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Intelligent wheelchair control strategies for older adults with cognitive impairment: user attitudes, needs, and preferences

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Abstract Intelligent powered wheelchairs can increase mobility and independence for older adults with cognitive impairment by providing collision avoidance and navigation support. The level and/or type of control desired by this target population during intelligent wheelchair use have not been previously explored. In this paper, we present user attitudes, needs, and preferences in a study conducted with a mock intelligent wheelchair offering three different modes of user control. Users wanted to be in the loop during wheelchair operation and/or high-level decision making, and also provided specific contexts where an autonomous wheelchair would be helpful. Participants identified benefits of and concerns with intelligent wheelchairs, along with desired features and functionality. The paper presents the implication of these findings and provides specific recommendations for future intelligent wheelchair development and deployment.

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1 Introduction

Powered wheelchairs (PWCs) can improve the quality of life of older adults who are unable to propel themselves in manual wheelchairs (Brandt et al. 2004); however, safe operation of PWCs requires a sufficient level of cognitive capacity, including decision-making, memory, judgment and self-awareness (Brighton 2003). It is reported that 60–80 % of long-term care (LTC) residents have dementia (Marcantonio 2000). Impaired attention, agitation, poor impulse control, memory loss, disorientation, and visuo-perceptual difficulties are known symptoms related to Alzheimer's disease and other dementias (Borson and Raskind 1997; Masson et al. 1996; Strubel and Corti 2008; Mosimann et al. 2004; Ricker et al. 1994), which make independent navigation difficult or impossible. When determining eligibility for PWC use, prescribers (therapists) are faced with the difficult decision of weighing their clients' need for independent mobility against the safety of the driver and others in the environment (Mortenson et al. 2005). Cognitive impairments can thus lead to decisions of PWC exclusion (Fehr et al. 2000; Hardy 2004), which in turn leads to reduced mobility and independence for a large number of long-term care residents.

In order to address the issues above, several researchers have developed intelligent wheelchairs capable of providing collision avoidance and wayfinding support, offering various levels of control to the user (Simpson 2005). Only a few of these systems, however, have been tested in studies with older adults with cognitive impairment, and have led to the identification of specific usability issues and areas for improvement (Viswanathan et al. 2013a). These studies have suggested that further testing with the user population is imperative in order to determine user needs and preferences, and to develop a system that is eventually adopted by the intended users. Specifically, user attitudes related to control while driving intelligent wheelchairs have not been explored in previous studies, and are important to consider in the design of this technology.

The study described in this paper is informed by quantitative and qualitative results acquired during studies conducted previously by the authors, as well as related work by other researchers. This study uses a mock intelligent wheelchair, implementing a Wizard-of-Oz approach that allows researchers to circumvent engineering challenges in building a fully functional system, and yet obtain quantitative and qualitative user feedback (Viswanathan et al. 2013b). The study described is the first (to our knowledge) to test different modes of intelligent wheelchair control with older adults with cognitive impairment. The system in (Urdiales et al. 2011) was also tested with users with varying levels of physical and cognitive impairment; however, the system implemented a single (shared) control strategy. This paper attempts to answer the following research questions related to intelligent wheelchair control:

(1) What are recurring themes across participants when discussing attitudes related to control?
(2) How do participants' preferences vary between different modes of control?
(3) What are the implications of the above for future system design?

This paper presents an overview of our study protocol, qualitative data collection and analysis approaches, and findings on the user population's attitudes, needs, and preferences related to control when using an intelligent wheelchair that provides three different modes of driving assistance. The paper offers insights and recommendations for the design of future intelligent wheelchair prototypes.

2 Related work

Research into intelligent wheelchairs dates back decades; see (Simpson 2005) for a comprehensive survey of early work. A vast majority of these systems are, however, either mostly autonomous (requiring minimal user input), or simply stop the wheelchair in the case of imminent collision. While the former may not be appropriate for users with cognitive impairment who may become confused or agitated in a wheelchair that moves on its own, the latter might not provide the level and/or type of assistance necessary for all target users to be able to navigate independently.

In addition, only a few systems have been tested with our target population (How et al. 2013; Viswanathan et al. 2011; Wang et al. 2011). These systems implemented a switched control strategy (where either the user or the system is fully in control at any given time). Study findings included reports of user frustration with the stopping mechanism, and the desire for user autonomy (Viswanathan et al. 2013a). A shared control (or collaborative control) approach, where real-time powered wheelchair driver input is combined with signals generated by computer control, might thus offer a more positive user experience for the target population. Although several shared control intelligent wheelchairs exist, we restrict the following review to those that implement shared control and have been tested (in the last decade) with users with mobility and/or cognitive impairment.

The Collaborative Wheelchair Assistant (Zeng et al. 2008a, b) provides the user with a graphical user interface for path selection in a pre-constructed map of the environment. An elastic path controller allows the user to steer away from the selected path while experiencing a passive attraction toward the path. The system was tested with five participants (16–48 years old), with cerebral palsy and traumatic brain injury (TBI), who had been excluded from powered wheelchair use. The system reduced the number of collisions and joystick movements. While no participant was able to drive a wheelchair independently prior to the trials, all participants were able to operate the powered wheelchair with the system, thus gaining mobility.

Urdiales et al. (2011) implement a shared control strategy that weighs and combines human and robot input based on the users' current and previous average relative efficiencies in three areas: "safety", "smoothness", and "directness". The system was first tested with 30 hospital in-patients with varying levels of physical deficits, and moderate to severe cognitive impairment. The key finding was that shared control was able to equalize navigation performance between users, despite the fact that they had heterogeneous capabilities. Subsequently, the authors use a database of 70 drivers (60 in-patient individuals with different levels of physical and/or cognitive impairment and 10 hospital staff members) to predict real-time user performance based on recorded performance in similar situations in the database (Peinado et al. 2011). In a study conducted with 17 participants with varying physical and cognitive disabilities, this new system compensated for lacking skills, while improving user performance of residual skills.

Li et al. (2011) blend the user's and an autonomous controller's direction inputs with the objective of increasing three measures of the final shared control signal: "safety", "comfort" and "obedience". These measures correspond to the safety, smoothness and directness measures discussed previously. The system was tested with older adults (75–84 years old) who had mobility impairment but were cognitively intact. The system improved the smoothness of wheelchair trajectories and reduced the likelihood of collision with obstacles. In more recent work (Wei et al. 2012), the user can specify intent, such as docking at a table, through the joystick and an augmented reality display; however, tests with users with disabilities have not yet been reported.

Carlson and Demiris (2012) use a collaborative control strategy that infers driver intention from the joystick input and generates elastic mini-trajectories in a mapped indoor environment, causing the user to be redirected when he/she deviates from the path. One manual wheelchair user with complex regional pain syndrome and arthritis tested the system. Safety, smoothness, and secondary task reaction times improved with the system. The user appreciated the system's help in preventing collisions while allowing her to get close to objects, but felt the system sometimes "overcompensated", making a larger detour than necessary to avoid collisions.

Most reports of the above studies have focused on user and system performance, with limited analyses of user perceptions and experiences. Qualitative data collection and analysis techniques have been used in previous studies to explore user perceptions on intelligent wheelchairs (Kairy et al. 2014; Rushton et al. 2015; Wang et al. 2013). The richness and depth of qualitative data collected in these studies is not possible to achieve through quantitative research methods, and is more useful at the requirements-gathering stage of assistive technology development. The study reported in this paper takes the above qualitative interviews a step further by soliciting feedback as users operated an intelligent wheelchair in their natural environments using three different modes of control, while the previous studies only either verbally described or showed video recordings of intelligent wheelchairs. In addition, unlike the above studies, our study specifically recruited long-term care residents with cognitive impairment. The findings in this paper, in combination with standard quantitative approaches used in related work, can lead to a more comprehensive understanding of the system and its use by target users in the real world, thus helping to further refine system design and functionality and better accommodate user needs.

3 Methods

3.1 Study design

The findings reported in this study are part of a larger mixed-methods study that included researchers of various backgrounds such as computer science, engineering, occupational therapy, and rehabilitation sciences. The entire research team was consulted in the study design, as well as data collection and analysis procedures. In addition, feedback and expertise was sought from clinicians, powered wheelchair sales representatives and technicians, and a statistician with experience in health research. The main study consisted of three different types of sessions: assessments, driving sessions, and pre- and post-driving sit-down interview sessions. Driving sessions collected self-report ratings of satisfaction through the QUEST 2.0 survey (Demers et al. 2002), and of task load index through the NASA-TLX survey (Hart and Staveland 1998), as well as qualitative data through semi-structured interviews (Wood 1997), think-aloud strategies (Lewis 1982), and ordering of modes based on preference. Data was collected through multiple sources, and triangulation was used to help increase validity and overcome the memory and recall issues seen in our target population. All trials were video-recorded for use in quantitative and qualitative analyses. Statistical analyses of the NASA TLX and QUEST 2.0 ratings have been provided in the Online Resource. This paper focuses on the qualitative data obtained during the driving sessions; statistically significant results from the quantitative data analyses are thus highlighted within the context of the qualitative findings. Preliminary findings from the pre- and post-driving semi-structured interview sessions are reported in (Rushton et al. 2014). Note that these interviews were conducted at least a day before or after the driving sessions.

3.2 Recruitment

Following ethics approvals from the researchers' host institutions and test sites, potential participants were contacted and screened by designated caregiving staff. The primary researcher then obtained informed consent. A purposive sampling method was used. To be included in the study, participants had to:

- be over the age of 50
- have mild-to-moderate cognitive impairment (as determined by clinical assessments such as the Mini Mental State Examination (Folstein et al. 1975) (MMSE), Montreal Cognitive Assessment (Nasreddine et al. 2005), and the Minimum Data Set Cognitive Performance Scale (Morris et al. 1994)
- provide written consent on their own or from a substitute decision maker
- be able to sit in a PWC for at least an hour per day
- be able to operate a joystick
- have basic communication skills in English
- have difficulties walking or self-propelling a manual wheelchair

Ten participants (six female and four male) from three different residential long-term care (LTC) facilities (A, B, and C) in the Lower Mainland of British Columbia, Canada were recruited over a period of three months. Facilities A and B were multi-floor residences with close to 200 residents.

Table 1 Preferences and relative odds of choosing a mode

Scenario	Comparison	% B preferred	% S preferred	% A preferred	% No preference	Odds Ratio	95 % CI Lower	95 % CI Upper
Elevator	S vs B	10.0	**70.0**	–	20.0	2.24	0.66	7.61
	A vs B	40.0	–	**50.0**	10.0	1.15	0.32	4.14
	S vs A	–	**50.0**	40.0	10.0	1.95	0.54	6.99
Table docking	S vs B	30.0	**40.0**	–	30.0	1.86	0.51	6.84
	B vs A	**40.0**	-	**40.0**	20.0	1.23	0.32	4.75
	S vs A	–	**50.0**	30.0	20.0	2.29	0.57	9.15
Back-in parking	S vs B	10.0	**50.0**	–	40.0	2.26	0.61	8.44
	A vs B	30.0	–	**60.0**	10.0	1.31	0.39	4.44
	S vs A	–	**60.0**	30.0	10.0	1.73	0.47	6.29
Hallway	S vs B	10.0	**50.0**	–	40.0	1.78	0.47	6.75
	A vs B	30.0	–	**50.0**	20.0	1.94	0.49	7.71
	A vs S	–	20.0	**50.0**	30.0	1.09	0.28	4.28
Maneouver	S vs B	30.0	**70.0**	–	0.0	3.31	0.92	11.91
	A vs B	40.0	–	**60.0**	0.0	1.21	0.36	4.00
	S vs A	–	**80.0**	20.0	0.0	2.74	0.80	9.43
Overall	S vs B	18.0	**56.0**	–	26.0	2.14*	1.31	3.52
	A vs B	36.0	–	**52.0**	12.0	1.20	0.72	1.98
	S vs A	–	**52.0**	34.0	14.0	1.79*	1.09	2.93

An odds ratio of 2.14 for S vs B means that the odds of a participant choosing mode S are 2.14 greater than the odds of choosing B. (B: Basic safety, S: Steering correction, A: Automatic). Percentages corresponding to the most preferred mode in each pair-wise comparison are bolded, with * Indicating statistical significance ($p < 0.05$) in the odds ratios

Facility C was a single-floor residence with roughly 120 residents with severe disabilities. This residence was constructed on a hill, thus consisting of sloped corridors that connect specific units and present challenges in manual wheelchair propulsion. Powered wheelchair use was permitted at all facilities following a safe driving assessment. All participants had mild-to-moderate cognitive impairment as per clinical assessments conducted by LTC staff, and were 62–98 years old. Three participants (3, 4 and 5) were PWC users, and the rest were manual wheelchair users. All participants completed the study protocol.

Since the test sites used different cognitive screening tools, the primary researcher (first author) conducted the MMSE with all participants to achieve a baseline for this study. Although the MMSE was chosen for its ease of use and short administration period, some of its limitations should be noted, including poor sensitivity to mild cognitive impairment (Wind et al. 1997). Refer to Table 1 in Online Resource for participant information.

3.3 System setup

This study used a commercial PWC that was modified by AT Sciences, LLC (http://www.at-sciences.com/) such that it could be controlled through the joystick on the wheelchair or through a laptop (see Fig. 1). The software provided by AT Sciences was further modified by our research team to allow the wheelchair to be controlled through a separate wireless (PlayStation® 3) joystick held by a tele-operator (the "wizard"), allowing him to override specific user joystick input, thus simulating a shared or autonomous control strategy through a Wizard-of-Oz approach (Riek 2012). Audio and haptic feedback was also provided in some cases. A visual interface for the tele-operator was mounted on the back of the wheelchair, allowing easy switching of modes and recording of data from sensors mounted on the wheelchair. Although these sensor data were not used during the trials, they provide a robot's eye view of the environment in LTC facilities that will hopefully prove useful in future development efforts.

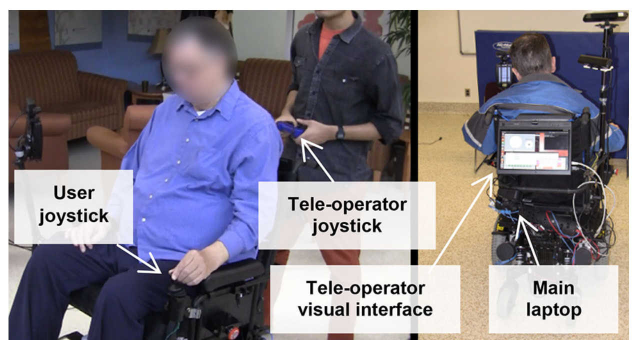

Fig. 1 Mock intelligent wheelchair with tele-operator interface

3.4 Experimental setup

Three different modes of user control were offered by the control strategies simulated with the mock intelligent wheelchair. In every mode, participants interacted directly and in real-time with the PWC. More details on these modes along with justifications for their selection can be found in (Mitchell et al. 2014). Note that a baseline mode without any intelligent control was not offered since this would likely not be an option for our target population (5/10 participants had already been denied powered wheelchair use; providing these users with a regular powered wheelchair would pose serious safety risks).

Basic safety mode (B) The maximum speed of the wheelchair towards the obstacle was decreased when the user was within 0.6 m (2 ft) of the obstacle, and the wheelchair was stopped when the user was within 0.3 m (1 ft) of the obstacle. The speed adjustments ensured that the driver was at least two seconds away from collision at all times, with the initial speed set to 0.3 m/s (determined to be a safe speed for the test environments). Once the user was stopped, he/she was not permitted to drive towards the obstacle but could drive away from it, except for scenarios where the user was required to approach objects closely when parking. In these cases, after the user was stopped, he/she could proceed towards the object at a very slow "docking" speed. An audio prompt was played when the wheelchair was slowed down or stopped (e.g., "Slowing down", "Stopping"). Vibration feedback was also provided on the joystick when speed was restricted.

Steering correction mode (S) If the user was within 0.3 m (1 ft) of an obstacle, the wheelchair automatically steered away from it (without slowing down or stopping). Speed correction was only used (as in the basic safety mode above) if: (1) the user approached objects that were parking destinations, (2) no free space was found ahead of the wheelchair, or (3) the user moved outside of the designated test area. A notification audio prompt was played upon system intervention (e.g., "Turning away"). Just-in-time audio direction prompts were offered to signal upcoming turns (e.g., "Turn right") when the user was off-route. Vibration feedback was also provided on the joystick when the heading and/or speed were corrected.

Automatic mode (A) The wheelchair completed the driving task, avoiding all obstacles in its path fully autonomously (and nearly perfectly due to wizard navigation). The user could stop the chair by pulling back on the joystick or by telling the researcher to stop. An audio prompt was provided at the beginning (e.g., "Driving in auto mode").

In all modes, the task/destination (elevator, table, etc.) was explained to the participant by the researcher, similar to a PWC assessment setting. It is thus assumed that the system is aware of the destination in every case. Future work involves providing the driver and/or clinician with an interface to specify the task or destination.

Before the driving sessions, participants completed up to two 20-min training sessions where they were taught basic movements (driving forwards and backwards, and turning) if they had no prior PWC driving experience, and were familiarized with each of the modes through a simple collision task in which they were asked to drive toward a chair, with the researcher explaining the system intervention(s) in each case. Over the next two weeks, each participant completed five driving sessions (no more than one session per day), lasting approximately 90 min each, during which he/she navigated in various realistic scenarios (ordered randomly) based on the Power Mobility Indoor Driving Assessment (PIDA) (Dawson et al. 1994):

(1) Getting in and out of an elevator (elevator).
(2) Docking under a table between two chairs or a chair and a table leg (table docking).
(3) Back-in parking against a wall between two chairs (back-in parking).
(4) Driving down a hallway, turning left/right at an intersection, and continuing to drive (making an L shape). Participants then turned around (180°), and drove back to the starting point, while avoiding unexpected obstacles in both directions (hallway).
(5) Maneuvering through an obstacle course (maneuverability).

During each driving session, participants completed one scenario in the three different driving modes. First, the ordering of scenarios was randomized for each participant. Subsequently, the ordering of modes was randomized for every scenario and participant. Additionally, each mode was tested three times consecutively in every scenario to allow participants to become comfortable with the technology and driving task. Each participant thus completed 45 trials in total. For example, participant 1 completed trials in the following sequence *(Day: scenario, mode ordering)*:

Day 1: table docking, B–B–B–A–A–A–S–S–S
Day 2: maneuverability, A–A–A–B–B–B–S–S–S
Day 3: hallway, B–B–B–A–A–A–S–S–S
Day 4: elevator, S–S–S–A–A–A–B–B–B
Day 5: back-in parking. S–S–S–B–B–B–A–A–A

The primary researcher (first author) supervised the driving sessions and collected user feedback. A second researcher tele-operated the wheelchair while standing in a relatively inconspicuous position such that he did not interfere with the driving task, but remained aware of the obstacles around the chair. Video recordings of all sessions were captured and transcribed verbatim by other members of the research team.

4 User attitudes

4.1 Data collection and analysis

As participants drove, a think-aloud approach was used to collect real-time qualitative feedback. In addition, semi-structured interviews were conducted after every mode and at the end of trials (see the interview guide in Online Resource) in order to solicit feedback in three different discussion areas: attitudes related to control, perceived benefits of the system, and participant concerns and needs. A thematic analysis (Patton 2002; Wang 2011) of interview data was carried out as follows. A representative transcript was selected and coded line-by-line by the first three authors independently and then discussed together. The remaining transcripts were then randomly divided into three groups (of three transcripts each), with each group of transcripts being assigned to a different researcher. In addition, one transcript from each group was randomly selected for validation by all three researchers. Thus, 40 % of the data was coded independently and validated by all three researchers, and the remaining data was simply discussed together to ensure agreement; cases of ambiguity or disagreement were noted. Within each discussion area, the first three authors identified categories by grouping observations with similar codes. Subsequently, an iterative process was employed, in consultation with the fifth author, to merge existing categories into fewer categories (themes and subthemes) by exploring the relationships between them. The final themes and subthemes that emerged from the data are presented in this section.

4.2 Results and discussion: themes

4.2.1 Attitudes related to control

Participants clearly indicated their desire to be kept in the loop during wheelchair operation and/or decision-making. Participants also provided specific examples of contexts where they were willing to relinquish control to an autonomous wheelchair. Results indicated that participants might want to be able to choose different levels of control depending on their cognitive and/or physical state, and/or the specific scenario.

4.2.1.1 Desire to be in-the-loop Participants commented that they wanted to be in-the-loop during high-level decision-making and/or lower level driving behaviors. One participant wanted a graded approach to system intervention.

Control over high-level decision making Participant 1 stressed that the automatic mode would need to be able to allow him to change his mind regarding his desired destination (in the hallway task). Participant 6 emphasized that she "wanted [the system] to go where [she] wants it to go and not where it wanted it to go, even if it was the wrong thing", as long as the wheelchair did not hurt anyone. Participant 8, who was initially nervous about the automatic mode, also expressed the desire to have "some control" in 4 of 5 scenarios, and was confused or frustrated when wayfinding prompts were issued, saying "but I do not want to go back that way". He often questioned why the system was telling him to go in a different direction, and later explained, "sometimes I would like to go my own way". Participants also expressed the desire to specify destinations as well as request and/or approve system behaviors using speech, joystick, touch-screen, and gesture-based interfaces.

Control over low-level driving behaviors While some users only wanted control over low-level driving behaviors in specific contexts, others wanted control at all times. Participants 1 and 3 expressed their preference for control during the maneuverability and back-in parking tasks respectively, with the latter mentioning later that she "always" preferred to be driving on her own. Participant 1 appreciated the ability to make fine adjustments himself while docking under the table. Participants 4 and 6 showed signs of anxiety during the automatic mode, and always preferred to have some control (in either steering correction or basic safety mode). Similarly, participant 5 said "it made me feel safer that I am in control" when using the steering correction mode. Participant 7 developed a preference over time for driving on her own with safety features, rather than being driven in automatic mode. Participant 9 rated the automatic mode as least preferred in 3 of 5 scenarios, and expressed that he wanted to drive on his own.

Graded level of user control Participant 1's comment that in a new environment "you want to have the chance to try it out first before you resort to the automatic mode". His suggested protocol "safety first, then train, then compensate," imply that a graded approach providing increasingly higher levels of intervention, depending on the user's abilities, would be desirable in order to encourage drivers to "use their mind…their mind, the memory, the brain."

4.2.1.2 Contexts for automatic driving Participants identified different user-, task-, and environment-related contexts in which they desired an autonomous wheelchair.

User-related contexts When the symptoms of Parkinson's Disease made physical movement difficult for participant 1 he mentioned that "right now, I don't have any choice. If I want to go to the dining room, I have no choice but to choose the automated mode…but in other times, I want to do it myself." Participant 2 said she would use automatic mode when she was "tired", "sore", and wanted to "move around". Participant 6 felt like the wheelchair should "take over" for novice, nervous, wandering, and/or temporarily incapacitated (sick, dizzy) drivers, or those with poor judgment. Participant 10 mentioned that she would like to use the autonomous mode "all the time, all day long" since she is "lazy".

Task-related contexts Participant 1 described hallway driving as a "frequent use of the system" and a task that would benefit from automation. Participant 2 felt that an autonomous parking feature to dock under tables would lead to time savings during mealtimes. Participant 6 felt an autonomous wheelchair could help the user drive in a straight line. Participant 7 wanted to use the autonomous mode to navigate uphill across the facility to see her friend. Participants 1 and 6 felt that back-in parking was a challenging task and an autonomous system could help the user by automating the task, similar to parallel parking assistance in cars.

Environment-related contexts Crowded areas are challenging according to Participant 1 who said "usually when I get into a certain somewhere, really packed with people, I would want the automatic to take care of it....I think it would do a better job." In general, he felt that dynamic environments and small spaces were the most challenging to navigate in. Participant 6 felt that an autonomous wheelchair could help with unknown and/or less familiar routes, with traffic, unknown table shapes/heights, crowded areas, blind spots, situations that pose a threat to safety, and situations with unknown information about bystander movements. Participant 3 felt that an autonomous system would help in "close corridors and quarters". Participant 8 also found that system intervention would be helpful while "going into the elevator", navigating to unfamiliar locations, and tight spots.

4.2.2 Perceived benefits

Participants highlighted several benefits of using an intelligent wheelchair, with impacts on the user, driving performance, and others in the user's environment.

4.2.2.1 Impact on the user Participants mentioned that the system, through the different modes, could and did compensate for lack of knowledge and/or ability, increased their awareness of their surroundings, and reduced workload and anxiety while increasing safety, confidence, independence, mobility, activity, and participation.

Compensation of ability/knowledge Participant 7, when using the automatic mode said "it stopped when I couldn't see" and expressed her satisfaction with the system when she said that it "helped in every way. I am not a good driver". Participant 6, who was often confused and disoriented, said "anything is helpful when you don't know what you're doing." She confessed "my judgment isn't always good" and felt "[the basic safety mode] was paying attention to what [she] was doing". Participant 8 had vision impairment and observed, "the chair has better depth perception than I do". The system was thus found to compensate for lack of vision, judgment, and orientation.

Increased awareness Participant 1 found the basic safety mode gave him an indication of speed, direction and angle of the wheelchair. Although participant 3 preferred smoother motion in general, she said "[the jerky behavior during abrupt stops/starts] was warning me, it was letting me know [...] I like that it lets me know that I am doing something wrong and it kind of hesitates". The haptic feedback provided a warning, with participant 5 interpreting it as "just watch out, something coming," and participant 8 calling it a "caution indicator".

Reduced workload Participants often felt that the steering correction and automatic modes additionally reduced mental and/or physical demand. For example, participant 1 found that steering correction made avoiding the box in the hallway task easier than the basic safety mode "because the machine is doing the work of avoiding objects and giving you the turn, the appropriate turn." Participant 10 found that the automatic mode "did all the thinking for [her]."

Increased feelings of safety and confidence Several examples were found where the system appeared to increase user confidence, feelings of safety and comfort, and pleasure, while decreasing anxiety about collisions. Participant 1 described, "[the basic safety mode] helps you to move smoothly and I don't have to panic". Similarly, participant 5 felt that the "[autonomous mode] keeps [her] away from trouble." Participant 7 said that she would feel "afraid" in a regular powered wheelchair without any safety features. In the training session with the steering correction mode, she expressed that the wheelchair automatically steering away from the obstacle made her "be more confident" and "proud".

Increased independence and mobility Participants also mentioned that the system could increase user independence, mobility, activity and participation, as seen in (Rushton et al. 2014). While some of above benefits are offered by any powered wheelchair rather than specifically an intelligent wheelchair, it should be noted that the manual wheelchair users who highlighted these benefits were in most (5 of 7) cases previously denied powered wheelchair use due to their inability to drive safely. Thus, these users would likely not be able to reap the benefits of powered mobility without safety features similar to those offered by the system trialed in this study.

4.2.2.2 Impact on driving performance All participants except participant 4, who said he would not use the system, found that the intelligent wheelchair assisted in or enhanced their driving performance by improving safety, and/or reducing their time in getting to desired locations. Participant

1 described how “[he] was able to smoothly drive away from the object” in steering correction mode. Participant 3 mentioned that “[she] would save a few walls” from potential damage with an autonomous wheelchair. Participant 6 explained “I would use [the basic safety mode] so I wouldn’t crash into anything, because I could crash into someone.” She shared her past experience with being assessed and denied a powered wheelchair: “they tried me on the power chair…I wasn’t a good driver,” but went on to say that the system made her “a better driver.” The safety features thus provided participants with a “dose of safety” (Rushton et al. 2014), as expressed by them in the pre- and post-driving interview sessions. Participant 10 also mentioned that an intelligent wheelchair would save time, saying “I wouldn’t have to get up as early”.

4.2.2.3 Impact on others The system was seen as a way to reduce burden on both the drivers and others in the environment (family and caregiving staff). Participant 1 explained, “especially these days because they are short of staff so I can do it myself…then I can go anywhere with more confidence…without asking for too much help.” Participant 2 felt that an intelligent chair would reduce the chaos in the hallways often seen during meal times and help everyone get to their meals faster, before the meals “get cold”. Participant 6 felt like a wheelchair that provided wayfinding prompts would reduce the need for caregiver assistance. Participant 5 mentioned that the system would lead to an improved perception of her by others as a “safe driver” due to the increased safety offered by the system. Finally, participant 6 recognized that the system would not only keep her safe, but also increase the safety of bystanders, saying “[the basic safety mode] would make me feel safe and it protects people from me in the chair”.

4.2.3 Participant-identified concerns and needs

While participants identified many benefits of using the system, they also expressed several concerns during and after trials. Although increased safety was seen as a potential benefit of the system, many participants continued to express safety concerns during the study and showed a lack of trust/familiarity in the system. Other concerns involved the level of assistance provided by the system. Issues related to the wheelchair’s environment and the people in it were raised. Participants also had several questions regarding system use and configuration, which were independent of the control strategies tested, but should be considered during clinical implementation and deployment. Some of the specific properties of the system that users were concerned with included: speed, instability, maintenance, durability, ease-of-use, comfort, form-factor, robustness, power consumption, outdoor use, sensor coverage, cost, and accessibility.

4.2.3.1 Lack of familiarity/trust Safety concerns were possibly linked to a lack of the users’ trust in and/or familiarity with the system coupled with an awareness of their own abilities and limitations. Note that although all participants were informed about the tele-operation protocol before each driving session, it was not clear that participants fully understood or remembered it while they were driving. Several comments made by participants suggested that they thought the wheelchair was intervening on its own. This phenomenon is similar to that seen in an autonomous driving simulation with cognitively intact participants (Baltodano et al. 2015).

Participant 2 explained in the back-in parking task that “the only problem that bothered me was being unable to see behind me I guess.” She also said, “I was worried and not sure that I was doing it right”. Participant 3 explained, “I was trying to run into something [...] I would make sure it works [...] I want confidence in the chair.” Participant 8 mentioned that the system helped with his “depth perception”, but he was still concerned that he might drive into obstacles he could not see. Increased concerns of safety were noticed in the table docking scenario with the automatic mode, possibly due to the proximity of the table surface to participants’ knees and hands, the limited space to maneuver while docking under the table (between two chairs) and the lack of trust in the system to stop the wheelchair in time (as indicated by participants waving their hands, yelling “stop!”, reaching over and tapping the table, etc.), despite the low wheelchair speed. In some cases, participants requested to be stopped further away from the table before the (minimal) docking speed was used, further demonstrating their anxiety and discomfort with the autonomous mode in this scenario.

4.2.3.2 Insufficient assistance or feedback Participant 1 mentioned that while the basic safety mode prevented him from driving into an obstacle, it was “not really doing much to help” and left the task of finding free space, through “trial and error”, completely to him. He was concerned that he would inadvertently drive into oncoming traffic while attempting to drive around the box in front of him (in the hallway scenario) and wanted more assistance in this situation. He also felt that the mechanism of assistance of the steering correction mode was confusing specifically in the back-in parking task and felt more comfortable only after further explanation of the system behavior. A total of three users wanted richer feedback on the location of obstacles and the correct steering direction.

4.2.3.3 Excessive or unnecessary intervention Participant 1 was highly frustrated by the steering correction mode in the back-in parking scenario where he initially felt that the system was hurting his performance by over-assisting him in a task that he felt he could complete on his own. Participant 8 was frustrated with wayfinding prompts that conflicted with his intent and wanted to be able to go "[his] own way", and wanted the system to be "less cautious of obstacles", perhaps to allow him to get closer to them. Participant 3 found the audio feedback frustrating throughout the study. She said, "I was just tired of hearing that voice", and wanted the system to just "do what it is doing" and did not feel like she needed any explanation. While participant 4 did not state any issues with the system, he mentioned matter-of-factly that he would not use the system since it "made no difference" to his driving, which was likely an accurate observation since he had high baseline driving performance and was the most experienced PWC driver in the study.

4.2.3.4 Loss of vigilance and/or ability with automatic mode Participant 2 felt concerned that "your mind can wander onto something else and maybe you should still pay attention" in the automatic mode. Participant 5, who often fell asleep during this mode wanted the wheelchair to "talk to [her]" and was concerned that she would "forget how to drive" if she always used the automatic mode.

4.2.3.5 Lack of speed or smoothness in motion Participant 1 felt that the basic safety mode "stopped a lot" and participant 10 similarly complained, "it takes hours to get in here". Although steering correction helped preserve momentum, it resulted in "jerky" behaviors noticed by participant 3 and 5 when there were large disagreements between the driver's and tele-operator's commands.

4.2.3.6 Environmental challenges and bystanders Participants were also concerned about challenges posed by the environment they would be driving in such as crowdedness, lack of space, unexpected events, dynamic obstacles, and unpredictable behavior of others. Participant 2 explained, "sometimes you know, some of the people in wheelchairs make me a bit nervous, once they have dementia, and uh, because you don't know what they are going to do." Participant 1 also mentioned the need for risk assessment (e.g., colliding into a box to prevent collision with a person) when determining the system intervention required in an environment with different types of obstacles.

While most of the participants did not seem to be concerned with how they might be perceived by others while driving an intelligent wheelchair, participant 2 mentioned that others might view an intelligent wheelchair as an unnecessary and overly expensive purchase for her. In addition, she felt that driving in an intelligent wheelchair might generate curiosity among bystanders, which was undesirable to her. Finally, participant 5 mentioned that others would think "what the heck is she talking about" if she was in a voice-commanded intelligent wheelchair.

5 User preferences

5.1 Data collection and analysis

At the end of each scenario, users were asked to provide an ordering of all three modes, based on their preference. During data analysis, these preferences were extracted from transcripts by the first, second, and fourth authors independently, and were reviewed and compared with other data collected during the semi-structured interviews to assess for corroborating or disconfirming evidence, with cases of ambiguity being noted. The final ordering of modes was then used to construct pair-wise rankings in each scenario across all participants, which were aggregated (summed) over all scenarios to obtain "overall" pair-wise preferences. Rankings that included cases of indifference (e.g., "I don't care"), ambiguity (e.g., "I don't know"), equal ranks (e.g., "I like them both the same") and contradiction (e.g., "I liked A more than B" followed by "I liked B more than A") were marked as "no preference". Statistical analysis was conducted using logit models for sets of ranked items (Allison and Christakis 1994). The discrete choice model was used in order to deal with all the "no preference" cases, where we assume that these cases (including tied ranks) imply a lack of underlying preference for the items being compared.

5.2 Results

As seen in Table 1, overall steering correction (S) was preferred to basic safety (B) in 28 of 50 rankings (56 %), while basic safety was preferred to steering correction in only 9 of 50 rankings (18 %). Steering correction was preferred to automatic in 26 of 50 rankings (52 %), and automatic was preferred to steering correction in 17 of 50 rankings (34 %). Finally, automatic was preferred to basic safety in 26 of 50 (52 %), while basic safety was preferred to automatic in 18 of 50 ratings (36 %). The remaining cases corresponded to "no preference" rankings.

Although there were no statistically significant results within each scenario, in 4 of 5 scenarios, steering correction had greater odds of being chosen than the other modes in both pair-wise comparisons, and automatic had greater odds of being chosen than basic safety. In the hallway task alone, automatic had greater odds of being chosen than the other modes. In only the table scenario, basic safety had greater odds of being chosen than automatic. Across all scenarios, the odds of a participant choosing steering correction were 2.14 greater than the odds of choosing basic safety ($p < 0.05$), and 1.79 greater than the odds of choosing automatic ($p < 0.05$). The odds of a participant choosing automatic were 1.20 greater than those of choosing basic safety, but this result was not statistically significant.

While it is not possible to statistically analyze day-to-day preferences due to limitations of the study design,[1] researcher observations and participant feedback suggest that familiarity and training with the system might impact user preference and usability. Participant 1 seemed to be more satisfied with and confident about using the steering correction mode after he "stress tested" it in the hallway scenario, through deliberate attempts to drive into obstacles as well as LTC staff passing by. While participant 2 was nervous about driving in general, and participant 8 was nervous about the autonomous mode, both mentioned that they were less anxious as they "got used to the chair". Similarly, while participant 6 preferred the automatic mode after her first session, she subsequently started preferring the steering correction and basic safety modes. Supporting evidence in her driving interviews suggests that while she thought she was a "bad driver" at first, she felt that the intelligent wheelchair with its safety features made her a "better driver" and increased her confidence, thus potentially resulting in her eventual preference for modes that offered her more control. In addition, the total number of "no preference" rankings was seen to decrease over time, with the maximum number of those rankings seen on the first day.

5.3 Discussion

The findings from both the User Attitudes and User Preferences sections lead to several insights related to the tradeoffs between user control and system usability, task difficulty, driving ability, and driving performance. They also suggest that preferences vary between users and scenarios, and even for the same user based on properties related to the user, task, environment, and the users' familiarity with the system.

It is likely that the overall highest preference for steering correction (in cases where preferences were articulated) was achieved by offering a better user experience than the basic safety mode, while simultaneously providing more user control than the automatic mode. This preference is similar to that of cognitively intact individuals in (Jipp 2013) and (Parikh et al. 2007) where higher acceptance and lower frustration respectively were reported with increased levels of user control, despite improved performances with the autonomous mode. Another recent study with older adults (with unreported cognitive abilities) also found that participants were more anxious or uncomfortable with locomotion capabilities of an autonomous wheelchair than a human caregiver wheeling them (Shiomi et al. 2015). These results suggest that PWC drivers might prefer semi-autonomous modes of control over fully autonomous modes of control, regardless of their cognitive status.

Participant preferences for maintaining wheelchair speed rather than being stopped corroborates reports of user frustration when the system stopped the wheelchair to prevent collisions in this study and previous studies (Viswanathan et al. 2013a). Since a key benefit offered by powered mobility is the ability to move faster and with less effort than while using a manual wheelchair or walker, it is reasonable that some drivers might want an intelligent wheelchair that ensures safety without compromising speed, and is enabling rather than disabling. Steering correction might have also lowered or eliminated the need for participants to think about how to avoid collisions in scenarios such as back-in parking and maneuver tasks, where mental demand was reported to be the highest when using the basic safety mode (see Table 3 in Online Resource). Thus, a steering correction approach might lead to higher satisfaction and usability than simply stopping the driver, although issues reported by some participants related to "jerkiness" (caused by disagreements between the driver's and tele-operator's joystick direction inputs) would need to be addressed to ensure a positive user experience. These issues might have led to some of the lower QUEST 2.0 ratings of ease-of-use and safety with the steering correction mode (see Table 2 in Online Resource).[2] Additionally, the steering correction mode could take away opportunities for the driver to learn and/or practice how to steer independently.

The preference for automatic over steering correction in the hallway task might be explained by participant 1's remark that this task is probably the most commonly encountered for most LTC residents (getting from their room to any other location of interest required navigating through the hallway). Results from the NASA-TLX ratings of physical demand for the hallway task were statistically significant, with both steering correction and automatic modes having the lowest mean ratings. A few participants mentioned that crowded hallways present challenges in their day-to-day lives, especially during meal times. Thus, the repetitive, dynamic, and possibly physically and/or mentally demanding nature of the task (in real life) might have resulted in a higher preference for automatic driving. Automatic mode thus helped participants by offering a higher level of intervention with tasks that users might have seen as mentally and/or physically challenging.

It is possible that participants perceived the table docking scenario, which was the shortest task with respect to completion times due to short route lengths (see Fig. 1 in Online

[1] Participants tested a different scenario each day, and the study was not counterbalanced such that an equal number of participants tested each scenario on a day.

[2] Despite some statistically significant results, note that the lowest median QUEST 2.0 rating for each mode in all scenarios and survey items was 4.0 ("quite satisfied"). Only two ratings below 3.0 ("more or less satisfied") were seen over all trials, suggesting that participants either felt uncomfortable to admit when they were unsatisfied, or were in fact generally quite satisfied with all modes.

Resource), to be easy enough that they preferred minimal intervention, thus preferring the basic safety mode over automatic. Additionally, increased safety concerns and lack of trust indicated by participants' remarks and gestures potentially resulted in the lower preference for the automatic mode in this scenario.

All participants, at some point, mentioned that they preferred to *drive themselves* (even with safety features) rather than to *be driven*, raising the question of how these concepts are differentiated between by users; in other words, how much control over which aspects of driving do participants need in order to feel that they are driving instead of being driven.

Not surprisingly, the most number of cases where users did or could not specify a preference occurred in comparisons between the steering correction and basic safety modes. While the mode of operation in the autonomous mode was quite different from the other two modes (no user input vs. modified user input), the difference between steering correction and basic safety was more subtle. Depending on the amount of intervention provided, the user might not have always felt the wheelchair correcting the drivers' steering. In addition, the steering correction and basic safety modes offered identical user experiences in the case that no steering correction was actually required. The decreased number of "no preference" rankings over time does, however, suggest that as participants continued to use the system, they were able to more easily distinguish between modes and/or they developed more defined preferences. Thus, an increased number and/or duration of driving sessions in future studies might allow further investigation of the changes in user preference over time.

6 Design implications and recommendations

The findings presented in this paper demonstrate that users, despite their cognitive impairment, are able to articulate some needs and preferences clearly. Instances of ambiguity and contradiction seen in user responses could be attributed to various factors: users may not have fully understood how the technology worked, they were unable to articulate specific thoughts, they were unsure of, confused about, or did not remember details related to the trial in question, they were hesitant to express how they truly felt, they changed their mind, or they simply had mixed feelings. Although the above factors present challenges in data collection and interpretation, given that all of these users were cognitively impaired and many are likely to deteriorate with time, these ambiguities and contradictions themselves need to be accounted for in the system design process. Key areas for future research and development are highlighted next.

6.1 Customizability and adaptiveness

It is unlikely that a one-size-fits-all solution will be accepted by the heterogeneous target user population. While a user with memory impairment might need a system that continually reminds him/her of what it is doing in order to prevent confusion or anxiety, as suggested by participant 6, a user who is easily agitated might prefer a system that simply intervenes without providing any feedback, and this preference might change from one day to the next as seen with participants 3 and 8. The above features would therefore need to be implemented in a system that is not only customizable to the user, but is also dynamic and can adapt appropriately to both short- and longer-term changes in functional abilities and preferences, as well as the environment.

Pineau et al. (2014) have used machine learning techniques to label safe and unsafe driving behaviors based on accelerometer and joystick input alone. In the future, this data can be supplemented with scenario/context, fatigue, prior experience with PWCs, visual ability, cognitive score, other physical disabilities (such as head and neck motion, spasticity, etc.), in addition to user preferences in order to predict driving ability and to determine the optimal control strategy. The participant-identified contexts for an autonomous wheelchair also provide a useful starting point for the development of automatic features. While the users' desire to be in the loop should be carefully considered and fulfilled, specific challenges faced by the target population can be overcome through increased system autonomy.

6.2 Increasing user control and awareness

Participants' preference for the steering correction mode when rankings were aggregated over all scenarios suggest that users would possibly be willing to temporarily give up control over heading in order to maintain control of speed while avoiding en-route obstacles. Since lost momentum was an issue identified with the basic safety mode, adding richer feedback on the correct steering direction and the environment could reduce the amount of time that participants remain stopped. Providing this feedback to the user earlier might encourage correct steering behavior before obstacles get too close, thus potentially eliminating the need for a full stop. Additionally, developing a more intuitive feedback interface could improve overall usability for users such as participant 9, who wanted to be able to steer the wheelchair on his own, but required more researcher assistance while using the basic safety mode. In general, it was found that participants needed more researcher assistance when using the basic safety mode than the steering correction or automatic modes, possibly resulting in the lower preference for the basic safety mode seen in Table 1.

Since the automatic mode, which ignored all user input except for stop requests was less preferred than the steering correction mode, it might be worthwhile to test a variant of the automatic mode that controls both wheelchair speed and direction as long as the user pushes the joystick, and stops upon joystick release (i.e., the joystick would act as a momentary on-off toggle). This strategy might offer users a higher level of perceived control of the wheelchair by requiring sustained driver input without the need for accurate direction or speed control while driving. Note that this modification would be similar to the steering correction mode, with the added functionality of direction control even in the absence of nearby obstacles, thus preventing wandering. Further modifications might allow users to deviate within a pre-specified distance from the optimal route, such as the elastic controllers in (Zeng et al. 2008a, b; Carlson and Demiris 2012), or allow more customized motion (Park and Kuipers 2015). Testing these variants might shed some light on how users differentiate between *driving* and *being driven*, how these perceptions vary between users, and what specific factors account for these differences (e.g., level of control over heading, speed, and/or movement).

Other recommendations include fulfilling user needs for fine user control when approaching parking destinations, explanations/justifications for system behaviors through various feedback modalities, and additional interfaces/methods for system interaction (e.g., through gestures, speech, and touch screens). The user's sensory channels (particularly visual) are already highly loaded during driving tasks; consequently, communication interfaces must be carefully designed. A full exploration of feedback options was beyond the scope of this study; however, future work will involve interfaces that are tailored to the control policy and customizable to the user.

While some attitudes and preferences reported might provide insights on the overall usability and acceptance of shared control and autonomous wheelchairs, it should be noted that the findings in this paper are contextualized by the specific control strategies presented to the participants in the study. Thus, minor or major modifications to system behavior could potentially lead to different results. In future studies, it might be beneficial to include an option to specify a preference for some mode other than the ones tested (i.e., a preference against the modes tested), along with open-ended questions to help inform new control and feedback strategies desired by the participants. Care must be taken, however, to limit the number of options presented at any given time to the target population, so as to prevent confusion and minimize cognitive burden.

The presence of two researchers nearby might have led to increased feelings of safety. Independent and extended use of the system will ultimately be necessary to explore user attitudes in a more realistic setting; however, issues around safety will need to be addressed first.

Finally, the small sample size, recruitment challenges, and heterogeneity in the target population, all often seen in studies with similar user demographics, typically pose challenges in generalizability/ transferability of findings. While the randomized controlled trial (RCT) is the gold standard for studies that measure intervention effectiveness, the objective of our study was information gathering for the purpose of informing design. In this case, a sample size is less of a concern, and a study approach that gathers information from a diversity of users to inform the breadth of technology capabilities needed is paramount. Designing for a constructed "typical" sample (i.e., taking a large sample and counting the majority needs) might result in a system that accommodates, at best, a very limited group of users.

7 Study limitations

Varying ability in communication led to different levels of depth in participant narratives and responses during interview sessions. In addition, memory impairments for certain participants might have led to difficulties in comparing the different modes directly at the end of each scenario (i.e., ordering the modes based on preference). In order to mitigate issues related to memory and recall, preferences were obtained immediately after the last mode, while the participants were still seated in the PWC. In addition, themes that emerged from data collected through think-aloud techniques while the participants were driving, and through semi-structured interviews immediately after each mode both contextualize and justify participant preferences. Corroboration was thus achieved through the use of different data sources (collected at different times during the trials).

8 Conclusions and next steps in deployment

The Wizard-of-Oz method of rapid prototyping allowed us to gain valuable feedback from users without developing a fully functional prototype. The identification of specific challenges in powered wheelchair mobility through this study have motivated the modular and iterative development of various intelligent functionality such as back-in parking (Adhikari 2014), and docking under tables (Foley et al. 2014). The modular approach to development will enable users to select specific features based on their capabilities and preferences. In addition to informing real intelligent wheelchair design, the tele-operation interface used in this study is being explored as a possible powered wheelchair training tool for therapists (Lo et al. 2014; Smith et al. 2014).

We also plan to release the anonymized sensor data (RGB-D, laser range finder, driver and tele-operator joystick movements, accelerometer, etc.) collected during the study. Due to the challenges in recruiting participants and running studies such as the one described in this paper, we hope that the data from our study can be used not only to help researchers understand the environment of long term care facilities, but also to facilitate preliminary and benchmark testing of algorithms and systems by other intelligent wheelchair developers, thus expediting research and development efforts in the field.

The results from this study have provided several insights into users' attitudes toward intelligent wheelchairs specifically related to user control, thus enabling the development of a system with a higher likelihood of adoption. User preferences and needs, along with the authors' recommendations, can inform the design of a system that can be used for larger scale testing in real life situations. Longer and increased trials with the system would also be helpful in understanding how preference and usability might change over time, and to explore issues that might be encountered with longer-term use of the system. Through features that are adaptable and adaptive to user needs and preferences, the system can evolve with the user, allowing him/her to age gracefully while ensuring safe and independent mobility.

Larger scale trials will require an increased number of wheelchair platforms. Although the system reported in this paper is only compatible with the AT Sciences PWC, the authors have developed new modular hardware and software components that enable the installation of intelligent features on commercial PWCs as an add-on system. This approach might also eliminate or lower some of the regulatory barriers faced when commercializing medical devices, as well as reduce overall cost.

A key barrier that needs to be overcome is the lack of clinician buy-in for longer-term trials (and eventual deployment) with older adults with cognitive impairment, due to consideration for safety and the capabilities of the target population. Clinicians and funders would require sufficient evidence for the benefits of the proposed technology compared to current practice. A possible approach is to conduct large-scale trials with existing powered wheelchair users who are deemed safe to drive, thus enabling real-life testing with fewer considerations for liability issues, and allowing the collection of data on longer-term robustness and reliability.

We have learned, through this study, about the importance of customization and adaptiveness of the system and have suggested possible implementation strategies. A key area of future research will be the investigation of interfaces for the user and/or therapist that will allow input of specific preferences and user abilities, as well as information regarding how and when to switch modes. Improved (richer and timely) feedback to the user will also be essential in increasing user awareness and satisfaction. Another important aspect will be integrating the intelligent system into current practices related to training and assessment in order to increase both user and clinician familiarity with the system.

Through continued exploration of user needs, development, and testing, we hope to eventually deploy a system that increases the independence and mobility of the target users, while satisfying their specific needs and preferences.

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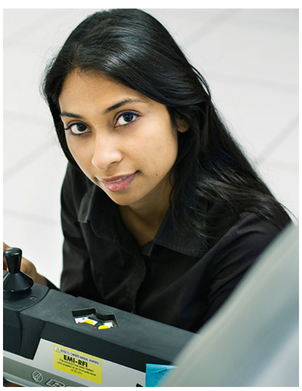

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