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Virtual Electric Power Wheelchair Driving Performance of Individuals with Spastic Cerebral Palsy

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Abstract

Objective—Upper limb spasticity may impair the use of control interfaces such as joysticks for many individuals with disabilities such as Cerebral Palsy (CP). The aims of this study were to compare driving performance of those with CP to control participants, to identify the impact of lead time on performance, and to compare the two joystick designs, a standard movement sensing joystick (MSJ) and a novel isometric joystick (IJ).

Design—This study used a repeated measures design to compare the performance of a group of participants with CP to those without disabilities in a two-dimensional simulated driving task on a computer screen using the two control interfaces. The driving trials utilized varying “lead time,” or the amount of warning time available to make movement decisions and turns. A total of 34 participants with CP and without disability were matched by age and gender into two groups.

Results—Participants with CP had lower driving performance in most variables of interest compared to controls. However, surprisingly, reducing lead time also reduced some performance errors, possibly due to more deliberate driving. The IJ outperformed the MSJ in terms of performance errors but contributed to a prolonged reaction time.

Conclusions—The IJ was preferred by participants over the MSJ in this study, and may be a future alternative for individuals with CP for both power mobility and computer access tasks.

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Keywords

Cerebral Palsy; Joystick; Rehabilitation; Spasticity; Wheelchair

Cerebral Palsy (CP) affects over 750,000 individuals in the U.S.¹. One survey study of adults with various subtypes of CP revealed that 77% had spasticity². Lower limb spasticity can impair mobility and necessitate the use of a wheelchair. In fact, 46% of adults with CP report limited mobility in their communities². However, upper limb spasticity can make the independent use of a wheelchair difficult. A survey study by Fehr, et al. showed that up to 40% of individuals who desire mobility via Electric Powered Wheelchairs (EPWs) are unfortunately precluded from using them because of a constellation of problems with upper limb function including motor, sensory, or cognitive impairments³. Individuals with spastic CP are known to have increased resting muscle tone, hyper-excitability reflexes, dystonia, and clonus⁴. Each of these problems can make the use of a conventional joystick difficult⁵, not only for power mobility but also for other tasks such as computer access. Two recent studies showed that standard positional joysticks outperformed other control interfaces for pointing tasks in children with CP^{6, 7}. However, few studies to date have demonstrated how spasticity affects the use of joysticks, and thus limited data are available to help guide the development of novel control interfaces.

Our first objective was to characterize driving performance of individuals with spastic CP and controls during a series of virtual EPW driving tasks. Hypothesis 1: compared to controls, those with spastic CP will have decreased performance because of the deficits already known to occur in grasping and reaching studies⁸⁻¹⁹. Understanding the differences in movement at the level of the joystick between people with spastic CP and controls is the first step to understanding the differences in motor planning between the groups.

Because participants with CP may need more “lead time,” or time to plan movements, and because EPW driving and computer access involve complex, multi-step tasks, it is important to evaluate the importance of planning time in successful joystick use. Our second objective was to determine if participants with spastic CP would have reduced performance when we limited the amount of warning available for driving decisions but that they would be able to complete fairly complex driving tasks if enough lead time was available. Hypothesis 2: the number of performance errors in participants with spastic CP would be inversely associated with the lead time that was given.

Our third objective was to determine if a customized isometric joystick might improve motor performance in those with spastic CP. Our prior work suggested that customization of the gain of a joystick may be important for those with spasticity²⁰. Hypothesis 3: a customized isometric joystick as compared to a standard joystick would result in better performance in virtual EPW driving for participants with spastic CP.

METHODS

This study was approved by the Institutional Review Boards of the University of Pittsburgh and the VA Pittsburgh Healthcare System. Participants were recruited using flyer mailings,

advertisements, research registries, and through contact from physiatrists in outpatient clinics at our institutions.

Inclusion Criteria

1. Participants must be between the ages of 12-80
2. Participants must be able to give written informed consent or consent by proxy to participate
3. Participants with the diagnosis of CP must have a score of 2 or 3 on the Modified Ashworth Scale in at least one of the following in the operating limb: wrist flexors, wrist extensors, elbow flexors, or elbow extensors
4. Control participants must have a Modified Ashworth score of 0 for all of the above muscle groups in both upper limbs
5. Participants must have the minimal motor ability necessary to participate in the trial, defined as being able to operate the joystick to complete practice trials.

Exclusion Criteria

1. Participants who are not able to tolerate sitting for 2 hours
2. Participants who have active pelvic or thigh wounds (they may be worsened by prolonged sitting)
3. Participants with a history of seizures in the last 90 days (uncontrolled seizures may be induced by a computer screen task)

“Operating limb” was defined as the limb controls or participants preferred to use. After giving informed consent, all participants underwent a brief upper limb neurological examination by a physiatrist to include Modified Ashworth Scale²¹⁻²³. Participants with spastic CP completed (with assistance if needed) a questionnaire that included questions on demographics, medical history including Barthel Index^{24, 25}, Penn Spasm Frequency Scale²⁶, and prior joystick use (for wheelchairs, video games, or computers). Participants were matched on both age (within 2 years) and gender and then placed into either the control group or group of participants with CP.

All participants were positioned so that their heads were 0.9 m (approximately 36 in.) from a 0.5 m (20 in.) flat screen computer monitor. All participants were tested in their own wheelchair when they had one. If a subject did not use a wheelchair, investigators optimized the seating of a test wheelchair with a pressure relief cushion (participants with CP) or office chair (controls) such that depth of the seat; and height of the seat, armrests, backrest, legrests, and footrests were comfortable.

Customizing the Joystick

We used a stock Quickie²⁷ brand joystick and a customizable IJ, which has been described in detail in prior studies^{5, 28-31}. The joysticks were connected to our computer system only and not to the EPW motor. We programmed the MSJ and the IJ with identical maximum speed, acceleration, and deceleration parameters for all participants. Because the

conventional MSJ is not further customizable, we then customized the IJ for each subject using a previously validated protocol which has been described in prior work²⁰. We adjusted dead zone, gain, axis, filter, and perimeter template. For comparison, the unchangeable parameters for the MSJ were as follows: Dead Zone was 0.8 N. The stick had peak deflection of 18 degrees in all directions and required 4.5 N to deflect maximally. Gain was linear. Axes were 90-degree angles. Perimeter template was a circular mechanical stop.

Testing Participants

Participants were tested in 6 virtual maze-like environments³¹⁻³³ that all consisted of a path from Bird's Eye view. The driving paths were designed with realistic proportional dimensions such that each path was 10 virtual meters long and 1.5 virtual meters wide (see Figure 1). A sprite, which was the square image on the screen representing the virtual EPW, had a virtual width of 0.635 m by 0.655 m (approximately 2.1 ft). The sprite was designed to have the momentum and inertia of a real EPW. Each Task contained at most 4 turns to allow sufficient recovery time for mistakes made during previous turns. The paths were either completely visible or appeared in increments based on time and the instantaneous velocity of the sprite. Lead time (LT) was defined as the number of seconds ahead of the sprite by which the path would appear. LT was deployed by adjusting the height of the virtual camera. The height of the virtual camera was adjusted based on driving speed. Within each task, the faster a subject would drive, the more of the path he or she would be able to see. Progressively more difficult tasks presented subjects with shorter LT for a given speed. The camera was adjusted as follows:

- Task 0: One 90-degree turn. Path is completely visible.
- Task 1: Four 90-degree turns. Path is visible 10 seconds ahead of sprite.
- Task 2: Four 90-degree turns. Path is visible 3 seconds ahead of sprite.
- Task 3: Four 90-degree turns. Path is visible 2 seconds ahead of sprite.
- Task 4: Four 90-degree turns. Path is visible 1 second ahead of sprite.
- Task 5: Four 90-degree turns. Path is visible immediately ahead of sprite.

In each trial, Time_{zero} commenced when the environment appeared on the screen. Participants were asked to drive as accurately as possible while maintaining a speed between 0.8 and 1.2 m/s, which discouraged them from driving at unrealistically low speeds to avoid errors. The sprite turned green when the subject was driving with acceptable speed, yellow if driving too fast, and red if driving too slow. These values were chosen to approximate average walking speed³⁴. To simulate driving a real EPW, the virtual path rotated as a subject turned the sprite so that a subject's forward movement was always facing the top of the screen. The end of the trial, or Time_{end}, occurred when the sprite reached the end of the path.

Participants were allowed to practice with each joystick for 5 minutes using Task 0. As part of the inclusion criteria, all participants were then required to complete 3 trials of Task 0 with both joysticks. Joystick order was random. Under the condition of both joysticks, an average minimum speed of no less than 1.2 m/s and an average trial time of no more than 18

seconds were required to continue in the study. These parameters were selected based on the assumption that indoor driving would be slightly slower than an average human walking speed of 1.4 m/s³⁴, and dimensions were based on ADA standard accessible route width of 1.54 m (60 in)³⁵. These minimal criteria ensured that participants were at least able to manipulate a joystick and to produce a slow forward velocity. Yet it did not exclude those participants who were not able to drive an EPW in real situations.

Tasks 1-5 were then tested. Each subject performed a total of 30 trials (5 tasks were performed 3 times (3 trials) using each of the 2 joysticks). Joystick order and Task order was randomized to minimize learning effect. The total number of left and right turns were equal in each Task and joystick combination to control for handedness.

Data Processing

The simulation program recorded various state variables in real time. Time instances; joystick voltages; sprite speed, acceleration, Cartesian position coordinates (x, y), sprite orientation (theta); and number of sprite collisions with walls were recorded. These data were post-processed using MATLAB to derive the performance outcome variables of interest, which were based on Mackenzie's work³⁶ and calculated using imaginary sampling gates. Sampling gates were drawn equidistant from each other and perpendicular to the boundaries defining the driving task. The locus of midpoints of these sampling gates was also the midline of that task, which was the ideal trajectory the driver was expected to take. The participants' actual driving trajectories were sampled at these imaginary gates and used to derive unbiased deviation from the center of the tasks. This approach was used to avoid bias arising from varied driving speeds among trials and has been described fully in a prior publication³⁷. For example, if a driver drove along the same trajectory twice, once going slowly and once quickly, the slow trajectory could produce a higher measure of error simply because of a higher number of data points being collected.

- Movement error (ME) was the average distance from the ideal trajectory from all deviations measured at the sampling gates, in m.
- Movement variability (MV) was the standard deviation of distance in m from the ideal trajectory from all deviations measured at the sampling gates.
- Trial Time (TT) was the total time in seconds from Time_{zero} to Time_{end}.
- Self-intersecting Loops (SIL) occurred when the sprite trajectory intersected a previous trajectory in the same trial. Units for this variable are a count.

Additional outcome measures were collected:

- Change in Heading (CH) was any sudden change in the sprite's heading angle. This was calculated by using the MATLAB function "Extrema"³⁸ to compute the significant changes in heading. The peak values used were local maxima and minima in the time series data of the chair heading angle. The units for this variable are a count.
- Average absolute speed (AAS) in m/s.

- Reaction Time (RT) was defined as the time when the initial force applied to the joystick moved the sprite 0.01 virtual meters, measured in s.
- Average absolute acceleration (AAA) in m/s^2 .

Statistical Analysis

The level of significance was set at 0.05 for all analyses. Forty nine (4.8%) erroneous trials were excluded prior to analysis. Erroneous trials were due to investigator error (software or hardware problem) or participants not completing a trial (incomplete trial or subject terminated study early). The variables TT and RT were log transformed (natural log) to correct for skewness in their distributions. To evaluate the first and third hypothesis, we performed a completely within subjects Multivariate Analysis of Covariance (MANCOVA) with LT as the covariate and subject group and joystick type as the within subjects repeated factors, respectively. The main and interaction effects were evaluated in a full factorial model. Univariate and post hoc pairwise multiple comparisons were performed for effects that were significant. Within the group of participants with CP, one-tailed Spearman Rho correlations were run between lead time and individual outcome variables.

RESULTS

A total of 34 participants were matched into two groups of 17. Table 1 shows the demographic characteristics of the matched groups. Given the inclusion criteria, all subjects with CP tested had bilateral upper limb spasticity and were tetraparetic. A total of 9 (52.9%) participants with CP and 11 (64.7%) controls stated that they preferred the IJ over the MSJ. Twenty-seven participants gave additional anecdotal feedback on their preferences. Those who preferred the IJ (17/27) stated that the MSJ was too sensitive (6), the IJ was easier to use (3), the IJ provided more control (5), or that they liked the rigid nature of the IJ (3). Those who preferred the MSJ (10/27) stated that the IJ required too much force to control (8) or they did not like the rigid nature of the device (2).

Table 2 shows outcome variables per subject group, with controls having better performance than those with CP in all outcomes except AAS.

Table 3 shows positive associations between lead time and the outcome variables ME and MV in the group of participants with CP. No other significant associations were found.

The IJ outperformed the MSJ in terms of ME, MV, SIL, and CH. The MSJ outperformed the IJ in terms of RT and AAS. There were no differences in joysticks with respect to TT and AAA.

DISCUSSION

The results supported our hypothesis that individuals with CP would have lower performance than control participants except for AAS. The anatomic and physiologic basis of spasticity may impair joystick use. That is, the arm has certain constraints on movement because of the effects of spasticity. However, it is also possible that some of the characteristics of control interface use are due to coping mechanisms that participants use.

For example, participants may avoid certain joint positions in order to prevent hyper-reflexia, or they may induce intentional movements in alternate directions to compensate for unintentional movements in the other direction, and thus “oscillate” toward a desired target. We have demonstrated that those with CP have significantly delayed reaction times when using control interfaces; however more work is needed to determine whether reaction time is delayed because movement is limited, or because it is a compensatory strategy to allow more time for anticipatory movement. We have observed some drivers changing direction or speed in a repetitive fashion in order to compensate for unintended excess movements that oppose what was intended. It is unclear how much of this is purposeful behavior.

Interestingly, the results contradicted our hypothesis that lead time would be inversely associated with performance for those with CP. Giving more lead time was associated with higher ME and MV. This seemingly paradoxical result may indicate that participants with CP drove more deliberately and thus made fewer errors when lead time decreased or task complexity increased. This notion is supported by the finding that, overall, TT was exceptionally slow when averaged across all trials (Table 2), despite the fact that participants were required to perform at faster speeds as part of the study criteria. Indeed, driving at speeds slower than walking speed would be realistic in environments with multiple turns.

Our results support the hypothesis that the IJ was significantly superior to the MSJ, at least in terms of performance errors. However, participants had slower RT when using it, possibly due to its rigid design which does not provide as much proprioceptive feedback as an MSJ, and lower AAS, which also may indicate more deliberate driving with an unfamiliar device. Despite these differences, a small majority of controls and participants with CP preferred using the IJ over the MSJ.

This study was designed to examine the multi-factorial deficits in joystick use in individuals with spastic CP. One limitation is that it did not isolate effects of cognition, vision, or attention that may be contributing to impaired joystick use. We plan future studies using more immersive three-dimensional (3D) virtual reality tasks to identify which specific driving deficits may preclude individuals from being candidates for power mobility. We specifically designed this study to involve virtual 2D tasks in order to test participants in a less visually demanding environment that also had a lower likelihood of inducing motion sickness. Another limitation is that EPW ballistics were not included in the model. Quite possibly, real world effects of EPW acceleration or deceleration or perturbations from terrain, could affect the results. We are currently testing subjects in a new study in 3D environments that include unexpected, moving obstacles and incorporate real EPW ballistics. Our future aims are to develop a virtual power wheelchair driving assessment and training system for individuals with various disabilities.

CONCLUSIONS

Participants with CP had lower driving performance for most variables of interest compared to control participants. However, surprisingly, reducing the warning time available to make movement decisions and turns reduced some performance errors, possibly due to more

deliberate driving. The IJ outperformed the MSJ in terms of performance errors but contributed to a prolonged RT. The IJ was preferred by participants over the MSJ in this study, and may be a future alternative for individuals with CP for both power mobility and computer access tasks.

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Figure 1.
an example driving path with sprite (square object) where path is completely visible.

Table 1

Descriptive data of the subject groups

	CP	control
N	17	17
Mean Age (SD)	36.5 +/-15.9	36.1+/-16.6
No. Female (%)	8(47.1)	8(47.1)
No. Caucasian (%)	13(76.5)	15(88.2)
No. African American (%)	4(23.5)	0
No. Asian-American (%)	0	2(11.8)
Mean Barthel Score (SD)	50.0 +/- 23.9	100 +/- 0.0
Median Penn Spasm Frequency (range)	1 (0,4)	0 (0,4)
No. with Prior Joystick Experience (%)	12(70.6)	10 (58.8)
No. with Preference for IJ (%)	9(52.9)	11(64.7)

CP indicates cerebral palsy; IJ, isometric joystick.

Table 2

Univariate tests for subject group after controlling for Lead Time

Outcome	Units	CP	control	p value
Movement Error	m	0.17+/-0.01	0.14+/-0.01	<0.001
Movement Variability	sd	0.19+/-0.01	0.17+/-0.01	0.037
Trial Time	s	78.13+/-8.01	37.54+/-1.74	<0.001
Self Intersecting Loops	count	4.36+/-0.81	0.82+/-0.18	<0.001
Changes in Heading	count	30.08+/-2.66	21.87+/-0.53	0.001
Average Absolute Speed	m/s	0.28+/-0.02	0.29+/-0.01	NS
Reaction Time	s	0.93+/-0.13	0.76+/-0.07	0.046
Average Absolute Acceleration	m/s^2	0.40+/-0.03	0.68+/-0.03	<0.001

Values are presented as mean T SD. CP indicates cerebral palsy; IJ, isometric joystick; NS, not significant

Table 3

Association of Lead Time with Outcome Variables in Subjects with CP

Outcome	Units	Correlation Coefficient	p value
Movement Error	m	0.141	0.038
Movement Variability	sd	0.154	0.027
Trial Time	s	NS	NS
Self Intersecting Loops	count	NS	NS
Changes in Heading	count	NS	NS
Average Absolute Speed	m/s	NS	NS
Reaction Time	s	NS	NS
Average Absolute Acceleration	m/s ²	NS	NS

CP indicates cerebral palsy; NS, not significant

Table 4

Univariate tests for joystick type after controlling for Lead Time

Outcome	Units	IJ	MSJ	p value
Movement Error	m	0.15+/-0.01	0.16+/-0.00	<0.001
Movement Variability	sd	0.17+/-0.01	0.19+/-0.01	<0.001
Trial Time	s	52.51+/-3.11	55.85+/-3.24	NS
Self Intersecting Loops	count	1.65+/-0.32	3.53+/-0.57	<0.001
Changes in Heading	count	24.11+/-1.17	27.84+/-1.75	<0.001
Average Absolute Speed	m/s	0.25+/-0.02	0.32+/-0.01	<0.001
Reaction Time	s	1.01+/-0.12	0.70+/-0.06	<0.001
Average Absolute Acceleration	m/s^2	0.57+/-0.02	0.54+/-0.02	NS

Values are presented as mean T SD. IJ indicates isometric joystick; MSJ, movement sensing joystick; NS, not significant.