Vibrotactile Feedback for Improving Power Wheelchair Driving Performance Using a Body-Machine Interface

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***Abstract*— Many spinal cord injury (SCI) survivors still have residual motor and sensory functions. Body machine interfaces (BoMIs) help SCI survivors in their rehabilitative goals by engaging them in fun, entertaining tasks. The BoMI maps users' residual movement to control commands for an external device, and is an effective way for subjects with motor disabilities to control assistive devices while engaging in meaningful and functional motor activity. The BoMI, however, can be difficult to learn. This experiment studies the effect of vibrotactile feedback on users' power wheelchair driving performance in a virtual reality environment. The results show that vibrotactile stimulation can be used as a powerful tool to improve BoMI learning and overall wheelchair driving performance.**

I. Introduction

Every year in the United States, 17,000 new people are affected by a spinal cord injury (SCI) [1]. Although most of these cases affect the cervical area of the spinal cord, many SCI survivors still have some residual motor control and sensory capacities. These remaining body movements can give different types of signals to control assistive devices, and for SCI survivors, understanding how to redirect their remaining motor functions is critical for efficiently controlling these devices [2]. These devices and computers can help SCI survivors begin to partially replace their motor functions and interact with their environment [3]. Using assistive devices is often very difficult because users need to reorganize their residual movements to create command and control signals in an optimal way on a device that is often hard to control and unintuitive. In addition, although sensory-motor practice can induce plastic changes in the spinal cord after an injury, most survivors do not have access to exercise and rehabilitation equipment after they are released from the hospital [4-6].

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Body-machine interfaces (BoMI) are a type of assistive device that may be able to help solve many of these problems. The BoMI uses the large number of degrees of freedom that are present in body's movements and maps this space to assign control variables in a low-dimensional space [7]. BoMIs have been shown to help SCI survivors reorganize their motor coordination patterns. Previous studies have indicated that with BoMIs, SCI survivors can operate assistive devices, such as power wheelchairs, at a performance level comparable to able-bodied participants [2].

There is room for improvement in BoMIs performance. Although BoMIs are far more intuitive than other control devices, such as a sip-and-puff wheelchair, they can be difficult to learn, and a standard joystick-controlled wheelchair is easier to drive than a BoMI-controlled wheelchair. Previous studies have indicated that vibrotactile feedback may be an effective method of complementing or replacing visual feedback for subjects learning how to control a simulated power wheelchair in a brain-computer interface [8].

This study seeks to build on the past research we have done by introducing vibrotactile feedback to the BoMI. We explored the concept of adding vibrotactile stimulation to the BoMI previously but found that the added feedback was not helpful to the subjects. This experiment seeks to improve that study, while having the same objective: to help improve BoMI power wheelchair driving performance by employing vibrotactile feedback.

II. Methods

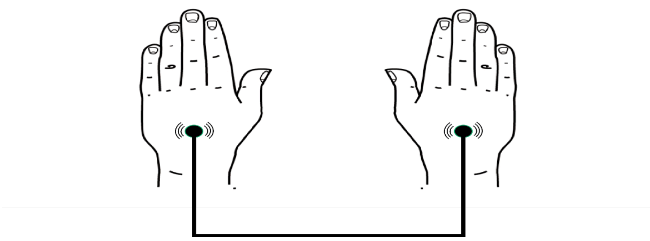
A. Hardware

A.1 Inertial Measurement Units

Two MTx (YEI Technology, 3-Space SensorTM Wireless 2.4 GHz DSSS) motion trackers were used to capture the roll and pitch of each shoulder. The inertial measurement units (IMUs) tracked the upper body motions of the subjects. Each IMU was mounted on a Velcro patch on an adjustable size vest.

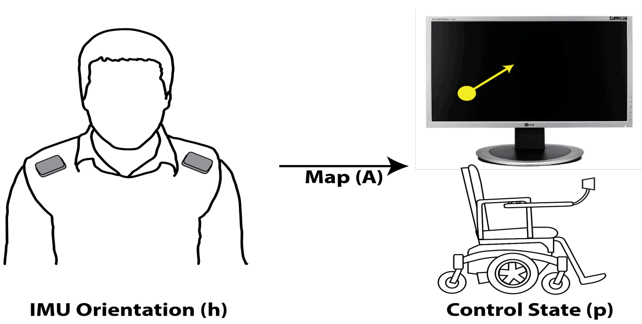
A.2 Delivery of Vibrotactile Stimulation

Stimulation was delivered to the top of the hands through vibrators taped to straps (Harbinger Fitness, USA) wrapped around the hands. The vibrators were connected with an Arduino (Arduino, USA) microcontroller. As the player moved around the virtual reality game, a message with the frequency of the vibration was sent from the Unity game engine to the Arduino, which then sent a signal to one of the tactors to turn on at a specific level.



B. Software

A calibration for each subject was done on random shoulder movements at the beginning of the experiment. Principal component analysis was then performed on the movements and a customized map *(A)* was created by taking the first two principal components.



IMU measurements (h) were then mapped to the vector of control commands (p) using the custom map (A). The components of p defined the rotational velocity of the wheels. Control commands could be varied continuously and independently.

$$p = \begin{bmatrix} p_1 \\ p_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \end{bmatrix} = Ah$$

C. Interface Modules

C.1 Reaching

Subjects performed a reaching task to different targets around the screen. Subjects had to move the cursor to the target and hold it there for a short amount of time.

C.2 Vibrotactile Familiarization

In our previous experiment exploring vibrotactile feedback with a BoMI, we found that the vibrotactile stimulation did not make an impact on subjects' driving performance. We thought that this may be due to the subjects already trying to figure out a very difficult task and that this added feedback mechanism was simply not being used by the participants. In this experiment, we sought to introduce the vibrotactile feedback in a more constructive manner. To do this, we created a vibrotactile familiarization game where the player controls a circle that moves horizontally across the screen. The circle is placed on some point of the screen, and the player needs to move the circle to the target, which is in the center of the screen. After the player moves the circle to the target, the cursor is then placed somewhere on the screen in a randomized order. As users played the game, they would feel vibrations on the hand corresponding to the side of the screen that that circle was on. The farther from the center of the screen the circle was, the greater the vibrotactile stimulation.

C.3 Virtual Navigation

At the end of the experiment, subjects controlled a power wheelchair in a virtual reality environment in the Unity game engine [9]. Participants navigated the environment to pick up coins that were generated in random target directions. As users turned the wheelchair, they felt vibrations on the hand which corresponded to the direction they were turning in. The higher the angular velocity, the greater the vibrotactile stimulation. There were 7 target directions, each used 5 times, for a total of 35 targets. In 3 of the directions, visual feedback was removed for the first 5 seconds of the trial.

D. Participants

4 unimpaired subjects participated in the study. No subjects had any prior experience with the BoMI. All participants gave their informed, signed consent to participate in this experiment, which was approved by Northwestern University's Institutional Review Board.

E. Experimental Protocol

Calibration was done in the first session and the same map was used for later sessions. Each session was around one hour in length. The sessions were done on consecutive days. 2 subjects were in Group 1, which was the control group, and 2 subjects were in Group 2, which received vibrations.

F. Data Analysis

Completion time and blind error were measured during Session 3. Blind error measures the subject's distance from the target when visual feedback reappears during the blind trials of the Driving activity. Path smoothness was also analyzed.

TABLE I. Experimental Protocol

Group	**Session 1**		**Session 2**		**Session 3**
Group 1	Reaching	Reaching	Driving	Driving	Driving
Group 2	Reaching	Reaching	Driving	Vibrotactile Familiarization	Driving with vibrations

III. RESULTS

As this experiment has not been conducted yet, this section gives a summary of the predicted results. We found that the group that received vibrotactile stimulation had a significantly better wheelchair driving performance in the last session than the group that did not receive vibrations. The 2 subjects who received vibrations had faster completion times and smaller blind errors than the 2 subjects who did not receive the vibrotactile feedback. In addition, while driving performance improved for all subjects from Session 2 to Session 3, Group 2's driving performance especially progressed.

IV. DISCUSSION

This study shows that vibrotactile feedback can be used as an effective tool to help users first learn how to use the BoMI and to improve overall wheelchair driving performance.

This experiment can be improved in a number of ways. Attaching the tactors to the body instead of taping them to a straps could help deliver the stimulation more effectively [8]. In addition, a further study could also use both unimpaired and SCI participants to give a fuller view of the effect of the stimulation. The stimulation should be moved up from subjects' hands to their shoulders so as to allow SCI survivors to participate in the study and actually feel the vibrations. Finally, further studies could also analyze the effectiveness of the vibrotactile feedback over a higher number of sessions to see how effective the stimulation is in further increasing driving performance over a longer period of time.

Overall, the results presented show that additional feedback mechanisms can aid in the performance of a BoMI. As the rehabilitative process from a SCI can be incredibly difficult, effective ways of increasing BoMI skills can be very helpful to users in their goal of reorganizing their residual upper-body movement skills. As we learn how to deliver the vibrotactile feedback most effectively, users will hopefully, at some point, operate the BoMI as effectively as a joystick-controlled wheelchair.

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