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Preliminary evaluation of a variable compliance joystick for people with multiple sclerosis

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Abstract—Upper-limb fatigue is a common problem that may restrict people with multiple sclerosis (MS) from using their electric powered wheelchair effectively and for a long period of time. The objective of this research is to evaluate whether participants with MS can drive better with a variable compliance joystick (VCJ) and customizable algorithms than with a conventional wheelchair joystick. Eleven participants were randomly assigned to one of two groups. The groups used the VCJ in either compliant or noncompliant isometric mode and a standard algorithm, personally fitted algorithm, or personally fitted algorithm with fatigue adaptation running in the background in order to complete virtual wheelchair driving tasks. Participants with MS showed better driving performance metrics while using the customized algorithms than while using the standard algorithm with the VCJ. Fatigue adaptation algorithms are especially beneficial in improving overall task performance while using the VCJ in isometric mode. The VCJ, along with the personally fitted algorithms and fatigue adaptation algorithms, has the potential to be an effective input interface for wheelchairs.

Key words: fatigue, joystick, MS, multiple sclerosis, outcome measures, tremor filter, variable compliance joystick, virtual reality, wheelchair, wheelchair driving.

INTRODUCTION

While technological developments over the past several decades have greatly enhanced the lives of people with mobility impairments, clinicians have reported that between 10 and 40 percent of clients who desired powered mobility found it very difficult to operate powered wheelchairs [1]. Researchers have explored a variety of innovative methods for individuals with movement disorders to control wheelchairs [2–6], but a lack of research still exists in this area for individuals with multiple sclerosis (MS) [7].

Approximately 211,000 people are living in the United States with MS [8]. MS is a progressive disease involving the central nervous system and can result in a variety of sensory, motor, and cognitive impairments.

Abbreviations: ANOVA = analysis of variance, COLL = number of collisions, HERL = Human Engineering Research Laboratories, MANOVA = multivariate analysis of variance, ME = movement error, MS = multiple sclerosis, MSPFA = multiple sclerosis personally fitted algorithm, MSPFA_FA = multiple sclerosis personally fitted algorithm with fatigue adaptation, NCH = number of significant changes in heading, RMSD = root-mean-squared deviation, RT = reaction time, TBI = traumatic brain injury, TT = trial completion time, VA = Department of Veterans Affairs, VCJ = variable compliance joystick, WFLC = weighted Fourier linear combiner.

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Although highly variable among individuals, the progressive nature of MS may lead to deterioration in physical capabilities requiring them to have human and/or technological assistance in completing activities of daily living. Noseworthy et al. reported that half of all people with MS will require assistance walking within 15 yr of disease onset [9]. Powered mobility devices, especially wheelchairs, have long been used by people with disabilities to achieve independence in personal mobility and improve access to activities of daily living in home and community settings. Fatigue is the most significant symptom for 50 to 60 percent of individuals with MS [10], and tremor is present in 75 percent and "incapacitating" for 10 percent [11]. Fatigue is one major reason that people with MS begin using power wheelchairs [12]. However, fatigue, when severe, can also limit the use of the control interface during flares, after a period of activity, or in a person with a more advanced condition. When selecting and customizing a wheelchair for users with complex needs, it is crucial to choose the control interface and programming carefully so that they do not induce or worsen upper-limb fatigue.

The user interface plays a pivotal role in a person's ability to drive a powered wheelchair [7,13]. It is the means by which the user supplies commands to the wheelchair's controller, which in turn sends commands to the motors. The most common control interface for powered wheelchairs is the position-sensing joystick [14]. Any tilting motion applied to the compliant joystick post of a position-sensing joystick is converted into motion commands for the wheelchair controller. The isometric joystick, on the other hand, transduces the pressure applied to its noncompliant, rigid post into commands for wheelchair motion. Few isometric joysticks are commercially available [15–16]. Preliminary research in people with traumatic brain injury (TBI) [17] and cerebral palsy [18] has shown that the isometric joystick could be a promising wheelchair control interface [4,17,19–20] that can help users drive more accurately. We expect that using a joystick with a rigid isometric post along with personalized controls [21–24] and advanced signal-processing algorithms [25] can further improve its ability to mitigate the effects of various upper-limb issues like fatigue and tremor. While control interfaces that are currently available with commercial wheelchairs are themselves programmable by the supplier and clinician, and users can have several custom settings available to choose from, fatigue still remains an issue for many users. As the effects of fatigue set in, users currently need to remember to change the custom joystick settings. A joystick that can automatically adapt its sensitivity to a user's fatigue level could provide more options for those whose needs cannot be met with programming options currently available on commercial joysticks. Also, such automated algorithms may prevent possible frustration the user may experience if he or she forgets to change the driving settings with the onset of fatigue. Such signal processing algorithms that run with variable compliance joysticks (VCJs) can incorporate different methods for adapting to the fatigue profiles, tremors, and other such upper-limb conditions of people with MS. The algorithms can be programmed to change according to time of day and length of use.

In addition to fatigue adaptation, the algorithms can also be programmed for tremor filtering, which might not be feasible to add to a conventional position-sensing joystick. The force limits on the conventional joysticks restrict the use of advanced signal-processing techniques. The force limits on the isometric joystick, however, are much higher and allow the signal-processing algorithms to be applied even after the user exceeds the force cutoffs.

One example of advanced signal processing for filtering tremor is the weighted Fourier linear combiner (WFLC) that Riviere et al. developed for microsurgical instruments [26]. Nho [27] further developed Riviere et al.'s [26] WFLC for powered wheelchair control by adding instantaneous bandwidth information to the filter inputs. Nho [27] found that the modified WFLC performed similarly and better than Riviere et al.'s [26] WFLC and a 3 Hz low-pass filter, respectively, in a virtual environment for wheelchair driving. Signal-processing algorithms can also be used to make the joystick more sensitive when the effects of fatigue are seen.

The aims of this research are to find new ways to increase access to mobility devices and to determine which—if any—customizable features provide the most benefit for individuals with MS. The first specific research objective of this study was to evaluate the effects of MS personally fitted algorithms (MSPFAs) on the virtual driving performance of people with MS. Our first hypothesis was that participants would have the best driving performance when the MSPFAs with fatigue adaptation (MSPFA_FAs) were being used. The second research objective was to evaluate whether the compliance or noncompliance of the joystick posts contributed to reduction in tremor or fatigue that could be reflected in the virtual driving of people with MS. Our second hypothesis was that using a VCJ in a less compliant, isometric mode would result in better driving performance metrics than when using a VCJ in a more compliant, position-sensing mode.

METHODS

Virtual Driving Simulator

Virtual driving simulators have been used by our [17,19–20,24,28] and other research groups [29–32] in the past to evaluate the feasibility of using specialized control mechanisms and/or algorithms in the real world. The dynamics of the virtual wheelchair in this simulator were based on the acceleration profiles of a Quickie P300 power wheelchair (Southwest Medical; Phoenix, Arizona), and an earlier study indicated no significant difference in driving performance between virtual and real-world driving [19]. A driving simulator feature that allows programming of the virtual wheelchair's response to input control mechanisms in real time makes this a potentially viable tool that a clinician could use in a busy clinical environment. For the purposes of this research study, the virtual driving simulator, similar to the one used in our previous research studies [17], featured four driving tracks: left turn, right turn, straight forward, and a docking track, as well as one practice track. The first two tasks were similar to driving a wheelchair straight along a hallway and taking a left or right turn midway. The third task was equivalent to driving straight along a wide hallway and entering a narrow elevator. The fourth task was equivalent to maneuvering a wheelchair in a tight office space. Driving data from the practice track were not used for data analysis.

Variable Compliance Joystick

The Human Engineering Research Laboratories (HERL) developed a VCJ with the intent to be a test bed for evaluating both isometric and position-sensing joysticks [33–34]. The VCJ allows clinicians and researchers to adjust the compliance of the joystick handle and hence the force required to deflect the handle across the continuum between a compliant position-sensing joystick mode and a rigid isometric joystick mode. The VCJ hardware, by the nature of its design, provides custom control enhancers including dead zones, bias axes, templates, and optimized joystick handles [20,24]. A force transducer and strain gauge bridge is used to convert the deflection of the joystick post into analog voltage signals. These voltage signals are amplified and noise filtered on the joystick board and sent to the recording computer through an analog to digital converter.

In a conventional position-sensing joystick, the joystick will start outputting data once the post is out of the dead zone and will hit a ceiling when the post touches the edge of the template that surrounds the post. The dead zone is defined as the minimum joystick deflection that is required to initiate motion in the wheelchair. Joystick dead zones are specifically maintained in order to make the wheelchair less sensitive to electrical noise and extraneous motion transferred to the post due to tremors in the user's operating arm. The joystick post is surrounded by a specifically shaped template, a stop ring that restricts post deflection beyond a certain range of angles. Axis gain controls are specifically implemented to change sensitivity of any axis of motion. The joystick post could also be rotated about an angle (bias angle) to accommodate for the user's preferred direction of pushing the joystick forward [20,35]. In a VCJ, dead zone, template, axes gains, and bias angle features are implemented in the driver software running on the recording computer [36]. A software implementation of these features allows precise and real-time customization of these features while performing the usability study. Additional programmable features such as a tremor filter and customized algorithms are also implemented in the VCJ software. The same features are also active in the isometric mode of the VCJ.

Customized Algorithms

The VCJ software supported three customized algorithms for processing joystick signals in this study.

Standard Algorithm

The standard algorithm simulated a conventional position-sensing joystick. It was part of the VCJ signal-processing unit software and implemented the essential features of a conventional position-sensing joystick such as dead zone, template, and axes gains [20]. The standard algorithm used circular dead zone and template shapes. The force required to tilt the VCJ handle beyond the dead zone in compliant mode was 1.02 N, and the force required to reach the template boundary was 3.98 N. The axes gains were derived such that the force needed to reach the template's extreme locations resulted in the wheelchair's maximum safe speed. This means the standard algorithm ensures that the VCJ output was equivalent to that of a conventional position-sensing joystick for the same amount of force applied to the joystick post. While the algorithm for the VCJ in isometric mode was the same as the algorithm for compliant mode, for consistency, we used different dead zone and template forces settings to match the HERL isometric joystick from previous studies. The force required to exceed the dead zone was 1.11 N, and the force required to reach the template was 6.63 N.

Multiple Sclerosis Personally Fitted Algorithm

The MSPFA allowed tremor filtration and personalization of the joystick for each user. It incorporated algorithms for bias angle, adjustable dead zone and template sizes and shapes, and independent axes gains. An adaptive WFLC filter similar to that designed by Riviere et al. was used to filter out tremor from the raw joystick data [26]. A second-order infinite impulse response high-pass filter was first applied to the raw data from the joystick to prevent the WFLC from removing the intentional movements that typically occur at less than 2 Hz. The input was rotated by the joystick bias angle followed by applying dead zone and template shapes. Dead zone shapes include elliptical and rectangular, and template shapes include elliptical, diamond, and asteroid [36]. Independent modification of axes gains allowed the speed of the wheelchair to be more or less sensitive to the force applied to the joystick by the users.

Multiple Sclerosis Personally Fitted Algorithm with Fatigue Adaptation

The MSPFA_FA was similar to the MSPFA but automatically adjusted gain as fatigue set in. Instead of applying a fixed gain to the joystick axes, a software program monitored the time users spent using the joysticks and changed the axes gains according to a predetermined gain schedule. The gain schedule was a function of the rate at which fatigue onset occurred in the user’s hands while using the VCJ in either isometric or compliant modes for a long time.

Research Protocol

The research team recruited participants through flyers posted at local rehabilitation clinics and local MS support organizations. Inclusion criteria were having a diagnosis of MS, being between the ages of 18 and 80 yr, and using a powered wheelchair as a day-to-day means of mobility. People who self-reported having pressure ulcers that would prevent them from sitting for 3 h and those who were unable to understand study procedures and provide informed consent were excluded from this study. We randomly assigned participants to two groups: VCJ in isometric mode or VCJ in compliant mode.

We invited participants to the research center for two visits, and they went through an informed consent process during visit 1. During each visit, subjects performed virtual wheelchair driving trials using the joystick mode they were assigned and two algorithms. A balanced randomization table was prepared a priori for the algorithm and joystick mode assignments for participants, such that half of the participants in each joystick group used the MSPFA during visit 1 and the MSPFA_FA in visit 2 and vice versa. Each newly recruited participant received the next available joystick mode algorithm combination. During every visit, participants first used the standard algorithm followed by either of the two specialized algorithms, MSPFA or MSPFA_FA. Participants were blinded to the algorithm that was being implemented to process their joystick inputs. Driving trials with the standard algorithm during each visit gave a baseline of the subject’s driving performance. The two visits were scheduled at least 2 d and no more than 10 d apart to avoid learning effects and the potential for significant change in physical capabilities because of their diagnosis.

After subjects completed the driving tasks with the standard algorithm, the research team determined optimal parameters for the MSPFA or MSPFA_FA for each participant by using an updated version of the joystick-tuning software published by Ding et al. [36]. This software was used for personalizing joystick dead zone and template settings for each of the four primary axes. To determine the best rates for gain adaptation, we measured participants’ fatigue index by asking them to push on a rigid isometric joystick at their maximum voluntary isometric contraction force for 30 s in the medial direction [37]. Participants further performed certain standardized driving tasks, and the driving data from this session were processed using a MATLAB program (The MathWorks; Natick, Massachusetts) to optimize parameters for the tremor filter and fatigue gain adaptation functions. Participants drove the virtual wheelchair using the respective joysticks and signal-processing algorithms along four tracks presented in a balanced random order. Participants performed six repetitions of driving trials on each track for every joystick and algorithm combination they used.

Performance Measures

Participants were instructed to drive the virtual wheelchair as fast as possible without hitting the track boundaries. Hence, participants were expected to drive along an ideally expected path that was the track centerline or the locus of midpoints of lines perpendicular to the track boundaries. During every driving trial, the simulator software saved time-stamped digital values of the joystick input and position and the velocity of the virtual wheelchair. The trajectory data were used to determine the virtual wheelchair's deviation from the ideally expected path.

While driving a wheelchair in the real world, safe driving practices involve avoiding collisions with walls, furniture, and people. Clinicians who train potential wheelchair users to drive power wheelchairs primarily emphasize maintaining the safety of the driver and surroundings. In addition, clinicians also teach wheelchair users certain other "good driving practices," like lane following along a hallway or sidewalk and adjusting wheelchair speeds around turns and obstacles to avoid possible accidents. The following outcome measures were derived during postprocessing of the trajectory data from the simulator:

- Root-mean-squared deviation (RMSD) of the participant's trajectory from the ideal trajectory was used as one measure of driving accuracy in our previous research [17,38]. Smaller deviation from the ideal trajectory indicates higher driving accuracy.
- Movement error (ME) was defined as the mean absolute deviation of the participant's trajectory from the ideal trajectory. Larger deviation implies that the participant has a tendency to drift away from the track centerline and has issues with effectively correcting the wheelchair's trajectory while driving.
- Reaction time (RT) was the time it took for the participant to consciously move the virtual wheelchair at least 2 ft from its resting state at the beginning of the driving session.
- Trial completion time (TT) was the total time taken to move the virtual wheelchair from the start to the finish of the driving task. According to Fitt's law [39] and steering law [40], higher task completion times imply a higher level of information processing load. In other words, participants are expected to take longer to complete a task with higher cognitive loads.
- Number of collisions (COLL) was the number of times the virtual chair hit the track boundaries.
- Number of significant changes in heading (NCH) of the virtual wheelchair was measured orthogonal to the track centerline. The NCH measures the tendency of drivers to take a "zig-zag" driving path with short turns, equivalent to a more than 90° change in heading, when they are supposed to drive straight.

We believe that while the outcome measures COLL and NCH would assist clinicians in evaluating safe driving behaviors, the trajectory-based driving accuracy measures, RMSD and ME, would add additional insights into the driver's capabilities. These outcome measures have added important insights to the clinical evaluation of virtual power wheelchair driving in other populations of wheelchair users [17,41]. With increase in fatigue or tremor in the upper limbs, participants may have a tendency to react more slowly, drive more slowly, and/or have difficulty maintaining the virtual wheelchair closer to the ideal path, and hence show higher RMSD and ME. While correcting the virtual wheelchair's trajectory or while reacting after an accident, some participants may show impulsive driving behaviors. If the participant has a tendency to apply oscillating jerks to the joystick, rather than a smoothly shifting motion, this may be reflected as higher NCH and COLL. Since participants performed the same set of tasks using multiple algorithms, comparing the safety and accuracy of task completion, as measured by the outcome measures, will assist in evaluating the effectiveness of the algorithms.

The driving tasks used in this study are similar to moving a computer cursor along a steering task. Throughput or index of performance, measured in bits per second, is a well-researched performance measure to compare computer pointing devices, including joysticks [17,42–43]. Being a standardized performance measure for ease of use of input devices, throughput presents another way to compare the driving performance using the algorithms and joysticks. Throughput is the inverse of index of difficulty of using a joystick to drive along a track. For a steering task, index of difficulty is calculated by integrating the ratio of forward distance moved over the task width [44]. As recommended by Soukoreff and MacKenzie, the throughput values for the six joystick algorithm combinations were computed by first averaging across the throughput values across four tracks (indexes of difficulty) within each subject and then averaging across the subjects, resulting in a single grand throughput value for each of the joystick and algorithm combinations [45]. Higher throughput value of a device indicates a better performance.

Statistical Analyses

SPSS (IBM Corporation; Armonk, New York) was used for all statistical data processing, and level of significance was set at 0.05. The outcome variables TT, RT, RMSD, ME, COLL, and NCH were used for statistical comparisons to answer the study hypotheses. The outcome variables that did not meet assumptions for normal distribution in statistics were checked for outliers and were log-transformed to correct the data distribution. A doubly repeated-measures multivariate analysis of variance (MANOVA) showed that the repeated factor “trial repetitions” did not have a statistically significant effect. Hence, the outcome variables from the six trial repetitions were averaged to get representative values of outcome variables for each algorithm and joystick combination.

The standard algorithm was used by the participants twice, once during each visit. Since there was no statistically significant difference between the standard algorithm outcome measures between the two visits (all $p > 0.05$), the values from both visits were averaged to get one reliable baseline estimate of the participant’s driving performance for the two VCJ modes. Every participant used all three algorithm modes. To address hypothesis 1, that participants would have the best driving performance when the MSPFA_FAs were used, the outcome variables were entered in a repeated-measures MANOVA model with algorithm type as the within-subject repeated factor and the VCJ joystick mode as the between-subject factor. To address hypothesis 2, that participants would have better driving performance with VCJ in isometric mode than with VCJ in position-sensing mode, post hoc univariate analyses of variance (ANOVAs) were performed for those within- and between-subject factors whose main effects were significant. Bonferroni correction was used wherever applicable.

RESULTS

Eleven participants participated in the research protocol. Five participants (age [mean ± standard deviation]: 56.82 ± 3.47 yr, 2 females) used the VCJ in isometric mode to complete the driving trials, while six participants (age: 54.89 ± 12.33 yr, 3 females) used the VCJ in compliant mode. Two participants from the isometric group did not complete second visits due to issues with personal health and transportation to the research center. Participants completed driving along the tracks in 32.59 ± 13.54 s with a total continuous driving time of 22.03 ± 7.10 min each visit. The MSPFA_FA algorithm changed the joystick axes gains according to a certain gain schedule. On average, the MSPFA_FA algorithm increased the joystick axes gains by 7.2 ± 4.3 percent from the values defined by the tuning software. **Table 1** shows the untransformed performance measures after averaging the six trial repetitions.

Hypothesis 1

The repeated-measures MANOVA showed a significant within-subject factor algorithm type ($p < 0.001$; partial $\eta^2 = 0.799$). Subsequent post hoc univariate ANOVAs indicated significant within-subject effects for TT ($p < 0.001$; partial $\eta^2 = 0.342$) and NCH ($p = 0.04$; partial $\eta^2 = 0.112$). When participants used the MSPFA, they took about 20 percent less time (5.03 s) to complete the driving trials than when they used the standard algorithms. Similarly, participants took 12.5 percent less time (3.66 s) with the MSPFA_FA than with the standard algorithm. There were no significant differences in TT when participants used the MSPFAs and MSPFA_FAs. Participants showed

Table 1.
Summary of performance variables for three algorithms (data presented as mean ± standard deviation).

Performance Variable	Standard		MSPFA		MSPFA_FA	
	Isometric Mode (*n* = 5)	Compliant Mode (*n* = 6)	Isometric Mode (*n* = 3)	Compliant Mode (*n* = 6)	Isometric Mode (*n* = 4)	Compliant Mode (*n* = 6)
RMSD (pixels)	5.84 ± 3.28	7.42 ± 4.02	4.60 ± 2.22	6.86 ± 2.94	5.56 ± 2.76	6.66 ± 2.94
Movement Error (pixels)	4.65 ± 2.65	6.52 ± 4.15	3.47 ± 1.44	6.03 ± 2.40	4.59 ± 2.42	5.82 ± 2.60
Trial Completion Time (s)	38.91 ± 16.71	28.41 ± 13.28	30.62 ± 8.09	24.28 ± 12.71	28.48 ± 9.91	22.78 ± 10.35
Reaction Time (s)	2.32 ± 1.55	1.26 ± 0.95	1.51 ± 1.20	1.06 ± 0.49	1.77 ± 1.03	1.01 ± 0.36
COLL (*n*)	0.41 ± 1.22	0.74 ± 0.96	0.13 ± 0.35	0.45 ± 0.65	0.20 ± 0.29	0.33 ± 0.56
NCH (*n*)	11.00 ± 2.61	11.00 ± 2.70	10.52 ± 1.91	9.51 ± 2.33	10.10 ± 2.09	9.46 ± 2.04

COLL = number of collisions, MSPFA = multiple sclerosis personally fitted algorithm, MSPFA_FA = multiple sclerosis personally fitted algorithm with fatigue adaptation, NCH = number of significant changes in heading, RMSD = root-mean-squared deviation.

9.1 percent fewer NCHs when using the MSPFA over the standard algorithm. There were no significant differences in the COLL, RMSD, and ME when the three algorithms were used while driving.

Hypothesis 2

The repeated-measures MANOVA also showed significant main effects of between-subject factor VCJ joystick mode ($p = 0.04$; partial $\eta^2 = 0.394$). Post hoc univariate ANOVAs indicated significant between-subject effects for RMSD ($p = 0.02$; partial $\eta^2 = 0.192$) and ME ($p = 0.01$; partial $\eta^2 = 0.264$). Participants who used the VCJ in compliant mode while driving, compared with those who used it in isometric mode, showed 70.1 percent higher RMSD and 85.3 percent higher ME. All other outcome variables were not significantly different between the two joystick mode groups. The interaction effect of joystick mode and algorithm type was not significant.

Table 2 shows throughput values for the two joysticks and three algorithms. For the VCJ in isometric mode, the throughput values showed that when participants used the algorithms, their driving performance showed a trend of standard algorithm < MSPFA < MSPFA_FA. For the VCJ in compliant mode, the trend in driving performance was standard algorithm < MSPFA_FA < MSPFA, despite there being a small difference in the MSPFAs and MSPFA_FAs.

DISCUSSION

Of the three algorithms tested, we expected that participants would show the best driving performance metrics while using the MSPFA_FA. However, the MSPFA and MSPFA_FA each enabled the participants to drive faster than did the standard factory settings of the VCJ as modeled by the standard algorithm. Having better-tuned joystick sensitivity while using the two customized algorithms did not significantly affect most of the driving accuracy measures compared with when participants used the standard joystick settings. Lower NCH values with customized algorithms and no significant trajectory-based errors indicate that even if participants, owing to their higher speed, were to swerve away from the ideal trajectory, they were able to recover again and faster without accumulating significant trajectory driving errors. The driving performances while using the MSPFA were marginally better than the MSPFA_FA but this difference was not statistically significant. Calibration of the sensitivity of the VCJ, especially the axes gains, according to the participant's upper-limb strength and fatigue profiles, definitely assisted participants compared with the standard joystick settings that they are used to on the conventional position-sensing controls.

Over the course of all driving trials, when the MSPFA_FA was in effect, there was, on average, about a 7 percent increase in axes gains over the values given by the tuning software. This increase in gains did not appear to affect significant improvements in the overall driving performance of participants. One possible reason could be that in this pilot evaluation of the MSPFA_FA, the researchers programmed the algorithm to change joystick gains according to a less aggressive gain schedule. In future studies, in addition to the quantitative measures used in the study, it will be important to use validated tools to quantify actual or perceived upper-limb fatigue. Since this was the first time the VCJ and the algorithms were evaluated, researchers had limited information about the number of driving trials that were essential to see the effects of fatigue in someone's virtual driving. Six trial repetitions completed in about 22 min of continuous driving time was a conservative estimate in order to avoid excessive fatigue in participants, considering they had to drive their own wheelchair back home from the research center. In future studies, more research trial repetitions should be performed. Also, the tuning process used to model participants' fatigue will be streamlined to better match the settings used in the context of real-world wheelchair driving using a VCJ.

We expected that the participants using the VCJ in isometric mode would show better driving performance metrics than participants using the VCJ in compliant mode. However, there were minor differences in the overall driving performance metrics of the two groups. Participants in the isometric group showed fewer driving errors

Table 2.
Throughput (bits per second) for two joystick modes and three algorithms (data presented as mean ± standard deviation).

Algorithm	Variable Compliance Joystick	
	Isometric Mode ($n = 5$)	Compliant Mode ($n = 6$)
Standard	0.243 ± 0.03	0.305 ± 0.10
MSPFA	0.255 ± 0.01	0.385 ± 0.18
MSPFA_FA	0.303 ± 0.09	0.376 ± 0.13

MSPFA = multiple sclerosis personally fitted algorithm, MSPFA_FA = multiple sclerosis personally fitted algorithm with fatigue adaptation.

than those in the compliant group. One possible explanation, which will need future experimentation, could be that the noncompliance of the VCJ in isometric mode could have contributed to better control while tracing the track centerline. This is consistent with our previous research findings [17,41]. Since the driving performances using the two joystick modes are equivalent to each other in most other outcome measures, in clinical settings a clinician could select the mode based on the client's clinical goals and personal preferences. The relevance of these findings in real-world wheelchair driving scenarios needs to be further explored in future research. The throughput values reported by this cohort of participants with MS were overall 0.20 to 0.35 bits/s lower than the values reported by participants with TBI who used isometric and position-sensing joysticks for driving tasks in our previous research [17]. In the previous research study, participants used a custom-designed isometric joystick and a commercially available compliant joystick, while in this study, participants used a VCJ in isometric and compliant modes. Due to issues with fatigue while using joysticks, and in particular with the isometric joystick, it was expected that people with MS might show poorer performance with the joysticks than people with TBI. More research is needed to determine whether the differences in throughput values were because of differences in the joystick hardware or a property of the cohort. Similar to our previous research, the VCJ in compliant mode showed higher throughput values than the VCJ in isometric mode [17]. Another interesting finding was that while participants used the VCJ in isometric mode, the throughput values for the MSPFA_FA were higher than the values when the MSPFA and standard algorithm were used. The rigid joystick post during the isometric mode was expected to induce fatigue, which could lead to overall decrease in task completion performance. This finding indicates that the MSPFA_FAs were effective when the VCJ was used in isometric mode. When the VCJ was used in compliant mode, the throughput values for the customized algorithms were very similar. Comparisons of wheelchair driving in real and virtual worlds, especially the throughput values, would add valuable insights to the clinical significance and relevance of these data values.

Results from this pilot study show no single combination of the custom algorithms, MSPFA and MSPFA_FA, or joystick mode configuration consistently having statistically significantly better driving performance metrics for all of the participants. Both of the custom algorithms showed significantly better performance than the standard joystick settings. The minor differences in driving performances while using the two customized algorithms need to be explored in future research. Those involved in evaluating clients for power mobility could therefore use their clinical judgment to tune these algorithms and joysticks to their client's needs.

Fatigue in people with MS can be lessened by selecting appropriate control interfaces and using appropriate programming. This study has shown the feasibility of using the VCJ as a new input device that can be customized to a user's upper-limb impairments. The actual physical interface of the joystick with the user's controlling hand or other body part may also contribute to fatigue. More research is currently being undertaken to evaluate the effects of using different types of handles on the VCJ [34]. Future research should explore the feasibility of other commercially available standard control interfaces like a mini joystick or trackpad along with the customized algorithms.

It is common for those with MS to have a higher level of fatigue at the end of the day [46]. This could be one of the reasons that, after calibration using the tuning software, configuration settings such as gain and dead zone size were different between visits 1 and 2. Since the optimal joystick settings for an individual could vary based on the time of day and level of activity and fatigue, a real-time calibration protocol could be designed and integrated with the joystick processing board. Also, machine learning algorithms can be employed to learn and adapt joystick settings according to a user's level of fatigue over different times of the day and periods of exacerbation after prolonged activity. In the current version of VCJ, dead zone, template, axes gains, and other algorithms are implemented in the joystick driver software that runs on the simulation computer. Once the filtering and MSPFA_FAs are validated using the current setup, these software algorithms and their calibration routines could also be installed on a joystick controller board. This would facilitate the use of VCJ with commercially available power wheelchairs.

Small sample size, attrition, and participants unable to complete the research protocol are some important limitations of this study. Issues with transportation to the research center, especially for participants who used wheelchairs, were one of the primary reasons for attrition and an obstacle for subject recruitment. We expect that a larger sample will indicate finer differences in the three algorithms and the joystick modes. A larger sample size may also give us an opportunity to develop the customized algorithms to accommodate the needs of people with more diverse motor abilities and fatigue levels than those in this sample. Since we used a repeated-measures design, our ability to detect statistical significance was increased. Care was taken to ensure that the data met assumptions for the statistical tests used in this analysis, and corrections for multiple comparisons were conducted. Before starting the research trials, participants did not know what kind of joystick they were using. However, once participants started using the joysticks, it was possible for them to guess the joystick mode depending on the compliance of the post. However, participants were blinded to the type of algorithms that were used. Since participants drove on the same set of four tasks multiple times, there is a slight possibility that their driving performance metrics may have been affected by habituation to the test scenarios. The sequence of driving tasks and algorithms was randomized to minimize habituation and carry-over effects between consecutive driving sessions. In future studies, multiple test scenarios that are of equivalent level of difficulty may be used.

CONCLUSIONS

Participants with MS showed better driving performance when using the VCJ in combination with the customized algorithms than when using it as a standard position-sensing joystick. The MSPFA_FA may be able to increase sensitivity of the VCJ to adapt the joystick according to the user's upper-limb fatigue profile and, hence, delay the onset of fatigue. This result may be especially important in the isometric mode of the VCJ, where the algorithms compensate for change in joystick sensitivity due to fatigue possibly induced by the rigid post. The isometric mode of the VCJ assisted participants in improving their driving accuracy compared with the VCJ in compliant mode. The VCJ along with the MSPFAs and MSPFA_FAs have the potential to be effective input interfaces for wheelchairs. The customizability and adaptability of the algorithms and VCJ make them ideal for people who have issues with fatigue and tremors.

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