International Conference on Virtual Rehabilitation 2011
Rehab Week Zurich, ETH Zurich Science City, Switzerland, June 27 - 29, 2011

Comparison of powered wheelchair driving performance in a real and in a simulated environment

Philippe S. Archambault
School of P&OT, McGill University
and CRIR
Montreal, Canada

Jodie Ng Fuk Chong, Gianluca Sorrento
School of P&OT,
McGill University
Montreal, Canada

François Routhier
IRDPQ
and CIRRIS
Quebec City, Canada

Patrick Boissy
Sherbrooke University
and CRV
Sherbrooke, Canada

***Abstract*—Powered wheelchairs (PW) are instrumental in promoting participation in meaningful life activities for individuals with impaired mobility. Because of their weight and speed, training is required. It is however often difficult to provide training in the clinic, due to lack of space or concerns for safety. The McGill Immersive Wheelchair simulator has been developed to provide a robust platform for the assessment and training of PW driving skills. In this study, we compared PW driving performance, as measured by the number of joystick movements and task completion time, in real and simulated environments. We found that driving performance in the simulator was similar for simpler tasks such as forward turns. Driving performance was significantly different for the more difficult tasks and for those requiring backward driving, such as a lateral maneuver. Overall, users experienced a strong sense of presence in the simulator and felt that it adequately reflected reality. Further developments are planned to optimize the simulator and joystick control in order to provide an effective evaluation and training tool.**

Keywords-powered wheelchair, simulator, driving performance, presence

I. INTRODUCTION

Mobility impairment is a major disability affecting individuals of all ages [1]. In North America, an estimated 1% of the population need a wheelchair for mobility, [2] while 15- 20% of these require a powered wheelchair (PW), because of limited arm strength or stamina necessary to propel a manual wheelchair all day long. For these individuals, a PW is instrumental in facilitating independence, promoting participation in meaningful life activities [3-7], and in decreasing the burden on caregivers [8]. As with any other type of assistive technology, training is essential in order to learn safe and efficient use of a PW. Driving a PW necessitates the acquisition of basic skills (e.g. moving forward and turning [9, 10]), complex skills, which include driving backwards, maneuvering in tight spaces (e.g. bathroom, elevator), avoiding collisions with fixed obstacles or with moving bystanders [9, 11-13], and properly positioning the PW for different activities (e.g. sitting at a table, grasping an object on a shelf or opening a door) [13-15]. Unfortunately, according to surveys and general consensus amongst both clinicians and PW users, the amount of training provided to new PW drivers is insufficient [13, 16-19]. This situation may lead to decreased motivation and confidence in one's ability to drive a PW, and therefore limit activity and participation [3, 5].

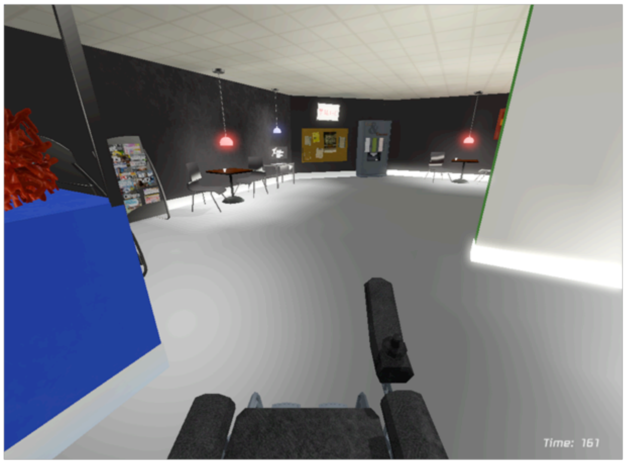

Figure 1. Scene from the miWe simulator

Safety is an important consideration for PW driving [20-22]. Indeed, because PWs weigh 200-250 kg (not including the user) and can attain a top speed of up to 13 km/h, depending on the model,

---

Supported by CRIR and NSERC (Canada)

they have an inherent risk of causing serious injuries to the user or to others, as well as damage to the environment [6, 16, 19-21, 23]. Interviews conducted in a group of 109 PW users have indicated that all of them had experienced at least one incident in the past five years, with 27% requiring medical attention or hospitalization [20]. Training is increasingly recognized as a means to improve PW safety [6, 13, 24]. However, the types of situations that may cause incidents can be practiced in a clinical setting only to a limited degree: tips and falls typically occur because of unexpected collisions with obstacles, suddenly braking on a slope or driving off a curb [19, 20, 23], while collisions with people occur in crowded environments [16]. Currently, rehab centers generally allow limited time for PW skills training and often lack the dedicated space to safely practice risky situations. This situation has motivated the development of a virtual-reality, PW driving simulator called the *McGill Immersive Wheelchair (miWe) simulator*. The *miWe simulator* runs on a regular personal computer and provides a first-person, 3D perspective view (Figure 1).

This study's main objective was to validate the use of the miWe simulator by comparing driving performance in both the simulator and in real life tasks. We hypothesized that driving performance, in terms of smoothness of joystick control and time needed to accomplish specific driving tasks would be the same if performed in real-life or in the miWe simulator. In addition, it is well accepted that to promote motivation, users of the simulator should develop a sense of presence, where they feel engaged and are truly participating in the simulated activity [25]. This would let the users focus their attention on the virtual scene in a way that would make them feel, temporarily, as if the simulation constituted a real space [26]. Therefore, a second objective was to measure the feeling of presence in the simulator.

II. MATERIALS AND METHODS

A. *miWe simulator*

The miWe simulator v1.0 was developed using a commercial-grade, 3D gaming engine (Unreal Development Kit, Epic Games, USA). The simulator runs on a regular personal computer, provides a first-person, perspective view (Figure 1) through a non-stereoscopic, 24" computer monitor running at 90 Hz. The first-person camera has a field of view of 90°. The simulator is interfaced through an USB joystick similar to those used for the control of many PW models (Penny & Giles joystick, Traxsys, UK). The joystick's x and y values are read at each frame of the simulation and are used as inputs for the control of the virtual PW. The simulator typically runs with a frame rate of 50 Hz, implying a delay of 20 ms between movement of the joystick and movement of the virtual PW. The parameters of the virtual PW, such as maximal acceleration, forward speed and turning speed, are configurable. These have been set to match the recorded movements of a real PW, set at a speed appropriate for indoor use (maximal forward speed: 1.5 m/s; maximal acceleration: 0.5 m/s^2) [27]. The 3D gaming engine handles the physical interaction of the virtual PW's motion with the environment and will correctly simulate the effects of inclined planes, different floor textures and collisions with objects or solid walls.

B. *Participants*

A total of sixteen healthy adults (*V-group*: 9 male, 7 female) participated in the project involving driving tasks in the simulator. A second group of thirteen healthy adults (*R-group*: 5 male, 8 female) performed the same driving tasks using a real PW. All participants were aged 25-35 and none had previous experience driving a PW. They provided their informed consent, as approved by the ethics committee of the Interdisciplinary Research Center in Rehabilitation (CRIR, Canada).

C. *Tasks*

In the virtual world, participants in the V-group navigated in a series of rooms and corridors representing a clinical setting, while being instructed to complete specific tasks. All subjects completed the simulator route three times; therefore each individual task was performed three times. PW driving tasks were modeled from a subset of the Wheelchair Skills Test (WST) (Wheelchair Skills Training Program, version 4.1, http://www.wheelchairskillsprogram.ca), a clinical assessment of PW driving skills, and consisted of the following: 1) driving backward 5m; 2) forward 90° turn (left and right); 3) backward 90° turn (left and right); 4) 180° turn within the limits of a 1.5m square; 5) opening a door, moving through and

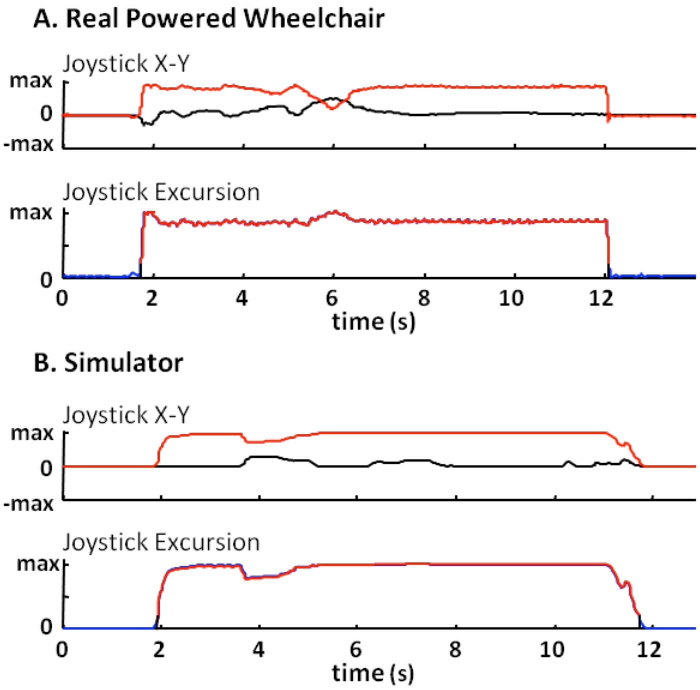

Figure 2. Joystick control during forward 90° turn. For Joystick X-Y, black and red lines represent left/right and forward/backward joystick movement, respectively. For joystick excursion, red lines represent joystick excursion above the threshold of 5%.

closing the door; 6) moving sideways, from one wall to another, inside limits of a 1.5m square. For the two tasks involving backward driving (driving backward 5m and backward 90° turn), the camera view of the simulator was flipped by 180°. For the doorway task, participants were required to position the PW at a distance and orientation where they could realistically reach for the door handle; the door was then automatically opened or closed. The time to complete all tasks was one hour.

Participants in the R-group completed the same tasks, three times, using a joystick-controlled, rear-traction PW (Oasis 2, Orthofab, Canada). The maximal speed and turning speed in both settings (real and virtual) were set at the same values.

D. *Data collection*

1) *Joystick control*

Joystick position data (e.g., x- and y- movement) were recorded. For the V-group, these data were recorded by the miWe system, at a frequency depending on the software (range: 40-50 Hz). For the R-group, we used a data logging system installed on the PW to record joystick movement [28]. Data was sampled at 200 Hz on a tablet PC placed inside a backpack that was attached to the PW.

2) *Presence*

Upon completion of the course, participants in the V-group answered the IGroup Presence Questionnaire (IPQ), a questionnaire designed to measure sense of presence in a virtual environment [29]. The thirteen questions are divided into four categories: spatial presence, experienced realism, involvement, global, and are scored on a scale of 0 to 6, with a score of 6 indicating a strong sense of presence.

E. *Data analysis*

In both the R- and the V-groups, we calculated the excursion of the joystick from its center position using the vector norm of the x and y displacements. For each task, we calculated the number of joystick movements, defined as the number of times where the joystick was moved away from its neutral position (threshold of 5%). We chose this method because, even though it does not account for smaller sub-movements, when the joystick reaches the neutral position the PW's brakes are automatically switched on. Thus, the number of joystick movements corresponds to the number of PW movements, circumscribed by instances of braking. Task completion time was calculated as the time from the beginning of the first to the end of the last joystick movement. Number of joystick movement and task completion time obtained in each driving

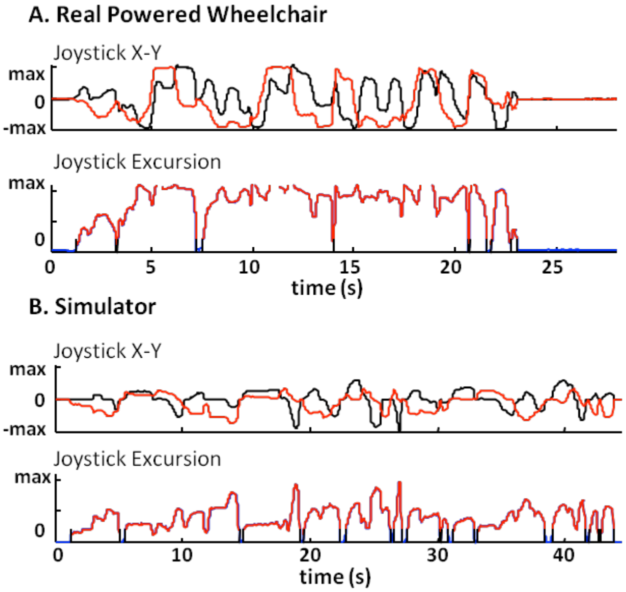

Figure 3. Joystick control during lateral maneuver. Line colors are the same as for Fig. 2.

task were then compared between the two groups using an unpaired t-test ($p<0.05$).

For the IPQ, a mean score was calculated for each category, and then scores were averaged across all participants. These were then compared to existing IPQ scores that were obtained in a study that examined sense of presence in videogames.

III. RESULTS

Fig. 2 illustrates a single trial of joystick movement for a forward 90° turn, performed either in a real PW (top) or in the miWe simulator. In both cases, the task lasted ~10 seconds and contained a single joystick movement. These values of task completion time and number of joystick movements were typical of what was observed across participants for forward turns. Typical examples of joystick control for a more complex task, the lateral maneuver, are displayed in Fig. 3. It can be noted that task completion time was close to twice as long when the lateral maneuver was performed in the simulator (~40 s) rather than in a real PW (~25 s). Number of joystick movements was also higher in the simulator with respect to a real PW.

Mean values obtained across participants in the R- and V-groups for all driving tasks are illustrated in Fig. 4 for task completion and Fig. 5 for the number of joystick movements. Comparisons between the two groups indicated that the V-group required a significantly higher task completion time than the R-group for the backward 90° turn, the lateral maneuver, the doorway crossing task and the 180° turn (Fig. 4; t-test, $p<0.01$). Similarly, the V-group used a significantly greater number of joystick movements than the R-group for the backward 90° turn, the lateral maneuver and the doorway crossing task (Fig. 5; t-test, $p<0.01$).

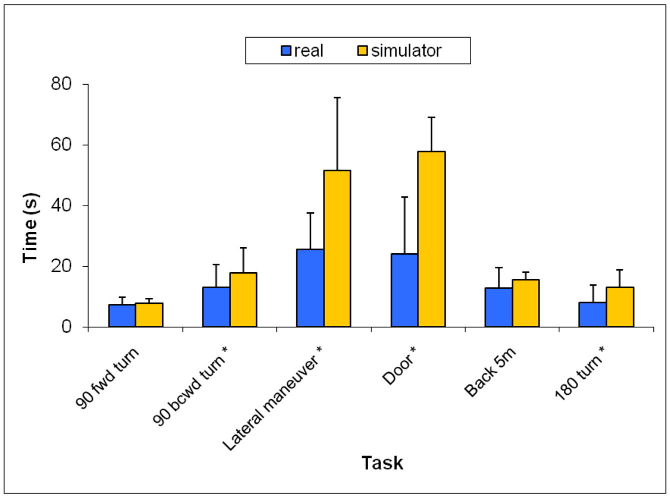

Figure 5. Mean task completion time in real and simulated environments. Error bars indicate standard deviation. *Significant group difference (t-test).

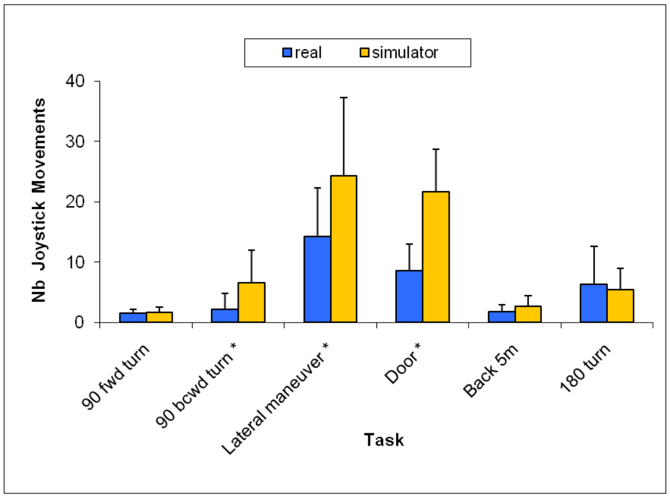

Figure 4. Mean number of joystick movements in real and simulated environments. Error bars indicate standard deviation. *Significant group difference (t-test).

As Fig 6 demonstrates, the average IPQ scores in all four categories were greater in the miWe simulator than the reported values for a 3D videogame calculated from the existing IPQ database [30], therefore indicating that participants reported a strong sense of presence in the simulator.

IV. DISCUSSION

Our research team expected to see no difference in driving performance in the simulator compared to real world driving, since the simulator was constructed to be used as a training tool and therefore was intended to be as realistic as possible. However, driving behavior was different in the

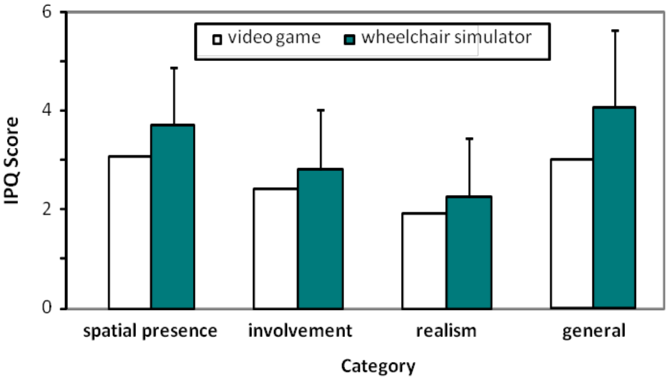

Figure 6. Results of the presence questionnaire (IPQ) obtained for the wheelchair simulator and compared to values obtained for a 3D videogame. Bars indicate standard deviation.

simulator for about half of the tasks and seemed to be more difficult since participants had an increased average number of joystick movements and task completion time. Out of the three tasks where such differences occurred, two were intrinsically more challenging (e.g., door crossing, and lateral maneuver), as the real-life data indicates that they required at least twice the amount of time and joystick excursion, with respect to the other tasks in this study (see Figs. 4 and 5). Another observation is that all three tasks showing differences in performance required some amount of backward driving: the backward turn was strictly a backward driving task, while the (door crossing and the lateral maneuver required frequent switching between forward and backward driving.

Differences in performance between the R- and V-groups could have occurred because of discrepancies between the control or response of the real and simulated PW. For example, the physical characteristics of the joystick used in the simulator may not have exactly matched that of a real PW. Even though we used in the simulator a joystick of the same brand name as that used for control of the PW (Penny & Giles), stiffness of the simulator joystick was lower, but maximal physical excursion was the same. It is possible that a stiffer controller, such as the one used in a PW, makes control of fine movements easier.

Also, although turning speed and maximal speed where equivalent in the two environments, the acceleration profiles were not exactly matched and this may have made control less precise in the simulator. Another possibility is that since the simulated environment was being displayed on a personal computer screen, the available field of view was limited by the scene and by the size of the monitor. Participants were not able to turn their heads as in the real setting and may have had difficulties gauging the distance between the simulated PW and limits such as walls and doors. Several other studies have indeed observed that participants performing tasks such as throwing or walking, in a virtual environment viewed through a head-mounted display, consistently underestimate distances when compared to a real world equivalent [31-33]. This discrepancy between distance estimation in real and virtual tasks is lessened when using a fully immersive virtual system, such as a CAVE [34]. However, artificially reducing field of view in the real world does not seem to impair the ability of estimating distances [35]. It is likely that field of view, together with other factors such as realism, can diminish the ability to estimate accurate distances in the virtual world and could have affected performance in the more complex tasks in the PW simulator.

Although we did provide participants with a backward view for all the reverse tasks (e.g., by flipping the camera), that situation may add an extra challenge compared to a real setting: in a real PW, one can turn the head and look backwards while driving backwards. In the simulator, the view flips back, so that one can now drive backward while still looking forward. This may be less intuitive and contribute to increases in task completion time and in the number of joystick movements.

The findings regarding sense of presence are encouraging since they suggest that the participants felt immersed in the virtual world and thus did not only believe that they were playing a game. Sense of presence should be high so that participants behave as they would in the real world. If presence was low, participants would likely drive more dangerously or out of character because they would pay less attention to negative consequences that could occur with their driving. We expect that sense of presence will increase with further developments to the simulator environment, such as the addition of virtual characters.

V. CONCLUSION

Through this experiment we were able to evaluate the potential of the simulator as a useful evaluation and training tool for PW driving. Completing the WST tasks in the simulator likely provided users with a realistic notion of the mechanics, difficulties and skills required to maneuver a PW. Further developments to the simulator would render it even more useful to users. The joystick control should be perfected so that it adequately represents the control one has during PW driving. Some components of the virtual environment could also be improved, such as making sure that all indications of limits remain within the field of view. The addition of a second computer monitor could also extend the field of view. Virtual PW training has immense promise and the findings from this study demonstrate that its standard use is well on its way.

ACKNOWLEDGMENTS

We would like to thank Stéphanie Tremblay for her help with data collection. This research was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC).

REFERENCES

[1] "Statistics Canada. A profile of disability in Canada. Statistics Canada 2001 (catalogue No. 89-577-X1E). Ottawa, CA."

[2] M. Shields: "Fauteuils roulants et autres appareils d'aide à la mobilité", Rapports sur la santé (Statistique Canada), 2004, 15, (3), pp. 41-46

[3] A. Brandt, S. Iwarsson, and A. Stahle: "Older people's use of powered wheelchairs for activity and participation", J Rehabil Med, 2004, 36, (2), pp. 70-77

[4] M.E. Buning, J.A. Angelo, and M.R. Schmeler: "Occupational performance and the transition to powered mobility: a pilot study", Am J Occup Ther, 2001, 55, (3), pp. 339-344

[5] A. Davies, L. de Souza, and A.O. Frank: "Changes in the quality of life in severely disabled people following provision of powered indoor/outdoor chairs", Disabil Rehabil, 2003, 25, (6), pp. 286-290

[6] S. Evans, C. Neophytou, L. de Souza, and A.O. Frank: "Young people's experiences using electric powered indoor-outdoor wheelchairs (EPIOCs): Potential for enhancing users' development?", Disability & Rehabilitation, 2007, 29, (16), pp. 1281 - 1294

[7] D.T. Reid, D. Laliberté-Rudman, and D. Hébert: "Impact of wheeled seated mobility devices on adult users' and their caregivers' occupational performance: a critical literature review", Canadian Journal of Occupational Therapy, 2002, 69, (5), pp. 261-280

[8] D. Reid, D. Laliberte-Rudman, and D. Hebert: "Impact of wheeled seated mobility devices on adult users' and their caregivers' occupational performance: a critical literature review", Can J Occup Ther, 2002, 69, (5), pp. 261-280

[9] A. Harrison, G. Derwent, A. Enticknap, F.D. Rose, and E.A. Attree: "The role of virtual reality technology in the assessment and training of inexperienced powered wheelchair users", Disabil Rehabil, 2002, 24, (11-12), pp. 599-606

[10] J. Chase, and D.M. Bailey: "Evaluating the potential for powered mobility", Am J Occup Ther, 1990, 44, (12), pp. 1125-1129

[11] D.M. Brienza, and J. Angelo: "A force feedback joystick and control algorithm for wheelchair obstacle avoidance", Disabil Rehabil, 1996, 18, (3), pp. 123-129

[12] N.D. Marchuk, D. Ding, and S. Gaukrodger: "Development of a Virtual Platform for Assessment and Training of Power Wheelchair Driving.". Proc. 30th RESNA International Conference, June 15-19, 2007, Phoenix

[13] P.J. Holliday, A. Mihailidis, R. Rolfson, and G. Fernie: "Understanding and measuring powered wheelchair mobility and manoeuvrability. Part I. Reach in confined spaces", Disabil Rehabil, 2005, 27, (16), pp. 939-949

[14] B. Cullen, B. O'Neill, and J.J. Evans: "Neuropsychological predictors of powered wheelchair use: a prospective follow-up study", Clin Rehabil, 2008, 22, (9), pp. 836-846

[15] L. Fehr, W.E. Langbein, and S.B. Skaar: "Adequacy of power wheelchair control interfaces for persons with severe disabilities: a clinical survey", J Rehabil Res Dev, 2000, 37, (3), pp. 353-360

[16] B. Salatin, I. Rice, E. Teodorski, D. Ding, and R.A. Cooper: "A Survey of Outdoor Electric Powered Wheelchair Driving ". Proc. RESNA 2010, Las Vegas

[17] R.A. Cooper, M.J. Dvorznak, T.J. O'Connor, M.L. Boninger, and D.K. Jones: "Braking electric-powered wheelchairs: effect of braking method, seatbelt, and legrests", Arch Phys Med Rehabil, 1998, 79, (10), pp. 1244-1249

[18] T.A. Corfman, R.A. Cooper, M.J. Dvorznak, S.G. Fitzgerald, and M.L. Boninger: "The ability of physical and occupational therapists to recognize electric powered wheelchair driving accidents". Proc. RESNA 26th International Annual Confence, Technology & Disability: Research, Design, Practice & Policy, June 19 to June 23, 2003, Atlanta, Georgia

[19] T.A. Corfman, R.A. Cooper, S.G. Fitzgerald, and R. Cooper: "Tips and falls during electric-powered wheelchair driving: effects of seatbelt use, legrests, and driving speed", Arch Phys Med Rehabil, 2003, 84, (12), pp. 1797-1802

[20] R.P. Gaal, N. Rebholtz, R.D. Hotchkiss, and P.F. Pfaelzer: "Wheelchair rider injuries: causes and consequences for wheelchair design and selection", J Rehabil Res Dev, 1997, 34, (1), pp. 58-71

[21] R.L. Kirby, and S.A. Ackroyd-Stolarz: "Wheelchair safety--adverse reports to the United States Food and Drug Administration", Am J Phys Med Rehabil, 1995, 74, (4), pp. 308-312

[22] W.B. Mortenson, W.C. Miller, J. Boily, B. Steele, L. Odell, E.M. Crawford, and G. Desharnais: "Perceptions of power mobility use and safety within residential facilities", Can J Occup Ther, 2005, 72, (3), pp. 142-152

[23] S. Ummat, and R.L. Kirby: "Nonfatal wheelchair-related accidents reported to the National Electronic Injury Surveillance System", Am J Phys Med Rehabil, 1994, 73, (3), pp. 163-167

[24] S. Beaumont-White, and R.O. Ham: "Powered wheelchairs: are we enabling or disabling?", Prosthet Orthot Int, 1997, 21, (1), pp. 62-73

[25] C. Heeter: "Being there: The subjective experience of presence", Presence, 1992, 1, pp. 262-271

[26] K. Bystrom, W. Barfield, and C. Hendrix: "A conceptual model of the sense of presence in virtual environment", Presence Teleoperators and Virtual Environments, 1999, 8, pp. 241-244

[27] P.S. Archambault, F. Routhier, M. Hamel, and P. Boissy: "Analysis of movement to develop a virtual reality powered-wheelchair simulator". Proc. Virtual Rehabilitation, 2008 pp. 133-138

[28] P. Boissy, M. Hamel, P. Archambault, and F. Routhier: "Ecological Measurement of Powered Wheelchair Mobility and Driving Performance using Event-driven Identification and Classification Methods". Proc. RESNA 2008 Annual Conference, Washington, DC.

[29] H. Regenbrecht, and T. Schubert: "Real and illusory interaction enhance presence in virtual environments.", Presence: Teleoperators and Virtual Environments, 2002, 11, (4), pp. 425-434

[30] http://www.igroup.org/pq/ipq/data.php, accessed 2011-01-12

[31] S.H. Creem-Regehr, P. Willemsen, A.A. Gooch, and W.B. Thompson: "The influence of restricted viewing conditions on egocentric distance perception: implications for real and virtual indoor environments", Perception, 2005, 34, (2), pp. 191-204

[32] S.R. Ellis, and B.M. Menges: "Localization of virtual objects in the near visual field", Hum Factors, 1998, 40, (3), pp. 415-431

[33] J.M. Loomis, and J.M. Knapp: "Visual perception of egocentric distance in real and virtual environments", in L.J. Hettinger, and M.W. Haas (Eds.): ‘Virtual and adaptive environments’ (Erlbaum, 2003), pp. 21-46

[34] J.M. Plumert, J.K. Kearney, J.F. Cremer, and K. Recker: "Distance perception in real and virtual environments", ACM Trans. Appl. Percept., 2005, 2, (3), pp. 216-233

[35] J.M. Knapp, and J.M. Loomis: "Limited Field of View of Head-Mounted Displays Is Not the Cause of Distance Underestimation in Virtual Environments", Presence: Teleoperators and Virtual Environments, 2004, 13, (5), pp. 572-577