

Joystick use for virtual power wheelchair driving in individuals with tremor: Pilot study

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Abstract—People with disabilities such as multiple sclerosis and Parkinson’s disease have difficulty operating conventional movement-sensing joysticks (MSJs) because of varying levels of tremor. We developed an isometric joystick (IJ) that has performed as well as a conventional MSJ when used by persons with upper-limb impairments in real and virtual wheelchair driving tasks. The Weighted-Frequency Fourier Linear Combiner (WFLC) filter has been used to cancel tremor effectively in microsurgery. In this study, we compared an MSJ, IJ, and IJ with the WFLC filter in individuals performing a virtual driving task. Although the WFLC filter did not improve driving performance in this study, the IJ without a filter yielded better results than the conventional MSJ and thus may be a potential alternative to the MSJ in minimizing the effects of tremor.

Key words: computer-user interface, filtering system, isometric joystick, movement-sensing joystick, multiple sclerosis, Parkinson’s disease, rehabilitation, tremor, wheelchair driving performance, wheelchairs.

INTRODUCTION

Approximately 2.2 million people in the United States currently use a wheelchair for everyday activities, including powered mobility [1]. According to Fehr et al., 40 percent of wheelchair users find steering nearly impossible with conventional power-wheelchair interfaces [2]. Tremor, defined as involuntary, oscillatory

motion, can hinder joystick control and is therefore an important issue in electric-powered wheelchair (EPW) driving and control interface use [3].

Human tremor and its effect on control interfaces have been a topic of interest for over 30 years. Randall, Stiles, and Rietz have described the range of frequency and amplitude of normal and pathological human tremor and developed a mechanical model showing that tremor properties may depend on mass loading of the hand as well as hand position because these both affect muscle tension [4–9]. Hefter et al. also corroborated the concept that altering hand mechanics affects tremor properties [10]. Riley, Rosen, and Adelstein compared isometric, or force sensing, and standard position-sensing controls in a target-selection task and found that no single control type worked

Abbreviations: EPW = electric-powered wheelchair, HERL = Human Engineering Research Laboratories, IJ = isometric joystick, MS = multiple sclerosis, MSJ = movement-sensing joystick, PD = Parkinson disease, RMSE = root-mean-square error, WFLC = Weighted-Frequency Fourier Linear Combiner.

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best for persons with tremor; instead, customization of the individual user interface produced the best results [11–12].

Although movement-sensing joysticks (MSJs) are the current standard for most EPW users, researchers at the Human Engineering Research Laboratories (HERL) in Pittsburgh, Pennsylvania, have developed a newly designed isometric joystick (IJ) that has performed as well as conventional MSJs in both virtual and real driving tasks [13–19] (**Figure 1**). The IJ has a rigid handle that does not move perceptively and provides no motion feedback as a user applies force [19]. This IJ was developed to limit changes in mass loading and muscle tension that occur when an individual uses an MSJ that requires positional changes of the hand and limb. Limiting changes in hand mechanics should theoretically make tremor easier to filter, since there are fewer changes in tremor properties. The HERL IJ can also be programmed with a variety of customized algorithms or filters not yet available on the market that could potentially improve control interfaces for people with tremor. Improving control interface use has application for not only power mobility but also computer access, augmentative communication, automobile driving, and environmental control.

The conventional means for filtering is a simple low-pass filter. While a low-pass filter may be effective for most users with physiological tremor and for vibrations transmitted to the device, such as from the ground when a wheelchair is used, tremor frequencies in individuals with multiple sclerosis (MS) can be as low as 3.5 to 5.0 Hz [20]. Setting the cutoff frequency this low will introduce a phase lag and potentially eliminate intentional commands.

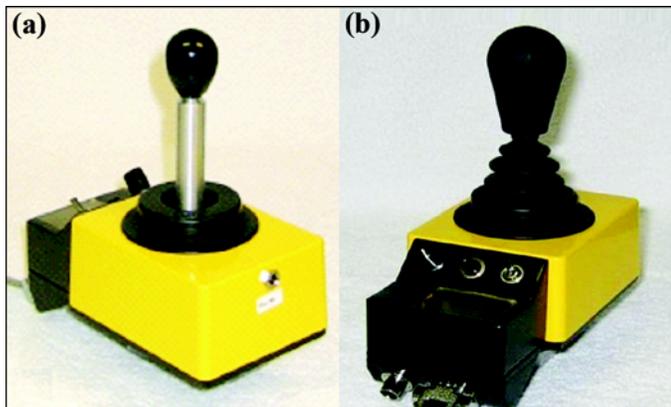


Figure 1. Human Engineering Research Laboratories joystick in (a) isometric mode and (b) movement-sensing mode.

Notch filters, on the other hand, have the advantage of suppressing only the tremor frequency and reducing distortion of intentional signals [21]. Adaptive filters, those that self-adjust their parameters, have an added benefit because tremor is not always constant [21]. An adaptive notch filter such as the Weighted-Frequency Fourier Linear Combiner (WFLC) [21–22] can filter a small band of frequencies without adding significant delay [22]. In fact, prior studies have shown improved performance with a WFLC compared with a low-pass filter when individuals with cerebral palsy used an IJ to perform virtual wheelchair driving tasks [23]. In that particular study, a high-pass filter was added as a safeguard to ensure that the WFLC did not track intentional movements.

In the current study, our primary objective was to evaluate the performance of individuals with tremor in operating a virtual wheelchair driving task using an IJ with WFLC filter, an IJ without a filter, and an MSJ. We hypothesized that in this environment, the subjects' performance statistics would rank from best to poorest in this order: IJ with filter > IJ > MSJ.

METHODS

Subjects

The Department of Veterans Affairs Pittsburgh Medical Center Institutional Review Board approved this study. We recruited subjects who attended the 2007 National Veterans Wheelchair Games in Milwaukee, Wisconsin. Individuals who approached our information booth and indicated an interest in participating were provided with an informed consent document and reviewed for eligibility.

We required subjects to be between the ages of 18 and 80 and have a pathological tremor. If a person was unable to sit upright for 3 h, had an active pelvic or thigh wound (since prolonged sitting could worsen skin breakdown), or had a history of seizures within the last 90 days (since seizures could theoretically be induced by video-game-like tasks), he or she was excluded. Subjects filled out questionnaires discussing daily living activities as well as previous computer and wheelchair use. A psychiatrist performed a brief neurological examination, including a tremor assessment.

We customized the IJ for each subject using custom tuning software. This protocol involves setting a dead zone and bias axes and establishing optimal gain; it has been validated and described in our prior work [19] (**Figure 2**). During the virtual driving tasks, subjects sat in

their own wheelchairs, while those who were ambulatory sat in a desk chair. Subjects sat in front of a computer screen to perform the tasks and used the interchangeable joysticks mounted on a table with an adjustable height. The driving tasks consisted of two tracks viewed at bird's-eye level, one simulating a left-hand turn and the other a right-hand turn (**Figure 3**). We instructed subjects to complete trials as quickly as possible while staying as close as

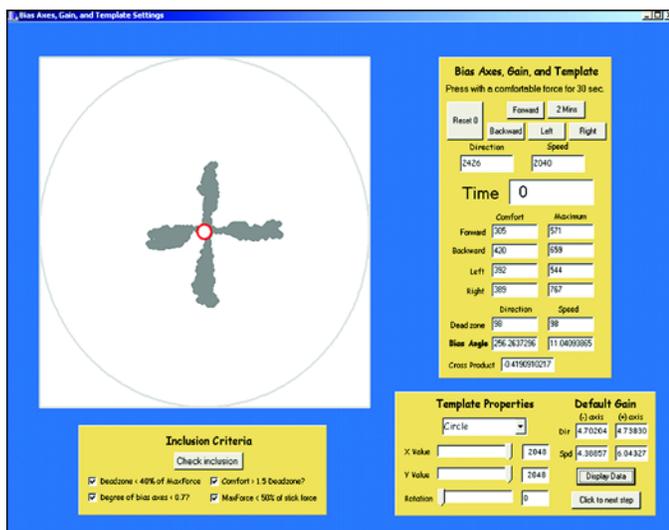


Figure 2.

Screenshot of software used to customize isometric joystick. Wide gray lines in cross shape represent bias axes that investigator customizes for subject.

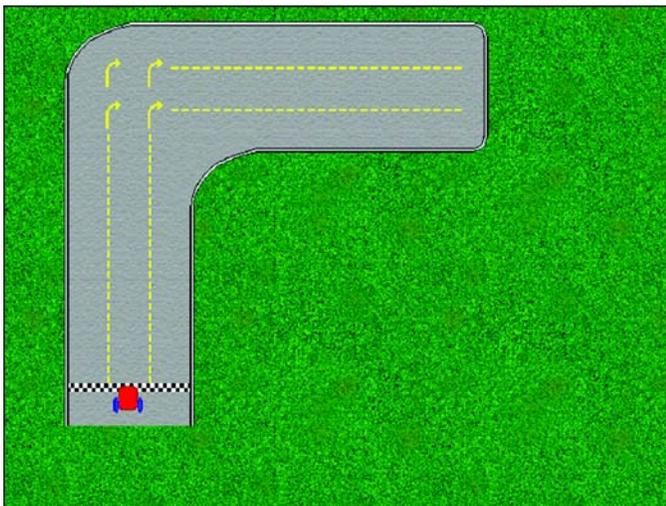


Figure 3.

In driving simulation, subject must move virtual wheelchair along center of two-dimensional track.

possible to the center of the path. Subjects practiced with the IJ and MSJ for 36 trials, up to 30 min.

We customized the WFLC filter by using data from the practice trials for each subject. We set the initial maximum frequency estimate based on the expected frequency range of the subject's diagnosis, using MS tremor at 3 to 5 Hz, Parkinson disease (PD) tremor at 3 to 7 Hz, and other pathological tremor at 2 to 8 Hz [20,23].

Next, we selected optimal filter parameters for each subject using a validated protocol [22–23]. We visually inspected frequency and power output curves generated from practice trials and adjusted the filter parameters, so the output to the controller with filter applied most closely matched the user's input on the device (**Figure 4**). For each subject, we applied these parameters only to the IJ with WFLC. We also added a high-pass filter to the IJ with WFLC set at 2 Hz for both speed and direction axis. Subjects then performed 20 trials with each of the three joysticks in a randomized design. Subjects navigated a virtual wheelchair along a track with left- and right-hand turns. We recorded joystick input and output at a sampling frequency of 59.39 Hz. From sampling data, we calculated total trial time, boundary violations that occurred when subjects drove outside the path, and the root-mean-square error (RMSE), defined as the average deviation from the center of the wheelchair path measured in pixels starting at the center point of the body of the wheelchair icon and following the shortest distance to the path mid-line. The boundary was four times the width of the virtual wheelchair, based on an environment tested in prior work showing subject performance in the virtual environment correlated with driving ability in a real environment with two different control interfaces [15].

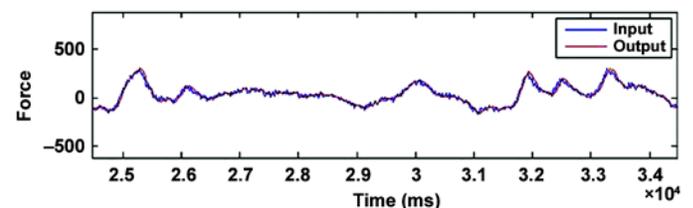


Figure 4.

Force output for selected trial during filter customization. Graph shows subject's force input on joystick (jagged curve) and output of device to controller when filter parameters were adjusted (smoother, superimposed curve). Units on x -axis are in $\text{ms} \times 10^4$, i.e., graph represents time between 25 and 34 s.

Statistical Analysis

We calculated average outcome variables over trials using MATLAB (The MathWorks; Natick, Massachusetts). All alpha levels were set to 0.05 a priori. We used R (Wien, Austria) and SPSS (Chicago, Illinois) to perform all analyses. We stabilized the variance and effects of outliers with log scale transformations. We ran mixed model analyses to evaluate for differences among joysticks with respect to RMSE and time, using subject as the random factor effect and joystick as the fixed effect. We used generalized estimating equations to evaluate for differences among joysticks with respect to boundary violations, because this variable was not normally distributed.

RESULTS

Participants

Four men and one woman participated in this study, all of Caucasian descent with an average age of 61.2 ± 12.2 yr (mean \pm standard deviation). Two subjects had a diagnosis of MS, one had paraplegia from spinal cord injury, one had PD, and one had tremor because of medication. Two subjects used a wheelchair, and only one regularly used a computer. Two subjects had intention tremor, and three had both intention and resting tremor. Average results of outcome measures are listed in the **Table**. No subjects were excluded.

Root-Mean-Square Error

Although the average RMSE was lowest for the IJ, no significant differences existed among joysticks regarding RMSE ($p = 0.5316$) (**Figure 5**).

Trial Time

The IJ produced significantly lower trial times than the IJ with filter and MSJ ($p = 0.0425$ and $p < 0.001$,

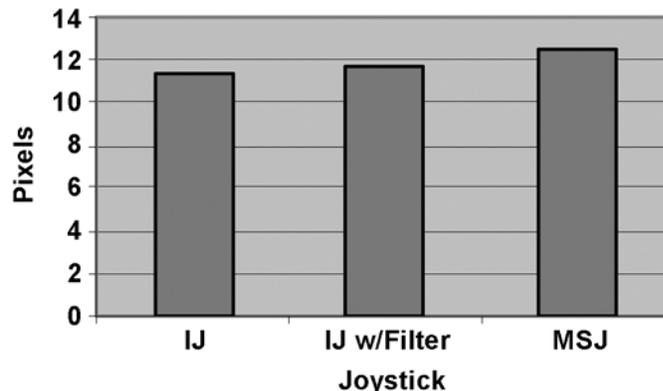


Figure 5.

Average root-mean-square error for each joystick type. IJ = isometric joystick, MSJ = movement-sensing joystick, w = with.

respectively) (**Figure 6**). The average driving time for the IJ was 32.4 s, while the average driving time for the MSJ was 41.7 s, illustrating an approximate 10 s difference, or 22 percent reduction in trial time. We found no differences between the other joysticks.

Boundary Violations

The IJ produced significantly fewer boundary violations than the MSJ ($p < 0.001$). No significant differences existed between the other joysticks (**Figure 7**).

DISCUSSION

The results did not support our hypothesis that the filter would improve driving performance. Since the WFLC has been used effectively in prior studies on handwriting and microsurgical tools, it may be most effective on higher-frequency, lower-amplitude tremor than what we saw in our study and what is common in neurological

Table.

Results of outcome measures based on joystick type of five subjects.

| Average Value | IJ (mean \pm SD) | IJ with Filter (mean \pm SD) | MSJ (mean \pm SD) | <i>p</i> -Value |
|------------------------|-----------------------|-----------------------------------|------------------------|------------------------------|
| Root-Mean-Square Error | 11.4 \pm 4.0 | 11.6 \pm 4.8 | 12.5 \pm 5.5 | 0.284 |
| Trial Time (s) | 32.4 \pm 11.4 | 39.1 \pm 22.2 | 41.7 \pm 20.9 | 0.0425*, <0.001 [†] |
| No. of Violations | 0.71 \pm 1.3 | 0.75 \pm 1.3 | 0.97 \pm 2.4 | <0.001 [‡] |

*Significance in trial time between IJ and IJ with filter.

[†]Significance in trial time between IJ and MSJ.

[‡]Significance in collisions between IJ and MSJ.

IJ = isometric joystick, MSJ = movement-sensing joystick, SD = standard deviation.

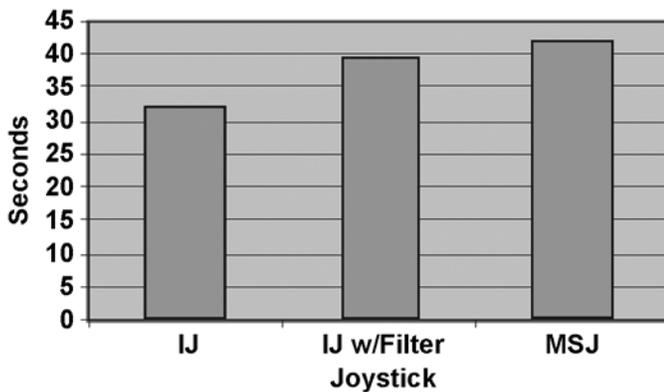


Figure 6. Average trial time (seconds) for each joystick type. IJ = isometric joystick, MSJ = movement-sensing joystick, w = with.

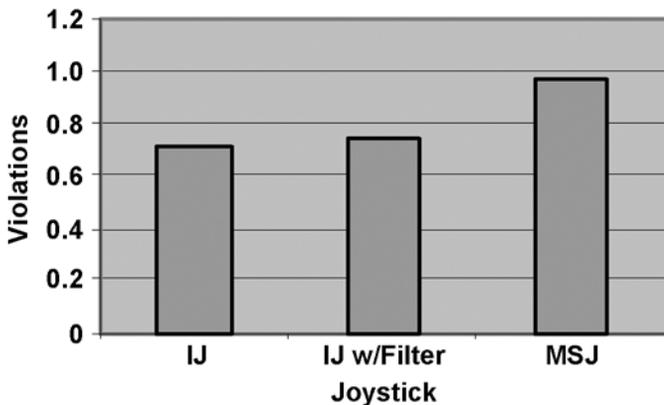


Figure 7. Average number of boundary violations for each joystick type. IJ = isometric joystick, MSJ = movement-sensing joystick, w = with.

impairments [21–22]. Here, the WFLC may have damped some of the subjects' intended movements.

Previous research has shown the benefits on performance when joysticks are customized for individual users with various upper-limb impairments but no specific tremor; specifically, IJs can perform just as well as MSJs in those circumstances [19]. However, we found that the IJ performed better than the MSJ for subjects with tremor. This finding suggests that either the tuning software, which helps to eliminate some resting tremor and excess force exerted beyond that needed for control, or the rigid handle, unique to the IJ design, may positively affect performance. It is likely that the rigid handle of the IJ may have some tremor damping effect.

The frequency range of the involuntary movements in this study that in some cases was within the 10 to

20 Hz range is higher than the frequency of typical voluntary movements needed for EPW control that can be in the 1 to 3 Hz range for control subjects. The frequency range of external vibrations, such as that from the environment, is typically higher than the frequency range of involuntary movements. An EPW itself would act as a low-pass filter, attenuating some components of input signal. However, since an EPW typically responds to input signals within the 10 to 20 Hz range, it would most likely not effectively attenuate the signals from involuntary movements seen in this study. Future work is planned to investigate IJs when tremor affects use of standard control interfaces. One possible future outcome measure is to investigate percentage reduction in tremor.

One limitation to this study was that the driving task is not an immersive virtual-reality environment and not all ballistic or momentum properties can be simulated. However, our previous work has shown that performance in this virtual environment represented driving ability in real environments [15]. Because the environment used in this study was from a bird's-eye view, it is analogous to a target array task, and in fact, virtual wheelchair driving could be considered a series of continuously updated targets. The straight and curved path shapes were chosen to create an environment that was applicable for not only power mobility but also computer access tasks that involve selected targets and steering through drop-down menus. However, this is not a true Fitts' law task since subjects' maximum speed was often constrained to the virtual wheelchair's top speed on straight paths, consistent with what occurs in real driving. During turns, however, subjects often drove below top speed. Real-world power mobility is also characterized, for example, by multiple turns, close quarter maneuvers, and obstacle avoidance that are not part of a simple Fitts' law task. Fitts' law, although highly respected as a quantifier of human motor skills, does not necessarily predict mobility competence in community settings. It is interesting to note that driving at top speed may in itself act as a tremor suppression method, since changes in force that exceed top output velocity may not reflect the speed of the virtual chair.

Another limitation of the study was the lack of homogeneity in tremor etiology. We anticipate future studies on larger groups of subjects. Because our technology now allows us to record a wide range of motor control parameters as individuals use joysticks, using parameters as a classification tool to quantify tremor is now feasible and will be the aim of future work. This may be particularly useful in measuring response to pharmacologic treatment in PD.

CONCLUSIONS

The IJ with customized tuning produced better virtual driving performance as measured by average boundary violations, RMSE, and trial times. Hence, individually customized isometric devices may be superior to commercially available proportional control for individuals with tremor. Although the IJ with WFLC filter did not improve wheelchair driving as we expected, additional testing could show alternative uses for the filter, such as studying response to tremor treatment. Future testing should include a larger number of subjects with a wider spectrum of tremor severity for researchers to better evaluate the effects of filters on joystick use.

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