study exploring the user's perceptions and expectations on power assist devices for UK users and the most recent after a previous study published in 2010 in which manual wheelchair users were interviewed after they used only the e-motion for 6 weeks [18]. The results of this study offers suggestions regarding different devices and interactions that could be prototyped and tested through participatory design workshops with manual wheelchair users. This study has shown that there is a general lack of awareness among users of the existing devices in the market and the literature that has tested and evaluated their designs and performance.

Manual wheelchair users work very hard and for long periods of time in order to develop and acquire wheelchair skills that help them negotiate inaccessible built environments, which prevail [40, 46]. During this process they also become so familiar with their wheelchair that it becomes part of them, as indicated by the users interviewed in this study. Users have stressed that an ideal power assist device would attach to their current and favorite manual wheelchair, preserving its current width, appearance and blend in with their wheelchair skills. Rather than forcing them to get a new wheelchair and learn to use it again. User's experience with power assist devices have meant that they have had to learn to use the wheelchair in an entirely different way, like if they have never used it before, especially with the e-motion wheels. Most power assist devices claim to offer assistance during everyday tasks; but in reality they offer assistance under their own conditions, which are frequently not representative of daily situations faced by manual wheelchair users.

The presentation of the outputs given to the users need to be improved, in particular outputs that do not require the user to take out a mobile and access an application. Alternatives to prevent the need of a "third hand" to handle a smartphone while propelling a wheelchair are needed. A possible chairable output and input device [10] we suggest is a thin flexible film LEDs or organic LED which combine touch sensitivity with luminosity [37], which could be attached to the wheelchair frame. Even greater interaction possibilities are possible as the assist devices are already detecting force which could be displayed to users to indicate effort or be used to activate/deactivate features. Another chairable device that power assist devices require is miniaturized network of sensors that should be able to sense the environment, for instance to identify the roughness of the surface travelled and be aware of people and other wheelchairs (to prevent unplanned collisions).

The results show that most users wish to maintain the social accessibility [48] of the wheelchair by preferring power assist devices that have minimal impact on the generally accepted appearance of the manual wheelchair. Evidently, there are users that give priority to functional accessibility over social accessibility, as seen in this study. Existing technology in power assisted bicycles could serve as a reference in order to create a power assist device capable of rotating the wheels through the axle and adding regenerative braking [19]. The alternative of propelling the wheelchair through the residual strength of the lower limbs is also possible [51]. Although some people and demographics (e.g. young adults) have suggested chairables, such as the LEDs on the handrim and clearly find these socially acceptable, these suggestions may not be the case for everyone [49]. Generally, personalization is an important factor in acceptability and one which requires further investigation.

The lack of will or motivation is a non physical barrier for wheelchair users that has been identified before [40]. Affective disorders (anxiety, depression, etc.) can cause muscular and joint pain and lack of attention to their immediate environment, which consequently can reduce the manual wheelchair propelling ability. Affective disorders can also cause apathy and carelessness which can put at risk the maintenance of the assistive technology. For instance, although there is no technical problem with the battery of power assistive devices, some users forget to charge the device overnight or not take care of delicate parts as they would when feeling positive and motivated. The technology to monitor the sympathetic nervous system and identify stress, arousal, engagement and excitement already exists [15]. We believe that power assist devices could be more responsive to the mental and physical status of the user and provide assistance not only based on requested power, surface roughness travelled, heart rate and fitness level but also based on the current affective disorders.

Seven interviews were performed before the announcement of the MX2+ and PushTracker on December 2016. It incorporates some of the most interactive features ever seen in power assist devices such as a wrist worn device that works as a Fitbit [16] but modified in order to measure wheelchair pushes and other mobility actions. These are similar to the latest Apple Watch Series 2 [4] but with the advantage of being less power hungry. The MX2+ can also synchronize with a mobile application in order to track mobility activity over time. However, since the release of the PushTracker, users have had problems regarding the battery consumption of the PushTracker wristband (battery lasts 3 hours only) and with the Bluetooth connectivity from the PushTracker with the SmartDrive (extending the arm wearing the wristband, 10 to 15 cm away from the wheelchair cuts connectivity and the SmartDrive turns off) [42]. Therefore, the promised user interaction features are not living up to the expectation due to battery and Bluetooth connectivity issues caused under the normal shoulder range of motion. These could potentially have been mitigated by more of a participatory design approach to the technology, including user behavioral analysis. The SmartDrive MX2 and PushTracker has been released in the UK since March 2017, where possible, we recommend a detailed user study of this device.

Generally, user behavior analysis with biomechanics and participatory design would enable the identification of current or new ways in which the users interact with the technology. These should take account of cultural factors. For example, European wheelchair users use public transport (buses, trains, metro) more frequently than cars, whereas areas of the USA would have high car usage. Therefore assuming wheelchair users in Europe frequently ascend multiple ramps and make longer journeys to get to and from the public transport options, they may have a greater need for power-assist and are at greater risk of shoulder. Thus, the results of this study should be interpreted in the context of a public-transport centric city.

There are still HCI features that could be improved upon and other major design features which require a rather urgent redesigns (delicate handrims, hub-installed power assist devices, and heavy hardware). Recent technology could enable the distribution of the battery “body” by dividing it into smaller cells and allocating it along unobvious surfaces of the wheelchair, for instance, below the seat [28]. Some wheelchair users, when pushing the handrim, may push off the wheel rather than parallel and forward to the wheelchair due to reduced muscular force control. In these cases, gestures read by a wristband will need to offer alternative calibration for those gestures that the user is capable of performing. Similarly, people with a SCI very often have a combination of muscular weakness, spasms and lack of feeling, which may interfere with articulating inputs through a wristband. Learnings from this study are transferable to other assistive technology. For instance, reducing the weight of any chairable device but also accounting for the need of robustness and personalization.

Beyond the individual form factors presented in this study, we believe that an ideal power assist device would affordable and consist in a mechanism that can be installed below the wheelchair seat or behind it or in front of the wheelchair mounted on a handbike. With traditional tools and 3D printers, manual wheelchair users should have access to well explained, open source DIY alternative attachments that they could produce as they are or modify them to their needs. This information could be readily available through DIY online communities such as Instructables, Thingverse and other online blogs [27]. Low cost solutions have been developed for interacting with wheelchairs [9] but we could not find anyone designing a propelling assistance device that can be either fully mechanical or powered, that can keep its production costs low, be reparable by the owner, adaptable to individual needs and preserve the socially accepted appearance of the wheelchair. A high quality, low cost propelling assistance device would not only enable a greater number of wheelchair users in developed countries to increase their independence, but also those users in in-development countries.

7. CONCLUSION AND FUTURE WORK

In this study we have explored the physical and non-physical barriers that manual wheelchair users face when propelling their wheelchair. We have also identified specific situations in which users consider power assistance paramount and the social and functional accessibility of the power assist devices currently available in the UK market. We discussed similarities found among form factors of 12 individual ideal power assist devices. We have described a system that is installed below the seat of the wheelchair and that enables the detachment of batteries. We have also gathered previous literature and users experiences regarding the methods of attachment of power assist devices and found evidence that strongly points out that power assist devices installed at the hub of the wheels suffer from fatigue failure, are too heavy and fragile for daily use. We encourage power assist designers and manual wheelchair users to give preference to devices that are either installed behind, below or in front of the wheelchair.

We present opportunities to design outputs for users of power assist devices and improvements to be made to the current user interfaces such as implementing hand gestures with existing wristbands. Most users are comfortable with wearing a wrist band to control the device and interact with mobile applications. But chairable input and output devices that allow users to control the wheelchair power assist device without the need of a mobile phone or a wearable device are required. Power assist devices that enable interactions through mobile phones and wrist worn devices are starting to appear in the market however they require improvements in terms of battery capacity and Bluetooth connectivity.

Our suggestions included the identification of a great opportunity in improving the interaction with the user by monitoring emotions and by providing interactive visual outputs while propelling the wheelchair. We also suggest the need for the design of two open source wheelchair propelling assistance devices that could empower manual wheelchair users by being do-it-yourself: a fully mechanical version and a powered version.

Future work should consider the role of caregivers/support workers which push and pull wheelchairs and that could benefit from using power assist devices to make their caring work easier. In addition, a field test of the latest monitoring devices and HCI inputs should be investigated. A core design challenge in the future will be in reducing device weight, which we believe can be achieved using novel power methods and these should be investigated; in particular those which offer modular power options.

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9. REFERENCES

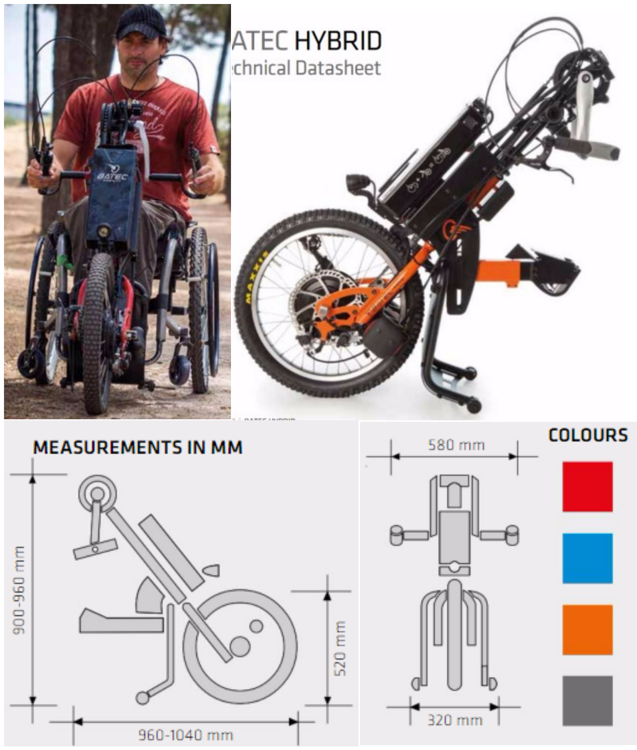
1. Akbar, M., et al., *Prevalence of Rotator Cuff Tear in Paraplegic Patients Compared with Controls.* The Journal of Bone & Joint Surgery, 2010. **92**(1): p. 23-30.
2. Algood, S.D., et al., *Impact of a pushrim-activated power-assisted wheelchair on the metabolic demands, stroke frequency, and range of motion among subjects with tetraplegia.* Archives of Physical Medicine and Rehabilitation, 2004. **85**(11): p. 1865-1871.
3. Algood, S.D., et al., *Effect of a pushrim-activated power-assist wheelchair on the functional capabilities of persons with tetraplegia.* Archives of Physical Medicine and Rehabilitation, 2005. **86**(3): p. 380-386.
4. Apple Inc. *Physical and Motor Skill Accessibility - Apple Watch*. 2017 [cited 2017 8th January]; Available from: http://www.apple.com/uk/accessibility/watch/physical-and-motor-skills/.
5. Arva, J., et al., *Mechanical efficiency and user power requirement with a pushrim activated power assisted wheelchair.* Medical Engineering & Physics, 2001. **23**(10): p. 699-705.
6. Asheghan, M., et al., *The prevalence of carpal tunnel syndrome among long-term manual wheelchair users with spinal cord injury: A cross-sectional study.* The Journal of Spinal Cord Medicine, 2016. **39**(3): p. 265-271.
7. Batec Mobility S.L. *Batec Mobility - Add-on handbikes for wheelchairs: manual and power handbikes easy to attach to the wheelchair. Revolutionary anchoring system.* [cited 2017 8th January]; Available from: http://batec-mobility.com/en.
8. Braun, V. and V. Clarke, *Using thematic analysis in psychology.* Qualitative Research in Psychology, 2006. **3**(2): p. 77-101.
9. Buehler, E., et al., *Sharing is Caring: Assistive Technology Designs on Thingiverse*, in *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 2015, ACM: Seoul, Republic of Korea. p. 525-534.
10. Carrington, P., A. Hurst, and S.K. Kane, *Wearables and chairables: inclusive design of mobile input and output techniques for power wheelchair users*, in *Proceedings of the 32nd annual ACM conference on Human factors in computing systems*. 2014, ACM: Toronto, Ontario, Canada. p. 3103-3112.
11. Chow, J.W., et al., *Longitudinal stroke cycle characteristics of pushrim-activated power-assisted wheelchair propulsion.* Journal of Biomechanics, 2007. **40**(Suplement 2): p. S468.
12. Cooper, R.A., et al., *Evaluation of a pushrim-activated, power-assisted wheelchair.* Archives of Physical Medicine and Rehabilitation, 2001. **82**(5): p. 702-708.
13. Dalyan, M., D. Cardenas, and B. Gerard, *Upper extremity pain after spinal cord injury.* Spinal Cord, 1999. **37**(3): p. 191-195.
14. de Groot, S., et al., *Consequence of feedback-based learning of an effective hand rim wheelchair force production on mechanical efficiency.* Clinical Biomechanics, 2002. **17**(3): p. 219-226.
15. Empatica Inc. *Real time physiological signals - E4 EDA/GSR sensor wirstband*. 2017 [cited 2017 8th January]; Available from: https://www.empatica.com/e4-wristband.
16. Fitbit Inc. *Fitbit Official Site for Activity Trackers and More*. 2017 [cited 2017 8th January]; Available from: https://www.fitbit.com/uk.
17. Fullerton, H.D., J.J. Borckardt, and A.P. Alfano, *Shoulder Pain: A Comparison of Wheelchair Athletes and Nonathletic Wheelchair Users.* Medicine & Science in Sports & Exercise, 2003. **35**(12): p. 1958-1961.
18. Giacobbi, P.R.J., et al., *Wheelchair Users' Perceptions of and Experiences with Power Assist Wheels.* American Journal of Physical Medicine & Rehabilitation, 2010. **89**(3): p. 225-234.
19. Guarisco, M., F. Gao, and d. Paire, *Autonomy and User Experience Enhancement Control of an Electrically Assisted Bicycle With Dual-Wheel Drive.* IEEE Transactions on Industry Applications, 2017. **53**(2): p. 1476-1484.
20. Guillon, B., et al., *Evaluation of 3 Pushrim-Activated Power-Assisted Wheelchairs in Patients With Spinal Cord Injury.* Archives of Physical Medicine and Rehabilitation, 2015. **96**(5): p. 894-904.
21. Gupta, M., et al. *A comparison between smartphone sensors and bespoke sensor devices for wheelchair accessibility studies*. in *2015 IEEE Tenth International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP)*. 2015.
22. Haubert, L.L., et al., *Comparison of Energy Expenditure and Propulsion Characteristics in a Standard and Three Pushrim-Activated Power- Assisted Wheelchairs.* Topics in Spinal Cord Injury Rehabilitation Fall, 2005. **11**(2): p. 64-73.
23. Holloway, C., et al. *Street rehab: Linking accessibility and rehabilitation*. in *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. 2016.
24. Holloway, C.S., et al. *Linking wheelchair kinetics to glenohumeral joint demand during everyday accessibility activities*. in *37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. 2015.
25. Howarth, S.J.a., et al., *Use of a geared wheelchair wheel to reduce propulsive muscular demand during ramp ascent: Analysis of muscle activation and kinematics.* Clinical Biomechanics, 2010. **25**(1): p. 21-28.
26. Hubbard, S., et al., *Poster 27: Characterizing Successful Pushrim-Activated Power-Assist Wheelchair Users.* Archives of Physical Medicine and Rehabilitation, 2007. **88**(10): p. e13.
27. Hurst, A. and S. Kane, *Making "making" accessible*, in *Proceedings of the 12th International Conference on Interaction Design and Children*. 2013, ACM: New York, New York, USA. p. 635-638.
28. Jervis, R., et al., *Design of a miniature flow cell for in situ x-ray imaging of redox flow batteries.* Journal of Physics D: Applied Physics, 2016. **49**(43): p. 434002.
29. Karmarkar, A., et al., *Evaluation of Pushrim-Activated Power-Assisted Wheelchairs Using ANSI/RESNA Standards.* Archives of Physical Medicine and Rehabilitation, 2008. **89**(6): p. 1191-1198.
30. Kloosterman, M.G.M., et al., *Exploration of shoulder load during hand-rim wheelchair start-up with and without power-assisted propulsion in experienced*

wheelchair users. Clinical Biomechanics, 2016. **34 Supplement**(C): p. 1-6.
31. Kloosterman, M.G.M., et al., *A systematic review on the pros and cons of using a pushrim-activated power-assisted wheelchair.* Clinical Rehabilitation, 2013. **27**(4): p. 299-313.
32. Kloosterman, M.G.M., et al., *Effect of power-assisted hand-rim wheelchair propulsion on shoulder load in experienced wheelchair users: A pilot study with an instrumented wheelchair.* Medical Engineering & Physics, 2015. **37**(10): p. 961-968.
33. Kloosterman, M.G.M.a., et al., *Comparison of shoulder load during power-assisted and purely hand-rim wheelchair propulsion.* Clinical Biomechanics, 2012. **27**(5): p. 428-435.
34. Levy, C.E., et al., *Variable-ratio pushrim-activated power-assist wheelchair eases wheeling over a variety of terrains for elders.* Archives of Physical Medicine and Rehabilitation, 2004. **85**(1): p. 104-112.
35. Levy, C.E.M.D., et al., *Use of Power Assist Wheels Results in Increased Distance Traveled Compared with Conventional Manual Wheeling.* American Journal of Physical Medicine & Rehabilitation, 2010. **89**(8): p. 625-634.
36. Lighthall-Haubert, L., et al., *Comparison of Shoulder Muscle Electromyographic Activity During Standard Manual Wheelchair and Push-Rim Activated Power Assisted Wheelchair Propulsion in Persons With Complete Tetraplegia.* Archives of Physical Medicine and Rehabilitation, 2009. **90**(11): p. 1904-1915.
37. LTM Consortium. *Light.Touch.Matters | The product is the interface*. [cited 2017 11th January]; Available from: http://www.light-touch-matters-project.eu/index.php?tag=home.
38. MAX Mobility. *PushTracker - MAX Mobility*. 2016 [cited 2017 8th January]; Available from: http://www.max-mobility.com/pushtracker.
39. Mercer, J.L., et al., *Shoulder joint kinetics and pathology in manual wheelchair users.* Clinical Biomechanics, 2006. **21**(8): p. 781-789.
40. Meyers, A.R., et al., *Barriers, facilitators, and access for wheelchair users: sbstantive and methodologic lessons from a pilot study of environmental effects.* Social Science & Medicine, 2002. **55**(8): p. 1435-1446.
41. MEYRA GmbH. *Servomatic, MEYRA*. 2017 [cited 2017 24th March]; Available from: https://www.meyra.de/hmv-suche/hmv-details/product-446/.
42. Milgate, N., *Current issues of the SmartDrive MX2 and Pushtracker*, M.R. Dafne Zuleima, Editor. 2017, Equipment for the Physically Challenged (EPC) Wheelchairs Ltd.: London, United Kingdom.
43. Nash, M.S., et al., *Power-Assisted Wheels Ease Energy Costs and Perceptual Responses to Wheelchair Propulsion in Persons With Shoulder Pain and Spinal Cord Injury.* Archives of Physical Medicine and Rehabilitation, 2008. **89**(11): p. 2080-2085.
44. Pavlidou, E., et al., *Rolling resistance and propulsion efficiency of manual and power-assisted wheelchairs.* Medical Engineering & Physics, 2015. **37**(11): p. 1105-1110.
45. Raspberri Pi Foundation. *Raspberry Pi - Teach, Learn and Make with Raspberry Pi*. 2017 [cited 2017 8th January]; Available from: https://www.raspberrypi.org/.
46. Rimmer, J.H., et al., *Physical activity participation among persons with disabilities.* American Journal of Preventive Medicine, 2004. **26**(5): p. 419-425.
47. Sabick, M.B., B.R. Kotajarvi, and K.-N. An, *A new method to quantify demand on the upper extremity during manual wheelchair propulsion1.* Archives of Physical Medicine and Rehabilitation, 2004. **85**(7): p. 1151-1159.
48. Shinohara, K. and J.O. Wobbrock, *Self-Conscious or Self-Confident? A Diary Study Conceptualizing the Social Accessibility of Assistive Technology.* ACM Trans. Access. Comput., 2016. **8**(2): p. 1-31.
49. Shinohara, K. and J.O. Wobbrock, *In the shadow of misperception: assistive technology use and social interactions*, in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2011, ACM: Vancouver, BC, Canada. p. 705-714.
50. Slowik, J.S., et al., *The influence of wheelchair propulsion hand pattern on upper extremity muscle power and stress.* Journal of Biomechanics, 2016. **49**(9): p. 1554-1561.
51. Stein, R.B., et al., *Improved efficiency with a wheelchair propelled by the legs using voluntary activity or electric stimulation.* Archives of Physical Medicine and Rehabilitation, 2001. **82**(9): p. 1198-1203.
52. Sunrise Medical LLC. *WheelDrive wheelchair power assist*. 2016 [cited 2017 8th January]; Available from: http://www.sunrisemedical.eu/wheelchairs/quickie/wheelchair-power-assist-wheeldrive.
53. Sunrise Medical LLC. *Quickie Xtender Power Assist Wheelchair Accessory*. 2016 [cited 2017 8th January]; Available from: http://www.sunrisemedical.com/manual-wheelchairs/quickie/manual-power-assist/xtender.
54. Ulrich Alber GmbH. *Wheelchair Drives*. 2017 [cited 2017 8th January]; Available from: https://www.alber.de/en/products/wheelchair-drive.html.
55. Weed, M., *Capturing the essence of grounded theory: the importance of understanding commonalities and variants.* Qualitative Research in Sport, Exercise and Health, 2017. **9**(1): p. 149-156.
56. Wheelchair Leadership Alliance. *NHS England - Improving wheelchair services*. 2017 [cited 2017 26th April]; Available from: https://www.england.nhs.uk/ourwork/pe/wheelchair-services/.
57. World Health Organization. *Assistive Technology, Fact Sheet*. 2016 [cited 2017 11th April]; Available from: http://www.who.int/mediacentre/factsheets/assistive-technology/en/.
58. World Health Organization, International Society for Prosthetics and Orthotics, and United States Agency International Development, *Guidelines on the provision of manual wheelchairs in less-resourced settings*. 2008, Geneva, Switzerland. 131.

Table 1. Images of six power assist devices available in the market.

<table>
<tr><th>Device</th><th>Image</th><th>Source</th></tr>
<tr><td>SmartDrive MX2+ with PushTracker</td><td>
</td><td>www.max-mobility.com</td></tr>
<tr><td>Twion wheels</td><td>
</td><td>www.alber.de</td></tr>
</table>

Device	Image	Source
e-motion wheels	 	www.alber.de
WheelDrive	  	www.sunrisemedical.co.uk
Xtender	 	www.sunrisemedical.com

Device	Image	Source
Batec hybrid handbikes		www.batec-mobility.com

All images are property of the manufacturers.