Title
Development and evaluation of two control methods for MOVit: An exercise-enabling driving interface for powered wheelchair users

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Development and evaluation of two control methods for MOVit: An exercise-enabling driving interface for powered wheelchair users

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Mechanical and Aerospace Engineering

by

Yinchu Dong

Thesis Committee:
Professor David Reinkensmeyer, Chair
Professor Athanasios Sideris
Associate Professor Shlomit Radom-Aizik

2018

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ABSTRACT OF THE THESIS

Development and evaluation of two control methods for MOVit:
An exercise-enabling driving interface for powered wheelchair users

By

Yinchu Dong

Master of Science in Mechanical and Aerospace Engineering

University of California, Irvine, 2018

Professor David Reinkensmeyer, Chair

The sedentary lifestyle of powered wheelchair users has a deleterious effect on their health. If they could exercise while driving their chair, they could potentially improve their health through integrated daily exercise. This dissertation presents the development of MOVit, a novel, arm exercise-enabling, wheelchair driving interface. MOVit consists of two custom-made, instrumented mobile arm. Instead of using a joystick to drive the wheelchair, the design goal was that the user moves the arm supports with his arms through a cyclical motion to drive the chair, like a "virtual lever drive" chair. We developed and studied two different methods for driving and clutching, compared to driving performance with a Standard Joystick. In the Squeeze and Height Clutch methods, the driver clutched the virtual levers by squeezing a handle or moving the arm support above a line, respectively. A total of 24 unimpaired subjects were randomized to one of the three control methods and performed a series of driving tests across two consecutive days in a 3D wheelchair simulator and in reality. The results showed that, after learning, the MOVit driving performance with Squeeze and or Height Clutch control was comparable to Joystick control. We also found that subjects exhibited good overnight retention of learned driving

abilities and transferred their abilities readily from the virtual training environment to the real environment. These results show for the first time the feasibility of a maneuverable, exercise-enabling powered wheelchair driving interface.

1 INTRODUCTION

The World Health Organization estimates that more than 70 million people worldwide need a wheelchair[1]. In 2002 in the United States, there were 2.7 million wheelchair users in the community, with approximately 30% of whom used powered wheelchairs or scooters [2]. The use of powered-wheelchairs is common among people with severe mobility limitations, such as people with cervical spinal cord injury, amyotrophic lateral scoliosis, stroke, multiple sclerosis, Alzheimer disease, or muscular dystrophy [3], [4]. With the estimation of powered wheelchairs increasing due to an aging population and an increase in chronic health conditions, it is critical to ensure that powered wheelchairs meet wheelchair users' needs to facilitate participation and enhance quality of life.

While the use of a powered wheelchair facilitates mobility, it also results in an increase of sedentarism compared to manual wheelchair users [5]. Numerous research studies indicate that sedentary behavior results in the decrease of physical and mental health and increases the risk for secondary health problems such as obesity, diabetes and cardiovascular disease [6]. Furthermore, a positive association has been found between physical fitness and quality of life in wheelchair users [7].

One possible solution is to develop manually-operated wheelchairs that allow people with greater levels of arm impairment to use the chair. One approach is the Pushrim Activated Power Assist Wheelchair (PAPAW) [8]. Another approach is the use of lever drives. For example, we have shown that individuals with a stroke who were thought not to be able to drive a manual wheelchair can in fact drive the LARA wheelchair which has one appropriate lever, arm support, and yoked-clutching scheme [9], [10].

Nevertheless, an important question is how to increase body movements and energy expenditure in powered wheelchair users. Toward this goal, different exercise devices have been proposed. These devices are generally stationary, which means that the user has a limited place and time to exercise [11]. These types of devices do not allow for integrated daily exercise, such as walking or biking to work, which is proven to be one of the most effective ways of promoting health [12], [13]. Wheelchair-mounted exercise devices that can potentially provide integrated daily exercise (e.g. [14]) are typically designed for manual wheelchair users, and most of them do not have a way to modulate the exercise intensity. To our knowledge, mobile exercise devices for powered wheelchair users have not yet been developed. The goal of this project is to provide similar access to integrated daily exercise for people who use powered wheelchairs using an innovative driving interface for their wheelchair that promotes exercise as the user drives the wheelchair. Our long-term goal is to provide a long-term dose of dynamic physical training to powered wheelchair users by sensing the overall amount of arm exercise achieved each day, and adapting the required arm motions to drive the chair.

This paper presents the development and testing of MOVit (Fig. 1), a novel, arm exercise-enabling, wheelchair driving interface. MOVit consists of two custom-made, instrumented mobile arm supports that are mounted on the lateral sides of a powered wheelchair replacing the armrests. Instead of using a joystick to drive the wheelchair, the user moves the arm supports with his or her arms through a cyclical motion, while the software simulates a “virtual lever drive” chair. A crucial element for controlling the direction and speed of a wheelchair using a cyclical motion is the *clutch function*, i.e. how the user tells the device when the movement of the arms is transmitted as a control command to drive the wheelchair in a specific direction and speed. In this paper we also present the results of a study done with unimpaired subjects that compares the driving performance of three different control methods (i.e. Standard Joystick control, Height Clutch control and Squeeze Clutch control). The main objective of this comparative study was to evaluate if people have an acceptable driving performance when exercising using MOVit (either with Squeeze or Height Clutch) compared to a Standard Joystick. Additionally, we also analyzed if subjects were able to retain overnight the motor skills required to drive the powered wheelchair with MOVit, as well as if subjects were able to transfer the motor skills from virtual driving into reality. Finally, we also evaluated if the learning rate of subjects would increase when training while receiving vibrotactile feedback indicating the right timing to activate the clutch.

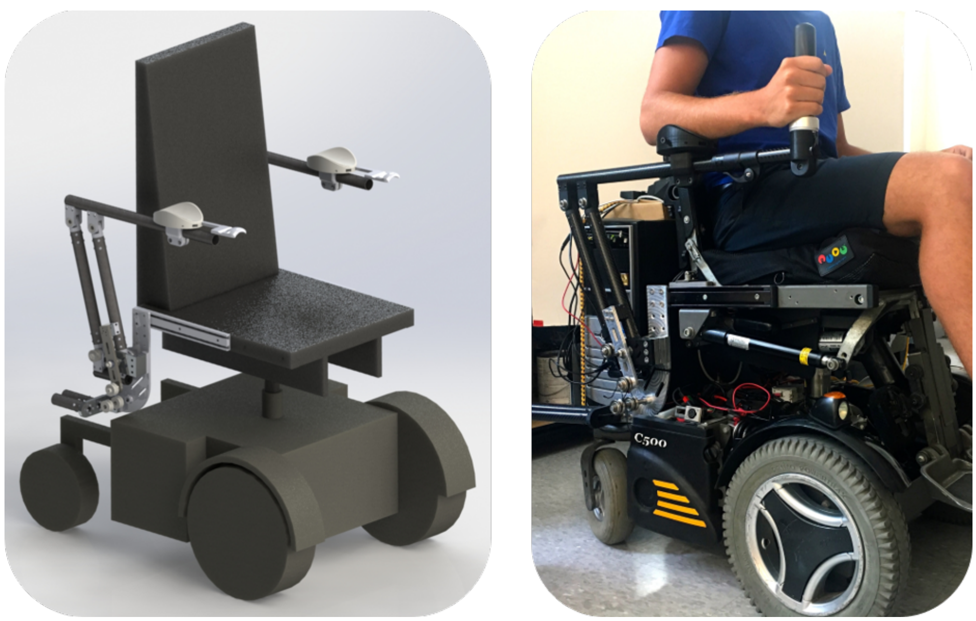

Figure 1. Left) CAD drawing of MOVit. Right) Prototype of MOVit mounted on a powered wheelchair. Consists of two custom-made, instrumented mobile arm supports that replace the armrests of a normal powered wheelchair. Instead of using a joystick to drive the wheelchair, the user moves the arm supports with his or her arms, while the software simulates a “virtual lever drive” chair.

2 DESIGN OF MOVit

2.1 Mechanical Design

As described in more detail in the M.S. Thesis of Gerard Moreso, the two mobile arm supports of MOVit are based on the design of Herder et al. [15], which uses a parallelogram mechanism and two springs to compensate the weight of the arm in the vertical plane. In our design the springs are placed at the back of the arm support and connected to the parallelogram using cables and pulleys (Fig. 2). Each spring is mounted on a lead-screw that is used to adjust the weight compensation force in the vertical and horizontal direction. The springs have a stiffness of 1489 N/m and the arm support can balance a mass of 3 Kg when the springs are set to mimic a zero-free length spring. We also added a revolute joint to the base of the arm cuff to allow movement outside the vertical plane so that user is able to perform movements such as reaching his or her face. This prototype of MOVit uses the pneumatic handle of the ArmeoSpring rehabilitation exoskeleton (Hocoma AG, Switzerland).

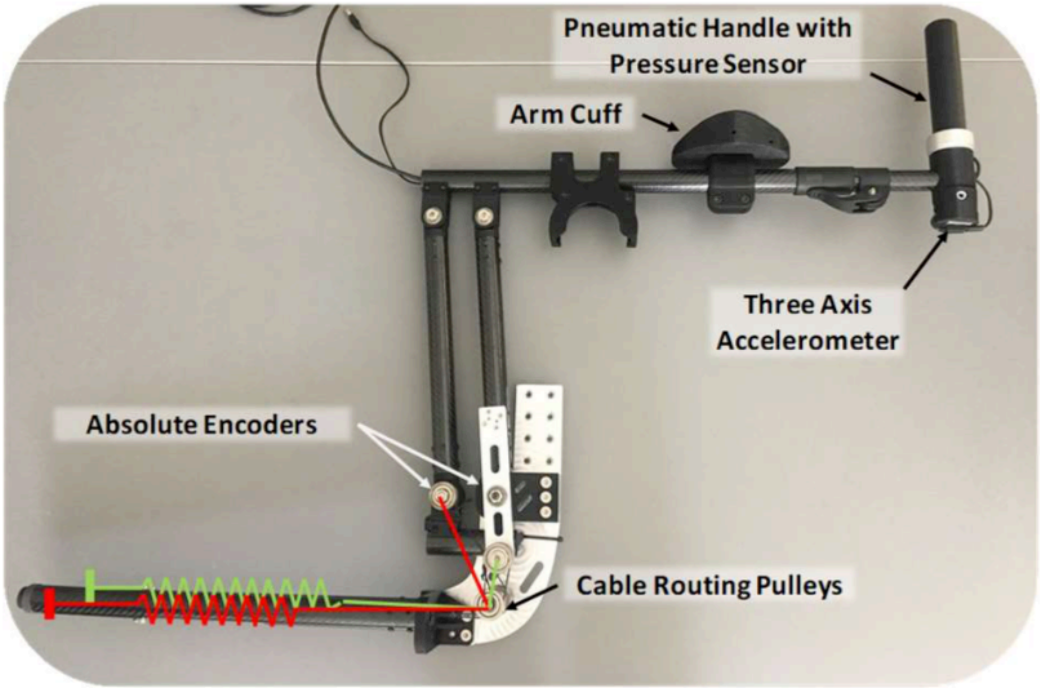

Figure 2. Overview of the arm supports of MOVit. The arm support of MOVit is based on the design proposed by Herder et al., 2006 were a parallelogram mechanism is used to provide gravity compensation in the vertical plane. The red spring compensates forces in the vertical direction while the green spring compensates forces in the horizontal direction Absolute encoders and accelerometers are used to measure the arm movement and the handle is equipped with a pressure sensor to measure grip force.

2.2 Sensors and Control

The mobile arm supports are instrumented with two magnetic absolute encoders (RMB20, RLS) mounted on the two lower joints of the parallelogram, a pressure sensor (ASDX015G24R, Honeywell) and a 3-axis accelerometer (ADXL335, Analog devices) in the handle to measure grip force and accelerations of the end-point. Besides the sensors on the arm support, there is also a 3-axis accelerometer mounted on the wheelchair, which detects the acceleration of wheelchair itself. We also added two incremental encoders (HEDL5540, Avago) on the motor axis of the wheelchair to measure wheel rotation and perform odometry measurements.

All the signals from the sensors are measured with a data acquisition card (NI PCI-6221), with a sampling frequency of 1000 Hz and 16-bit resolution. The signal processing and control is programmed in Matlab Simulink 2016b running in a Windows 10 Operation System and compiled to run on a Simulink Real-Time Target computer. The controller outputs the desired speed and direction of the powered wheelchair (Permobile c500) by sending two analog signals to the wheelchair controller through the R-Net Omni interface (PG Drives Technology).

The control interface of MOVit, referred here as the *virtual lever drive* control, was designed to mimic the movement of propelling a manual wheelchair. In a manual wheelchair the user goes forward by grasping the push rims and moving the wheels forward, then releasing the push rims to go back and grasping them again. In effect, the hands act like a clutch, coupling the arms with the wheels. For MOVit we developed two different clutching methods.

In the *Squeeze Clutch* method users couple the movement of the arms with the movement of the wheels by squeezing the handle (measured with the pressure sensor) to activate a "virtual clutch". To go forward the user needs to move the arms forward while squeezing the handle and move the arms back without squeezing the handle, and to go backwards the handle needs to be squeezed while moving the arm support backwards. Each arm support controls the movement of its corresponding wheel. To turn, the user needs to move one of the arms faster than the other, and to spin in place the user needs to move the arms in opposite directions while properly activating each clutch out of phase. In the *Height Clutch* method users couple the movement of the arms with the movement of the wheels by moving their arms above a certain height to activate the "virtual clutch". To go forward the user needs to move the arms forward when they are above the threshold height and move the arms back when they are below the threshold height, following a circular pattern. To drive backwards the user needs to perform the same circular pattern but in the opposite direction. To turn, the user needs to move one of the arms faster than the other, and to spin in place the user needs to squeeze the handle of the side he wants to turn to and move the arm of the other side in a circular motion. In this control method, we made the turning radius proportional to the squeezing pressure (i.e. high squeezing pressure results in a small turning radius). The details of both control methods are described in Fig. 3.

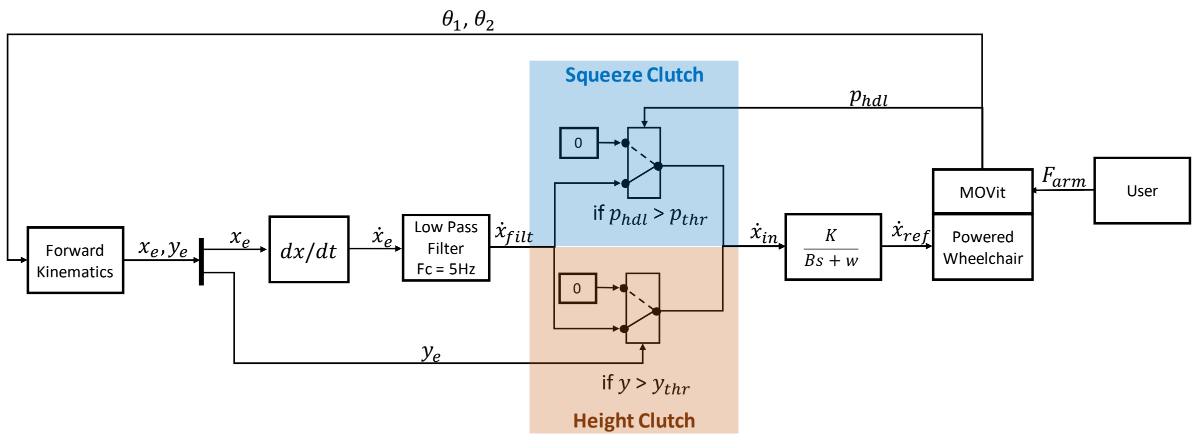

Figure 3. Diagram of the Squeeze and Height Clutch control methods. The user moves the mobile arm support of MOVit (θ_1 *and* θ_2) by applying a force (F_{arm}). The end-point position of the arm support (i.e. the handle, x_e, y_e) is estimated using the forward kinematics equations. The endpoint horizontal velocity $\dot{x}_e$ is filtered with a low pass filter (1st order Butterworth filter with 5 Hz cut-off frequency) to remove high frequency noise. In the case of the Squeeze Clutch the resulting filtered velocity ($\dot{x}_{filt}$) is gated if the pressure measured at the handle (p_{hdl}) is larger than the threshold pressure p_{thr}. For the Height Clutch the resulting filtered velocity ($\dot{x}_{filt}$) is gated if the vertical position (y_e) is larger than the threshold height y_{thr}. We refer to this conditional gate as the "virtual clutch". If the clutch is activated, the velocity $\dot{x}_{in}$ goes through a 1st order low pass filter with Fc = 0.19 Hz which outputs a reference velocity that is sent to the low-level controller of the powered wheelchair.

3 METHODS

The study was divided into three parts. First, we wanted to compare the driving performance of the three control methods (i.e. Squeeze Clutch, Height Clutch, and Standard Joystick), both in virtual driving and in real driving. Subjects were randomized to one of the control methods and drove a square track and a U-shaped track in a virtual environment, and also drove U-shape track in reality. Second, we wanted to evaluate the effect of providing vibrotactile feedback that gives information about the right timing to clutch. This was evaluated while driving the virtual square track. Last, we wanted to evaluate the long-term learning retention across the two days of the experiment.

3.1 Participants

A total of 24 unimpaired healthy participants novice to all three control methods were involved in this study. These 24 participants were randomly divided into three groups: 8 people tested the Squeeze Clutch, 8 people tested the Height Clutch, and 8 people tested the Standard Joystick. All subjects provided informed consent to participate in this experiment, which was approved by the U.C. Irvine Institutional Review Board.

3.2 Experimental Task and Protocol

This study included 2 different tasks (i.e. Square Track and U-shaped Track) across 2 days. A diagram of the experimental protocol and an illustration of the tracks are shown in Figure 4.

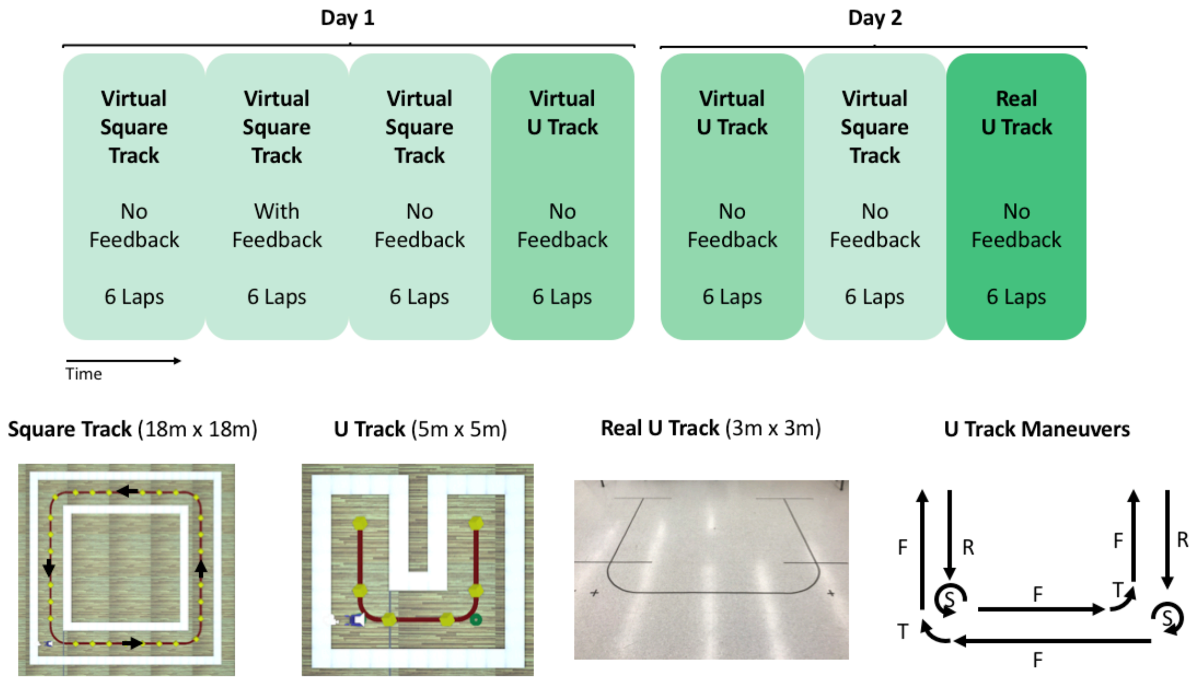

Figure 4. Top) Experimental protocol. The experiment takes two days. In the first day, participants performed 3 sets (6 laps/set) of driving around the Square Track in Virtual Driving, followed by 1 set (6 laps) of driving around the U Track. During the second day, participants performed two sets of Virtual Driving (U track and Square track), then they drove 6 laps of the U Track in Real Driving. Bottom) Pictures of the for Square Track, U Track, and Real U Track. For every lap of Square Track, subjects would drive 4 forward straight lines and 4 left turn corners. For every lap of U Track or Real U Track, subjects would drive 4 forward straight lines (F), 2 backward straight lines (R), 1 left turn and 1 right turn (T), and 2 spin in the place (S).

The first day participants performed the driving tests using a 3D wheelchair simulator (Fig. 5 right). For the virtual driving, the powered wheelchair with MOVit mounted on it was stationary and located in front of a computer screen (Fig. 5 left). Frist, the participants watched a short video showing the basic instructions of how to control the movement of the wheelchair with the control method that they were going to use. Subjects were asked to drive three sets (6 laps/set) of the Square track. Each lap of Square track consisted of 4 straight lines (14 m long) and 4 corners (2 m radius). The tracks had red lines on the floor at the center of the corridor, as well as small cubes spread evenly along the red lines that indicated the optimal path. The instruction to the participants was "Follow the line and pick up cubes as fast as you can".

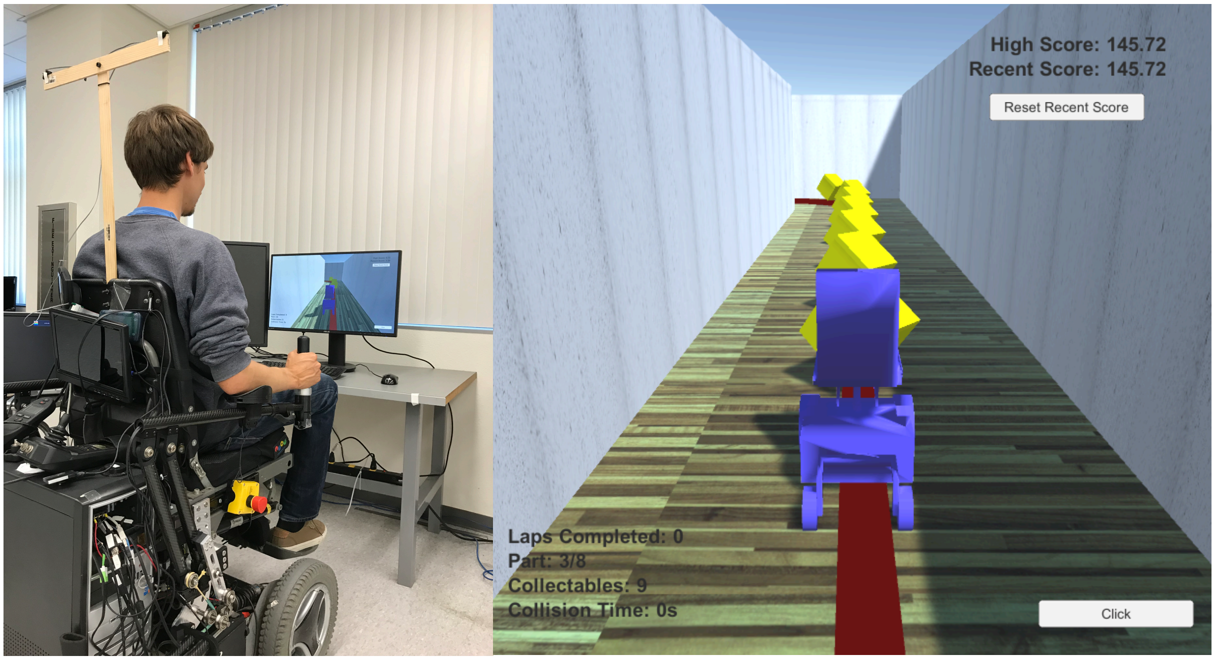

Figure 5. Left) Picture of the set-up for Virtual Driving. Wheelchair is stationary and in front of monitor. Right) Picture of the 3D wheelchair simulator shown in the monitor. There's red line on the floor at the middle of corridor, as well as cubes spread evenly along the red line showing the optimal path. The instruction is "Follow the line and pick up cubes as fast as you can."

The participants that were randomized into the Height and Squeeze Clutch groups received vibrotactile feedback on their thigh during the second set. For the Squeeze Clutch method, subjects received vibrotactile feedback when $\dot{x}_{filt}$ was positive. For the Height Clutch method subjects received vibrotactile feedback when y was higher than y_{thr}. During the first and third sets participants did not receive any vibrotactile feedback. Note that the joystick group did not receive feedback for any of the sections.

After the three sets of diving the virtual Square track, participants were asked to drive 6 laps following the virtual U-shaped track, which was used to test maneuverability.

The virtual U-shaped track was 3 m long with a radius of 1 m and included straight driving, reverse driving, 90 degrees left and right turns and spinning in place 270 degrees in both clockwise and counterclockwise directions.

The next day (day 2), participants came back to repeat the virtual U-shaped track and the Square track, and were also asked to drive the U-shaped track in reality. The real U-track was 2 m long and with a turning radius of 0.5 m and included the same maneuvers as the virtual track.

The maximum velocity of the Joystick control was matched to the maximum average velocity measured using the Squeeze Clutch control for both the virtual and real driving (max. velocity virtual driving: 2.8 m/s; max. velocity real driving: 0.9 m/s). Note that the dimension in the 3D wheelchair simulator was calibrated based on the size of the wheelchair. The speed in the simulator was chosen subjectively in order to mimic the driving experience of real driving, which resulted in a higher speed.

After each set of task, participants were asked to rate 8 statements (Shown in Table. 2) based on the task they just did. The score varied from 1 (i.e. I do not agree with the statement at all) to 7 (i.e. I agree with the statement very much).

ID	Topic	Statement
1	Competence	After this activity for a while, I felt pretty competent.
2	Performance Satisfaction	I'm satisfied with my performance from this task.
3	Difficulty	This task was hard to do.
4	Nervousness	I felt nervous doing this activity.
5	Exercise	I felt that I was doing exercise.
6	Soreness	I feel that my muscles are sore.
7	Comfort	I felt comfortable using this device.
8	Fatigue	How fatigue do you feel (1-10)

Table 2. Table of 8 statements that participants need to rate after every set of task. The rate score varies from 1 (i.e. I do not agree with the statement at all) to 7 (i.e. I agree with the statement very much). Each statement belongs to a topic that we are interested about.

3.3 Data Analysis and Statistics

Driving performance was evaluated using average speed, straight path error (average RMS error for the straight lines), corner path error (average root mean square error for corners), and path smoothness, which was measured using the Spectral Arc Length (SPARC) [16]. Arm movement performance was evaluated by clutch efficiency, range of motion and motion frequency (see Table 1). Clutch efficiency (CE) was used to evaluate if participants were activating the "virtual clutch" at the right time. It was calculated by taking the ratio between the sum of velocity gated through the clutch, and the sum of all positive velocity in a trial.

$$CE = \frac{\sum \dot{x} \cdot Clutch}{\sum \dot{x} > 0}$$

For the Squeeze Clutch, the clutch is activated when the handle pressure exceeds a threshold:

$$Clutch = \begin{cases} 1, if\ p_{hdl} > p_{thr} \\ 0, if\ p_{hdl} < p_{thr} \end{cases}$$

For the Height Clutch, the clutch is activated when the height of handle is above a threshold:

$$Clutch = \begin{cases} 1, if\ h_{hdl} > h_{thr} \\ 0, if\ h_{hdl} < h_{thr} \end{cases}$$

The threshold height was customized to each participant. They were asked to perform circular motions with their hands in a comfortable way and the position data from these circular motions was used to select the threshold height. The threshold pressure was about 25% of the maximum grip pressure.

The Driving Performance metrics were calculated from the path data of the wheelchair that was measured from the 3D wheelchair simulator for the virtual driving tasks, and from an active motion capture system (Impulse X2, PhaseSpace Inc.) with eight cameras and two markers mounted on the wheelchair for the real driving tasks.

Statistical analyses were carried out using R 3.5.0 [17] with *lme4: Fitting Linear Mixed-Effects Models* [18], *lmerTest: Tests in Linear Mixed Effects Models* [19], and *lsmeans: Least-Squares Means* [20], Distribution assumptions were examined throught inspection of q-q plots.

To compare the overall performance of three control group, a linear mixed effects analysis was conducted on all metrics shown in Table 1. We modeled *CONTROL METHOD* as a fixed effect and used an error term with random intercepts grouped by *SUBJECT* and *TRIAL*.

To evaluate the retention of driving skills (i.e. from day 1 to day 2), a linear fixed effect analysis was conducted on all metrics of Squeeze Clutch group and Height Clutch group. We selected *CONTROL METHOD*, DAY, and their interaction to be the fixed effects. The error term included random intercepts grouped by *SUBJECT* and *TRIAL*.

One-way repeated measures ANOVAs were used to compare the performance scores for all the metrics. Wilcoxon signed-rank test, Tukey and Bonferroni tests were applied for pairwise comparison. We used $\alpha = 0.05$ as the level of significance.

	Metric	Description / Formula
Driving Performance	Average Speed	Actual path length divided by the time spent
	Straight Path Error	Average root mean square error for straight lines
	Path Smoothness	Measured by Spectral Arc Length (SPARC)
	Corner Path Error	Average root mean square error for corners
Arm Movement Performance	Clutch Efficiency	Calculated by taking the ratio between the sum of velocity gated through clutch, and the sum of all positive velocity in one trial
	Range of Motion	Average arm movement distance on horizontal axis
	Motion Frequency	Average arm movement frequency on horizontal axis

Table 1. Driving Performance and Arm Movement Performance metrics.

4 RESULTS

4.1 Overall Performance Analysis

Figure 6 shows path examples from three subjects in the second day driving along the Square track, U track, and Real U track. Each subject is from one of three control methods (i.e. Squeeze clutch, Height clutch, Joystick) separately. All subjects were able to complete all the driving tasks.

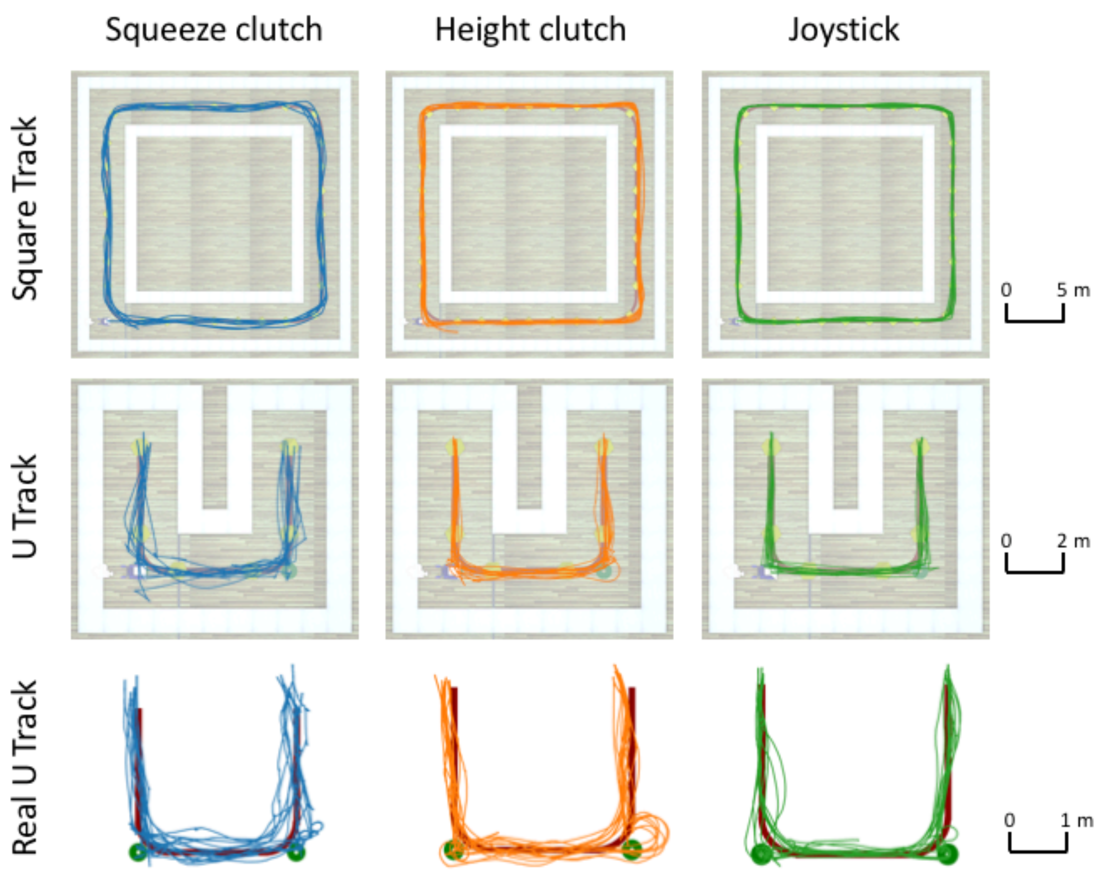

Figure 6. Example paths from three subjects driving Square track, U track, and Real U track. Each subject was from one of the three control methods (i.e. Squeeze clutch, Height clutch, Joystick) separately. The path in every track shown above is the overlap of the whole section (6 laps).

Figure 7 left column shows the bar plots for all the metrics of driving performance during the second day square track. We found significant differences in terms of average speed (ANOVA test, $p < 0.0001$) and path smoothness (ANOVA test, $p = 0.018$). The post-hoc analysis revealed that Joystick control group was significantly faster than the Squeeze clutch group in average speed (mean difference: 1.16 m/s, p-value < 0.0001) and more accurate in corner accuracy (mean difference: 0.08 m, p-value = 0.016). Also, Joystick control was significantly better than the Height clutch in corner path error (mean difference: 0.08 m, p-value = 0.016). Height clutch was significantly faster than Squeeze Clutch in average speed (mean difference: 0.33 m/s, p-value = 0.018).

Figure 7 middle column shows the bar plots for all the metrics of driving performance during the second day virtual U track. We found that three control methods were comparable in all metrics except average velocity (ANOVA test, p-value < 0.0001). The post-hoc analysis showed that Joystick was significantly faster than Squeeze Clutch in average speed (mean difference: 1.01 m/s, p-value < 0.0001), and significantly faster than height clutch in average speed (mean difference: 0.94 m/s, p-value < 0.0001).

Figure 7 right column shows the bar plots for all the metrics of driving performance during the second day Real U track. Note that the speeds were significantly slower during real driving because the gain for three control methods in real driving is smaller comparing to the gain in the virtual driving. We found significant differences in terms of average speed (ANOVA test, $p = 0.045$) and path accuracy (ANOVA test, $p = 0.003$). The post-hoc analysis showed that Joystick control was significantly faster than Squeeze Clutch in average speed (mean difference: 0.10 m/s, p-value = 0.047). In terms of straight path error, Joystick was also significantly smaller than Squeeze Clutch (mean difference: 0.01 m, p-value = 0.004) and significantly smaller than Height Clutch (mean difference: 0.01 m, p-value = 0.040).

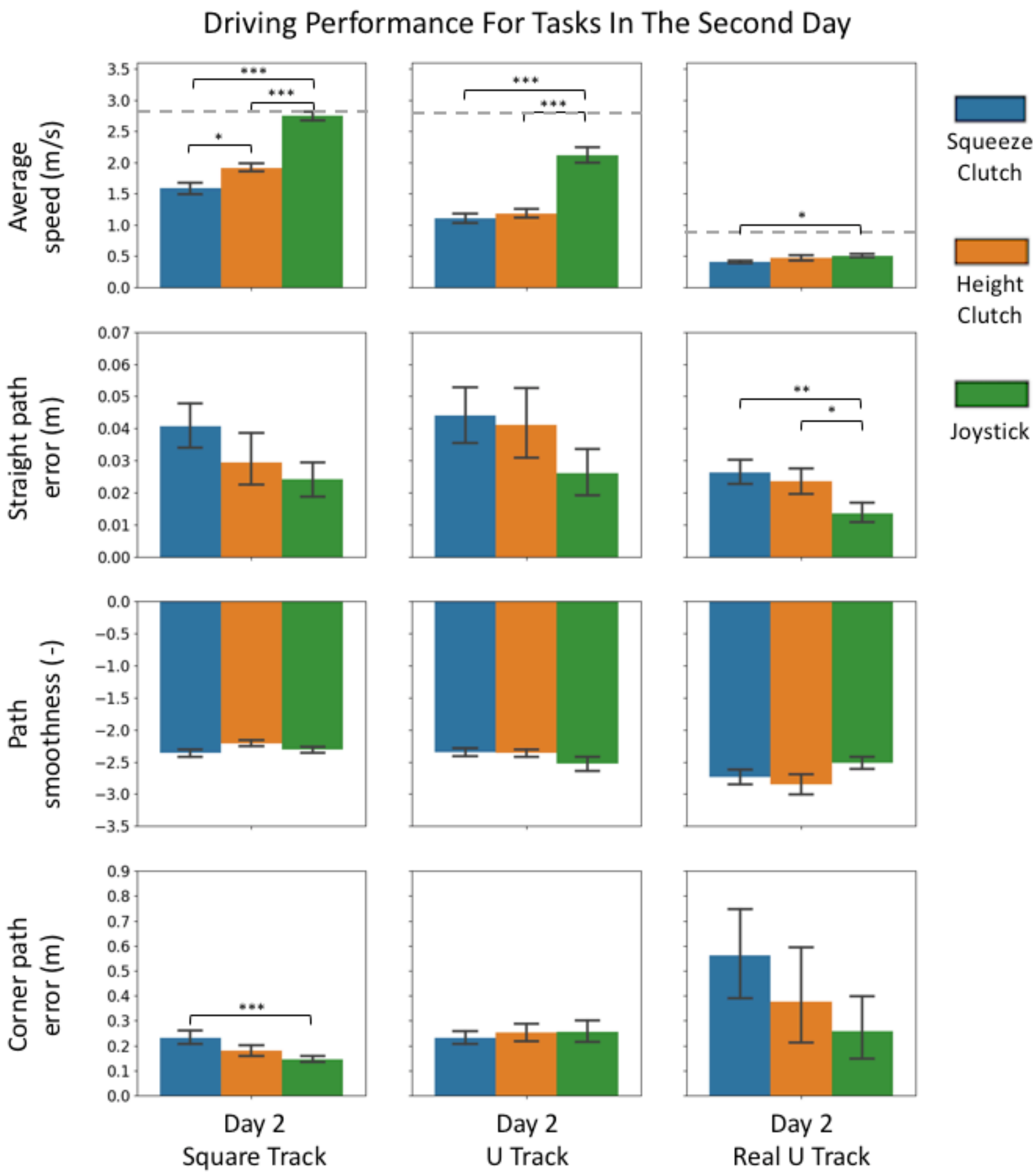

Figure 7. Box plots for metrics of Driving Performance during the second day. Left, middle, and right column represent for Square track, U track, and Real U track separately. Note that in the plot of average speed, the dashed lines represent the maximum speed (2.8 m/s in virtual driving and 0.9 m/s in real driving). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.0001$

Figure 8 left shows the bar plots for all metrics of arm movement performance. Left column, middle column and right column represent second day Square track, second day U track, and second day Real U track separately. We found that in all three tracks, Squeeze Clutch and Height Clutch were comparable in range of motion and motion frequency, and they were significantly different in clutch efficiency (ANOVA test, $p < 0.0001$ for Square track, $p = 0.0002$ for U track, and $p < 0.0001$ for Real U track). In second day Square track, Height Clutch was significantly higher than Squeeze Clutch in clutch efficiency (mean difference: 25%, $p < 0.0001$). In second day U track, Height Clutch was significantly higher than Squeeze Clutch in clutch efficiency (mean difference: 26%, $p = 0.0002$). In second day Real U track, Height Clutch was significantly higher than Squeeze Clutch in clutch (mean difference: 29%, $p < 0.0001$).

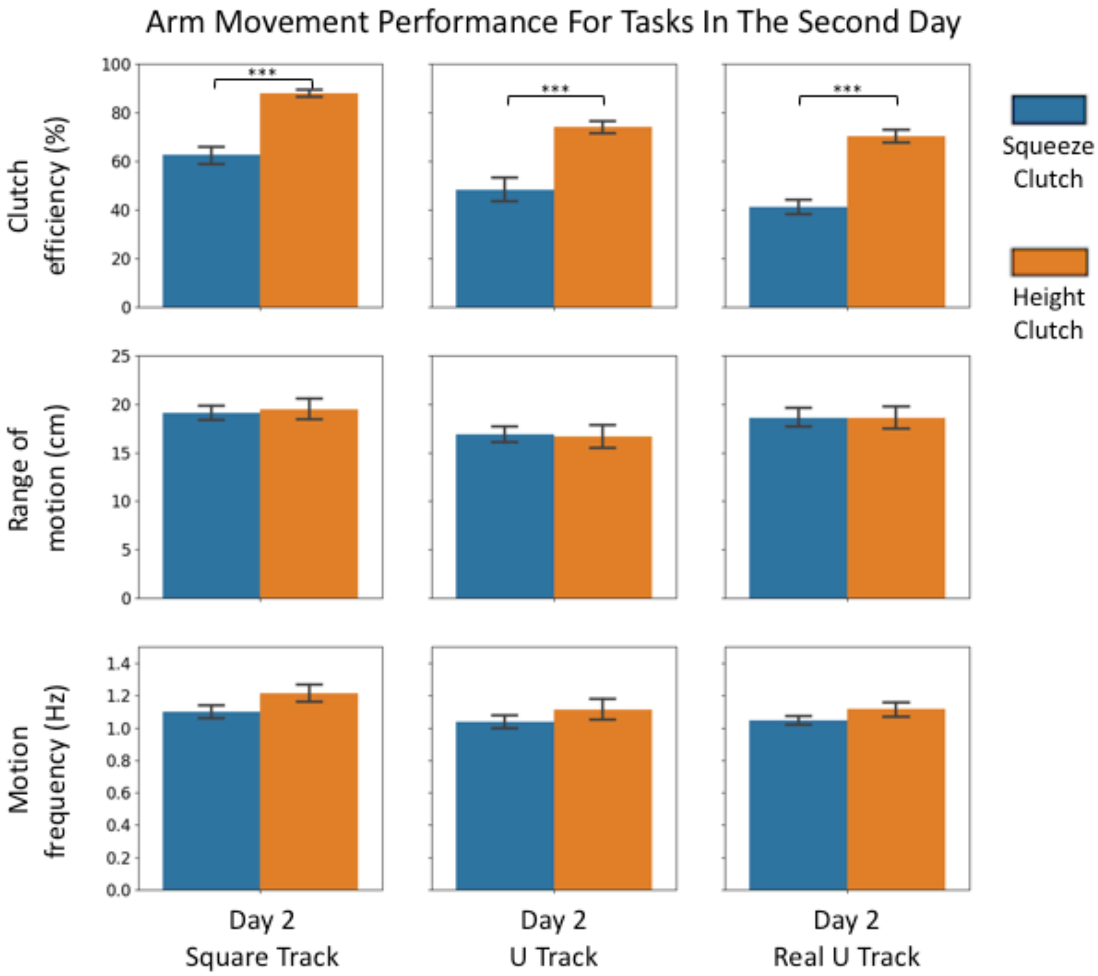

Figure 8. Box plots for metrics of Arm Movement Performance during the second day. Left, middle, and right column represent for Square track, U track, and Real U track separately.

4.2 Retention Analysis

Figure 9 left column shows the bar plots for all the metrics of driving performance during U tracks in the first day and the second day. We found significant differences in average velocity (ANOVA test, $p < 0.0001$), significant differences in straight path error (ANOVA test, $p < 0.0001$), significant differences in path smoothness (ANOVA test, $p < 0.0001$), and significant differences in corner path error (ANOVA test, $p = 0.017$). The post-hoc analysis revealed that Joystick became significantly faster in average speed (mean difference: 0.35 m/s, $p < 0.0001$), and significantly higher in path smoothness (mean difference: 0.31, $p < 0.0001$) than the previous day. Height Clutch became significantly smaller in terms of straight path error (mean difference: 0.03 m, $p < 0.0001$), and significantly smaller in corner path error (mean difference: 0.06, $p = 0.017$) than the previous day. Squeeze Clutch became significantly smaller in straight path error (mean difference: 0.01 m, $p = 0.035$) than the previous day.

Figure 9 right column shows the bar plots for all the metrics of arm movement performance during U tracks in the first day and the second day. We found significant differences in motion frequency when comparing the second day with the first day (ANOVA test, $p = 0.0004$). The post-hoc analysis revealed that Squeeze Clutch was significantly higher in motion frequency than the first day (mean difference: 0.05 Hz, $p = 0.008$).

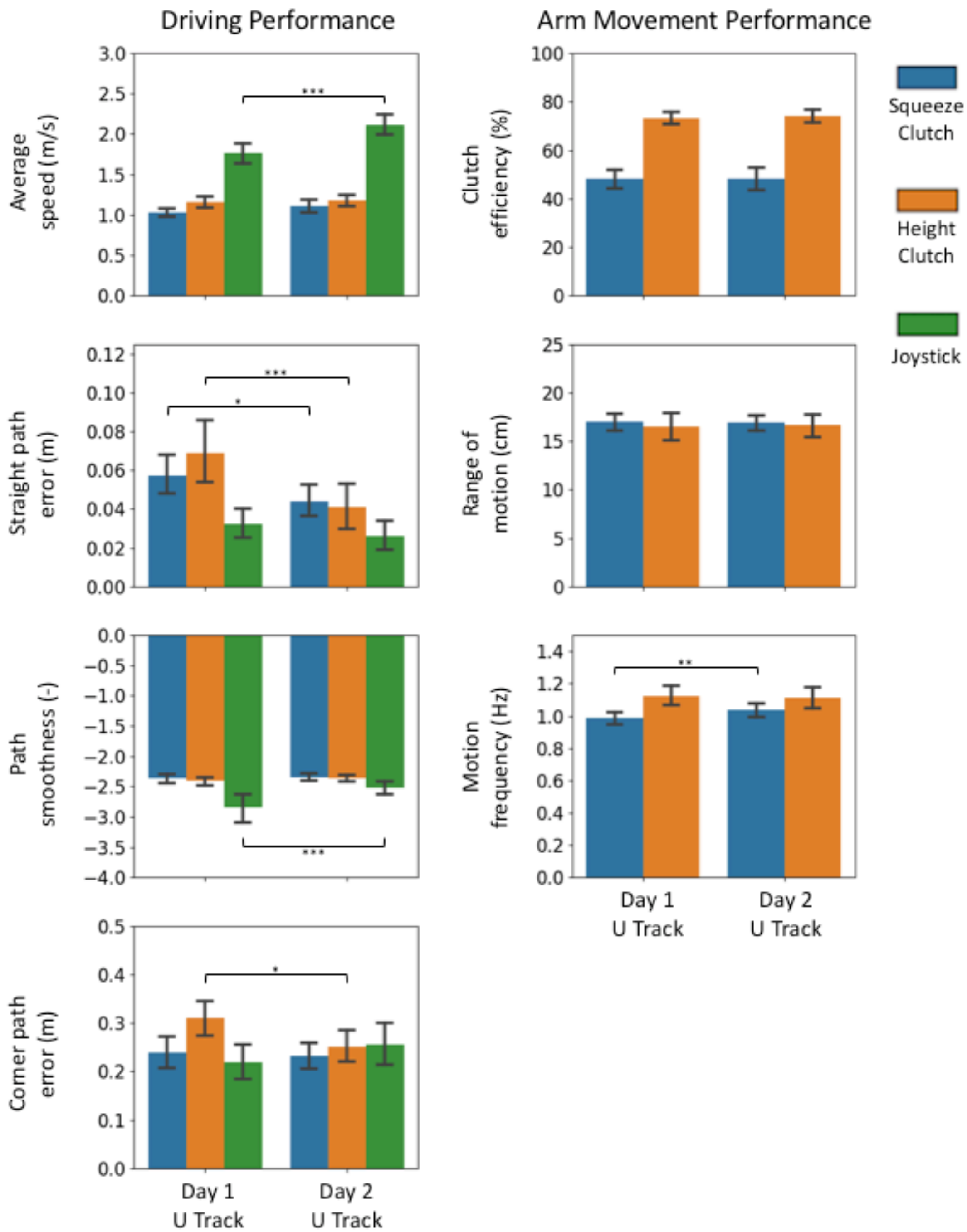

Figure 9. Left) Box plots for metrics of Driving Performance for the first day U track and the second day U track. Right) Box plots for metrics of Arm Movement Performance for the first day U track and the second day U track.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.0001$

4.3 Learning Curve Comparison

Figure 10 left column shows all metrics of driving performance for the three sections of Square track in the first day. Every section contained 6 laps and they are separated by red dashed lines shown in the figure. The solid lines represent the mean of scores, while the shaded areas represent the standard deviation. We found that for all three control methods, average speed and path smoothness tended to increase during the first section of Square track, while straight path error and corner path error tended to decrease. Then for squeeze clutch and height clutch, there seemed to be a small "jump" at the beginning of the second section. The performance of all three control methods were similar when comparing the second section with the third section.

For each section of Square track, we fitted a linear regression for each subject based on Linear Mixed Effect model, where we used the slope of the regression to indicate the learning rate. During the first set of Square track, we found that Height Clutch was significantly larger in terms of learning rate comparing to Squeeze Clutch in path smoothness (Wilcoxon test, $p = 0.002$). Height Clutch was also larger in learning rate comparing to Joystick in path smoothness (Wilcoxon test, $p = 0.015$).

Figure 11 left column shows all metrics of arm movement performance for the three sections of Square track in the first day. We found that during the first section of Square track, Squeeze clutch had a larger learning rate in terms of range of motion comparing to Height Clutch (Wilcoxon test, $p = 0.028$).

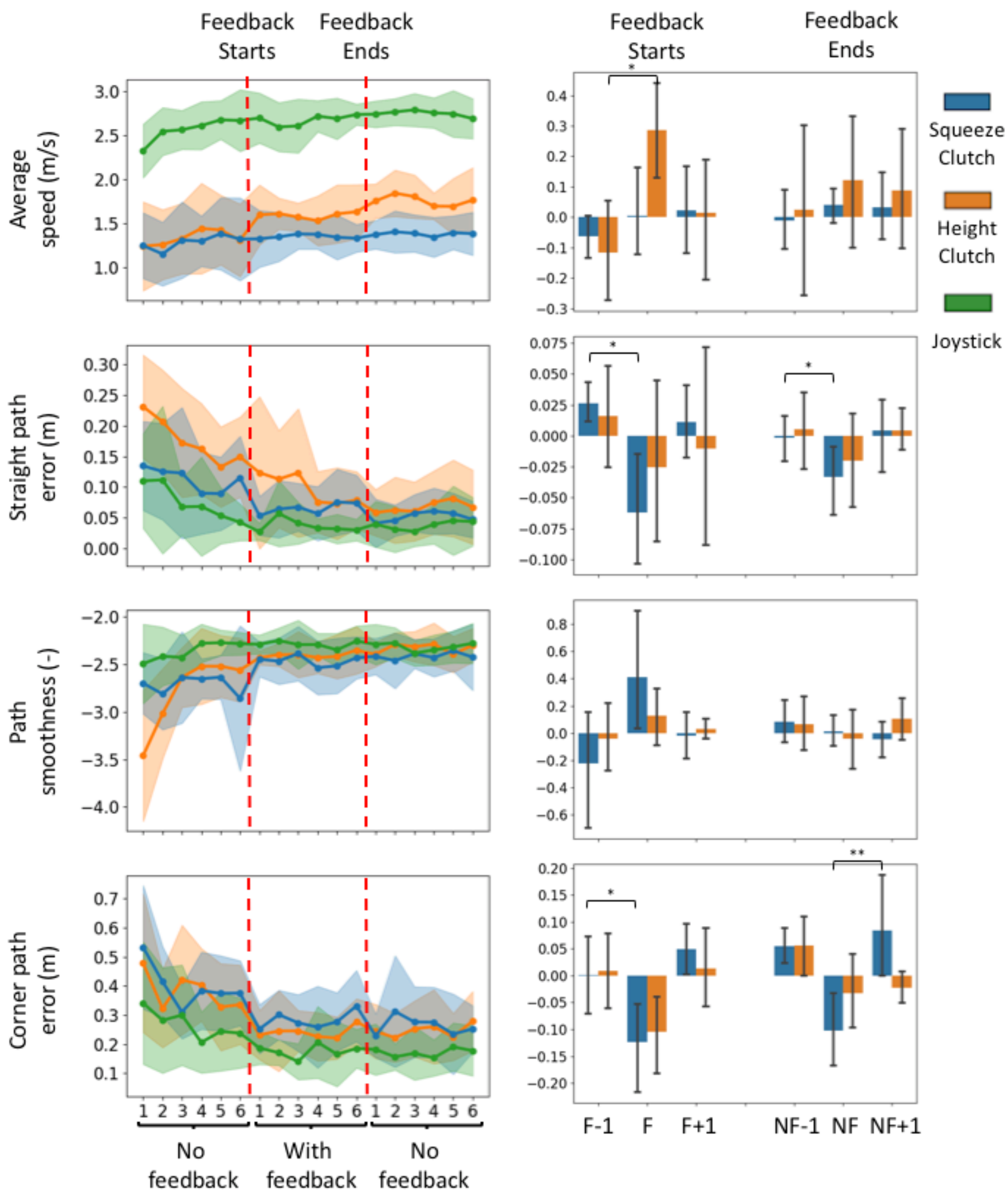

Figure 10. Left) Driving Performance metrics for the three sections of Square track (shown are mean +/- 1 SD). Each section (6 laps) are separated by dashed line. The solid lines represent for the mean of scores, while the shaded areas represent for the standard deviation. We added feedback during the second section and we removed feedback during the third section. Right) Box plots of Driving Performance metrics for learning amount (the score at some certain lap minus the score of previous lap) at 6 laps: the lap right before we added feedback (F-1), the lap we just added feedback (F), the lap right after we added feedback (F+1), the lap right before we removed feedback (NF-1), the lap we just removed feedback (NF), and the lap right after we removed feedback (NF+1). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.0001$

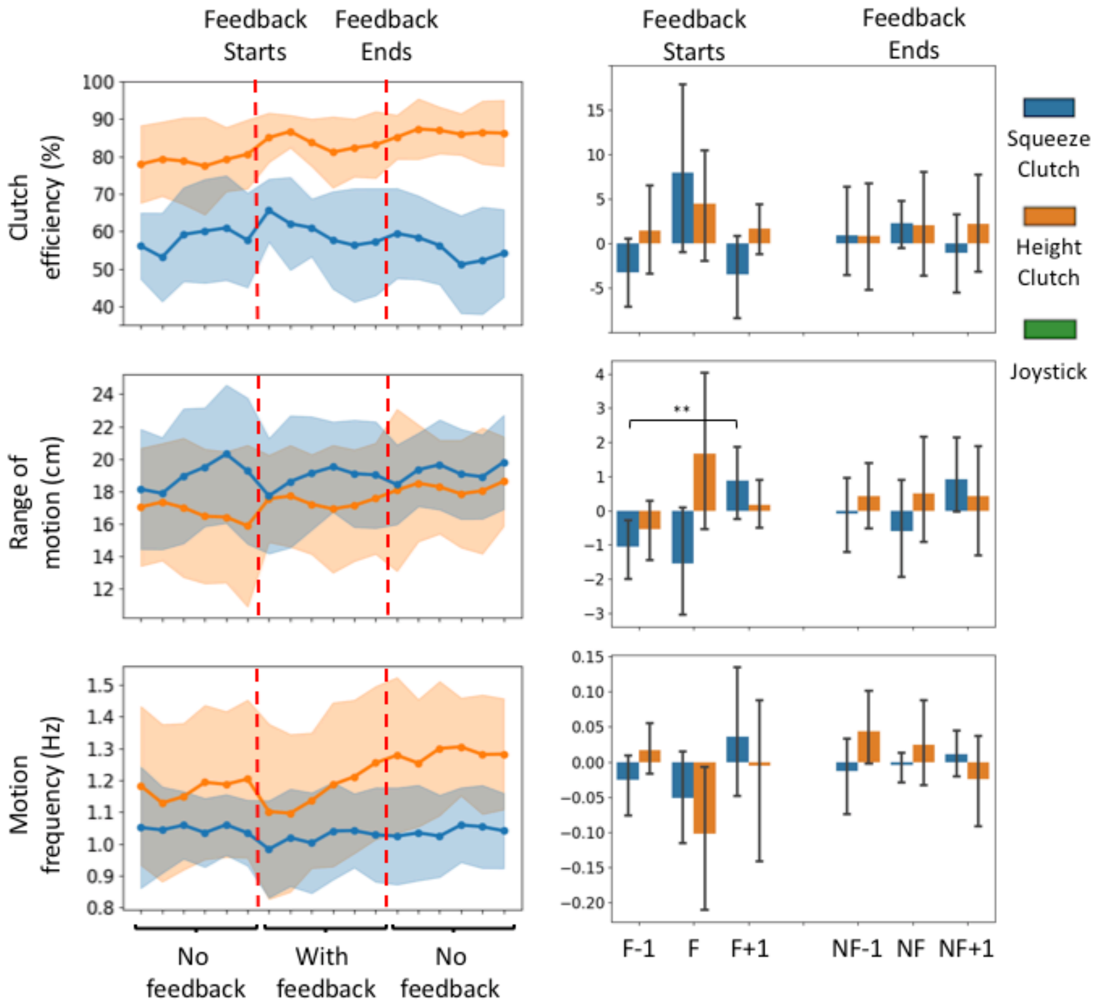

Figure 11. Left) Arm Movement Performance metrics for the three sections of Square track (shown are mean +/- 1 SD). Each section (6 laps) are separated by dashed line. The solid lines represent for the mean of scores, while the shaded areas represent for the standard deviation. We added feedback during the second section and we removed feedback during the third section. Right) Box plots of Arm Movement Performance metrics for learning amount (the score at some certain lap minus the score of previous lap) at the position of 6 laps: the lap right before we added feedback (F-1), the lap we just added feedback (F), the lap right after we added feedback (F+1), the lap right before we removed feedback (NF-1), the lap we just removed feedback (NF), and the lap right after we removed feedback (NF+1).
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.0001$

4.4 Effect of Vibrotactile Clutch Feedback Analysis

The left part of Figure 10 right column shows the learning amount (the score at some certain lap minus the score of previous lap) for driving performance metrics at three laps: the lap (F-1) right before we added feedback (the last lap of the first section), the lap (F) when we added feedback (the beginning of the second section), and the lap (F+1) after that (the second lap of the second section). The right part of Figure X right column shows the learning amount at three laps: the lap (NF-1) right before we removed feedback (the last lap of the second section), the lap (NF) when we removed feedback (the beginning of the third section), and the lap (NF+1) after that (the second lap of the third section). We found that Height Clutch became significantly higher in terms of velocity when we added feedback (Wilcoxon test, $p = 0.023$). For Squeeze Clutch, straight line error became significantly lower when we added feedback (Wilcoxon test, $p = 0.039$) and when we removed feedback (Wilcoxon test, $p = 0.039$). Also, in terms of corner path error, Squeeze Clutch was significantly lower when we added feedback (Wilcoxon test, $p = 0.008$) and when after we removed feedback (Wilcoxon test, $p = 0.023$).

Figure 11 right column shows the learning amount for arm movement performance when we added feedback and when we removed feedback. We found that Squeeze Clutch was significantly larger in range of motion comparing the second lap when we added feedback with the lap right before we added feedback (Wilcoxon test, $p = 0.015$).

4.5 Questionnaire Analysis

Figure 12 shows the rate scores for all 8 statements. The statistics need to be further analyzed.

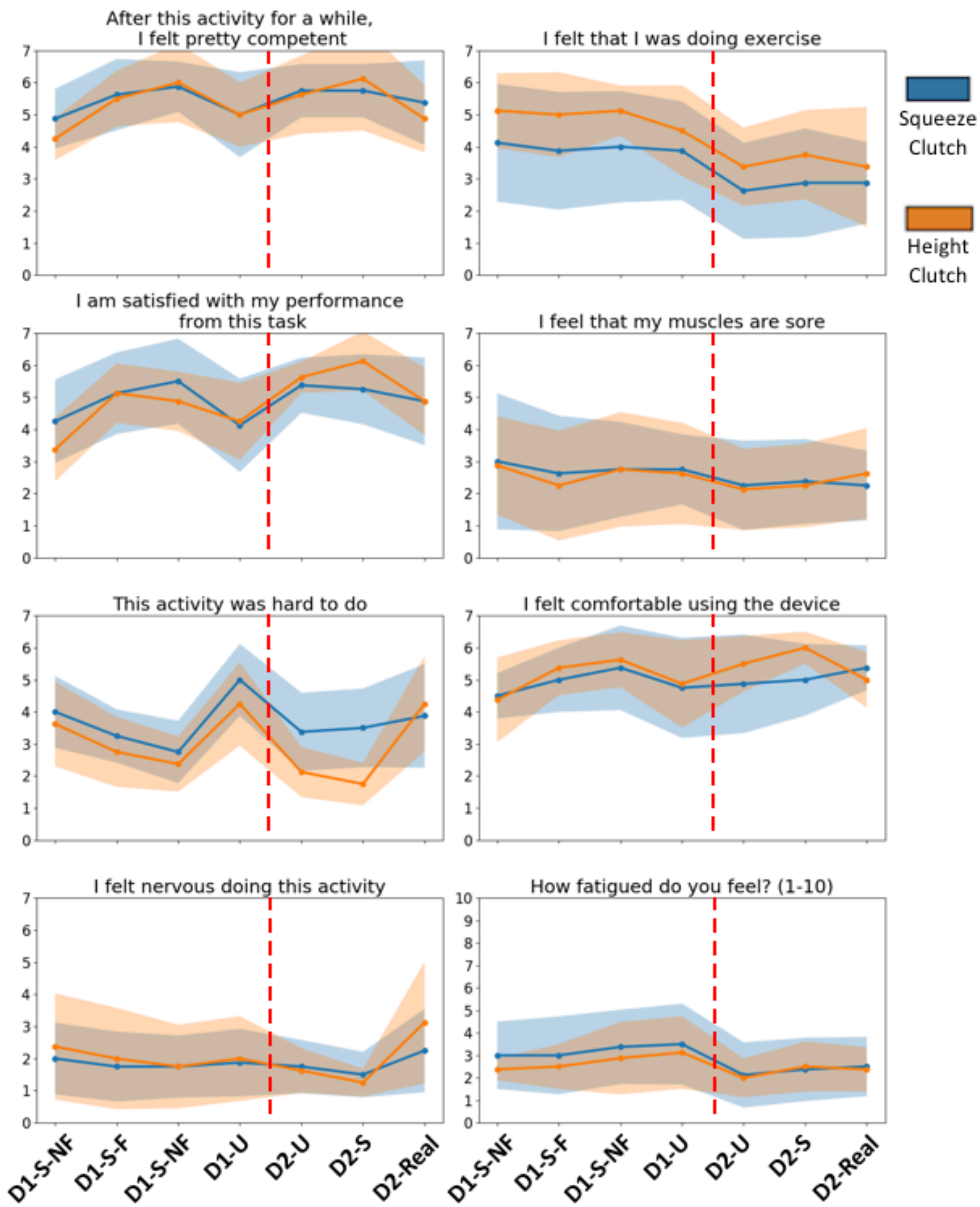

Figure 12. Rate scores of 8 statements for all tasks (shown are mean +/- 1SD). The rate score varies from 1 (i.e. I do not agree with the statement at all) to 7 (i.e. I agree with the statement very much). The sequence of tasks is: the first day Square track with no feedback, with feedback, with no feedback (D1-S-NF, D1-S-F, D1-S-NF), the first day U track (D1-U), the second day U track (D2-U), the second day Square track (D2-S), and the second day Real U Track (D2-Real).

5 DISCUSSION

5.1 The Driving Performance of Height and Squeeze Clutch is Comparable to the Joystick Control

The results of the driving performance analysis showed that the participants drove faster in the virtual training environment with the Joystick control method (double the speed of Squeeze and Height Clutch), as well as more accurately. The higher speed with the Joystick control method was almost certainly due in part to the way we set the speed gain: for both the Squeeze and Height Clutch we chose the speed gain such that the chair moved at the maximum possible speed of the Joystick method when subjects moved their arms as fast as possible. Subjects chose not to move their arms as fast as possible while learning to drive with the Squeeze and Height Clutch methods. Nevertheless, subjects who used Joystick control was also more accurate, even though they drove twice as fast, highlighting the intuitive nature of this established control technique relative to the clutching methods.

However, after training in the virtual environment, with the same speed gain between Joystick and two control methods, the driving performance of the Height and Squeeze Clutch control in the real U-track was comparable to the Joystick control. Note that the differences in speed and accuracy, while sometimes statistically significant, were small (mean speed difference: 0.1 m/s; mean path error: 0.01 m).

We found that the average speed of Joystick control drops significantly from the maximum speed compared to the performance during virtual driving. This might because the dynamics of the wheelchair leads to a slower acceleration due to the short path length in reality. This might also because subjects tended to drive more cautious in reality.

We also found that the driving performance between the Squeeze and the Height Clutch control methods were comparable, with the Height Clutch control method showing marginally better performance in terms of average speed (mean speed difference virtual square track: 0.33 m/s) and clutch efficiency (mean clutch efficiency difference: 27%).

5.2 Joystick is More Intuitive

The results of the learning rate analysis indicated that the Joystick control required a comparable amount of practice to reach the performance plateau compared to the Squeeze and Height Clutch control methods. However, Joystick control showed a relatively better performance during their first task (the first 6 laps of Square track during the first day), which implies Joystick control had a better performance baseline. This result suggests that joystick control is more intuitive to use.

5.3 Providing Feedback on Clutch Timing has a Marginal Performance Increase

The results of the feedback effect showed that the vibrotactile feedback that the subjects received on clutch timing resulted in a significant, yet marginal performance increase for most of the performance metrics (average speed, straight line error, corner path error). Removing the feedback did not show a significant reduction of the performance.

5.4 High Motor Learning Retention

The comparison of the driving performance in day 1 and day 2 for the virtual U-shaped track showed that subjects had a good retention. We found that all the performance metrics of Day 2 were similar if not better than the ones measured on Day 1.

5.5 Driving Abilities Learned in the 3D Simulator Transfer to Real Driving

Several studies have found that virtual driving simulators can be used to train people and supplement real-world training [21], [22]. In accordance with literature, we found that the motor skills learned in the 3D wheelchair simulator were transferred to the real driving.

5.6 Limitations of This Work

The experimental protocol is not perfect for testing the effect of vibrotactile feedback to learning, since the performance during feedback (the second set of Square track during day 1) is contaminated by the previous learning (the first set of Square track during day 1). Ideally, we need to have two groups of subjects, where one group receive the feedback from beginning and the other group do not receive feedback at all.

Also, the 3D wheelchair simulator is not exactly the same as real driving (e.g. the speed and the dynamics of the wheelchair). This could be improved further in order to align virtual driving with real driving.

5.7 Future Work

Future studies will include testing the feasibility of MOVit with powered wheelchair users. We also plan to improve the kinematic structure of MOVit in a way that it can be adjusted to different body sizes. Finally, we are considering the option to incorporate actuators in series with the springs used for weight balancing of MOVit to provide assistance or resistance to the user.

6 CONCLUSIONS

This dissertation has presented the design and control of MOVit, a novel exercise-enabling driving interface for powered wheelchair users. Using the Height or the Squeeze Clutch control methods the user is able to control the direction and speed of the wheelchair while exercising his arms with cyclical motions. We evaluated the driving performance of the three control methods using a set of driving tests that were performed in a 3D wheelchair simulator and on a real driving track. The driving performance using MOVit (either with Squeeze and or Height Clutch control) was comparable to that with Joystick control. We also found that the driving abilities had a good retention and were transferable from the virtual environment to the real environment. Finally, we found that providing vibrotactile feedback to the users on the clutch timing had a minor benefit. In conclusion, we have demonstrated that MOVit can be used as an alternative control interface that allows for powered wheelchair users to exercise while driving.

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8 APPENDIX

TASK EVALUATION QUESTIONNAIRE

For each of the following statements, please indicate how true it is for you, using the following scale:

1	2	3	4	5	6	7
Not at all			Somewhat true			Very true

Day 1:

Square track with no feedback

1. After working at this activity for a while, I felt pretty competent. _______
2. I am satisfied with my performance at this task. _______
3. This activity was hard to do. __________
4. I felt nervous doing this activity. _______
5. I felt that I was doing exercise. ________
6. I feel that my muscles are sore. _______
7. I felt comfortable using the device. ___________
8. How fatigued do you feel? Rate 1 to 10: ______

Square track with feedback

1. After working at this activity for a while, I felt pretty competent. _______
2. I am satisfied with my performance at this task. _______
3. This activity was hard to do. __________
4. I felt nervous doing this activity. _______
5. I felt that I was doing exercise. ________
6. I feel that my muscles are sore. _______
7. I felt comfortable using the device. ___________
8. How fatigued do you feel? Rate 1 to 10: ______

Square track with no feedback again

1. After working at this activity for a while, I felt pretty competent. _______
2. I am satisfied with my performance at this task. _______
3. This activity was hard to do. __________
4. I felt nervous doing this activity. _______
5. I felt that I was doing exercise. ________
6. I feel that my muscles are sore. _______
7. I felt comfortable using the device. ___________
8. How fatigued do you feel? Rate 1 to 10: ______

For each of the following statements, please indicate how true it is for you, using the following scale:

1	2	3	4	5	6	7
Not at all			Somewhat true			Very true

U shape track

1. After working at this activity for a while, I felt pretty competent. _______
2. I am satisfied with my performance at this task. _______
3. This activity was hard to do. __________
4. I felt nervous doing this activity. _______
5. I felt that I was doing exercise. ________
6. I feel that my muscles are sore. _______
7. I felt comfortable using the device. ___________
8. How fatigued do you feel? Rate 1 to 10: ______

General Comments:

TASK EVALUATION QUESTIONNAIRE

For each of the following statements, please indicate how true it is for you, using the following scale:

1	2	3	4	5	6	7
Not at all			Somewhat true			Very true

Day 2:

U shape track

1. After working at this activity for a while, I felt pretty competent. _______
2. I am satisfied with my performance at this task. _______
3. This activity was hard to do. __________
4. I felt nervous doing this activity. _______
5. I felt that I was doing exercise. ________
6. I feel that my muscles are sore. _______
7. I felt comfortable using the device. ___________
8. How fatigued do you feel? Rate 1 to 10: ______

Square track

1. After working at this activity for a while, I felt pretty competent. _______
2. I am satisfied with my performance at this task. _______
3. This activity was hard to do. __________
4. I felt nervous doing this activity. _______
5. I felt that I was doing exercise. ________
6. I feel that my muscles are sore. _______
7. I felt comfortable using the device. ___________
8. How fatigued do you feel? Rate 1 to 10: ______

Real driving

1. After working at this activity for a while, I felt pretty competent. _______
2. I am satisfied with my performance at this task. _______
3. This activity was hard to do. __________
4. I felt nervous doing this activity. _______
5. I felt that I was doing exercise. ________
6. I feel that my muscles are sore. _______
7. I felt comfortable using the device. ___________
8. How fatigued do you feel? Rate 1 to 10: ______

Over all

1. This activity was fun to do. ____
2. I prefer this interface more than a standard joystick to drive a wheelchair. _____

General Comments: