Intelligent Wheelchairs For Cognitively-Impaired Older Adults In Long-Term Care: A Review

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ABSTRACT

Cognitively-impaired older adults in long-term care (LTC) facilities are often excluded from powered wheelchair use because of safety concerns, even when manual wheelchair operation is difficult or impossible. Although several intelligent wheelchairs have been designed recently, and can potentially help restore mobility and independence for cognitively-impaired LTC residents, very few systems have been tested with these users. This paper summarizes the key findings of studies with our target population, identifies research and development challenges, and provides recommendations to overcome these issues. We hope that this paper is able to guide future development and deployment of intelligent wheelchairs in LTC facilities, and thus help improve quality of life for elderly residents with cognitive impairment.

INTRODUCTION

There is currently an increased need for improved health care and new assistive technologies for the growing older adult population, in order to ensure continued independence and a high quality of life (QoL). Independent mobility has been identified as an integral component of physical well-being and happiness (Bourret, Bernick, Cott, & Kontos, 2002). Unfortunately, the mobility and independence of many older adults are often reduced due to physical disabilities. Powered wheelchairs (PWCs) are usually prescribed to older adults who lack the strength or ability to propel themselves in manual wheelchairs; however, safe operation of PWCs requires a significant level of cognitive function. It is reported that approximately 60-80% of long-term care (LTC) residents have dementia (Marcantonio, 2000). These residents are often excluded from PWC use because of safety hazards (Hardy, 2004), thus making them reliant on caregiving staff to porter them around the facility. Reduced independent mobility can, in turn, lead to social isolation and depression (Iezzoni, E. McCarthy, Davis, & Siebens, 2001).

PREVIOUS WORK

The issues discussed above highlight the need for intelligent systems that can compensate for the lack of cognitive capacity required to safely maneuver PWCs. Several intelligent wheelchairs have been developed, and are reviewed in (Simpson, 2005). These wheelchairs are capable of various functionalities including collision avoidance, autonomous navigation to locations, wall following, and virtual path following. In addition to common interfaces such as joysticks, some wheelchairs have also used brain-computer and voice recognition interfaces (Jia, Hu, Lu, & Yuan, 2007; Honore et al., 2010). These wheelchairs have been developed for users with various disabilities, and thus vary in design goals and implementation approaches. A small proportion of existing intelligent wheelchairs, however, have been tested with cognitively-impaired older adults. Thus, performance and usability issues faced by our target population are poorly understood and documented.

To our knowledge, only four intelligent/modified PWCs have been tested with our target population. These systems have been designed and tested by the authors of this paper and their collaborators. We thus summarize key findings from previous user studies, identify limitations and challenges, and provide recommendations on future areas for research, development, and testing. We hope that the insights gained from testing with the target population will help guide future work in intelligent wheelchairs for cognitively-impaired older adults, and help restore mobility and independence for a population that is currently excluded from powered mobility.

FINDINGS

We summarize our findings in four areas: collision avoidance, wayfinding, prompting and adherence to prompts, and usability. Details regarding the systems and studies can be found in (How, Wang, & Mihailidis, 2011; Viswanathan, Little, Mackworth, & Mihailidis, 2011; Wang, Gorski, Holliday, & Fernie, 2011; Wang, Mihailidis, Dutta, & Fernie, 2011). All systems were tested in the participants' LTC facilities. All participants were at least 60 years of age, and had mild-to-moderate cognitive impairment (according to the Mini Mental State Examination). The number of users who completed each study ranged from two to six.

Collision Avoidance

The systems in (How, Wang, & Mihailidis, 2011; Viswanathan, Little, Mackworth, & Mihailidis, 2011) used a stereovision camera to detect obstacles within a pre-specified distance, and prevented motion of the wheelchair towards the obstacle. We refer to these intelligent wheelchairs (IWs) as IW1 and IW2, respectively. In contrast, (Wang, Gorski, Holliday, & Fernie, 2011) used a bumper skirt system (BSS) that required less than 1N (0.22lb*F*) of contact force to stop the wheelchair upon collision (for the full 10 cm stopping distance of the wheelchair). In (Wang, Mihailidis, Dutta, & Fernie, 2011), the wheelchair was stopped by a tele-operator; thus, collision avoidance performance was not measured. We refer to this system as the tele-operated wheelchair (TOW).

The number of frontal collisions with and without the system were reported in a controlled environment (an obstacle course consisting of foam boards) by both vision-based systems, IW1 and IW2, through an A-B single-subject study design. IW2 also randomized phase ordering in order to control for ordering effects. Both systems increased safety by lowering the number of frontal collisions for all participants who completed the study (i.e., two and six participants in IW1 and IW2, respectively). System errors in detecting obstacles were due to glare in windows, occlusions and interference with the camera by users. It was found, in IW2 trials, that the users' collision avoidance performance was linked to their visual capabilities, attentiveness and mood. The number of collisions with and without the system was not compared in the BSS study. It was noted, however, that the limited sensor coverage provided (from 1.5 cm to 19.5 cm above the floor) led to a risk of collisions with obstacles above (and below) the skirt.

Wayfinding

Only IW2 required users to navigate to a pre-specified location and provided wayfinding assistance (through audio prompts) using a probabilistic user model that estimated the cognitive state of the user. The system was able to maintain or improve wayfinding performance for all six users tested. The system was able to ensure that users always navigated along the shortest route by providing appropriate audio prompts. However, the system did increase completion times for three out of six users due to its stopping behavior. Wayfinding performance was found to be related to memory and self-reported user confidence regarding the route.

Prompting and Adherence

Upon imminent collisions, IW1 determined the area around obstacles with the greatest amount of free space, and prompted the driver in this direction through audio prompts. Low adherence to correct audio prompts was reported in trials (56% and 77% for each participant, respectively), and was attributed to: 1) low overall prompting accuracy (63%) due to delayed prompts and incorrect free space detection, and 2) the prompting modality (i.e., only audio). It was recommended that prompting modalities (visual, audio and haptic) should be customized to the user.

Audio prompts in IW2 were based on free space detection as well as computation of the optimal route to the goal location. Audio prompting accuracy in this system was found to be high across all users and trials (87%). While prompting adherence to correct prompts was high for all users (89% - 99%) in this study, users who were less confident about the route (four out of six users) tended to rely on the system more. These users adhered to 25% - 60% of incorrect prompts issued to them, while confident users (two out of six) correctly disobeyed more than 93% of incorrect prompts issued to them. Errors in wayfinding prompts were due to errors in localization caused by fast turns and camera interference by the user. In areas where turns were required in quick succession, delayed prompts resulted in detours. In addition, wayfinding prompts were often issued in cases when the user did not need them due to intentional stopping by the users that were perceived by the system as errors.

The BSS used directional indicator lights as visual prompts that identified free space, and was tested with six users. These lights, however, were found to be difficult for users to understand. Rather than using the lights to determine directions of allowed movement when the wheelchair was stopped, users tended to move the joystick randomly until the wheelchair moved again.

With the TOW system, users were prompted to drive around encountered obstacles through various feedback modalities (audio, visual and haptic). When all modalities were tested together with a total of five participants, the audio and haptic modes were found to be effective in guiding most users around obstacles.

Usability

The main usability issues were wheelchair speed and joystick operation in all studies. Several users wanted to be able to drive faster, while a few users wanted the wheelchair to be slowed down. During IW2 trials, the stopping behavior of the chair led to frustration among users with high baseline collision avoidance abilities, and especially when these users perceived their manoeuvers to be safe. IW1 used the same control strategy upon detection of imminent collisions; thus, although not previously reported, similar usability issues could potentially occur with IW1 as well. Additionally, users of the BSS found the system to be bulky, and were either unable or chose not to use it. Audio was the preferred modality for all five participants in the TOW trials. One resident found the haptic modality "too controlling" and expressed a desire for warning prompts before the wheelchair was fully stopped.

LIMITATIONS AND CHALLENGES

Several limitations exist when interpreting the results. The test environments for both IW1 and IW2 were static and free of safety hazards, thus possibly reducing anxiety and fear of collisions and potentially making participants more likely to drive through the foam obstacles. It was noted in the IW2 study that two participants attempted to push away nearby obstacles with their hands on a few occasions, rather than driving around them. During survey sessions, as noted with IW2 and the BSS, some users tended to provide inflated ratings, possibly in order to please the researcher. In addition, it is highly unlikely that some of the more cognitively-impaired users could remember details regarding their interaction with the system during the study, thus leading to validity issues for self-report measures.

Furthermore, there are various challenges to conducting evaluation studies with intelligent/modified PWCs. Scheduling constraints of participants and the researcher, limited laptop/wheelchair battery life, and the availability of only one PWC limited the number of trials that were conducted in a day. The small number of participants in all studies discussed in this paper presents challenges in generalizing the results to the larger population of cognitively-impaired older adults. The large variation in functional abilities observed within this population also necessitates testing with several users to identify areas for further improvement. A possible future approach would be to better characterize users according to specific impairments/symptoms (e.g., short-term memory loss, spatial disorientation, or decreased activity initiation) that present challenges in independent powered wheelchair use. The performance of the intelligent wheelchair system can then be measured across these symptoms, and the system can be customized, as necessary, to meet the needs of specific user subgroups.

Consent from substitute decision makers (SDMs) was difficult to obtain from some potential candidates. Since SDMs ultimately decide on PWC use by the target population, it is essential that study findings on the potential benefits of intelligent wheelchair are conveyed to them. This dissemination of knowledge can increase the number of test users for future studies, and eventually allow operation of the intelligent wheelchair by a larger number of users.

Several challenges lie ahead in developing and deploying intelligent wheelchairs for cognitively-impaired older adults. Many technical issues must be addressed before intelligent wheelchairs can be deployed, such as increased speed while ensuring safety, robustness to complex and cluttered environments, and compatibility for use with universal controllers that are able to interface with any PWC. Other major issues include the high cost of powered mobility devices and issues in funding and reimbursement schemes (because of the lack of sufficient evidence for powered mobility outcomes improvement). Acceptance of the technology by clinicians and LTC facilities is a concern with respect to device safety and reliability, as well as perceptions about the functional gains and benefits of powered mobility use by people with cognitive impairment. Manufacturers' liability and the need for ongoing technical support present further challenges in intelligent wheelchair adoption. In addition, there are many issues related to users' attitudes towards assistive technologies that must be overcome. For example, sensors such as stereovision cameras and bumper skirts might lead to stigmatization for users, resulting in abandonment of the technology.

RECOMMENDATIONS

In order to tackle some of the deployment issues outlined above such as safety and speed, and to address issues identified in our studies, the following avenues of research are recommended.

Collision Detection

Future work should involve investigating alternate control strategies that enable rather than disable motion. Possible strategies could include time-to-collision and/or steering correction approaches. Methods to achieve computational speeds should be explored in order to prevent delays in detecting and avoiding obstacles. In addition, detection of textureless objects should be improved through the use of projected light as in the Kinect camera. Cameras with wider viewing angles should be used to improve sensor coverage, and additional (cheap) sensors such as bump sensors should be investigated for use as failsafe backup mechanisms. High-level scene analysis (including object recognition) should be performed to accurately differentiate between safe and unsafe scenarios.

Wayfinding

Wheelchair localization should be carried out at a faster rate to prevent prompting delays seen in our studies. Most state-of-the-art vision-based localization methods are still too slow for real-time driving. Localization accuracy can be improved by using additional information acquired from wheelchair encoders and/or inertial measurement units (IMUs), which provide accelerometer and gyroscope data. In addition, pre-registered visual landmarks in various parts of the environment can be used to correct location estimates.

Prompting

Results suggest that richer user models would lead to better prompting strategies. A useful research direction would be to use the video data captured during the trials as input to machine learning techniques in order to discover user-specific and general behavior trends. These behaviors can then be encoded in the user model in a more data-driven manner, rather than the current method used by IW1 that involves manual specification of the model. Natural language can be used to provide justifications for prompts (Dodson, Mattei, & Goldsmith, 2011). Timing of prompts is also a key issue that needs to be investigated. While users in the our studies seemed to find the just-in-time prompts effective, more experiments are required to determine optimal prompting times, frequencies, and number of repetitions. In addition, issuing earlier prompts might be necessary for users with delayed reaction times.

User Studies

Rather than testing fully-developed systems, user studies could evaluate different collision avoidance and prompting strategies through the use of virtual reality driving simulators or Wizard-of-Oz studies (Green & Wei-Hass, 1985), which involve rapid prototyping of systems partially or fully operated by a hidden human expert, the “Wizard”. Testing through these methods will allow the researcher to eliminate hardware and engineering issues that are often time-consuming to resolve, and instead focus on the improving the feedback interface.

Future studies should be conducted to allow residents to drive the intelligent wheelchair in a realistic environment for a longer period of time. During this time, quantitative and qualitative data can be collected regarding issues such as acceptability and usefulness, which are difficult to interpret in studies as short as the ones described in this paper.

CONCLUSIONS

Previous intelligent wheelchair studies with cognitively-impaired older adults have helped identify areas for future research and development. Specifically, accuracy, speed and usability should be improved in order to ensure a positive user experience. Rapid prototyping methods should also be used to evaluate different designs in a quick and timely manner.

Despite the limitations of the current technology, study results have been promising, with one user stating, “[With this PWC], I would go to all the places I can’t currently go to” (Viswanathan, Little, Mackworth, & Mihailidis, 2011). We hope that continued development and testing of the system will help refine user needs and allow us to create an intelligent wheelchair that truly improves QoL of older adults with cognitive impairment.

ACKNOWLEDGEMENTS

This research was funded by NSERC and CanWheel, the Canadian Institutes of Health Research (CIHR) Emerging Team in Wheeled Mobility for Older Adults (AMG-100925).

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