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Comparison of virtual wheelchair driving performance of people with TBI using an isometric and a conventional joystick

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Abstract

Objective—To compare wheelchair driving performance in a driving simulator using a conventional joystick and an isometric joystick.

Design—Study participants with a Traumatic Brain Injury (TBI) drove a simulated wheelchair within four tasks, in two driving orientations (forward and reverse) and with five repetitions each. A total of forty driving trials were completed for each of the two joysticks.

Setting—A research facility based in a hospital or in an independent living center.

Participants—Twenty participants (age: 30.62±10.91; 12 male, 8 female) who were at least one year post a traumatic brain injury.

Intervention—Driving performance using an Isometric joystick compared to a conventional movement joystick.

Main Outcome Measures—Average trial completion time, and trajectory specific measures measured orthogonal to the center of driving tasks: Root mean squared error, movement offset, movement error, number of significant changes in heading.

Results—After statistically controlling for driving speed, participants were able to complete the driving tasks faster with an Isometric Joystick than while using a conventional movement joystick. Compared to the conventional joystick, an isometric joystick used for driving forward demonstrated fewer driving errors. During reverse driving the conventional joystick performed better.

Conclusions—The customizable Isometric Joystick seems to be a promising interface for driving a powered wheelchair for individuals with TBI.

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Keywords

Assistive Technology; Rehabilitation; Traumatic Brain Injury; User-Computer Interface; Wheelchair Simulator

INTRODUCTION

At least 1.4 million people with Traumatic Brain Injury (TBI) are seen in emergency departments every year in the United States. (1) According to estimates of the Centers for Disease Control and Prevention, about 5.3 million people (2% of the population) in United States are living with long term disability resulting from TBI. An additional 80,000 to 90,000 new cases arise every year. (2) Firearm-related injuries, vehicular crashes, and falls are the most common causes of TBI. With the escalation of the conflict in Iraq and Afghanistan, the number of soldiers with polytraumatic injuries, including TBI, has increased. As many as 28% of the personnel evacuated to the Walter Reed Army Medical Center have, in addition to other injuries, a diagnosis of TBI, with 56% of these cases being moderate or severe. (3)

Many people with TBI experience long-term sensory, cognitive, and motor changes that limit independent mobility. These individuals with TBI require some independence in personal mobility to carry out Activities of Daily Living and Instrumental Activities of Daily Living. Independence in transportation is identified as one of the largest barriers for people with TBI to overcome to maintain societal participation in activities like employment. People who reported a higher impact of these barriers on daily activities also reported lower levels of participation and life satisfaction. (4) Environmental barriers also affect outcomes after injury and, hence, the lives of survivors of TBI. In order to address some of the problems emerging from environmental barriers, effective policy level initiatives are required. Some of these policies are already in place, such as those improving architectural accessibility. However, at the individual’s level, by selecting and fitting appropriate assistive technologies to the user’s needs and capabilities, the impact of these barriers can be reduced. In this way, some degree of independence in mobility and transportation may be achieved.

Up to 40% of those who use Powered Wheelchairs (PWC) regularly have problems with steering, and 5-9% cannot steer at all in a clinical setting. (5) Improperly customized device features and user interfaces contribute to these problems and may eventually lead to abandonment. About one-third of all assistive technology devices are abandoned by users within the first year of using these devices. (6-8) With the sensory and cognitive issues that remain after a TBI, the demand for device interfaces and controls that can be tuned to the user’s residual capabilities is even greater. This customization is especially important to prevent abandonment of the technology. One objective of this research is to address some of the aforementioned needs for customizing and improving user interfaces with power wheelchairs.

Proportional movement sensing joysticks (MSJ) are commonly used to control PWC wherein the wheelchair’s velocity changes in proportion to the amount of deflection of the spring loaded joystick post. Users require proprioception and dexterity at joints to efficiently use proportional controls. In other words, the joystick post of an MSJ deflects under the applied force and the amount of deflections determines the speed of wheelchair. Isometric controls, on the other hand, respond to the forces applied to their transducers and theoretically may require less strength and dexterity for transduction. (9,10) The Isometric Joystick (IJ) post is rigid and does not deflect. Past research using IJs as a wheelchair control interface has demonstrated that key driving performance metrics gathered while using the IJ were comparable to those achieved using a conventional MSJ. (11-14)

In our prior work, a force sensing algorithm was used with the IJ and tuned to the user's arm strength. Inexperienced joystick users with TBI were observed to adapt to the IJ faster than they could to the MSJ (9,15,16) Moreover, using an IJ did not significantly compromise their driving performance in a wheelchair simulator as compared to the MSJ. (10) The current study aims to evaluate if the pilot results from this latter study (10) can be replicated in a larger set of participants with TBI. The metrics for evaluating driving performance that were used in our previous work (10) were average driving speed and Root Mean Square of deviations from the center line of the driving path. Additional performance metrics are introduced in this study and an improved additional statistical analysis is presented.

Participants with TBI were hypothesized to have better driving performance while using an IJ, than while using an MSJ, to direct a simulated wheelchair in forward and reverse directions. Wheelchair users have varying levels of information processing demands during their daily wheelchair usage. A secondary objective of this research was to evaluate the wheelchair driving performances with the two joysticks under different levels of information processing loads induced by changing the width of tasks. According to the law of Steering, moving along a narrow pathway induces higher information processing load which induces a higher number of errors while driving.

METHODS

A prior publication (10) describes the instrumentation and research protocol in detail. This study extends the analysis used in the prior publication to a larger set of participants with Traumatic Brain Injury (TBI). This research protocol was approved by the Institutional Review Boards of University of Pittsburgh and Department of Veteran Affairs. Participants were recruited from a local Independent Living Center and an outpatient assistive technology clinic. Participants were pre-screened on the telephone to determine their eligibility to participate. All participants were invited to the Human Engineering Research Laboratory or Hirem G. Andrews Independent living center to participate in the protocol. The inclusion criteria were that participants should be between 18 and 80 years of age and at least one year post TBI. Because of difficulties in recruiting and a higher attrition rate in regular PWC, the inclusion criterion was updated to include both ambulatory and non ambulatory participants who had a TBI. Exclusion criteria were self reported active pressure sores that would prevent participants from sitting in wheelchair for two hours and a seizure within the past 6 months.

Experiment Setup

Due to short attention span and other cognitive limitations that are typically seen in people with TBI, distraction from the task at hand is common. Some people with TBI also presented with some degree of visual neglect. Studies have shown that one strategy to improve task efficiency of people with visual neglect is to cue them in using a light house visual imagery strategy while performing functional tasks. (17,18) A horizon illuminating light house typically has a light at its top that sweeps left to right to guide ships at sea to safety. The light house visual imagery strategy encourages users to scan the environment around them by turning their heads as and when required. In this study we encouraged users to adopt a light house strategy while driving in a simulated environment by presenting the driving tasks as if they were viewed from "bird's eye" perspective or in orthogonal projection. See Figure 1. Use of the 6′ × 8′ screen further encourages this visual imagery strategy. The simulation environment was built using simplistic graphics to avoid a certain amount of risk of participants getting overwhelmed and fatigued from increased information overload from fast changing and immersive 3D graphics. Even though the 2 dimensional graphics of the test environment were simplistic, they were presented at a resolution that created sharp images when projected on the screen.

The participants used their dominant hand to operate the joysticks which moved a 2D icon of a wheelchair. The tasks simulated typical maneuvers one might perform during their day to day wheelchair driving. The first two tasks were equivalent to driving along a hallway that took a turn (left and right) along the way from its start to finish points. The third task was equivalent to driving along a hallway and entering a small elevator. The fourth task was equivalent to maneuvering in a tightly spaced office area. A custom built head position monitor (HPM) recorded the participant's head orientation. The HPM has an array of Hall Effect sensors built into a head rest mounted on the participant's wheelchair. The participants wore a headband with a magnet. If the participant became distracted and looked away from the screen, the wheelchair icon would stop moving. During driving a real wheelchair, such a safeguard would warn and/or correct users who are about to hit an obstacle because they got distracted from the direction they intended to move their wheelchair. During this study, the HPM encouraged participants to focus on the screen while driving. Real time data from the joystick, the wheelchair icon's orientation, trajectory, speed, boundary violations, and head position violations detected by the head position monitor were recorded during every update of graphics frame by the simulation software and used for data analysis. After completing the protocol, participants were asked about their subjective experiences while interacting with the IJ and simulated wheelchair.

Experiment Protocol

All eligible participants were invited to complete two visits to the research center. During the first visit, after informed consent, a certified clinician evaluated all participants for their arm range of motion and strength (shoulder, elbow, and wrist), visual acuity, and field of view. Any limitations in motor coordination of participants were evaluated using a Finger Nose Test, visual tracking of H and X pursuits and saccades. The purpose of this evaluation was to guide the clinician in setup of the equipment and determine if the participant's visual and motor skills were sufficient to interact with the experimental setup (view/scan the entire screen and operate both joysticks). If participants had their own wheelchair they sat in it during the testing. Otherwise a test wheelchair was provided to them. Any seating and positioning requirements of the participant were addressed by the clinician. The participant's real world wheelchair driving skills were rated on a 7 point Likert scale as they drove their own or a test power wheelchair along a driving course comprised of driving straight along a hallway and turns.

A conventional MSJ was used for driving. This MSJ had attributes such as dead zone, joystick template, bias axis rotation, and directional gains that shape the joystick's response to the user's physical inputs (deviation of joystick post) (9). Since the IJ has a rigid post, these attributes were simulated in the joystick interfacing software. A validated tuning protocol (9,10) was used to derive values for these attributes when the participant used an IJ. By tuning the IJ to have similar attributes as the conventional MSJ, variations in joystick usage performance could then be attributed to differences in the physical interfaces of joysticks and not to the actual software used. During the computer based driving evaluation, participants parked their chairs in front of a 6′ by 8′ back projected screen. A custom bracket was used to position the joystick being used so that it was in a functional position for the user. During the first visit, after these customizations, each participant was acquainted with the computer based driving environment and joysticks by driving a simulated wheelchair on the screen. The participant was trained to use both the IJ and MSJ to drive the simulated chair along a practice task. The practice task was a wide rectangular hallway loop with four turns at equal intervals and participants drove along the task in two driving orientations (forwards and backwards). The clinician made a judgment about the participant's confidence in driving in the simulation by their ease in controlling the simulated chair along the practice task. The aim was to achieve a plateau in the participant's learning curve with the experimental setup. After a participant felt sufficient confidence in using each joystick, he/she was asked to drive once along each of the 4 test tasks designed for this study. Since all trials from first visit were used for familiarization and training of the participants, data from this visit were not used for statistical analysis. Tuning the IJ and practicing driving with both joysticks was accomplished in about one hour. During the second visit each participant was re acquainted with the experimental setup by driving along the practice task once before starting with the experiment trials. This was followed by the actual driving protocol in which a participant drove on the 4 test tasks in 2 driving orientations (forwards and backwards) performing 5 repetitions of each combination. These 40 driving trials were performed with each of the two joysticks (IJ, MSJ). The order of these two blocks (joysticks) was randomly selected. All trials within a 40 trials block performed with each joystick, were randomized using the Random Permutation (randperm) function in MATLAB. This way the trials with both the joysticks were performed in a single session one block of trials followed by the other. Participants were instructed to drive the simulated chair by keeping the chair along the center of each task segment and complete each task as quickly and as accurately as possible. Only the data from the second visits of all participants were used for further analysis.

Trajectory data processing

At times, the sampling frequency of the main program loop was higher than the rate at which the user would respond to change the wheelchair icon's position. This would result in redundant trajectory data recordings. For example, if the wheelchair icon stayed parked far away from the track centerline without moving, it would accumulate large position errors for the time segment when the wheelchair was not moving. To account for this, only the unique position coordinates of the simulated wheelchair were considered for further analysis and the records representing repeated/redundant readings of position coordinates were deleted while computing outcome measures involving trajectory data.

The participants traversed the trajectories with different self selected speeds. In order to ensure consistency, the performance measures from trajectory data were evaluated by sampling each trajectory at equal number of sampling gates at regular intervals of spatial coordinates. Figure 2 shows one tenth of the sampling gates used for part of task 4. Screen coordinates (in pixels) of boundaries of the four tasks were extracted from their screen captured images using the boundary recognition tool in the MATLAB curve fitting toolbox. A space based sampling technique, adapted from Roduit et al. (19) was implemented for all four tasks. Briefly, this sampling technique gives non-intersecting sampling gates that are most orthogonal to the inner and outer boundaries of the task. Sampling gates are hypothetical landmarks on the tasks where the user's trajectory is sampled or interpolated and recorded as valid observation points. Thus the ideally expected path was considered to be the locus of midpoints of these sampling gates. Such a sampling strategy is especially important to extract trajectory deviation from tasks that involve turns. The real world equivalent of sampling gates is a clinician checking the wheelchair's position every few meters when a user is driving along a hallway. During such a driving activity, it is important that the wheelchair driver takes a path that does not endanger his or her own safety and of others sharing the hallway.

Performance Measures

In addition to the driving performance measure "Root Mean Square of deviations from the center line of the driving path" which was used in our previous work (10), this study introduces new performance measures trial time, movement offset, movement error, and number of significant changes in heading. These new performance measures were derived from their equivalents in computer access applications that evaluate a user's performance in moving computer cursor along steering tasks in a graphical user interface (GUI). (20) A steering task in a GUI based application has a predefined pathway, defined by at least two boundaries such as Menu navigation in Windows applications. During menu navigation, if the user does not keep the cursor within a narrow vertical and/or horizontal path while dragging through the menu choices, the menu linkage will be dropped and the pull-down menu task must be restarted. Hence this task has two objectives, first to move the cursor from start to end of the pathway as quickly as possible and second, to maintain the cursor within the boundaries. The task of driving a wheelchair along a predefined path along a hallway or a pathway is similar to performing a steering task on a computer screen. Maintaining accuracy while driving is important since it encourages the wheelchair user to avoid bumping into hallway walls or to fall off a curb.

We expect these new performance measures from computer access research to give insights into certain unique aspects of the user's driving performance. Task completion time is one of the most important performance metrics to estimate a user's efficiency in completing a task. Movement offset and movement error indicate whether users have a tendency to drive closer to one boundary wall when they are specifically instructed to drive along the center of the path. Root mean square error gives an estimate of mean deviation from the center line. The number of significant changes in heading indicates whether the users drive mostly straight or follow a "zig zag" driving pattern with many small turns. The new measures of errors in driving are computed orthogonally to the driving task and, hence, are not affected by the length of the task. Since lack of foresight and awareness of hazards are frequently compromised by a person with TBI, a wheelchair driving simulator must be used to train in pathway adherence if it is to be an effective training tool. Throughput or Index of Performance is a measure that captures both speed and accuracy of an input device on a given set of tasks. Measured in bits per second, higher throughput values indicate a better performance by the input device (20,21).

Three clinically relevant measures of wheelchair driving were also recorded by the simulation software. The HPM was installed to restrict the simulated wheelchair's motion if the participant got distracted from the driving task. The number of times the HPM detected violations was recorded. While driving a wheelchair in the real world, it is important that the drivers steer away from walls/boundaries lining a hallway. In cases of a crash with walls or when they just stop short before a crash, the drivers must be able to get themselves out of the situation and continue driving safely. Hence the variables, number of times wheelchair crashes into outer boundaries of driving task and the number of times wheelchair is stuck in place for more than 3 seconds, were recorded. A cumulative sum of each of these variables over five trial repetitions is reported here.

Statistical Analysis

Tasks one and two were grouped as "wide tasks" (average width 125 pixels or 3.18 meters equivalent in the real world) while tasks three and four were grouped as "narrow tasks" (average width 86 pixels or 2.19 meters equivalent in the real world). The wide tasks were about twice in length (612 pixels or 15.54 meters equivalent in the real world) of the narrow tasks (309 pixels or 7.84 meters equivalent in the real world). A power analysis based on pilot data from our earlier studies indicated that a sample size of 20 would yield a power of 70% (9,10,15) A net throughput was calculated for both joysticks by averaging throughput values across the four tasks (four Indexes of Difficulties) and then across all participants. (22) Since driving the wheelchair in forward and backwards orientations in the computer based testing environment required considerable change in perspective, these were considered two different experimental paradigms and outcome measures from each of these paradigms were analyzed separately. Although the participants were allowed to practice with the joysticks, it is possible that a learning effect while performing the experiment may have biased some driving scores. Hence the scores from the five repetitions of each of the joystick, task, and driving direction were averaged to give a better representation of the participant’s driving score. Averaging the trials also simplified the repeated measures mixed models that were built for statistical analysis.

Since all participants completed driving trials with all possible combinations of tasks, joysticks and driving directions, the participants served as their own controls and so repeated measures analyses were selected. The distributions of the variables ‘trial completion time’ and ‘absolute average speed in a trial’ were significantly and positively skewed. We corrected for these skewed data with a base ten logarithmic transformation. (23) A repeated-measures Analysis of Covariance (ANCOVA) was performed using SPSS Linear Mixed Modeling procedure to test if log of trial time was different for the two joysticks when they were used by participants to complete tasks of two different widths. The log of ‘absolute average speed of the simulated wheelchair was used as a covariate for this ANCOVA model. A Mixed model approach was employed for trial time instead of a General Linear Model because the covariate was different for each level of the repeated factors. A base ten logarithmic transformation was used to address significant deviation from normal data distribution for absolute Movement Offset (MO), Root Mean Squared Error (RMSE) and Movement Error (ME). A 2×2 (joystick type × task width) completely within-subjects repeated measures Analysis of Variance (rmANOVA) was performed for each of these outcome measures and for median ‘Number of significant Changes in Heading’ (NCH). Post hoc pair-wise comparisons were performed if significance was found for any of the within-subjects independent variables. A multivariate analysis was avoided for this study due to the small sample size. For each combination of driving direction and task type T tests with bonferroni correction were used to compare joysticks using the performance measures number of HPM violations, number of boundary crashes, and number of times wheelchair was stuck for more than 3 seconds.

RESULTS

Overall, 29 participants were recruited, out of whom 8 participants did not complete the two required visits. One participant died from medical reasons unrelated to this research and hence was withdrawn. Demographics of all participants are shown in Table 1. There was almost twice the number of ambulatory participants than regular wheelchairs users in those who completed the complete protocol. To avoid bias in statistics the two mobility groups were not separated during analyses. All participants had sufficient arm strength and range of motion to interact with the experiment setup. On average, the participants took 3.2±2.3 seconds to complete the Finger Nose Test. All participants were able to complete the visual tracking tasks except four ambulatory participants who had little difficulty in smoothly following the H and X trajectories. All participants had sufficient visual field and visual acuity to view the display screen. The net throughput of both joysticks after averaging over all indexes of difficulty and across all participants was comparable for both joysticks. Throughput was 0.444 for the MSJ and 0.465 for the IJ.

Forward driving

The mixed model repeated-analysis for trial time indicated a significant main effect of joystick ($p=0.001$, $F(1,136)=12.02$). The mean trial time for the MSJ was 3.4% higher than the mean trial time for the IJ, after controlling for wheelchair icon speed. As expected, a significant main effect of task-width ($p<0.005$, $F(1,135)=5968.25$) was found. The average trial time on wider tasks was 110.38% higher than the average trial time on narrow tasks. All other interactions were not significant.

Univariate repeated-measures tests for the other outcome measures gave the following results. All outcome measures did not show a significant main effect of joystick type. The joystick*task-width interaction effect was significant for RMSE (p=0.035, partial η^2= 0.109). For wider tasks RMSE on driving trials using the MSJ was 12.7% higher than on trials using the IJ. No significant differences were found in other outcome measures when compared across the two joystick groups. However, all of the outcome measures were significantly different across the two task widths groups. Compared to the narrower tasks group, the wider tasks group had higher MO (p=0.005, partial η^2= 0.187), higher RMSE (p<0.001, partial η^2= 0.633), higher ME (p<0.001, partial η^2= 0.609), and higher NCH (p<0.001, partial η^2= 0.381). Table 2 describes the outcomes measures number of HPM violations, number of boundary crashes, and number of times wheelchair was stuck for more than 3 seconds for each combination of driving direction, task width, and joystick type. For both wide and narrow tasks there were more boundary crashes when participants used the MSJ instead of the IJ for driving. This difference in number of boundary crashes was significantly different for wider driving tasks. On all task types, the number of HPM violations observed was similar with both joysticks. While driving along the wider tasks using an MSJ the wheelchair icon was stuck more often than while using an IJ.

Backwards driving

From the mixed model analysis for trial time, the interactions of joystick and task width with the covariate absolute average speed were not significant. However, a significant difference in log of trial times between the two joysticks (main effect, p=0.038, F(1,135)= 4.38) was observed. The mean trial time when using the MSJ was about 2.5% higher than the trial time when using the IJ. As expected, a significant main effect of task-width (p<0.005, F(1,137)=3645.5) was found. The average trial time on wider tasks was 112.32% higher than the average trial time on narrow tasks.

Univariate repeated-measures tests for the other outcome measures gave the following results. The log of absolute Movement Offset (MO) was significantly different (p=0.027, partial η^2= 0.119) across both joysticks. On average, participants had 38.04% higher MO while using the IJ than while using the MSJ. A significant joystick* task-width interaction effect was seen for log of Root Mean Squared Error (RMSE, p=0.002, partial η^2= 0.217) and log of Movement Error (ME, p=0.006, partial η^2= 0.177). For wider tasks no differences were found in either RMSE or ME if driving trials were performed using the IJ or MSJ. For narrow tasks, driving trials using the IJ showed 15.88% higher RMSE and 17.76% higher ME than trials using the MSJ. Median Number of significant Changes in Heading (NCH) was not significantly different across the two joysticks. As seen during forward driving, all of the outcome measures were significantly different across the two task widths groups. Compared to the narrower tasks group, the wider tasks group had higher MO (p<0.001, partial η^2= 0.321), higher RMSE (p<0.001, partial η^2= 0.679), higher ME (p<0.001, partial η^2= 0.664), and higher NCH (p<0.001, partial η^2= 0.683). No statistically significant differences were seen between the two joysticks in driving performance measures boundary collisions, number of HPM violations, and number of times wheelchair got stuck.

DISCUSSION

Attrition in subject population was mainly due to problems with transportation of the participant to the research center, prolonged medical illness, or loss of contact from participants moving away. On average the PWC users had 10.61 years of experience of real world wheelchair driving compared to the ambulatory participants. This may have led to bias in joystick performance because of practice effect with the MSJ. We presume the ample training sessions and averaging of repeated trials might have reduced the bias in the subject's driving from prior practice effect with the MSJ. Some ambulatory participants had used power wheelchairs during their rehabilitation after injury. A few others had experience with commercial joysticks to play computer games. The commercial joysticks have a proportional control like the MSJ but may have slightly different grasping mechanisms.

Throughput values of both joysticks were similar. This indicates that joystick usage performance using both joysticks is not significantly different. While driving the simulated wheelchair, the goal was to complete the driving tasks as quickly and as accurately as possible. During both forward and backwards driving, participants completed driving tasks faster with the IJ than with the MSJ after we controlled for their driving speed. Our hypothesis that the IJ would outperform the MSJ was confirmed when participants drove in the forward direction. While driving in the forward direction, participants drove with a lower root mean squared error when using the IJ than when using the MSJ. This suggests that with the IJ the participants were better able to control the heading of the simulated wheelchair and keep it closer to the centerline of the track. This difference in RMSE values was more prominent on wider tasks than on narrow tasks. On wider tasks, participants had fewer boundary crashes and the wheelchair got stuck fewer times while driving using the IJ than while using the MSJ.

While driving in reverse in real world, wheelchair drivers use their peripheral vision to gather environmental cues for maintaining heading and for estimating distance from their destination. From a bird’s eye view drivers have a clear view of their trajectories while driving in reverse. Although this minor advantage may decrease some cognitive load on drivers it might not significantly affect the number of driving errors they would perform. Our hypothesis that the IJ would also outperform the MSJ was not confirmed when participants drove in the reverse direction. During backwards driving, participants showed a tendency to drive farther away from the centerline, that is, with a higher movement offset, when using the IJ compared to when using the MSJ. On the narrow tasks, the RMSE and ME were significantly higher when participants used the IJ than when they used the MSJ. During a force application task, applying a pushing force away from body is comparatively easier than applying a pulling force towards the body. The participants had to exert a considerable pulling force while grasping the IJ post in order to instigate a backwards or reverse motion of the simulated chair. This could be one possible reason that that the participants found it difficult to maintain the heading of the simulated chair using an IJ. While using the MSJ for driving, users typically grasped the joystick post between their thumb and index finger but they had to use their whole hand to grasp the IJ post. Since the IJ reacts to force applied to its post, the effectiveness of using an IJ also depends on the effectiveness of the user’s hand grip on the joystick post. Difficulty in properly maintaining a hand grasp on the joystick post especially while pulling on the post could be one reason for the poorer backwards driving performance (higher RMSE and higher ME values) using an IJ compared to MSJ. Future studies will explore an ergonomically better fitting grip on the joystick post.

As seen in previous research studies, participants who did not use any wheeled mobility devices on a regular basis appeared to adapt better to an IJ compared to an MSJ. (24,25) A similar trend was seen from the comments participants gave after they completed this study. Some ambulatory users felt comfortable in learning to use the IJ before the MSJ. Some of the regular wheelchair users were initially somewhat frustrated with the IJ since it required them to apply a higher amount of force to produce the same amount of transduction in the simulated wheelchair. However, with enough practice, all participants were comfortable in driving the simulated wheelchair with both joysticks. Recent studies have shown that performance in computer access tasks and navigation in simulated environments can be modeled using similar information processing laws. (26)

According to the steering law, which has been validated in computer access tasks and navigation in simulated environments (26), people tend to move their cursor with fewer errors on a narrow task than while on a wider task. Similar results were seen in this study, regardless of joystick used. The wider tasks had a higher margin of error; thus participants had more driving errors on wider tasks compared to the narrower tasks. The wider tasks were about twice as long as the narrow tasks, and after statistically controlling for speed, participants took twice as long to complete the wider tasks. This suggests that length of tasks was not a confounder and outcome measures were not affected. During this research study, the participants were free to choose a how accurate they were while driving (measured as closeness to the center of the tasks) and their driving speed. Different self- selected speeds by the participants were a primary reason for statistically controlling for average driving speed of the participants. During the steering law evaluation paradigm, participants were asked to complete tasks of different widths as fast as possible, and thus the researchers derived a relationship between task width and trial completion time. Such a relationship was hard to derive during this study given the different self-selected driving speeds and cognitive abilities of participants.

The outcome measures MO, RMSE, ME, and NCH used in this research are borrowed from well documented research on computer input devices. (20) In accordance to the law of steering, these error measures were higher on wider tasks than on narrow tasks. These measures can give some insights and help us to describe certain aspects of a power wheelchair user's driving performance in computer-based and simulated reality based driving simulators. The seven-point Likert scale used to score the participant's real world driving showed a ceiling effect. Hence it was difficult to draw direct correlations between the scores from real world and simulated driving tasks. While analyzing their simulated driving performance, because of this ceiling effect, we could not control for the participant's real world driving skill. In our future research, we plan to use validated evaluation tools for the participant's visual motor coordination, functional performance, and wheelchair driving skills. The clinical significance and validation of the outcome measures of this study as predictors of the power wheelchair user's real world wheelchair driving performance is still an open research question. Future research studies will address some of these questions about determining appropriate outcome measures for wheelchair driving in simulated environments and validating them with reliable qualitative and quantitative performance measures of wheelchair driving in real world using a larger cohort of wheelchair users.

CONCLUSION

People with TBI were able to learn to drive a simulated wheelchair using an IJ. During both forward and reverse driving and after statistically controlling for driving speed, participants were able to complete the tasks faster with an isometric joystick than with a conventional movement joystick. While forward driving the simulated wheelchair, participants showed equivalent or lesser trajectory errors with an IJ, than while using a conventional MSJ. During reverse driving the MSJ showed better performance metrics. The IJ may be a promising interface for driving a real world PWC.

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LIST OF ABBREVIATIONS

TBI	Traumatic Brain Injury
PWC	Powered Wheelchairs
MSJ	Movement Sensing Joystick
IJ	Isometric Joystick
HPM	Head Position Monitor
GUI	Graphical User Interface
MO	Absolute Movement Offset
RMSE	Root Mean Squared Error
ME	Movement Error
NCH	Number of significant Changes in Heading

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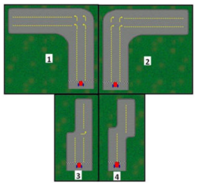

Figure 1.

Driving Tasks; Task 1: Left turn along hallway, Task 2: Right turn along hallway, Task 3: Drive straight along hallway and enter an elevator, Task 4: Maneuver in a tight office area.

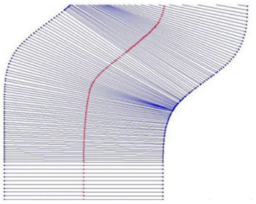

Figure 2.

Sampling gates (in blue). The task trajectory is sampled to generate gates that are most orthogonal to the two boundaries. Locus of midpoints (in red) of these gates defines the ideal path in that task segment.

Table 1

Demographics of participants and withdrawn candidates*

Demographics		Participants	Withdrawn candidates
Gender	male	12	6
	female	8	2
Average age (years)		30.62±10.91 (n=18)	41.22±6.15 (n=4)
Average time since Injury (years)		10.34±7.56	7.5±6.75
Median gap between 2 visits (days)		10.5	NA
Day to day mobility	Using PWC	7	5
	Ambulatory	13	3
Experience with PWC (years)		10.61±7.67	6.95±6.5
Joystick Preference	Left	6	3
	Right	14	5
Real world driving Score (median)		6.2 (n=19)	6.6 (n=7)

[*] Except wherever mentioned, all variables were measured for n = 20 for participants and n = 8 for withdrawn candidates.

Table 2

Summarizes the number of boundary collisions, number of times HPM detected that the participant was distracted from driving task, and number of times the wheelchair was stuck for more than 3 seconds along the driving task. After bonferroni correction, statistically significant differences were seen in the joystick pairs a-b (p = 0.007) and c-d (p = 0.016).

Direction	Track Type	Joystick	Crash Count	HPM Violations	Stuck Count
Forward	Wide	IJ	1.3 ±2.7[a]	3.6 ±10.6	0.6 ±0.9[c]
		MJ	4.1 ±5.6[b]	3.6 ±9.9	1.6 ±2.3[d]
	Narrow	IJ	1.9 ±2.6	0.9 ±3.0	1.0 ±1.4
		MJ	3.2 ±3.3	0.8 ±1.9	1.0 ±1.5
Backwards	Wide	IJ	3.6 ±5.8	2.6 ±9.1	1.4 ±1.9
		MJ	4.7 ±6.1	4.3 ±9.9	1.7 ±1.9
	Narrow	IJ	4.0 ±4.2	1.2 ±3.4	1.2 ±1.1
		MJ	4.1 ±4.2	3.5 ±9.2	1.5 ±1.6